Temporary condition of reinforcement cages prior to concreting:
Part 2 (technical guidance)

Published – November 2022

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Document: TWf2021: 01
Corrigendum No. 2, April 2023 (pg.12,13,14, 95, 118)

NOTE: If you need to print this document, be aware that the pages are prepared with alternate (even) pages offset for your duplex (double sided) printing.

Temporary Works forum

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Thanks

Particular thanks are due to the following:

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Connor McHugh, Lee Martens and Mihai Chelmus (Swantest) – Testing
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Synopsis

Prior to being encased in concrete a reinforcement cage should be considered as an item of temporary works. This guide ('Part 2') has been produced to supplement 'Part 1' (Ref. TWf2020: 03) by providing further detailed engineering explanation of the issues involved. It also provides design guidance for cages assembled in their final position on site and those pre-fabricated and requiring lifting, transporting and positioning in their final position.

Notes

The working group recognises that some photographs may show breaches of current safety regulations, but the photographs have been retained in the guide to illustrate particular items of interest.

At various points in this guide, formal design processes are recommended. This recommendation is made despite the inexact nature of design in the subject area of this document. Experience is thus a pre-requisite and any designer new to design for temporary stability of reinforcement is urged to seek expert advice.

Disclaimer

Corrigendum No.1, January 2023 (pg.76)
Corrigendum No. 2, April 2023 (pg.12,13,14, 95,118)

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1.0 Terminology

1.1 The following terms are used within this guidance:

Bespoke

Custom made (non-proprietary) product.

Buildability / constructability

Both terms are commonly used and relate to good design and good detailing and should consider safety, speed and ease of assembly, cost effectiveness, modularisation for easy repetition, speed and ease of removal and minimising waste by making use of available resources. The construction process should be reviewed to ensure buildability has been considered.

Captive bar

In relation to lifting cages, a bar that is enclosed by other bars within the body of cage and is not the outermost bar of a cage (the bar is 'captive' within the cage and is unable to fall out of the cage).

Carrier bar

A bar that carries (supports) other bars. Carrier bars are part of the load-carrying system and form part of the defined load-path. Like 'set bars' they are usually tied at every intersection. Designers should nominate the location and spacing of carrier bars.

Competent person

A person who has acquired, through a combination of qualifications, training and experience, the knowledge and skill to perform the task required.

Cruciform connection

Two reinforcing bars positioned at right angles to each other and joined with tying wire.

Engineered connection

The connection of bars and framing members using engineered components, materials and design techniques that are well-defined and specified in design standards. For example: approved and controlled welding; bolted connections; bolted clamps with defined torque and bar couplers.

Factor of safety

Ratio of failure load to the maximum working load which gives the 'safe working load'.

Fixer

Steel fixing operative.

Framing bar

An individual bar forming part of the framing member. For example: a permanent works bar forming a chord within a truss or a temporary z-bar contributing to truss action. The connections between framing bars should be designed and specified to transfer loads.

Framing member

A universal term for load-carrying bars in flat mats, 2D and 3D frames within cage (mattress), contributing to explicit load-paths or the stiffening system within a cage. These are typically sacrificial temporary works introduced by the designer to make a cage rigid through truss action. The designer can also 'nominate' some of the permanent works bars, as framing members.

Link knuckle lapping point

The overlap position when a bar is bent to form a closed link.

Life cycle of cage

Consideration of the cage at all temporary works stages from assembly, transport, lifting, etc. until the cage is finally encased in concrete.

Load carrying system

Defined load path(s) with each component forming part of the load path (components include frames, trusses, carrier bars and their connections).

Multi-wrapped strong tie

Doubled wire wrapped multiple times around the bar connection; mainly used for lifting purposes or for high load points where there are no alternative load paths available.

Nips

Tool used in the UK by fixers for cutting and tying wire (see Figure 1).

NOTE: These may differ to those used in other countries.

Positional ties (as required by BS 7973-2)

Any form of single wire strand tie, to ensure position of a bar for quality purposes during concreting.

Positive support

Bar-to-bar contact in compression. Ties are essentially positional and are not expected to form part of a load path.

Proprietary

Owned by a private individual, business or corporation, typically under a trademark or patent.

Robust tying

Tying for designed structural robustness throughout the entire temporary works life cycle to ensure the cage remains stable and intact during its entire life cycle.

Figure 1: UK 'nips' as used by fixers for cutting and tying wire

Robustness

Ability of a structure to withstand unforeseen events without undue damage.

Safe working load (SWL)

The maximum allowable unfactored load that may be imposed on a given member, element, connection or structure. It is obtained by dividing the ultimate capacity with an appropriate factor of safety to allow for uncertainties, construction tolerance, etc.

Set bar

A bar tied at intersection with every intersecting bar. It 'sets' the intersecting bars in place, ensuring correct spacing and intended to keeping bars in correct position.

Statutory

A legal requirement and must be complied with.

Strong ties

Multi-strand and multi-wrapped wire ties. Examples include 4 strands of wire used to form one tie and 3 or 4 doubled wire slash ties at the same location.

Structural capacity

Ability of a member or structural element to resist the applied loads.

Structural robust ties

Always formed with **doubled wire** strands, 1.6 mm dia., 280 N/mm^2, or 1.2 mm stainless steel. Examples are doubled-wire crown ties, hairpin ties, looped hairpin, and splice ties. Single wire ties should not be used as structural ties.

NOTE: Ties are double-wire and have eight strands when cut

Supported bar

Bar that is supported by a carrier bar. Typically secured to a carrier bar by tying wire and the supported bar self-weight is imparted onto the load carrying system.

1.2 For simplicity, this document uses the following terminology:

Cage

Descriptive term used for reinforcement cage.

Designer

Descriptive term used for 'permanent works designer', 'principal designer', 'temporary works designer', 'specialist consultant' and 'reinforcement detailer' as all are involved in the design of cages as set out in the definition of "designer" within the Construction (Design and Management) Regulations 2015 (CDM2015).

Load

Descriptive terms for loads/actions that could be applied to a cage. Can include permanent (e.g. self-weight), imposed (e.g. live) and environmental (e.g. wind and impact).

Tying

Descriptive term used for joining/fixing reinforcing bars together using tying wire.

2.0 Introduction

2.1 Until a cage is encased in concrete it is a temporary structure made from vertical, longitudinal, diagonal and transverse bars which are generally connected with tying wire, though sometimes welded connections may be used. Tying wire does not contribute to the final strength of the reinforced concrete structure but plays an important part in cage stability prior to concreting. Cages can be pre-fabricated in workshops off-site (especially if welded intersections are preferred), pre-fabricated on-site and lifted into place or assembled in-situ. All these options are susceptible to inaccuracies and variations in workmanship to some extent.

2.2 Cages are a common feature on construction projects and on any single project they may be different sizes; some with complex geometries, with different bar diameters and assembled by operatives with different levels of competence. The engineering assessment of their temporary condition during assembly, transportation and lifting, prior to concreting, is commonly dealt with by 'custom-and-practice' as limited definitive guidance on these issues has been available. A large reinforcement cage can represent a considerable danger to those working on, adjacent to, or within it, should it buckle, collapse or fail during lifting. Collapses can cause death and injury along with financial loss. Cages periodically collapse through lack of strength or lateral instability; or a lack of cage robustness prior to it being fully stabilised through containment in concrete. Maintaining the overall shape of the element is an important consideration, as the stiffness comes from the connections between bars. As such, tying (i.e. where reinforcement bars meet/cross and are connected using wire) of the bars becomes critical, particularly if the cage is to be lifted. Tying is perhaps the greatest variable factor, and the strength of these tied joints can vary significantly. The tying of joints gives a cage strength and robustness which is vital for safety and this guidance considers this in detail and makes recommendations.

2.3 The increase in frequency of reinforcement cage collapses may be connected to changes in the way cages are assembled on-site (e.g. a declining use of purpose-designed access scaffolds in lieu of MEWPs); with a trend towards fixing taller cages with smaller diameter vertical bars (due to more refined analysis methodology) and an increase in pre-fabrication. Many designers do not appreciate the dangers involved, or that buckling of bars can occur suddenly and with little warning. Also, that cages built in-situ can become progressively less stable as work progresses; something that can be counter-intuitive. There is also a perception that the experience of operatives on-site is reducing, thereby putting a greater expectation on designers; even though most permanent works designers' contracts exclude temporary works design. Many permanent works designers (PWDs) adopt the position that temporary works and buildability are solely the responsibility of the contractor and, as a result, rarely consider the temporary condition of cages. This is not tenable under the Construction (Design and Management) Regulations 2015 [1], which put a statutory obligation on all designers to follow the 'principles of prevention' and produce cage designs that can withstand foreseeable loading at all stages before concreting, and can be built safely, or highlight the risk of potential instability. It is questionable how often and how rigorously this is carried out currently and hence there are a significant number of cage failures in the UK. It is not unusual for this to be left to the means and methods of the site team without consultation with the designer.

NOTE: Permanent works designers should liaise with contractors and temporary works designers (TWDs) to ensure the stability of cages at all stages in in life-cycle. To mitigate risks the permanent works designer should, where possible, detail the permanent works to suit the contractor's preferred method of working. The Principal Designer (PD) has an important role in coordinating this cooperation. Also, the stability of cages is not addressed in structural design codes as they focus on the final permanent state of the member.

2.4 Designers should assess the risks at each individual location to consider the positioning of construction joints (viz. the lapping of bars) and the stability of the cage to ensure that it remains stable and intact throughout its whole life cycle. Cage life cycle could include assembly, transportation, lifting, handling, turning, placing, installing temporary support measures, installing formwork and finally concreting. Designers are not expected to advise on risks for "normal situations" where a competent contractor is expected to manage any residual risks but should advise on unusual risks pertinent to the actual project. Any design assumptions should be clearly stated by the designer and information provided on how the assumptions are to be confirmed on site.

2.5 There are several possible contractual arrangements for the design of cages and their stability (all designers – whether permanent, temporary or specialist have the same CDM2015 duties):

- The contractor also acts as the cage designer (temporary works designer).
- The permanent works designer also acts as the cage designer.
- Third party acts as cage designer on behalf of one of the above parties (independent specialist consultant).

2.6 Contractual arrangements should clearly state responsibilities and ensure that the responsible party has sufficient experience in this field, with appropriate policies, procedures and insurances.

3.0 Scope and target audience

3.1 This guide applies to organisations and individuals involved in specifying, managing, designing, detailing, assembling, transporting, lifting and stabilising cages. It develops on the hazards and risks highlighted in Part 1 of this Guide [2] and the management recommendations made. It provides specific technical and design guidance to ensure stability and robustness and thus safety. It also provides further specific advice to the various parties involved in the process.

3.2 An extensive literature review has been carried out and the guide summarises and develops into a single document the available information and experience on this subject in the UK and further afield (including from industry and academia in the USA, Hong Kong, Australia and New Zealand).

3.3 Limited experimental and analytical investigations by academia and industry have been carried out to understand the lateral behaviour and stability of cages and ties. The Temporary Works Forum (TWf) have undertaken some testing on ties (Appendix A) and prepared a specification for on-site testing (Appendix B).

3.4 Conclusions and guidance are made, based on existing research, historic testing and new testing carried out by TWf. At various points in this guidance, formal design processes are recommended. The recommendations are made despite the inexact nature of design in the subject area and experience is thus a pre-requisite. At each individual location and during all stages in the life of the cage, stability should be considered, with a risk assessment carried out. Any designer new to design for the temporary stability of cages is urged to seek further expert advice. Some recommendations are also made on possible future research and development to help better understand the issues involved.

3.5 This guide reminds all ‘designers’ of their responsibilities under CDM2015 eliminate hazards where possible (using the principles of prevention), highlight residual risks with cages in the temporary condition and consider assembly sequences and ‘constructability’. It:

- provides guidance on “what good likes like” (what is inherently safe and does not require further design) and “what can become unstable” and requires further detailed consideration, analysis and design.
- provides guidance so that loading can be assessed, analysis and calculations can then be carried out to justify stability and a safe system of work.
- if stability cannot be justified, guidance is provided on different stability solutions.
- makes further recommendations on the division of responsibility between the parties involved (in addition to those made in Part 1 of this guide)
- provides example calculations.
- provides simplified checklists that can be used as an ‘aide memoire’ (see Appendix C and D).

Reference should also be made to the TWf’s Constructability: A guide to reducing temporary works [3].

3.6 This guidance considers pre-fabricated cages and those built in-situ and it provides further practical guidance for those involved in the assembly, transportation, lifting and rotation of cages to ensure robustness and safety.

3.7 Plastic, epoxy-coated and GRP reinforcing bars are outside the scope of this guidance.

3.8 Whilst this guidance mentions finite element analysis it does not cover this subject in any depth as there is significant further development required on this matter.

4.0 Overview of recommendations

4.1 This section provides a summary of the general recommendations made in this guidance and there are also specific recommendations made in each section:

a) Until encased in concrete the stability of cages should be considered as temporary works and their safety should be managed in accordance with BS 5975 [4] and Part 1 of this Guide [2].

b) There should be clear allocation of responsibility at all life-cycle stages (from design, assembly, transport, lifting, etc. through to concreting).

c) Site teams and fabricators should develop a better understanding (and recognition) of the hazards associated with the temporary condition of cages.

d) Designers (of cages) should develop a better understanding (and recognition) of the hazards associated with the temporary condition of cages (and follow the ‘principles of prevention’) and take greater responsibility for ensuring the safety and stability at all stages in the cage life cycle and minimising construction risks. Stability measures should be designed, and it should not be assumed that the risks can purely be managed adequately by the site team.

e) Designers (of cages) need to further develop a better understanding of 'buildability' issues and this may involve additional training, site visits, discussions with site teams / fabricators; supplemented with external specialist advice to ensure that a robust, buildable, cost effective and safe solution is provided.

f) Designers should follow the 'principles of prevention' (see Appendix E) for the temporary support and stability of cages by using the recommendations of this guidance, as follows:

   (i) Justify that the cage is stable during all stages in its life cycle without any additional measures, in which case no further design action is required.

   (ii) If the cage is potentially unstable, then re-design the whole cage, amend specific cage details (e.g. add extra bars) or amend the assembly methodology / sequence to provide stability (e.g. reduce cage heights by limiting individual pour heights or using precast concrete elements).

   (iii) If the cage cannot be redesigned or the methodology / sequence cannot be amended, then design additional independent stability measures (see Section 9.3).

g) Cage designers should clearly communicate 'non-standard' residual risks and sites should determine appropriate solutions to address these risks (e.g. where bars are to be installed in a particular sequence to maintain stability) and apply the designs correctly.

h) Cage designers should exercise engineering judgement and carry out analysis and design appropriate to the risk and complexity of the cage (see Table 7), i.e. simple conservative analysis/design for simple cages and more rigorous and complex analysis/design for complex cages in high-risk locations.

i) For high-risk and complex operations, inexperienced cage designers should seek expert advice and ensure that independent third-party design checking (BS 5975, Cat 3) is carried out, in combination with peer review by persons who are competent and experienced in this type of work. See BS 5975: 2019, Tables 1 and 2 [4] and Part 1 of this Guide [2].

j) Cage designers should follow the following generalised temporary works sequence:

   (i) Identify and eliminate (where possible using the 'principles of prevention') hazards and risks and consider the overall buildability. Consideration should be given to how the cage is likely to be constructed, e.g. assembled in-situ or pre-fabricated, transported and lifted into position.

   (ii) Determine loads / actions, and combinations, that may apply to the cage in its temporary condition.

   (iii) Carry out a structural analysis of the cage at the various stages in its life cycle, to justify stability at all stages. The analysis should be appropriate to the risks and complexity (see Table 7).

   (iv) Consider site constraints in detail and liaise with the site team (or external specialists) and fabricators to determine possible preferred solutions.

   (v) Liaise with site team if additional testing is appropriate and, if carried out, consider the test results.

   (vi) Design suitable solutions which could range from modifying the details of the cage to ensure stability or assembly sequence to designing external support measures. Use a conservative or less conservative design approach based on risk and whether any site testing has been carried out. Designs should be appropriately reviewed, checked and external approval (from stakeholders) may also be required.

   (vii) Provide detailed and unambiguous information to the assembly team. These may include assembly sequences, drawings, weights and centres of gravity for lifting cages, lifting points, BIM models, residual risks, assumptions made in the design, details of external support measures, etc.

   (viii) Review the proposals with the site teams responsible for assembling, transporting or lifting the cage to ensure the designs are 'buildable'.

   (ix) Ensure that when design assumptions are confirmed they do not adversely affect the design (i.e. integration and coordination of the temporary works design with the permanent works design).

   (x) Advise site (if requested and appropriate) on suitable measures to control 'unusual' residual risks.

   (xi) Respond to any requests for changes to the agreed design during the life cycle of the cage.

k) A clear distinction should be made between traditional **non-structural positional tying** of bars (used to simply keep bars securely in place during concreting operations) and **structural robust tying** of bars (where a design is necessary and double wire ties are used), used to transfer significant forces safely through the cage and prevent the cage from excessively deforming or collapsing (see Section 6). Slash ties are only suitable for **positional tying**. Whichever methodology is adopted for ties, the designer should always adopt a philosophy of "safety in numbers" and provide alternative load paths to allow for the possibility of some ties being ineffective.

l) Two methods can be adopted for structural robust tying of bars:

(i) **Method A** (see Section 6.2.1)

If site testing is not carried out (due to cost or time limitations) a conservative approach should be adopted for tie strength so that movement at the tied bar connections is negligible. This guidance recommends a tie SWL of **0.35 kN** is used for 1.6 mm black annealed wire for method A and 1.2 mm stainless steel wire. (The effect of the larger diameter of the 1.6 mm wire is cancelled out by the higher strength of the 1.2 mm stainless steel wire).

(ii) **Method B** (see Section 6.2.2)

This method requires ties to "do more" than in method A and it is assumed there is some stretch of ties which must be considered in the structural analysis as a small p-delta second order effect. If site testing is carried out, then quality standards for tying can be established on site and a less conservative approach may be adopted for tie strength. However, designers should carefully consider the consequences of greater displacement (i.e. establish realistic serviceability limits) at tie positions and provide alternative load paths to prevent 'un-zipping' of ties. This method should only be used by designers with relevant experience and should not be used if alternative load paths cannot be provided.

m) Operatives should not work inside a cage unless unavoidable and only if the stability of the cage (e.g. from collapse onto the operatives) can be assured and suitable safety measures (e.g. stability measures, safe access, emergency plan, etc.) are in place.

n) Hydraulic 'Tirfors' are not recommended to tension any guy wires used to stabilise cages.

o) Operatives should not climb on cages during assembly (alternative means of access should be provided) and safety exclusion zones should be established and enforced around the cage where possible.

p) For complex cages on congested sites, BIM models are useful to identify potential clashes and providing detailed assembly sequences.

q) Designers should set anticipated performance parameters (e.g. deflection) and site teams should monitor cages for potential instability and develop plans to recover the situation.

r) The safe working loads of ties recommended in this guidance are based on an analysis of tie testing results carried out on behalf of TWf (see Appendix A and B) and historic tests carried out by others.

s) There are recommendations on the minimum number of "twists" that a tie wire should have to ensure it is more likely to break rather than unwind during loading (see Section 6.0 and Figure 5).

5.0 Assessment of loads on cages

5(i) The loads applied to cages in their temporary condition need to be assessed, so that a realistic analysis can be carried out and appropriate stability solutions (if required) designed. Not all loads can occur at the same time and the designer should assess the most likely combination. Designers should exercise engineering judgement and consider the risks, complexity, timescale, and costs when determining how accurately to calculate loads. For relatively small simple cages, a quick conservative approach is likely to be adequate whereas for high-risk complex cages or operations, a more accurate methodology should be adopted. Designers should consider that the complex determination of loads is time-consuming and can be costly which can disproportionately out-weigh the cost of additional stability measures. A clear and detailed design brief is essential for a complex analysis to be carried out.

5(ii) The principal loads that a designer should consider are listed below (some may be static and some dynamic). The designer should determine the magnitude of each load, and which can occur in combination:

a) Self-weight of bars (see BS 4449 [5] and Table 1 for useful bar properties), any couplers and tying wire.

b) Self-weight of any temporary or permanent formers, spacers, proprietary splicing systems or restraint systems used to join or maintain the shape of the cage.

c) Self-weight of any cast in items or 'box outs' (often made from timber) which may be necessary for services or openings passing through the cage.

d) Self-weight of any instrumentation, cables, brackets or pipework (e.g. for base grouting of piles) or anything else inserted into the cage.

e) Possible accumulation of ice or snow. In exposed locations the influence of accumulation of ice on reinforcement should be considered. This includes the increased gravity loads due to ice self-weight and increased wind drag due to the ice deposit. See BS 5975 [4], BS EN 1993-3-1, Annex C [6] and ISO 12494 [7].

f) Wind loading (see Section 5.1), including second-order effects from additional deflection (see Section 8.1).

g) Live loading (see Section 5.2), representing the self-weight of operatives and any small tools used to place concrete and generally applied to horizontal mats (boards should be provided to prevent operatives having to walk directly on bars and to spread the load). In the UK, operatives are discouraged from climbing on wall cages during assembly; however, this is relatively common elsewhere (e.g. in North America).

h) Self-weight of any larger equipment used for placing (e.g. pump lines) or compacting concrete. These are generally applied to horizontal mats and could also include horizontal and dynamic components.

i) Self-weight of any materials (e.g. reinforcing bars) being stored on the cage.

j) Suction from proximity of passing trains or traffic (see BS EN 1991-2, Clause 6.6 [8]).

k) Eccentric loading and sway effects due to self-weight of vertical bars caused by a lack of verticality (construction tolerance for 'out of plumb' often taken as 1 in 50 for freestanding cages and base support chairs and deflection due to sway may be greater than this), general construction tolerances (which account for poor workmanship) and splices.

l) Eccentric loading due to self-weight of horizontal bars being fixed to one side of the vertical bars and 'L'-shape bars, overhangs, corbels, starter bars, etc. positioned on one side of the cage.

m) Horizontal and vertical reactions from inclined guy wires and props used for stability or 'plumbing'.

n) Horizontal reactions from inclined

Table 1 - Section properties for reinforcing bars

Bar diameter (mm)	8	10	12	16	20	25	32	40	50
Area (A) πr^2 (mm²)	50.3	78.5	113.1	201.1	314.2	490.9	804.2	1256.6	1963.5
Weight (7850 kg/m) (kg/m)	0.395	0.617	0.888	1.578	2.466	3.853	6.313	9.865	15.413
Shear area (A_v) $J/\pi r$ (mm²)	32	50	72	128	200	312.5	512	800	1250
Second moment of area (I) $\pi r^4/4$ (mm⁴)	201	491	1018	3217	7854	19175	51472	125664	306796
Torsional constant (J) $\pi r^4/2$ (mm⁴)	402	982	2036	6434	15708	38350	102944	251327	613592
Radius of gyration (r) r/2 (mm)	2.0	2.5	3.0	4.0	5.0	6.3	8.0	10.0	12.5
Plastic modulus (S) $4r^3/3$ (mm³)	85	167	288	683	1333	2604	5461	10677	20833
Elastic modulus (Z) I/r (mm³)	50	98	170	402	785	1534	3217	6283	12272
Torsional modulus (T) J/r (mm⁴)	101	196	339	804	1571	3068	6434	12566	24544
Tension capacity (Rd,t) $A.f_y/\gamma_m$ (kN)	21.9	34.1	49.2	87.4	136.6	213.4	349.7	546.4	853.7
Compression capacity (Rd,c) $A.f_y/\gamma_m$ (kN) *Assumed perfectly restrained (stocky)*	21.9	34.1	49.2	87.4	136.6	213.4	349.7	546.4	853.7
Bending capacity (Rd,m) $S.f_y/\gamma_m$ (kNm)	0.04	0.07	0.13	0.30	0.58	1.13	2.37	4.64	9.06
Re-bend capacity (Rd,rm) $0.8S.f_y/\gamma_m$ (kNm)	0.03	0.06	0.10	0.24	0.46	0.91	1.90	3.71	7.25
Shear capacity (Rd,v) $Av.f_yv/\gamma_m$ (kN)	8.0	12.6	18.1	32.1	50.2	78.4	128.5	200.8	313.8
Torsional Capacity (Rd,mt) $T.f_yv/\gamma_m$ (kNm)	0.0	0.0	0.1	0.2	0.4	0.8	1.6	3.2	6.2

Notes: Yield stress = 500 N/mm² *Material factor = 1.15*
Factored axial stress = 435 N/mm² *Factored shear stress = 251 N/mm²*

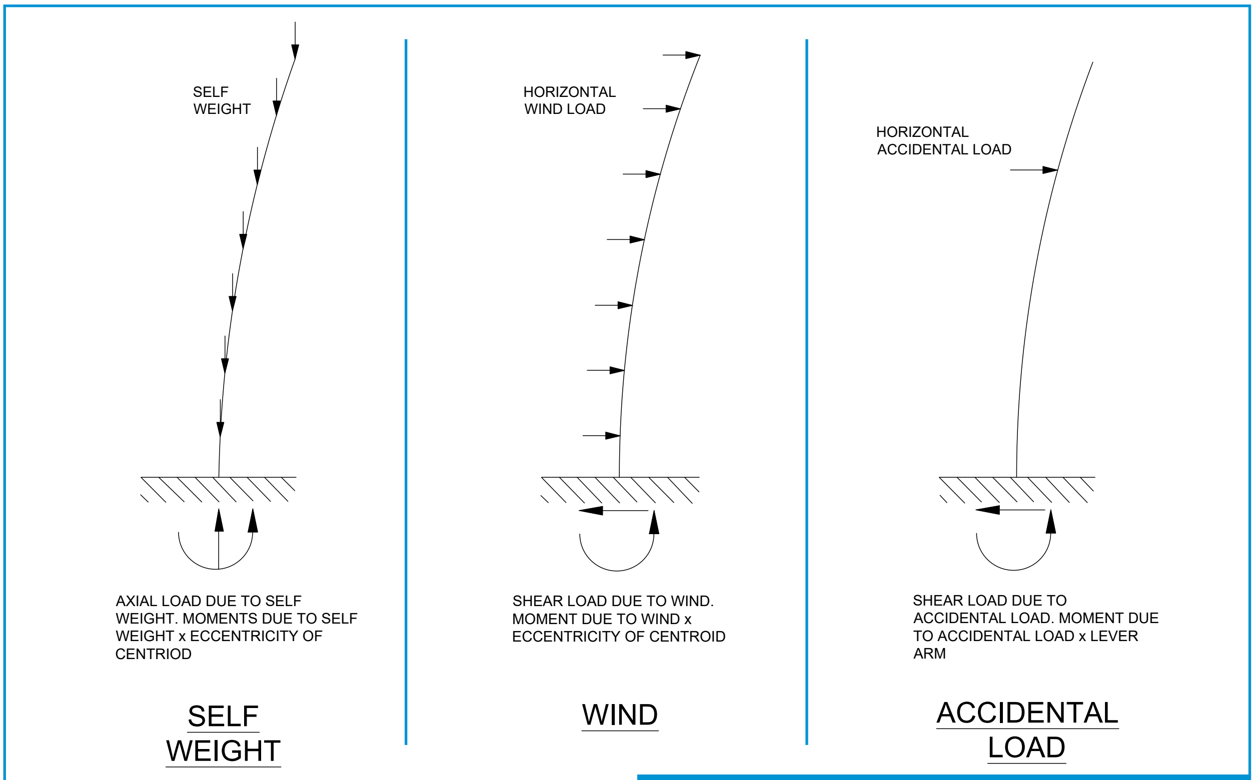


Figure 2 - Axial and bending moments in reinforcing steel

chains or soft strops during lifting of cages.

o) Dynamic vertical loads from stacking, lifting, moving and positioning bundles of bars or small machinery, applied mainly to horizontal mats. These loads can typically be between 10 % (when using manually operated lifting gear with good control measures) to 25 % (when using mechanically operated lifting gear with limited control measures or when lifting 'blind') of the self-weight of the object being lifted. If the rate of travel of load cannot be restricted to below 1.3 m/s (3 mph) then the horizontal force should be 33 % (see BS 5975: 2019, Clause 17.4.3.4 [4]).

p) Accidental impact loads (see Section 5.3).

Concrete placement loading may have two components:

(i) Falling concrete during placement by crane and skip

Good site practice should limit the distance concrete free falls (tremie pipes may be required for placement) to avoid damage to the cage and possible concrete segregation. See Formwork: A Guide to Good Practice [9].

(ii) Placing concrete by pump or pneumatic placer through a pipeline

An additional horizontal force can be applied to horizontal mats. BS 5975: 2019, Clause 17.4.3.4 [4] provides further guidance.

q) Notional horizontal load (see Section 5.4).

r) Dynamic loads during transportation (see Section 10).

s) Dynamic loads during installation, e.g. pre-fabricated pile cages are often installed by vibration into the concrete pile. Specialist advice should be sought, and this is not considered in this guidance.

t) In some parts of the world earthquake loading may need to be considered. This is generally not an issue in the UK and is not considered in this guidance.

u) The applied loads could be vertical, horizontal or dynamic. Any applied loads could cause an overturning moment, when multiplied by a lever arm to the centroid of pressure or line of action of a force. Axial compression and bending are produced in the cage.

5(iii) The designer should determine the magnitude of each load and which can occur in combination (some examples are shown in Figure 2).

5.1 Wind loading

5.1.1 Wind loading is not a constant and can vary with location, altitude, proximity to the sea, etc. It can also vary along the length of long wall and can increase near corners, free ends and openings. Often, complex wind calculations on cages cannot be justified and assumptions / approximations based on engineering judgement should be made.

5.1.2 A distinction should be made between:

- a maximum wind force that can apply to a cage, but at this wind velocity it becomes unsafe to carry out any further work on the cage.

NOTE: Concreting, impact and live loads, etc. would not act in conjunction with this wind force.

- a working wind force at which velocity normal site operations proceed. In the UK this is normally limited to gust up to 40 mph and represents a working wind pressure of 200 N/m^2 (allowing for gusting and duration less than 1 year).

NOTE: Concreting, impact and live loads, etc. may act in conjunction with this wind force. See BS 5975: 2019 [4] for further guidance.

5.1.3 Wind loading can be calculated using BS EN 1991-1-4 [10] or a simplified method in BS 5975: 2019 [4] that allows for a reduced probability factor of 0.9 for an exposure duration of less than 1 year (considered appropriate for cages unless there are specific requirements to the contrary, e.g. Network Rail). Some nuclear projects may have different factors of safety based on return periods to increase the basic wind speed for freak weather events. This guidance recommends that during high winds work should not be carried out on a freestanding cage and an exclusion zone around the cage enforced (unless appropriate external restraint is provided).

COMMENTARY: A wind probability factor of 0.9 is used in this guidance, as proposed in draft of BS 5975: XXXX (and Hoardings – A guide to good practice (TWf)).

5.1.4 From BS 5975: 2019, Clause 17.5.1.10 [4]:

$$\text{Wind force, } F_w = C_s \times C_d \times C_f \times q_p(z) \times A_{ref} \times \eta \qquad \text{Equation 1}$$

where:

F_w = wind force (in N)

C_s and C_d = size and dynamic factors

C_f = force coefficient

$q_p(z)$ = peak velocity pressure (N/mm^2)

A_{ref} = reference area on which wind acts (m^2)

η = shielding factor

5.1.5 For analysis, the wind force is the summation of the forces on individual bars using a force coefficient of C_f = 1.2 (for circular shapes with no other external effects). However, if permeability is less than 20% then the cage should be considered as a 'wall' in accordance with BS EN 1991-1-1-4, Clause 7.4.1. There is no specific guidance on the force coefficient when considering the shape of lapped bars, however BS EN 1991-1-4, Clause 7 [10] and BS 5400-2, Table 8 [11] may assist. This guidance considers the various options (e.g. the translation between an open framework and a solid wall as well as considering the shape of lapped bars to be a rectangle with curved corners) and recommends that C_f = 1.2 should be used for the overall cage. (Further wind tunnel testing would provide better clarity, but until then this document recommends C_f = 1.2.)

5.1.6 The wind pressure acts on the windward near face and the leeward far face wall mats. The effective area (A_{ref}) is the projected area of the steel reinforcement and embedded items (for each layer). Depending on the stagger, if any, lapping splice continuity zones may locally double the effective area acted upon by wind pressure. Large box-out forms and/or polystyrene void forms fixed into a cage act as a 'sail', thereby substantially increasing the wind load acting on the cage. When acted upon by the wind, lapping zones towards the top of a cantilever cage have a greater destabilising effect than those located at or near the starter bars. Unless most of the laps are located toward the top of the cage (raising the level of the force resultant due to wind pressure) the designer may make a reasoned engineering judgement to calculate an average effective area of reinforcement over the whole structure, by proportion.

NOTE: BS EN 1992 [12], Clause 8.7.2, provides guidance on staggered laps.

5.1.7 In Figure 3 the change in wind area between a non-lapping zone (1) and a double lapping zone (3) due to the splices *typically* increases by between 1.5x to 2.0x.

5.1.8 For example, in Figure 3 the hatched lapping zones account for approximately 60% of the overall cage area. The lapping zones can be considered as evenly distributed and their centroid is not above the midpoint of cage height. In this instance, the designer can reasonably take an average projected area of reinforcement.

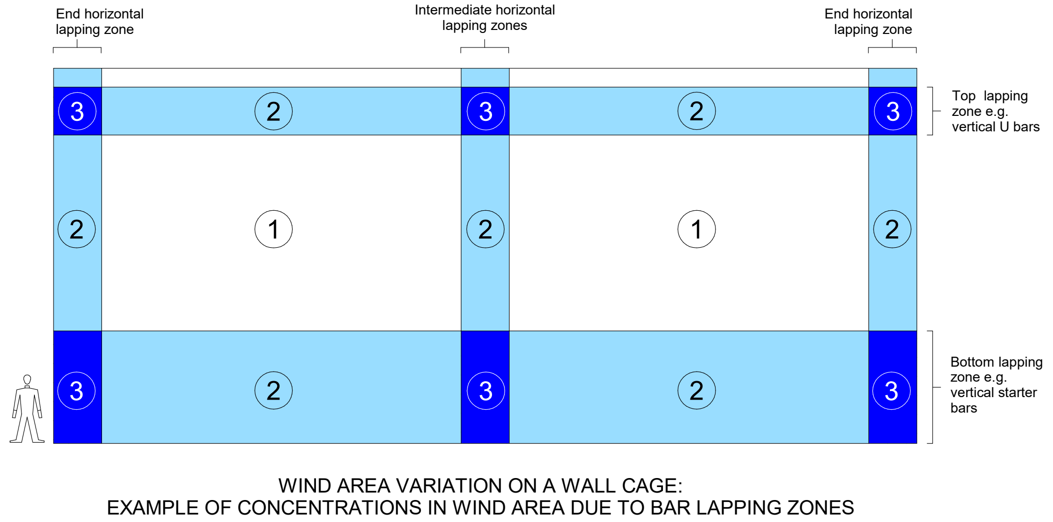


Figure 3a – Example of concentrations in wind area due to bar lapping zones

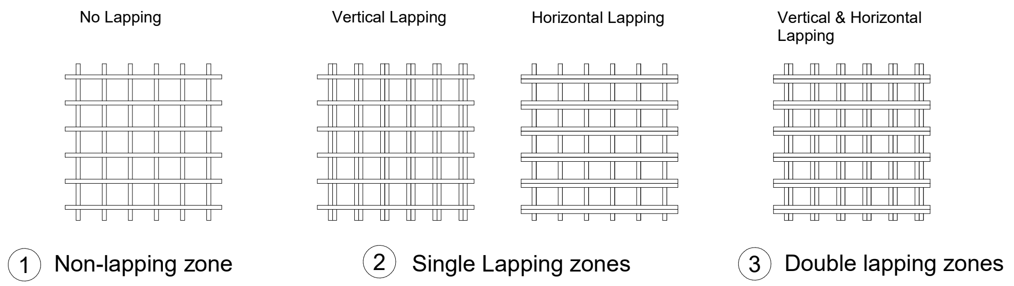


Figure 3b – Lapping zones (detail)

5.1.9 In this example, each stagger lapping zone is approximately:

1.7 x the effective area of a non-lapping zone.

The effective wind area by proportion, over the whole cage is:

Effective average to windward cage face

$= (60\% \times 1.7 \times A_b) + (40\% \times 1.0 \times A_b)$

$= 1.42\ A_b$

where:

A_b = basic rebar projected area in a non-lapping zone 1

NOTE 1: A_b is NOT the overall cage area (sometimes called the overall envelope area), it is the projected area of reinforcement in a non-lapped zone.

NOTE 2: This calculation is for the above example. The actual proprtion of lapped bar areas should be calculated on a cage-by-cage basis and the increase in bar diameter (see Table 2) used to calculate the wind area. If using the nominal bar diameter, the wind area should be increased by at least 15%.

5.1.10 An additional wind force acts on the leeward cage face. The bar arrangement and lap locations of the near and far face reinforcement may differ. It is, therefore, important to check whether areas and force resultants for one face are valid for the other wall faces.

5.1.11 The nominal bar diameter should be increased by 10% (Table 2) to account for the ribs around the bar circumference (the minimum projected wind diameter is the average of the nominal and maximum rib-to-rib diameters).

Table 2 - Increased bar diameters

Nominal bar diameter (mm)	12	16	20	25	32	40	50
Minimum projected wind diameter (mm)	13	18	22	27	35	43	54
Maximum bar diameter (ribs) (mm)	14	19	24	29	37	46	57

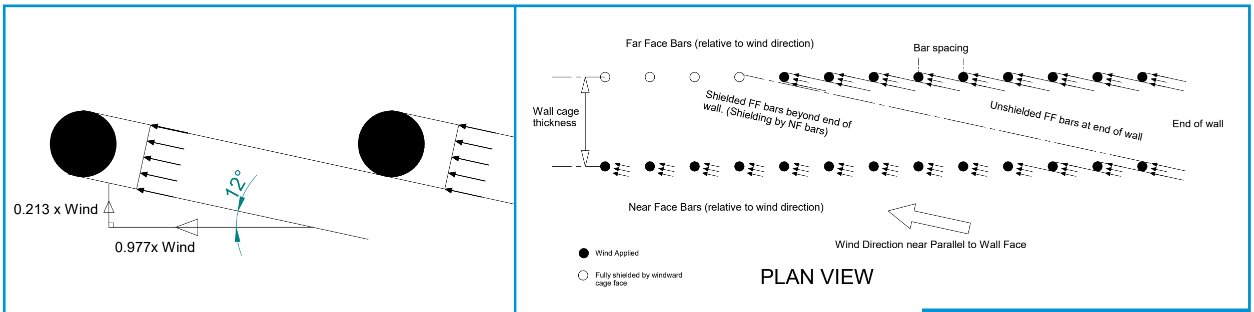


Figure 4: Wind effects on bars

5.1.12 If a designer can justify undertaking a more comprehensive and complex analysis (when compared to a simple analysis that, for ease, makes numerous assumptions and simplifications) then three wind direction load cases should be considered:

(i) *5 degrees to the normal of the wall cage (to ignore shielding from front-face and rear-face)*

Consideration should also be given to the cage bending out-of-plane (see Section 7.1).

(ii) *Near-parallel to the plane of the cage (circa 12 to 14 degrees)*

With the wind blowing near parallel to the plane of the cage, this generates large in-plane wind loading (see Figure 4). 98% of the wind load acts on every vertical bar in the windward face and the cumulative load can be substantial on a long wall. Consideration should be given to the possibility of racking (see Section 7.5) and note that circa 20% normal loading acts in conjunction with the in-plane load component on each vertical bar. The windward near-face fully shields the leeward far-face (except at the end of the wall). With this load case the horizontal lacer bars are shielded by the vertical bars if they are on the windward face (near-face 2 layer). If the lacers are on the windward face (near-face 1 layer) then they form part of the effective area.

(iii) *45 degrees to the cage plane*

This direction imposes significant load components parallel and normal to the cage simultaneously. Consideration should be given to the possibility of an onerous combination of in-plane racking and out-of-plane bending.

5.1.13 If the bars are very closely spaced and there are multiple layers of bars, designers can consider wind shielding (η) from windward to leeward faces of bars relative to the wind direction (see BS 5975: 2019, Annex M). Therefore, the global wind force acting on the cage is less onerous. The wind can blow from any direction, so the unshielded side can be on either face. This is a consideration for general cage stability and for the design of bar-to-bar connections or tie-back to wind posts within the cage. When considering the possibility of wind shielding, the tolerance of bar placement and the effect of non-alignment, (e.g. in skew bridge piers), should be considered. This should be defined within the specification (typically 1 x bar diameter) and then reflected in the design brief. Designers should exercise engineering judgement when considering sheltering or funnelling effects from adjacent structures (see BS EN 1991-1-1-4, Clause 7.4.2 and Annex A.4).

5.1.14 For complex analysis, dynamic wind effects may also need to be considered (see NOTE) and expert advice sought if necessary. Where a cage is rigid and propped, a dynamic factor of 1.0 is appropriate, but a larger dynamic factor of 1.25 (on second order P-delta displacements; see Section 8.1), should be used for flexible, freestanding cantilever cages, especially if it is being assembled in a high-risk area (e.g. adjacent to a railway line where suction loading from trains passing may need to be considered) and a permissible stress design approach adopted for structural robust tied bar connections (see Section 6.2.1).

NOTE: BS 5975: 2019 [4], recommends that vortex excitation is considered if a cage is exposed to long periods of laminar wind velocity (e.g. in an estuary) where in rare occasions the vibration caused may cause fatigue effects in members.

5.1.15 For simple analysis, in a low-risk environment, the cost of complex calculations cannot be justified, and a simplified approach is appropriate. An estimate can be made of the overall cage 'permeability' (depending on the diameter of the bars and number of layers and other inserted items). For a simple wall cage, with an inner and outer layer, a permeability of 50% is a conservative assumption.

Some simple rules to follow:

- Wind on simple low-risk cages can be considered by estimating the "permeability" of the cage.
- Work should not be carried out on a cage in high winds and an exclusion zone established (unless appropriate external restraint or suitable internal additional stability bars are provided).
- A wind probability factor of 0.9 should be taken as this is appropriate to cages and the exposure is less than 1 year (with specific exceptions as specified by some clients, e.g. Network Rail).

5.2 Live loading

5.2.1 This guidance recommends the following live loading to be considered:

- 0.75 kN/m², for operative access only.
- 1.5 kN/m², if tools, light equipment or a few loose bars need to be stored.
- If larger machinery or large bundles of bars or mats are stored (in specified areas on slab or foundation mats), then the weight of these should be calculated. For cages this can generally be taken as 5 kN/m² (unless calculated otherwise). Bundles of bars are positioned by crane, so an impact load should be allowed for (see Section 5.3). These bundles of bars are likely to be placed on timbers (so the chains or slings can be removed from beneath the bundle), hence the designer should consider line loading rather than uniformly distributed loading.

5.2.2 Operatives should not climb on cages during assembly and safety exclusion zones should be established and enforced around the cage where possible.

5.3 Accidental impact loading

5.3.1 Cages may be struck accidently during lifting operations (e.g. during the positioning of formwork) or by site vehicles. In general, many cages are relatively lightweight and not sufficiently robust to withstand a significant impact load so, where possible, the 'principles of prevention' should be applied and the risk eliminated, by establishing control measures to prevent or limit impact loads. These may include limiting crane speeds when lifting near a cage or setting up and enforcing exclusion zones around the cage.

5.3.2 However, the likelihood of impact can be difficult to eliminate, so the designer should assess the risk by considering the likelihood of impact (e.g. more likely on congested sites) and the consequences of failure (e.g. severe consequences when adjacent to railway line). Where applicable (where lifting operations or plant impact are possible), for the purpose of design calculations (and unless specific impact calculations are carried out) this guidance recommends an impact force being the most likely / severe of:

- horizontal force between 1 kN and 2.5 kN depending on the likelihood, consequences of failure and size of object causing the impact (engineering judgement is required);

or

- a notional horizontal force equivalent to 10% of the weight of the object causing the impact (e.g. formwork);

or

- vertical force when placing bundles of bars or from concrete placement plant, equivalent to the weight of the item plus additional 10% to 25% of the weight for impact during positioning.

5.3.3 A simplified conservative approach is to apply the impact load at the most severe position (e.g. at the top of a freestanding cantilever cage). A less conservative approach would be to consider the most likely point of impact based on an assessment of the risk.

5.3.4 This guidance recommends that a global factor of safety on collapse due to impact of 1.0 should be achieved if an impact load is eliminated or mitigated by risk assessment, e.g. exclusion zones or other control measures are in place; and a minimum of 1.5 if an impact load is considered possible or for high-risk locations or where operatives are working adjacent to the cage (e.g. in scissor lifts or MEWPs).

5.4 Notional horizontal loading

5.4.1 This guidance recommends that a notional horizontal load - allowing for distortions, 'out of plumb', slippage at joints, etc. (and these tend to be more onerous than for other typical temporary works considerations) - is applied in any horizontal direction, which is the greater of:

- *(a) For simplicity a conservative approach*

  Consider 5% of the total cage self-weight for a vertical cage applied at the centre of gravity; and for a horizontal cage consider 5% of the top mat weight applied at the top mat level.

or

- *(b) For a more accurate approach*

  Calculate all the known horizontal loads and then add 2.5% of the total cage self-weight and applied as in (a).

6.0 Tying bars

6(i) This guidance recommends that a clear distinction be made between traditional non-structural positional tying of bars and structural robust tying of bars (See Flowchart 1 and Section 6.1 and 6.2):

(a) Traditional, non-structural, positional tying of bars

Used to simply keep bars securely in place to maintain cover and spacing, during concreting operations. Not required to transfer any significant forces and some degree of cage displacement not deemed to be detrimental (see Section 6.1).

(b) Structural, robust, tying of bars

Where load paths are identified to transfer significant forces safely through the cage without excessive deformation and to maintain stability. Ties which are relied upon to transmit temporary works loads should be designed to be sufficiently robust (see Section 6.2).

6(ii) Tying is the method of holding bars in a cage together using wire. Nodes (where bars overlap or cross in the same plane) are commonly connected using single or multiple strands of tying wire that is drawn tight around the bars, pulled taught and twisted together to hold the node in place. If the tying wire is not pulled sufficiently tightly then the connection will be relatively loose, more ductile (with a relatively large and unsafe plastic zone before the wire fails) and the bars may slip or move excessively. If the wire is over tightened the connection is much stiffer and displaces less under load but it can be brittle and easily strained at relatively small displacements, to leave little working margin (leading to failure under additional load). If the nodes are not tied together then there is free movement between bars and the cage has no rigidity. Tying of intersection and lap joints keeps the bars in place, before concreting, and gives the cage rigidity and robustness; allowing it to be transported, lifted and/or rotated. Inadequate or insufficient tying is a major cause of instability during assembly or lifting. The only 'written rules' for tying are those to maintain cover and spacing in BS 7973-2 [13].

6(iii) Unlike bolted and welded connections (that have well-known design parameters) wire ties, by their nature, are un-engineered connections with complex behaviour, including sliding movement at small load. However, they may be required to transmit quite large loads in the temporary condition. The strength and quality of ties can vary significantly depending on the skill, experience, technique of the fixer; diameter of bars being tied; configuration of the wire; type and condition of wire being used; the tension in the wire (when the tie is made by the fixer); and the length and number of twists of the tie. Most fixers still tie by hand. However, there are machines available which are constantly being improved.

6(iv) The number and spacing of ties required to secure a bar depends on the bar length and diameter. Long bars of small diameter with infrequent ties deflect (especially cantilever 'flying ends' subject to dynamic effects such as those during transportation), which causes prying and twisting forces in the ties. Dynamic effects can stretch, weaken, and break ties; which can put additional load into adjacent ties, resulting in further ties failing and potential for 'un-zipping'. The number of ties required to secure a bar depends on bar length, more than bar weight (which is a secondary consideration). For this reason, close spacing of ties and multiple load paths are essential to allow for the possibility of some ineffective ties.

6(v) UK tying wire is generally 16 gauge – 1.6 mm diameter British Standard Wire Gauge (16 SWG), with a minimum strength of 280 MPa and typical strength range from 280 to 320 MPa. A recent study by a TWf members, showed that 1.4 mm (17 SWG) is also used by some fixers and it has become increasingly common to use 1.2 mm diameter (18 SWG) soft stainless-steel wire (Grade 1.4301, 304-S31, with a typical strength range of 600 MPa to 800 MPa and a minimum tensile strength of 500 MPa and a minimum elongation at fracture of 40%) for exposed surfaces. The surface of stainless-steel wire is smooth and, as such, is more likely to slip and unwind; hence the need for additional ties to compensate (especially where there are prying forces). The wire is also more brittle. This guidance recommends that **1.6 mm diameter (16 SWG)** is used for assembling pre-fabricated elements and for fixing heavy bars of weight 50 kg and more. Smaller diameter tying wire (1.2 mm or 1.4 mm) is easier for steel fixers to wrap and cut on site and is considered adequate for lighter bars and in-situ fixing. Tying wire is often specified in contract conditions, e.g. Manual of contract documents for highways works. Volume 1 [14]. When specifying and ordering tying wire, it is recommended that the wire diameter is quoted explicitly, in preference to quoting a wire gauge. This avoids confusing British 'Standard Wire Gauge' (SWG) and 'American Wire Gauge' (AWG) (see Table 3). Given that wire is often sourced internationally, suppliers and re-distributors may not differentiate, so a site check is necessary to ensure the correct wire has been procured by checking the diameter using a micrometre. On larger projects, site testing can be used to gauge the performance of the wire and tying practice. Designers and those involved with fixing, supervising or inspecting tying on site should be aware that the relative strength of 1.2 mm and 1.4 mm wire reduces to 56% and 76% compared to 1.6 mm wire (see Table 4). These smaller wire diameters are also more vulnerable to stretch and damage and this can be a particular risk for prefabricated cages or when lifting cages. It is essential that designers clearly communicate which wire type they are assuming in their design and measures should be taken on site to comply.

6(vi) Tying wire is a soft metal which is vulnerable to damage by over-tightening. When a relatively small load is applied the wire can stretch and, under cyclic loading (e.g. wind or repeated lifting), can work loose or even break. This leads to a partial or total loss of bar-to-bar friction contact placing a high strain on the wire. The ends of the wire can also unwind (especially stainless-steel wire which is less ductile and smooth) before the full capacity is reached. Wire stretch or loosening can lead to a reduction in shear connection between bars, causing larger deflections and a deterioration in cage stability. No amount of tying prevents a slender cage from buckling, bending or racking; whereas a stiff structure can fail at connection points. The number of tie wire turns after trimming is not critical for positional tying but is important for structural robust tying. A minimum number of twists (see Figure 5) to ensure the tying wire is more likely to break rather than unwind during loading. It is also important to ensure that the tie is tight to ensure it is unlikely to unwind at relatively low loads. Stainless steel is particularly smooth and can be prone to unloading if the wire is trimmed too near to the bar. Conversely if the tail is not trimmed sufficiently and is left protruding, it can compromise the cover zone. The tails should be bent flat with the nips (not with a hammer). Kinked, nicked or corroded tie wire also results in weak ties. Period inspections should be carried out in accordance with an approved temporary works process (e.g. after adverse weather).

6(vii) Plastic-coated wire, for fixing epoxy-coated bars, is outside the scope of this guidance.

6(viii) For complex cages designers should, from concept stage, consider buildability and site preference issues. This should involve discussions with experts in this field, the site team and fixers. Designers should specify tie patterns, the minimum numbers of ties and the maximum tie centres; and site supervisors should then ensure that the correct ties are used.

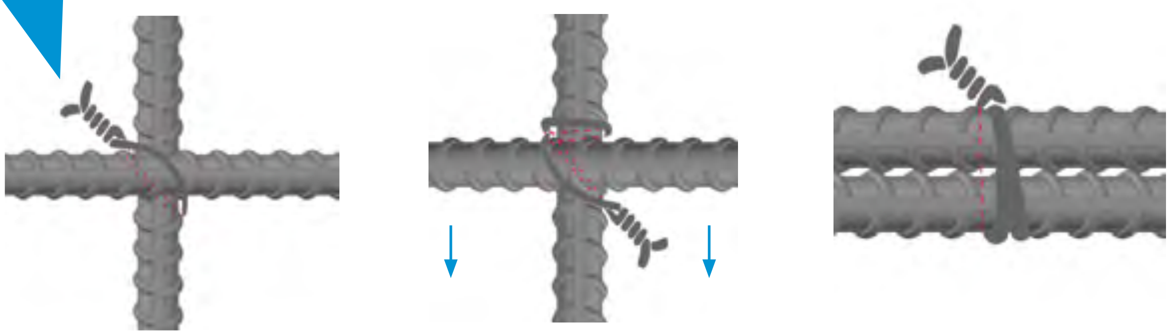
Table 3 - Difference between SWG and AWG

Wire gauge number	British Standard – Standard Wire Gauge (SWG) diameter (mm)	American Wire Gauge (AWG) diameter (mm)
15	1.829	1.4503
16	1.626	1.2903
17	1.422	1.1506
18	1.219	1.0236

Table 4 - Wire strength comparison (as a proportion of 1.6mm strength)

1.2 mm	1.4 mm	1.6 mm
56 %	76 %	100 %

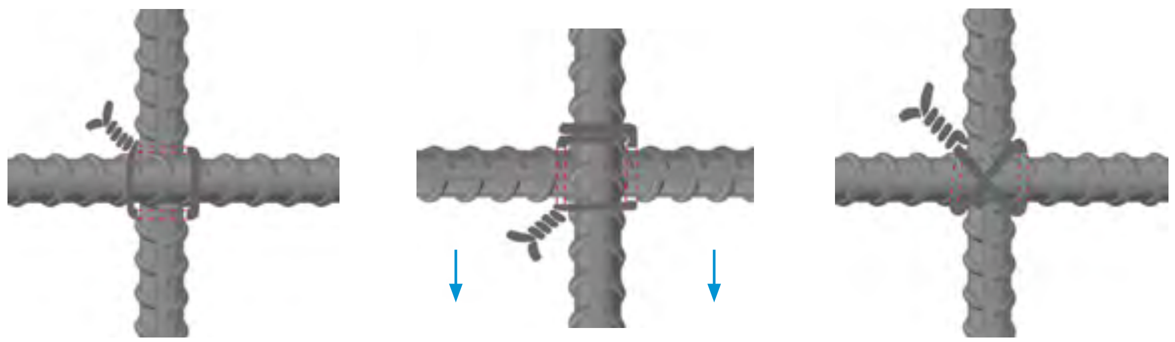
To prevent tying wire unwinding during loading: For **structural robust ties** there should be at least 3.5 twists (630 degrees) using 1.6mm (16 SWG) tying wire (double wire ties), with bars up to and including 25mm diameter; increasing to 4 twists (720 degrees) for 32mm and 40mm bars. For 1.2mm stainless steel wire – and all bar diameters - the number of twists should not be less than 4 (to prevent the wire unwinding during loading) and not more than 5 (the wire is likely to break during tying).



Slash tie
Commonly used as an infill tie preventing bar displacement in slabs and walls.

Ring slash tie
Commonly used in walls to tie heavier horizontal (lacer) bars to verts. The ring forms an anchor point and must be tied to the static bar (vert), on the opposite side to direction of movement being resisted so that the wire goes into tension under load.

Splice tie
Used to tie lapped lengths together.



Hairpin tie
Used to tie perimeter bars and other set up bars (set bars) firmly in location. Very popular for fixing the corner bars into beam shear links.

Looped hairpin tie
Used to tie set up bars (set bars) firmly in location. Loop (ring) is tied to the static bar to form an anchor to the moving bar direction indicated by the arrows.

Crown tie
Used to fix perimeter and set up bars firmly in location. Provides a positive and even clamping force in multiple planes. Useful where the bars want to pull apart (spring).

Figure 5: Different types of single wire ties

Source: BRANZ Builder's Mate (April/May 2004)

NOTE: 'Wrapped splice tie' and 'double wire ties' not shown

Appendix F shows tie symbols, abbreviations and typical use

6(ix) Tie capacity can vary but is of fundamental importance if cages are to be designed elements rather than 'custom and practice' based elements. It is assumed that ties do not provide a significant 'clamping action' between bars (although, in reality, a small clamping action exists) - and simply hold the bars in place - and that the tie wire can stretch and eventually break. Bar-to-bar tie wire connections – which, in quantity, have the potential to transfer temporary works loads; but in isolation - large spacing – have little (if any) reliable temporary works load carrying capacity. Movement and slip can occur at tied bar-to-bar connections at approximately 5 to 10% of the theoretical tensile strength of the tie wire. Examples of non-engineered connections include:

- tying wire;
- nylon bands formed with banding machines;
- jubilee clips;
- nylon ties.

6(x) When designing to transfer temporary works loads with non-engineered connections, the designer should, in sequence:

1. focus on the tying pattern and number of ties, in order to prevent an excessive concentration of load in a few ties;
2. consider effects of joint movement on deflection and hence cage stability (excess deflection makes the cage more prone to buckling failure);
3. ensure that 'un-zipping' of ties cannot occur, e.g. by load share, positive support and careful detailing.

6(xi) Only use the safe working load as a confirmatory check, after considering the failure modes and a robust 'strength in depth' solution has been developed, taking account of 6(x), 1. to 3.

6(xii) It is important to realise that some ties may be ineffective due to poor workmanship or issues with the tying wire and may stretch and become damaged. Designers should adopt a 'SAFETY IN NUMBERS' approach rather than simply satisfying a factor of safety as the load capacity of ties can vary greatly. It is prudent to assume that up to half the ties in a large cage may be in some way ineffective (too tight, too loose, broken etc) and thus allow for significant redundancy. Designers also need to have a clear understanding of load paths and provide alternative load paths to ensure the cage remains intact (if some ties are ineffective), does not "un-zip" and displacement is not excessive.

6(xiii) Stronger ties can be formed by doubling the wire forming the tie and these tend to be used for larger diameter bars and for semi structural ties. It is considered good practice to assume that half the ties may be loose or broken (and the factors of safety take this into account) in the design and ensure that there is sufficient redundancy to make sure that every bar is still secure.

6(xiv) For two parallel bars (splice) and a cruciform connection the ties have:

- a shear value along the bar axis.
- a shear value orthogonal to the bar axis.
- a shear value in twisting.
- a tension value.

6(xv) In each case the capacity is dependent on the slip available at the joint, the strength and ductility of the tie and the definition of failure.

6(xvi) The correct tying of bars is essential to maintain bar position during work by other trades, stacking, transport, lifting and during concrete placement (see Figure 5).

- **Slash tie** - Used in flat horizontal work to secure bars in position against displacement due to work done by other trades and by concrete placing. Simple tie which is wrapped once around the two crossing bars in a diagonal manner with the two wire ends on top. The wires are then twisted together with a pair of UK 'nips' until they are tight against the bars. The wire is cut with nips and the ends flattened, to prevent them from snagging clothing and from protruding through the concrete surface. Can be made stronger by doubling the wire and then it is called a 'double snap tie' or 'single tie-double wire'.
- **Ring slash tie** - Normally used when tying wall reinforcement and holds bars securely in position so that the horizontal bars do not move while work is done by other trades or during concrete placing. The tie is made by wrapping the wire 1½ times around the vertical bar, and then diagonally around the intersecting horizontal bar, completing the tie in the same manner as for a slash tie.

- **Splice tie** - Used to tie two parallel bars together at a splice position, e.g. at starter bars.
- **Hairpin tie** - More complicated, it is used for tying of starter bars or other mats to hold hooked ends of bars in position; it is also used for securing column links to vertical bars. The wires pass halfway around one of the bars on each side of the crossing bar, then are brought squarely around the crossing bar and then up and around the first bar where they are twisted.
- **Looped hairpin tie** - Similar to the hairpin tie except that the wire is wrapped 1½ times around the first bar, then completed as for the hairpin tie. This type can be used to secure heavy mats that are lifted by crane and for securing column links to vertical bars where there is a considerable strain on the ties.
- **Crown tie** - Commonly used in the UK in walls instead of the hairpin tie.

6(xvii) CIRIA Special Publication 118 [15], Sections 9 and 10, has some useful information on cutting, bending and site fixing of reinforcement.

6(xviii) Appendix G shows example of poor workmanship.

6(xix) Tie failure load (disintegration) is the point at which the tying wire snaps or when the twisted ends of the tie have un-wound. This load can vary significantly. This guidance recommends that a clear distinction is made between tie failure load (disintegration), and permissible ('safe') working load (SWL). SWL should be capped, based on serviceability, by limiting displacement (see Section 6.1 to 6.3):

- To date, there is limited information on the load-displacement behaviour of different tie types under different loads. There has been no agreed standard or apparatus for testing. Several UK contractors and some universities (UK and International) have undertaken a variety of ad-hoc tests on tie strength over several years. TWf has assessed the limited results of the historic testing and to better understand the behaviour of ties under load, TWf has also developed a standard testing methodology (specification) with portable apparatus and carried out further testing (The results and conclusions are presented in Section 6.3 and Appendix A). The aim is to encourage on-site testing (where this is deemed viable) of ties to further improve knowledge and to provide a benchmark ('what good looks like') for steel-fixers and ultimately improve the quality and consistency of ties.
- Permissible ('safe') working load (SWL) is the tie failure load (disintegration) divided by a suitably large factor of safety (see Section 6.2) to allow for ineffective ties. **However, designers should treat the word 'safe' with caution and pragmatism**. The tie failure load (disintegration) can vary significantly, due to the quality of on-site tying, tie displacement may be large (before the tie fails) and the consequences of failure may be severe. Designers should adopt a philosophy of considering acceptable tie displacements by caping the SWL and specifying 'SAFETY IN NUMBERS' for ties with alternative load paths. This allows for ineffective ties; and the benefit of additional ties outweighs potentially disastrous consequences of failure.

6.1 Traditional non-structural positional tying of bars

6.1.1 This approach would be suitable for 'lower risk' cages or mattresses, where the ties are not required to transmit significant loads but generally hold the bars in place until concrete is poured. The risk and consequences of failure are relatively small and any potential issues (e.g. displacement) could be easily rectified. The minimum number and position of non-structural tied connections is described in BS 7973-2, Clause 5 [13], and this provides for a stable cage in many circumstances. However, compliance does not guarantee robustness or stability in the whole temporary works life cycle of the cage. BS 7973-2 does not provide specific guidance on ties transmitting temporary loads (e.g. for resisting wind or for lifting) and there is still reliance on 'custom and practice'. Infrequently tied bars are also more susceptible to dynamic oscillation which can stretch and weaken ties. A single defective or loose tie puts more burden onto adjacent ties, resulting in potentially larger prying forces. It is prudent to provide ties at relatively close centres ('SAFETY IN NUMBERS'), which ensure there are multiple load paths and to consider the effect of excessive displacement and ties being loose, damaged or broken, which could potentially lead to progressive un-zipping.

6.1.2 For non-structural positional tying a simple check by another steel fixer should suffice prior to an overall formal inspection (which includes items such as checking bar spacing, formwork, access provision, cleanliness, etc.) before the concrete is placed.

6.1.3 However, the use of additional ties at starter bars, lifting points and any other highly stressed areas is recommended. The use of welding - or of 'bulldog' type clamps - should be considered when the connection is highly stressed. Where slabs are heavily reinforced, very deep or are required to support heavy construction loads, then the vertical load capacity of the chairs should be checked.

Simple rules to follow:

- Single wire ties (slash ties) are vulnerable and should not be used for structural robust tying (only positional tying).
- Mechanical rebar tying tools are recommended for slash ties, all others ties should be hand tied using "nips".

6.2 'Structural' robust tying of bars

6.2(i) The objective of 'structural' robust tying (viz. the engineered design of tied connections for higher risk cages or where significant loads are to be carried by ties) is to ensure that the cage remains safely intact, i.e. joints do not displace excessively or break throughout the whole temporary works life cycle, and that there are distinct load paths to transfer temporary works forces. Structural robust tying is not achieved solely by keeping within the safe working load (SWL) limit of the wire-tied bar connections. The bar length, tie types, cage form, range of actions over the temporary works life cycle, potential effects of excessive displacement and cage risk profile all influence the tying patterns and number of ties required. The designer should prioritise tie patterns primarily based on bar length and general cage form. The consequences of some ties being "weak" or ineffective (through natural variations in workmanship) or working loose over time (e.g. under larger, reversible loads) must be anticipated and accounted for in the design. Although only a few ties are theoretically required to support the bar weight, the designer must also consider displacement (see Section 6.3) and adopt a 'SAFETY IN NUMBERS' approach to tying, so that there is significant redundancy in the connections and loads can be re-distributed safely through alternate load-paths if some ties work loose. Structural robust tying requirements should be designed and specified by a designer who is competent to do so. Designers should be aware of the limitations of ties and when it is more appropriate to use a connection with better defined engineering properties (e.g. clamps, bolts, welded frames). The designer should also consider dynamic loads which induce greater displacement into longer bars which are tied at infrequent centres. For structural robust tying the designer should define:

(i) the bar assembly sequence required to maintain stability at all stages

(ii) the tie pattern required to resist anticipated loads

(iii) requirements for quality control inspections to ensure the types, quality and number of ties conforms with the design requirements

These equally apply to cages fixed on site (in situ or prefabricated) and those prefabricate off site.

6.2(ii) Examples where structural robust tying should be specified include:

- large pre-fabricated cages which are to be lifted;
- all medium and large freestanding wall cages;
- deep base slabs.

6.2(iii) These cages usually require:

- additional bracing bars for truss action to stiffen the cage;
- additional anti-racking bars to resist side sway;
- assurance of temporary works load continuity at lap splice connections.

6.2(iv) All additional bars are subject to approval by the permanent works designer.

6.2(v) Bars in cages can be subjected to a variety of loads which can cause the ties to be subjected to twisting, pulling apart and sliding.

6.2(vi) The design process for structural robust tying can be based on a non-numerical expression:

Structural robust tying pattern = (R x A x F x L) plus check on tie capacity (SWL) where the order of review is:

- R = intrinsic risk associated with the temporary works life cycle (location-specific and determines whether a non-engineered connection is suitable or whether a designed connection is necessary)
- A = actions on cage throughout the temporary works life cycle (to develop a load path and involves designated framing members from the permanent works bars, additional temporary works bars and considering discontinuities)
- F = cage form (shape, size, type)
- L = function of bar lengths and diameters

6.2 (vii) double wire hairpin, double wire crown and double wire wrapped splice ties are used for structural robust tying.

6.2(viii) 1.2 mm stainless steel wire is commonly specified on Highways and Rail projects. In theory it has a similar capacity to 1.6 mm soft black annealed wire (approximately half the cross-sectional area but double the tensile strength), however it is smooth and can have a greater tendency to unwind at lower loads, especially if the ends (tails) are cut too tight to the bar. Where practicable longer "tails" should be left on stainless steel wire with more twists after cutting than 1.6 mm black annealed wire (see Figure 5) to prevent unwinding.

6.2(ix) Two design methodologies are proposed for structural robust tying and these are described in **Clause 6.2.1** (Method A) and **Clause 6.2.2** (Method B).

6.2.1 Structural robust tying design - Method A

6.2.1.1 This is a simplified method which adopts a conservative tie SWL so that any movement at the tied bar connections is negligible. The practical benefit of this method is that tied connections are unlikely to work excessively loose under variable load actions (e.g. those induced by repeated lifting or wind). The benefit for designers is that joint slippage (a small p-delta affect) does not need to be considered, making the structural analysis and design methodology straightforward. A limitation of this method is that many ties will be required to resist moderately high temporary works loads, but this is offset by ties being quick and cost effective to install). This method is simple to apply, more conservative and more appropriate where there is less overall quality control on site.

6.2.1.2 On many projects it is unlikely to be viable to carry out on-site testing of ties to determine tie capacities and to establish a standard for quality and consistency of workmanship. Due to the lack of any specific site information Method A recommends a conservative SWL of **0.35 kN** (see box) for tie capacity and is based on providing a distributed pattern of ties and sufficient ties to ensure that only small strains are developed within the ties throughout the temporary works life cycle. If the tied joint displacements are small, then tie stretch is negligible so the joint is unlikely to work loose over time. Load re-distribution can be achieved by providing alternative load paths through the tied system. This 'safety in numbers and distribution' approach ensures that if some adjacent ties are defective at a point in the cage, or if 50% of all ties distributed throughout the cage are poorly executed/become damaged or are otherwise ineffective, the cage remains intact. The designer needs to arrange tie patterns so that they spread tie loads evenly through the entire cage using multiple load-paths.

> To ensure the cage does not displace excessively and remains intact, this guidance recommends for **Method A** that a SWL for tie capacity of **0.35 kN** - for double wire tie capacity - is used for both 1.6mm soft black annealed and 1.2mm stainless steel wire. This value is based on a TWf assessment of historic test results carried out by others and recent TWf testing which show some consistency (see Appendix A). This is a "capped" value to ensure displacement is limited. It provides for a typical minimum factor of safety of 8 on ultimate tie strength (this equates to an effective factor of safety of typically 4 on ultimate tie strength, assuming 50% of ties are potentially in some way ineffective).
>
> Sites should also adopt a robust quality control and inspection regime to ensure correct wire is being used, the wire is in good condition, competent and experienced fixers are employed and 5% of all robust structural ties for **Method A** in critical areas are physically inspected (see Appendix D) to ensure they are not excessively loose and have correct number of twists (see Figure 5).
>
> *NOTE: This guidance recommends that the use of higher tie SWL would have to be justified as described in* ***Method B****.*

6.2.1.3 Method A assumes the bars remain in contact, even if load reversal occurs and relies on the assumption that on mass some of the ties have a small clamping force (preloading from the tying action) to keep the bars in contact. Due to natural variation in tying workmanship, other ties in the cage may not be pulled taught and have no effective clamping preload. These passive ties take up load immediately after the joint undergoes a small tangential / sliding displacement depending on bar diameters and orientation. This displacement is not noticed as it occurs as a natural part of the fixing process when the weight of a bar is released by the fixer onto the ties. If the displacement increases individual ties could stretch, yield and break, leading to possible "un-zipping" and failure of the cage.

Table 5: Common rules that apply to Method A and Method B

Rule	Explanation
All structural ties are formed with doubled wire ties and the form of the ties is: hairpin, crown, splice or wrapped splice	Forms stronger ties; less vulnerable to damage; can pull tighter in fixing process; smaller bar displacements and less tie stretch.
All ties are performed by competent fixers using standard UK fixing nips that tension the wire throughout and at the final twisting of ends	Hook tools and square jaw pliers are unlikely to provide the natural leverage required to draw bars together, closing any gap between them. This is also true of some tying machines which can fail to draw bars together tightly.
1.6 mm black annealed wire or 1.2 mm stainless steel wire is used for robust tying for bar diameters >= 25mm. Designer may consider 1.2 mm or 1.4 mm wire for 10 to 16 mm bar diameters. A high factor of safety should be used on SWL for redundancy relating to risk of tie damage (see Section 6.2.1.2 and 6.3).	1.6 mm black annealed wire is less vulnerable and minimises displacements. It can draw springy bars together better than small diameter black annealed wire. Stainless steel wire has a higher tensile capacity then black annealed wire, so ties formed with 1.2 mm stainless steel are of similar capacity to those formed with 1.6 mm black annealed wire. However, stainless steel wire tends to fail by unravelling (due to being smoother) at the twisted ends at smaller displacements compared to 1.6 mm black annealed wire. 1.2 mm and 1.4 mm wire may be considered on small diameter bars (10 mm to 16 mm dia.) but must be designed with a high factor of safety (see Section 6.2.1.2 and 6.3).
Designated 'set bars' and 'carrier bars' are always tied at each intersection. The number and location of set/carrier bars should be specified by the designer.	Set bars represent the main load path bearing.
The number of ties on any supported bar should always exceed the minimum tying requirements specified in the Method A. Tying requirements may be different depending on the type of assembly and sequencing, i.e.: a) for traditional in-situ tied back to a propped shutter/ access scaffold; b) fixed in-situ self-supporting (freestanding); c) fixed for transport and lifted.	Prevents any individual bar from falling from a cage.
Structural ties should not be wrapped around multiple layers of bars but tied from bar layer to bar layer. After tying adjacent bar layers, an additional 'lashing tie' should be wrapped around the whole multi-layer bar set. This lashing is a safety tie and can also prevent displacement of bars during pour.	This minimises the overall length of ties, reducing tie elongation (hence joint displacement) and helps to reduce prying forces in the connection.
The cage should not be hung from tied lap splices.	Considered bad practice as the entire mass of the cage is suspended on ties alone. It is safer to use the use full length bars as the key load path (viz. framing members, lifting points). These can be rescheduled bars by agreement with the PWD; or additional temporary works (if space allows), and/or splices replaced by couplers.
Loads should not be hung from a single horizontal tied bar, e.g. a horizontal set bar at the top of a wall cage. Introduce a positive connection via vertical hook bars.	There is a likelihood of high load concentration on individual ties nearest the lifting attachment point. This could result in the ties 'unzipping'. Lifting attachments can be wrapped around vertical carrier bars or attached to full length vertical hook bars or to a horizontal carrier bar provided it is contained by the hook (i.e. positive bar-to-bar contact connection).

6.2.1.4 With Method A the all the following rules should be implemented:

(i) Comply with all ‘common rules’ (see Table 5).

(ii) The designer should ensure that the bars remain in contact at all times, even if load reversal occurs (e.g. by considering a small strain to prevent slippage).

(iii) After carrying out the design and applying the tie patterns, the designer should check that individual tie loads do not exceed Method A SWLs (see Section 6.2.1.2) in any direction, assuming doubled wire ties using 1.6 mm black annealed or 1.2 mm stainless steel wire.

(iv) Each tie should have one function (e.g. hairpin / crown / slash tie at a cruciform connection coincidental with a splice location should primarily secure the horizontal bar to the vertical bar. A separate splice tie would be assigned to lap the vertical splices.)

6.2.1.5 A number of ‘carrier bars’ and ‘set bars’ should be defined by the designer (of the cage). The number and spacing of set, carrier and/or framing members depends on the cage form and temporary works life cycle and are specified by the designer. As a rule-of-thumb for the concept design stage, 0.9 m to 1.2 m centres (or 50 D centres for large cages); with large diameter bars 1.2 m to 2 m may be acceptable; for smaller, lighter cages and this document recommends not less than 100 D or 3 m centres (and a minimum of four load paths), whichever is smaller. Splice ties can be used to prevent scissoring (see Failure Mode 5, Section 7.5) using Method A, by positioning the splice ties evenly within each outer third of the splice length. This gives a reasonable lever arm, while maintaining a uniform clamping force to keep the lapping bars in tight contact. Conversely, if all the ties are placed toward the centre of splice, the ties form an undesirable pivot point about which scissoring could occur. The number of ties required to resist the full plastic moment of a splice are proposed in this guidance and are shown in Table 6. (It is not normally necessary to resist the full bending capacity of the bar at every single bar splice in a wall, so it is usually possible to reduce the number of “full moment capacity splices”, e.g. to one every 3 or 5 bars. This depends on bending moment per metre width of wall cage, noting the bars can bend in two directions, in plane and out of plane).

6.2.1.6 For laps in heavy cages (e.g. tall walls with 32 mm-plus diameter bars) with less than 6 doubled wire double wrapped splice ties (3 toward each outer third of the splice) this guidance recommends that two horizontal ‘set bars’ are introduced (4 if laps are staggered). These ‘set bars’ should be positioned as close as possible to the end of the vertical splice lap zones. The horizontal set bars should be tied with alternating doubled wire hairpin and doubled wire crown ties. The crown ties are used where the horizontal set bar intersects each pair of vertical splice bars. The hairpin is tied on the single staggered vertical bar immediately adjacent to the splice. This is shown in Figure 6.

Table 6: Minimum recommended number of splice ties to prevent scissoring for Method A

To resist full bar bending capacity based on 40D minimum splice length

Bar diameter (mm)	12	16	20	25	32	40
Full plastic moment (σ_y x 1.698 x Z) kNm	0.14	0.34	0.67	1.30	2.73	5.33
Assumed minimum splice length (40D)	480	640	800	1000	1280	1600
Double wire splice ties (DWS)	3	3	4	7	–	–
Double wire double wrapped splice ties (DWW)	2	2	3	4	7	10

NOTE: It is recommended that two anti-scissoring lacer bars are in place in addition to the splice tie arrangement (This has been justified by calculation but has not been proven by current testing).

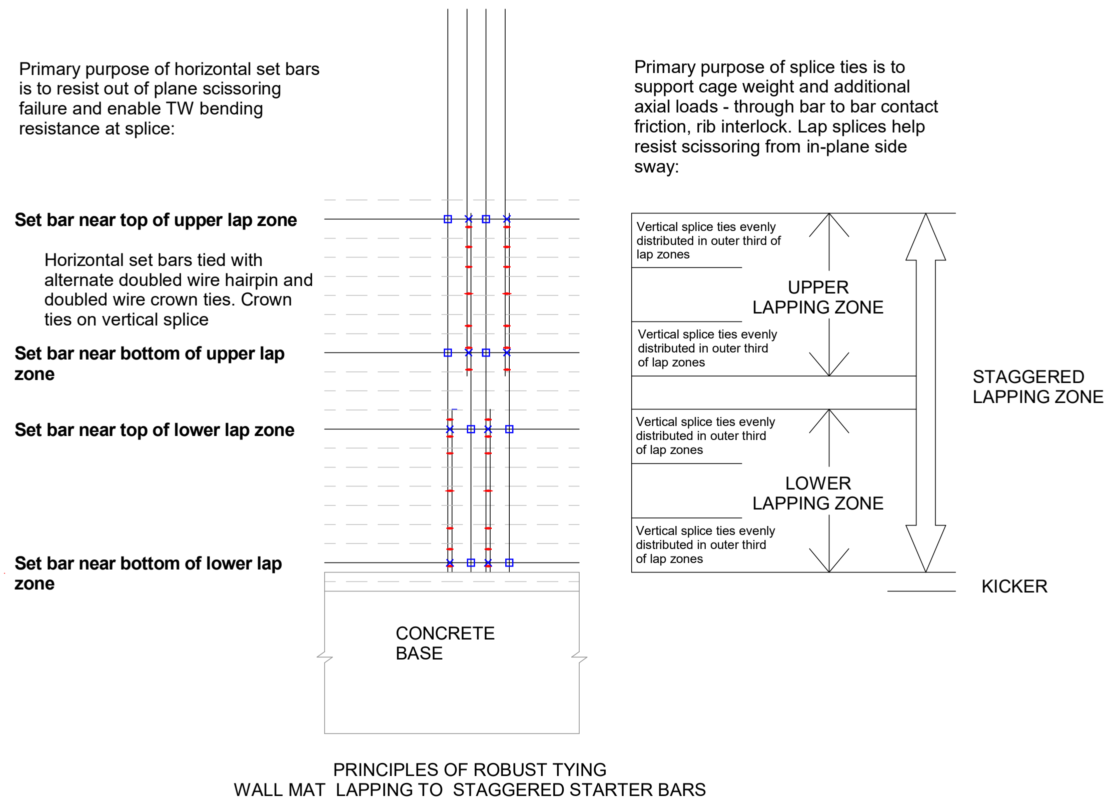


Figure 6: Example of robust tying of a tall, heavy wall cage at starter bar location

NOTE: If ties are used to carry a higher proportion of their failure load, they stretch and become loose if load reversal occurs. This is discussed further in Method B.

6.2.2 Structural robust tying design - Method B

6.2.2.1 In **Method B** the ties are asked to do 'more' and it is assumed there is some stretch of the ties and that load reversal is possible. This is a more complex and less conservative method based on load/displacement behaviour where a higher tie SWL (i.e. greater than the 0.35 kN and could be in the range of 0.5 kN to 1.0 kN for double wire crown ties and for lapped spliced connections. This can be justified by on site testing of ties and robust checking of workmanship (see Appendix B for test specification). This method is likely to be justifiable on larger more complex / higher risk projects where very large cages are being used. Designers must carefully consider displacement (p-delta effects) in analysis / calculations and the tie SWL should be "capped" to limit displacement (see box and Section 6.4). If tie loads are high then mechanical fixings or welding should be considered as displacement analysis / calculations could prove more costly than the provision of mechanical fixings or welding.

Tie Example 1:

Question

12 m long, 40 mm diameter bars, each weighing 118 kg (1.18 kN), are to be tied to create a flat mat. The mat is to be lifted and the designer assumes each doubled wire crown tie has a SWL of 35 kg (0.35kN). Is it safe to fix each 12 m long bar with 4 ties, giving a maximum combined SWL of 140 kg (1.40 kN)?

Answer

'No'. It would not be acceptable to suspend a 118 kg bar with only 4 ties. Theoretically, 4 ties with a SWL of 35 kg (0.35 kN) each could carry the load but there is insufficient 'safety in numbers' and the consequences of failure could be high. The cost of providing some additional ties would be small in relation to the consequences of failure.

Figure 7: Multi-wrapped strong tie

To ensure the cage does not displace excessively and remains intact, this guidance recommends that for **Method B** on site testing is carried out to establish an appropriate SWL for tie capacity and improve quality and consistency of tie workmanship. With this method the designer should consider how many ties are carrying the applied load and 'SAFETY IN NUMBERS' with alternative load paths should always be a paramount consideration. Designers should agree tie patterns with fixers.

Sites should also adopt a robust quality control and inspection regime to ensure correct wire is being used, the wire is in good condition, competent and experienced fixers are employed and at least 20% of robust structural ties in critical areas are physically inspected (see Appendix D) to ensure they are not excessively loose and have correct number of twists (see Figure 5). This guidance recommends a less conservative (when compared to **Method A**) factor of safety of **4** on ultimate tie strength (if robust quality control is carried out on site this will equate to an effective factor of safety of **greater than 2** on ultimate tie strength, as it will ensure less than 50% of ties are in some way ineffective). However, any SWL value determined from site testing should be capped to limit displacement as described in Section 6.3 and 6.4.

NOTE: Method B higher tie SWL should not be used if a large cage is being lifted where the load is fully supported by the ties alone and if the cage has to be lifted several times (more than 3 times – unless the cage is inspected and any necessary remedial measures undertaken between lifts).

6.2.2.2 With Method B, as loading increases, tie wire stretches, causing slip and displacement at the bar-to-bar connection. The tie stretch is irreversible, and the bar-to-bar connection becomes loose if the load is reversed. This method allows more load to be resisted by ties, but the designer must consider the risk and consequences of greater displacement caused by tie stretch. Designers should set safe and realistic serviceability limits (see Section 6.3, 6.4 and Appendix A) for the tied bar connections to ensure the tie cannot snap or become excessively loose under load. As mentioned previously designers should be aware that there is significant variability in tied connections and some ties are likely to be ineffective.

NOTE: The tie is likely to fail in serviceability well before the wire snaps.

6.2.2.3 The consequences of excessive tie stretch, and displacement, could include:

- increased global deflection of the cage caused by slip at joints. This might increase the displacement by a factor of at least 2 to 3 (perhaps significantly more), compared to an analysis assuming no movement at joints (This is referred to as "small p-delta" – second order effects, see Section 8.1).
- increased likelihood of overall instability of the cage.
- repeated lifting cycles and wind loading can cause load reversal throughout the temporary works life cycle. The resulting

loss of bar-to-bar contact and 'play' in the joints may result in bars moving from their design position and effecting structural performance of the cage.

6.2.2.4 Multiple load sharing systems comprising good tying patterns and alternate load-paths, become an especially important feature of the design solution when using Method B. Designers must consider the risks and consequence of adjacent ties failing and if the load cannot be re-distributed to adjacent ties or 're-routed' through alternate load-paths - the designer should consider other solutions such as mechanical fixings or welding.

6.2.2.5 Consider using Method B:

- to stiffen a cage to resist wind loading in lower risk areas (e.g. working in a field with lower wind events and where ties can be reinspected and remedial action carried out after any high load event);
- for framing members used to stiffen a cage, e.g. to resist bending, when the cage is rotated from horizontal to vertical;
- to resist one off loads (e.g. impact).

6.2.2.6 It should not be used to:

- fully suspended loads wholly reliant on ties;
- exposed areas prone to high winds;
- in high-risk areas (e.g. cage adjacent to a railway line which can only be accessed for inspection or remedial work in a possession).
- if only 1 or 2 ties are used to carry the load then the designer should default to the SWL value from Method A regardless if test results justify higher values.

6.2.2.7 This method should only be used by designers with relevant experience who can correctly assess joint displacement and its effect on the integrity and stability of the cage structure over the whole temporary works life cycle (by carrying out a suitable risk assessment). The designer is expected to provide alternate load paths and 'SAFETY IN NUMBERS' to provide inherent robustness and this method should not be used if alternative load paths cannot be provided.

6.3 Displacement considerations when determining tie capacity

6.3.1 When considering tie capacities (ultimate and SWL), the designer should also consider the effects of significant displacement. If a cage or mattress displaces significantly under load it is likely that ties may fail, this may affect the cover to the bars or perhaps it may collapse. To prevent excessive displacement the designer should apply a serviceability "cap / limit" on displacement.

6.3.2 With wire tied bar-to-bar connections, some connections will be loose and therefore less stiff, but more ductile – with a large and unsafe plastic zone before the wire fails. Other ties will be excessively tight, much stiffer, displacing less under load, compared to a loose tie. However, overly tight ties are potentially prone to brittle failure at relatively small displacement.

6.4 Analysis of historic test results carried out by others and confirmed by recent TWf tests

6.4.1 A limited number of ad-hoc historic tests have been carried out by various contractors and Universities. TWf assessed these tests and formulated some conclusions. However, it was realised significant additional testing would be necessary to better understand the issues and behaviour of ties. An aim has been to develop a more standardised testing methodology and equipment. This can then be used to determine a more realistic and less conservative "capped" tie SWL, by providing a benchmark for quality and consistency of tying on site. Figure 8 shows the three directions of load application that TWf has considered (also see Appendix A and B).

6.4.2 Historic tests generally show that the experience of the fixer (experienced fixers generally produce tighter ties which will displace less when loaded), condition and type of tie wire and direction of load application, play significant roles in the strength of ties and displacement. The tests generally quote the maximum sliding load sustained at or just before the point where the tie snapped or un-ravelled. They indicate that cruciform connections can undergo large sliding displacements before they break. Tangential sliding displacements of 0.8 D to 1.2 D and up to 1.7 D (where D is the bar diameter) have been recorded when the wire breaks. Latent defects in a tie can result in tie disintegration at about 0.5 D (usually by premature unwinding of stainless steel, or over-tightened or nicked soft black annealed wire). Under reversible actions, most cage forms would lose structural integrity, becoming unstable well before this magnitude of bar-joint displacement is reached. Joint displacement leads to tie stretch and upon load reversal, these ties become loose. Bar-to-bar friction and interlock contact is lost, putting more node load into highly strained wire. If this joint displacement occurs at framing members, it increases overall cage displacement significantly leading to buckling and structural collapse.

6.4.2.1 Cruciform normal (Test Type A)

The tests and TWf analysis show that cruciform connections with double wire hairpin ties, using 1.6 mm wire, with pulling force normal to the plane of the cruciform joint (see Figure 8(a)) can resist loads typically in the range 1.0 kN to 1.6 kN. However, a displacement serviceability limit should be applied whereby, displacement normal to the plane of the cruciform joint is limited (capped) to:

$0.073D_{min}$ (where D_{min} is the average diameter of the smaller bar at the cruciform connection)

The presumed displacement at 1.6 kN load is 3.2 mm for a single tie and 1.2 mm if the load is shared across at least 4 ties (it is acceptable to interpolate between 1 tie and 4 ties).

Hence, applying displacement limit to a single tie gives a SWL of (1.2 mm / 3.2 mm) x 1.6 kN = **0.6 kN**.

NOTE: 0.073 is a function of the bar ribs to ensure that bars do not slip over the ribs.

6.4.2.2 Cruciform tangential (Test Type B)

The tests and TWf analysis show that cruciform connections with double wire hairpin ties, using 1.6 mm wire with tangential sliding force along either bar axis (see Figure 8(b)) can resist a load typically in the range of 0.4 kN to 1.1 kN but slip displacement occurs in the range of 5 mm up to 30 mm. This displacement is necessary in order to engage the wire with the bar (as the wire may be slack) and transverse ribs under tangential sliding loads.

For serviceability the displacement should be limited (capped) to an upper bound value equivalent to $0.63D_{av}$ (where D_{av} is the average diameter of the two tied bars). However, consideration needs to be given to global cage displacement and the individual node displacement should be limted to the range of 10 to 13 mm. Assuming 4 or more ties with load sharing the capacity is capped at **1.1 kN**. Designers should recognise that ties subjected to this magnitude of load becomes loose and bar-to-bar friction contact is likely to be lost if load reversal occurs. Also, the possibility of 'un-zipping' failure increases if alternative load paths have not been adequately considered.

This limit should be considered to prevent movement over a bar rib and could be considered for a one-off load such as accidental impact. However, this guidance recommends that an inspection of the cage should be carried out afterwards. If this is not possible then the lower limits below should be applied.

NOTE: 0.63 is based on the average distance between ribs and above this limit it is likely that bars will move over ribs.

When considering double wire, wrapped splice ties in sliding lap resistance and if load sharing is assumed with a minimum of 4 ties, the load cap per tie is **1.1 kN** in a range of 10 to 15 mm displacement.

6.4.2.3 Splice connection – lapping bars (Test Type C)

The tests and TWf analysis show that a double wire, wrapped splice tie, using 1.6mm wire with a parallel pulling force (see Figure 8(c)) is capped at **1.1 kN** with a typical displacement range of 12 to 16 mm.

6.4.3 Load caps have been set based on limiting displacement and these are not a SWL, so designers must recognise that ties subject to this magnitude of load becomes loose and important bar-to-bar friction contact could be lost if the load subsequently reverses. There is also a higher risk of 'un-zipping' failure if the tied solution is not thought through. Care should be exercised when lapping bars of different diameters and a maximum difference of two bar diameters should apply (e.g. 12 mm bar to a maximum 20 mm bar).

NOTE: Torsional resistance of ties is considered as zero as displacement is large and ties stretch excessively. It is better to add bracing than rely on torsional resistance.

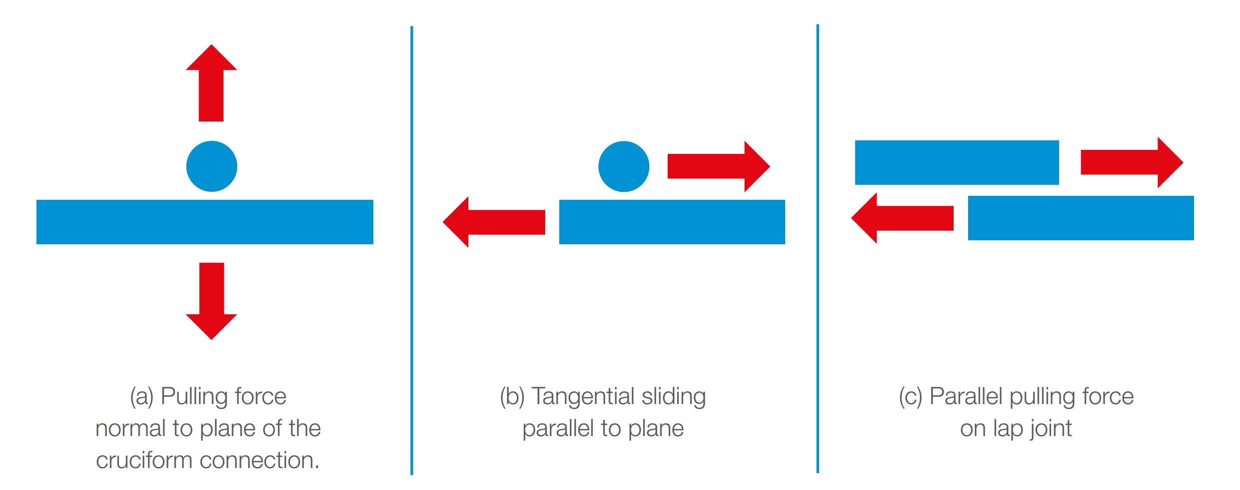


Figure 8 – Testing load application

NOTE: Torsional resistance of ties is considered as zero as displacement is large and ties stretch excessively. It is better to add bracing than rely on torsional resistance.

6.4.4 1.2 mm stainless steel wire has a tendency to unwind (as it is relatively smooth) at higher loads and this guidance recommends additional wire twists (see Figure 5) but no reduction in SWL when compared to 1.6 mm black annealed wire.

6.4.5 TWf developed testing apparatus and recently carried out a significant number of additional tests to better understand the behaviour and to justify the recommendations in this document.
A summary of the TWf tests results are presented in Appendix A (see https://www.twforum.org.uk/resources/rebar-tie-testing) and can be used to justify the recommendations published in this guidance.

Some simple rules to follow for tying:

1. Positional tying of slabs

Some simple rules to follow for positional tying of slabs, which are supplementary to BS 7973 [12]. Note that the positional tying of walls is covered in BS 7973:

- there should be some positive support to every bar, tying is required to prevent bar displacement during the concrete pour.
- set bars around each perimeter, usually with a "strong tie" (hairpin or crown).
- slash ties to be used on diagonal intersection lines (50d centres along the bar for 20 mm diameter bars and greater).
- where it is important to maintain bar alignment it is good practice to nominate "set bars" at 100d to 200d centres. Along the line of a set bar, every intersection is tied.
- splice bars: where base slab splices are touching, 1 tie in outer third of each end.
- where there is no direct contact at splice laps (in base slabs the bars are typically apart by one bar diameter – this is not the case in walls): secure by cruciform connection if there is obvious bar displacement under light load.
- where a base slab is built up of welded pre-fabricated mats or carpet mat reinforcement, it is usually permissible to reduce the amount of tying (as there is inherent rigidity especially in larger diameter bars).
- how to determine if bars are loose (not tied correctly and additional ties are required):
  - (i) bars to bar connections (laps or cruciform intersections) can move easily relatively to each other, when gripped between finger and thumb (for 10-16 mm diameter bars).
  - (ii) bars can be displaced by approximately 50% of bar diameter when pulled lightly with one hand (this could equate to around 5-8 kg of force). If bars are loose, they may displace when concrete is poured affecting cover and structural performance.
  - (iii) within a horizontal mat the individual bar ends at splices can move when walking over the cage on boards.
  - (iv) there is a lack of friction contact between the bars (friction helps keep the bars in place otherwise they can roll or rotate from foot pressure).
- Where there are multiple layers of reinforcement (3 or more), the ties should be wrapped around the adjacent bars. For example: Layer 1 to Layer 2 and Layer 2 to Layer 3. Wrapping ties around multiple layers increases the stretch in the wire and reduces the capacity of the ties.
- Connection to "rider or spacer bars" that connect main mat to the B dimension of a chair should be designed, including the spacing of chairs and number of ties.
- Add ties at starter bars, lifting points and any other highly stressed areas.

2. Structural robust tying of slabs and walls

Some simple rules to follow for structural robust tying of slabs and walls:

- method A – if testing is not carried out, then this document recommends a conservative SWL of 0.35 kN is used for all double wired ties, using either 1.6 mm diameter soft black annealed or 1.2 mm stainless.
- method B allows higher SWL for ties to be justified by on site testing and designers considering the risks and consequences of instability / failure due to larger displacements at tied joints. Higher tie SWL should not be used if a large cage is being lifted where the load is fully supported by the ties alone. The designer must set safe and realistic serviceability limits (displacement) to ensure ties cannot become excessively loose or snap under load.
- when specifying ties, designers should realise that numerous ties could be stretched, be loose, could break or be otherwise ineffective and allow for "safety in numbers" (provide sufficient ties and alternative load paths to ensure some redundancy due to ineffective ties - see Section 6.1 and 6.2 and Example 1) rather than just satisfying safe working load criteria (engineering judgement required).
- the consequences for cage failure can be high and the cost of additional ties is small and there should be sufficient ties to provide alternative load paths to prevent "un-zipping".
- cages should not be lifted from spliced tie connections regardless of factor of safety or from any bar in a layer where ties alone are required to support the cage during lifting – use full length vertical "carrier bars". This may require some changes to detailing (by agreement with the designer), otherwise, full length temporary works bars should be added.
- large cages in high-risk areas should not rely on ties alone.
- designers should avoid relying on a single tie – it is better to have multiple ties ('safety in numbers') and alternative adjacent load paths.
- each lap should have a minimum of two splice (1 pair) ties to provide robustness and prevent excessive displacement, e.g. during lifting and concreting operations.
- designers should provide alternative engineered connections (rather than ties can use bull-dog grips, bolted connections, couplers, welding etc) when one or more of the following occur:
  - (i) large loads are being resisted with little chance of re-distribution into other members.
  - (ii) the resistance load requirement at a bar connection exceeds 25 kN. This load limit is set for two reasons. Firstly, many ties are required to resist loads above this limit – economic balance. Second, it is less likely that loads above this can be re-distributed safely if this connection point deteriorates, e.g. through several load cycles during lifting and handling or repeated wind loading).
  - (iii) the intrinsic temporary stability risks are high and cannot be mitigated.

Non-Structural Positional Ties

Ties are not required to carry any significant load. Mainly required to hold a bar in place and maintaining cover until concrete has been placed. (see Section 6.1)

Tie capacity is not critical and a design is not required.

A simple visual inspection of ties required.

Structural Robust Ties

Where load paths are identified to transfer significant load through the cage and to ensure the cage remains safely stable and intact (e.g. during lifting). Tie capacity may be critical hence a design is necessary and tie capacity and displacement should be considered. (see Section 6.2)

Double (or more) wire ties to be used.

Method A

On-site testing cannot be justified.

A tie capacity value that is conservative (0.35 kN per tie) should be used. This tie value allows for a high factor of safety (typically around 8) and assumes negligible displacement.

Sites should employ a robust quality control and inspection regime (see Section 6.2.1.2 and Appendix B).

Method B

On-site testing can be justified.

A quality and consistency benchmark for tie workmanship can be established and an actual value for tie capacity can be determined by the testing.

A higher tie capacity value (than method A) can be justified by using a lower factor of safety (of 4). Designers need to carefully consider displacement (p-delta effects) in analysis and the tie SWL should be capped to limit displacement.

Sites should employ a robust quality control and inspection regime (see Section 6.2.2.1 and Appendix B).

This method should only be used by designers with relevant experience.

In all circumstances designers should consider 'SAFETY In NUMBERS' with ties

NOTE: See Appendix A.

Flowchart 1: Tie methodology selection

7.0 Detailed explanation of failure modes (Further to Part 1)

7(i) Cages can fail in a variety of ways depending upon size and shape and how it is moved or placed. When cages are lifted, individual bars may drop from the cage, or the cage may be unstable and/or break up due to lifting forces being imposed. All cages are subject to self-weight (including eccentricity and tolerance) and sway from buckling, accidental impact and environmental loads.

7(ii) Gravity acts on a cage throughout all stages of assembly and its temporary works life-cycle and its effect on the cage should be assessed by the designer. It is not widely appreciated by site personnel that cages can collapse under the action of gravity alone, without other external forces. Gravity is likely to cause a progressive 'creeping' collapse, which site personnel often do not recognise the imminent danger of this 'slow motion' failure mechanism, assuming the cage is merely 'out-of-plumb'. Freestanding wall and column cages are prone to vertical buckling (elastic instability) because the bars forming the cage have a high self-weight to slenderness aspect.

7(iii) The main causes of cage collapse are:

- vertical instability due to self-weight and eccentricity.
- applied horizontal loading from wind.
- Inadequate restraint at base of cage.
- accidental impact by crane or formwork.
- guy wires being tensioned to give asymmetric loading or wires being released incorrectly.
- inadequate construction planning including temporary frames to allow a cage to be safely assembled.

7(iv) Five main modes of failure are highlighted (Also, refer to [2], Part 1, Section 9):

- Failure Mode 1 – Out-of-plane bending
- Failure Mode 2 – Bending induced discontinuities (scissoring)
- Failure Mode 3 – Vertical buckling elastic instability (leading to bending)
- Failure Mode 4 – Vertical discontinuity sliding and buckling (at splices)
- Failure Mode 5 – In-plane side sway

7(v) Different types of cages - such as foundations, beams and slabs - are considered. Section 10 and 11 consider some specific issues for pre-fabricated cages which are transported, lifted and perhaps rotated into position

7.1 Failure Mode 1 – Out-of-plane bending ('Toppling over')

NOTE: See Part 1, Figure 3

7.1.1 Any initial out-of-plumb, off-set centre of gravity (overhangs, etc.) and vertical cage deformation can cause gravity to bend the cage. Tall thin walls and tall column cages, with small diameter vertical bars, can be flexible, so this mode is usually recognised in thin walls. Thick wall 'mattresses' with large diameter vertical bars are often considered to be self-supporting. However, this perception often cannot be justified and these walls are vulnerable to this mode of failure. It should NOT be assumed that traditionally tied u-spacer bars (normally positioned at 50 D spacing and assuming they are well tied) provide a composite action between the near and far faces of reinforcement in large wall cages. As such, it is not possible to consider such cages to be significantly more stable, unless composite action between the faces can be guaranteed (see Section 8.7). Designers should check the bending capacity for the most onerous combination of applied loading.

A simple rule to follow:

- if you cannot justify free-standing a single wall mat unsupported, then a combined "well-tied mattress using traditionally tied u-bar spacer bars at 50D centres" is equally unstable. A specific design should be carried out to justify composite action between the two faces of vertical reinforcement.

7.2 Failure Mode 2 - Bending induced discontinuities ('Scissoring')

NOTE: See Part 1, Figure 6

7.2.1 This occurs when the wall leans over due to applied loads. The lean sets up a scissoring action between the vertical bars joints, particularly at the splice with the starter bars where cantilever bending is greatest. When a load such as wind, accidental or out-of-plumb is applied the ties can break at the splice location. Cages with short starter bar splice lengths and insufficient tying are particularly prone to this mode of failure. Tall cages are vulnerable when several splice levels are introduced over the height of the cage. Shorter bars are sometimes specified by designers to limit manual handling, but the discontinuities could cause an increased risk of overall collapse unless temporary stability solutions are provided (e.g. external propping).

7.2.2 Mechanical splices (couplers) may be considered - these can be used to give full continuity - although they are not always a buildability or commercial preference. Early involvement with the designer may enable detailing of couplers to coincide with strategic framing members at designed centres (e.g. stiffened frames at 0.9 m centres). When specifying couplers, the dimensions of the coupler body must be considered by the designer, to ensure that concrete cover and the alignment of other bars meets the design intent.

7.2.3 It is critical that designers identify this problem by studying reinforcement drawings to identify splice discontinuities and eliminate the hazard if possible. If it is not possible to eliminate discontinuities, they should be highlighted on drawings as residual risks. Designers should identify the principal load paths required to carry tension and compression forces through the bars (generated by actions such as self-weight, wind, and impact). Based on these actions and load-paths, tying patterns should be developed which might be split into principal load paths for strategic framing members and secondary load paths involving the routine tying of individual bars. Robust tying of splice locations should be adopted. The designer should also consider the strategic use of couplers within the permanent works. For example, if primary support is provided by framing members at 1 m centres in a large cage, and the high loads cannot be resisted by tying alone, a coupler can be used at the framing member (e.g. 1 in 7 splices might be coupled, depending on framing member centres). Alternatively, specifically-designed temporary welded fabrications or mechanical clamping with bull-dog grips could be adopted at framing member locations.

Some simple rules to follow:

- designers should stagger joints in cages to eliminate a single plane of weakness (unless in walls where the stagger is more than the lapping of the bars).
- designers should specify robust splice tie arrangements.
- maximum bar length for pitching starter bars from horizontal to upright – 4 m for 32 mm diameter and 2 m for 12 mm diameter (these are realistic length that two fixers can stand vertically, and the bars can be self-supporting and allow for a staggered lap length). The supporting leg should be a minimum 1/3 of the starter bar length and securely tied to bottom mat at both ends (designers may be able to justify other dimensions by calculation).

7.3 Failure Mode 3 - Vertical buckling elastic instability ('Euler buckling followed by bending')

NOTE: See Part 1, Figures 4 and 5

7.3.1 Elastic instability due to slenderness (many cages are tall) and lack of bending resistance is the most likely mode of failure for freestanding cages. Even thick wall cages with large diameter bars have relatively little bending rigidity and this makes them prone to vertical buckling (elastic instability) under their own self weight (as bars have a high self-weight to slenderness ratio). Once the cage starts to lean over, then gravity acts on the deformed shape causing further deflection (P-Delta), eventually leading to collapse. This action acts in combination with Failure mode 1 and greatly reduces the resistance of the cage to bending (because the utilisation under compression is so high there is little remaining utilisation available to resist bending). Failure can also occur if external horizontal restraint is provided to a wall (e.g. propping or scaffolding). However, once the restraint is removed to allow formwork to be installed the wall can 'fold' under its own weight.

7.3.2 Cages spanning between lifting points can also buckle and bend under the action of gravity and due to compressive reaction from inclined slings. In practice, buckling is exacerbated by bar-to-bar eccentricities at lap locations and by 'out-of-plumb' tolerances. Tying together two parallel wall mats with traditionally tied u-bar spacer bars at 50 D centres does not increase the buckling capacity to any significant degree because:

(i) traditional u-bars are relatively flexible.

(ii) the u-bars need to be placed at extremely close centres to provide any useful additional stiffness.

(iii) the tied fixity and bend radius reduce the rotational and shear stiffness at the connection.

(iv) the weight causing buckling is cumulative; there may be twice as many bars providing rigidity, but the self-weight has also doubled so there is little net gain in resisting elastic instability (see Section 8.6 for further guidance on the use of u-bars).

7.3.3 Restraint created by transverse z-bars and diagonal longitudinal bracing in a slender wall cage can improve overall buckling resistance by providing 'truss action'.

7.3.4 Two sub-modes can be considered:

(a) The risk of buckling is increased if "Tirfors" and guy wires are used to provide restraint (their use is not recommended in this guidance). The inclined tensioned wires can be difficult to balance and there is a reaction (see [2], Part 1, Figure 10) which results in an additional compression force in the cage (additional to the cage self-weight).

(b) The deformed shape of an un-propped cantilever is shown in [2], Part 1, Figure 3. The cage appears to lean to one side but is actually taking up a buckled shape. Gravity acts on the deformed cantilever shape causing further deflection. As this gets more pronounced, the cage eventually fails in bending. This is progressive deflection, P-Delta – see Section 8.1.

7.3.5 The assessment of buckling is not straightforward due to the position of laps. Designers should be aware that this is the most common failure mode for vertical cages, especially for freestanding cages assembled with MEWPs, as there is no additional external restraint available. The initial out-of-plumb caused by elastic instability (vertical buckling) leads to a creeping failure as gravity acts on the initial cage deformation. The degree of fixity at the base of the cage, the distribution of self-weight and cage stiffness affects the buckling parameter.

7.3.6 A combined axial and bending capacity utilisation check should be carried out as follows (unfactored loads):

$$f_{ac} / P_{ac} + F_{bc} / P_{bc} <= 1 \qquad \text{Equation 2}$$

where

f_{ac} = calculated axial compressive stress

P_{ac} = permissible compressive stress

F_{bc} = calculated maximum compressive stress due to bending about both principal axes

P_{bc} = permissible compressive stress in bending

7.3.7 On long wall cages, it is also prudent to check the bending capacity of horizontal set or framing bars. This may be more important if using welded trusses at large centres.

7.3.8 The two main means of preventing elastic instability are: (i) to stiffen the cage; or (ii) to introduce intermediate lateral restraint. Cage stiffening is normally achieved by introducing framing members into the cage (typically by well tied z-shaped bars to form trusses). As little as 5 kg/m run of width along the wall (assuming a 10 m high cage and based on a structural analysis), is sufficient horizontal restraint to prevent out-of-plane side sway buckling under self-weight of a typical large wall cage. This demonstrates that a small amount of additional lateral restraint can prevent vertical buckling. Lateral restraint can be provided by external means, such as:

- propping (see Section 9.3.2); or
- tying back to a sufficiently rigid structure such as a designed scaffold (see Section 9.3.4); or
- by using sacrificial or re-useable kingposts or trusses (see Section 9.3.5). This, however, would not be sufficient to resists wind or other out of plane force and these should be considered separately.

Some simple rules to follow:

- if it is not possible for designers to eliminate slender cages, they should be identified as a residual risk with clear warnings on the reinforcement drawing.
- designers should specify the maximum unsupported height of a cantilever cage or specify the maximum unsupported interval between lateral tie in points.
- an early warning sign is out-of-plumb deflection or a slow swaying movement. If this occurs the work area should be cleared, with an exclusion zone being enforced. It may prove difficult to stabilise a swaying cage without putting operatives at risk and an option could be to use an excavator to 'push the cage over'.

7.4 Failure Mode 4 - Vertical discontinuity sliding

NOTE: See Part 1, Figure 6

7.4.1 This is slippage of the vertical lapping joints where the weight of the cage is supported only by the ties, which could slip under load, causing combined bending and bucking. Where there are several discontinuities (splices) in the height of the vertical reinforcement, the weight of the cage above the discontinuity is carried primarily by the tying wire splice connections. The risk is greatest at the starter bar location where the whole weight of the cage is being supported but consideration should also be given to intermediate laps within the height of the cage. If the spliced bar does not bear directly onto the concrete base or kicker, all the cage weight is carried by the splice ties. There is a high risk that splice ties may become overstressed by the combined effect of gravity and prying / scissoring induced by bending and buckling actions. Slippage of the vertical lap joints may be a creeping effect. The redistribution of loads throughout the cage may overload adjacent connections leading to overall failure.

7.4.2 Designers should be receptive to requests for on-site changes, e.g. creation of a number of discrete 'framing members' within a rebar assembly, substituting laps with mechanical splices or long bars.

7.4.3 Among the common issues which could exacerbate any tendency for slippage of vertical laps leading to weakness and instability in the cage are:

(i) buildability decision to eliminate or reduce the planned kicker height – when rebar has been scheduled to sit directly on a kicker of a specific height;

(ii) where the detailer has introduced vertical tolerance by elongating the starter bar and giving the splice bar a tolerance distance above the planned construction joint;

(iii) mitigation of manual handling by introducing multiple splices in tall cages;

(iv) using guy wires (especially when tensioned by Tirfors) and push pull props both of which may be provided to maintain stability, without considering induced compression (reactions) and resistance load-path through cage especially through splices and discontinuities.

7.4.4 Slippage of the vertical lap joints may be a creeping effect. The redistribution of loads throughout the cage may overload other adjacent connections. If there are insufficient connections overall, eventually, the joint is likely to fail. There is a high risk of splice ties becoming over-stressed through the combined effect of gravity action and prying/scissoring induced by bending and buckling actions.

7.4.5 A large cage (e.g. 10 m high, with 32 mm and 25 mm bars at 150 mm centres) would typically require at least 6 doubled wire splice ties to each starter bar lap. A cage of this size would be tied with doubled-wire, double-wrap splice ties (DWW). 3 DWW ties would be sufficient to resist the vertical load component at each splice. However, this guidance recommends at least 4 to ensure there is an equal number of ties in top and bottom thirds of the splice. It is also good practice to introduce horizontal set bars at the top and bottom of each splice. Where the splice is staggered, then 4 horizontal set bars would be used. Most fixers use 'ring slash' ties, at the cruciform connection between horizontal and vertical lapping bars, but for the heaviest bars doubled wire crown ties are significantly stronger. The splice ties resist the vertical load and the cruciform ties and carrier bars resist scissoring. The cruciform ties and set bars can also support the vertical weight component and carrier bars can act as a bridge to spread the vertical load through the cage. The splice ties, positioned in the outer third of the lap zone, can resist scissoring in addition to vertical load. The net effect of having both produces a robust splice with inherent redundancy, particularly at the starter bar location (see Figure 6).

7.4.6 Designers need to carry out checks on joint connections which could be tied, clamped or welded. Due to the complex nature of reinforcement cages (including workmanship issues, unknown connection, stiffness between bars and the eccentricity between lapped bars) it is common to use simplified analytical models and a permissible stress approach aligned to BS 5975: 2019, Section 3 [4].

Some simple rules to follow:

- designers should be aware that the more splices (e.g. for manual handling) in a vertical bar, the higher the risk of discontinuity/slip failure at the lap locations. In addition, there are additional cost implications with cutting, bending, handling time, fixing time and tonnage (laps), if a bar is split into several pieces.
- if it is not possible to eliminate multiple splices the designer should clearly highlight this residual risk.
- every splice should have at least two splice tie connections regardless of the weight of the cage, with additional splice ties being added to suit the weight of the cage.
- to recognise early warning signs of slippage (due to insufficient ties), large cages should be monitored by using 'tell-tails' in the form of pencil marks and levelling points across splice bar locations.
- framing members' can be used within the permanent works typically at 0.9 m to 1.2 m centres (wider centres are acceptable for mechanical splices and factory welded members). Where permanent works bars are used as framing members, mechanical splices (couplers) are used. If cover remains un-affected, then bull-dog grips can be used on the framing bars at splice locations or framing members can be introduced in the form of additional temporary works bars (e.g. single length bars or factory welded splice connections from a CARES approved facility). Robust splice tying arrangements can also be used to withstand the temporary design loads at framing members.

7.5 Failure Mode 5 – In-plane side sway ('Racking')

NOTE: See Part 1, Figure 7

7.5.1 This mode of failure is often overlooked because there is an incorrect perception that the cage is stiff in plane, due to the number of vertical bars tied together by the lacer bars. All cages are vulnerable to side sway due to horizontal loading. The tied connections between horizontal and vertical bars are pinned connections so there is, in fact, no in-plane 'diaphragm' resistance to sway and racking.

7.5.2 Beams and any slabs are at risk of collapse through sway and potentially buckling (Failure Mode 3). Operative working or accessing inside any cage should be avoided unless stability is proven by calculation throughout all stages of assembly. Fatalities have occurred because of sway failure, when fixers have been working inside the cage. Vertical bars should not be relied on to provide sway resistance and inclined props, cross bracing bars or z-bars with suitable fixity need to be incorporated to provide the necessary stability. A safe means of access and egress, including emergency evacuation procedure should be in place.

7.5.3 Every bar intersection is effectively a pin and the whole cage can sway and collapse, unless effectively restrained. Bars which are set normal to an incline can increase the risk of sway and cage collapse.

7.5.4 Sway and buckling deflection can occur if the vertical load is excessive and/or through any horizontal loading such as: wind, out-of-plumb in verticals, slight incline in base, accidental impact loads, concrete pumping line loading, landing and adjusting bundles of steel, un-rolling carpet mat reinforcement and live loading (operatives walking). Cages should also be checked for any applied horizontal loading plus a notional horizontal load (see Section 5.4), and sway should be checked in both directions (transverse and longitudinal to the cage). A horizontal 'set bar' can be positioned towards the top of the cage connected with doubled wire crown ties at each intersection with vertical bars. Face bracing bars or guy wires can then be provided for stability. If face bracing bars are used, they should be anchored into the slab beneath and robustly anchored with a 1 m long splice, to the horizontal set bar (see Figure 9).

Some simple rules to follow:

- Additional diagonal bracing bars or guy ropes can be designed and installed to provide stability. It is preferrable to install the bars on the inside of the cage to prevent compromising cover, but this can be difficult to achieve due to issues with safe access and placing long bars.
- Cage end bars for slabs and beams - not walls which utilise face bracing (see Figure 9) - could be designed to provide sufficient 'portal action' to resist sway. However. these bars would have to be fixed first to provide this stability.
- Consider the use of a sacrificial braced top mat support using scaffolding or similar.
- Vertical bars should not be relied upon to provide sway resistance. Generally, inclined props or z-bars with suitable fixity, should be incorporated into the cage to provide the necessary stability.

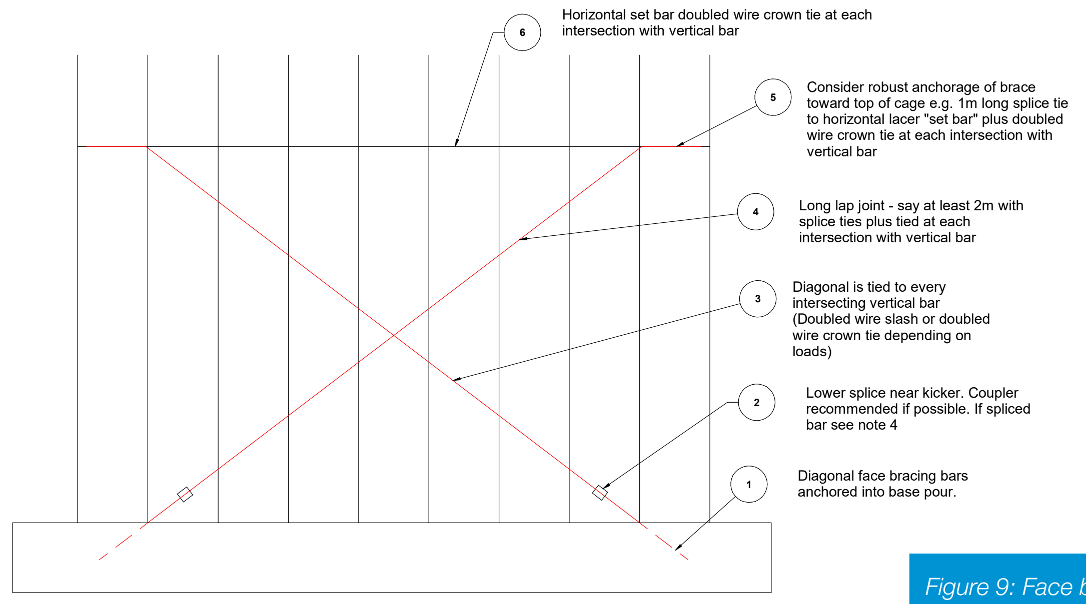


Figure 9: Face bracing

7.6 Other modes (and combined failure modes)

When a cage collapses, one of the five aforementioned failure modes often causes secondary and tertiary failure mechanisms. For example, a long wall may fail due to in-plane sway (Failure Mode 5), the initial displacement may lead to out-of-plane bending further along the wall. A combination of out-of-plane bending and buckling, followed by a discontinuity failure, may then occur. Another combination failure mode for large bar diameter, thick wall cages (incorrectly perceived as 'rigid' and 'stable') is cantilever buckling mode (Failure Mode 3), followed by progressive creeping deflection and then a bending (Failure Mode 1) or combined bending and discontinuity failure.

7.7 Section 10 and 11 discuss other failure modes which should be considered during transportation rotation and lifting.

8.0 Design methodologies

8(i) This guidance adopts the same approach for ensuring the temporary stability of cages as outlined in BS 5975 [4]. Different load combinations, states of restraint and structure stiffness can apply throughout a cage's temporary works life-cycle. It is important to carry out these checks for the various phases of assembly.

8(ii) BS 5975: 2019, Clause 19.4.1.1 [4] recommends four principal design checks (These checks are used for falsework but this guidance considers them appropriate for cages):

- Structural strength of individual members (including any framing members) and connections to transmit applied forces. Tied bar-to-bar connections of main load bearing members also need consideration.
- Lateral sway stability of the whole cage and individual members. Most vertical cages fail as a result of buckling induced side sway, whereas horizontal elements (slabs and beams) fail through racking/side sway as well as buckling of inadequate chair spacers.
- Overturning. Applicable to pre-fabricated and in-situ cages, caused by eccentric loading (e.g. corbels), accidental impact, or wind (in-situ cage is more likely to fail due to a loss of strength or lateral stability).
- Positional stability (sliding/movement). This does not usually occur when a cage is well tied to existing cast in starter bars (horizontal slabs or vertical wall starter bars cast into concrete). However, it could be an issue for cages which are stacked and transported. Slabs and beams can also slide at an interface with blinding unless restraint is provided.

> *"Within these four checks subsidiary checks may be necessary to allow for different phases of construction and carrying stability and restraint conditions. Restraint should be satisfied for all the above cases individually but not cumulatively". (Source: BS 5975: 2019, Clause 19.4.1.1)*

8(iii) Designers and construction teams should be aware of the potential modes of cage failure. Designers should eliminate failure mechanisms where reasonably practicable and clearly communicate any residual instability risks that remain which are to be addressed by the site team. Anticipating cage instability, having the knowledge to identify risks and prepare suitable temporary works design briefs is crucial. The site team must also know when to stop work and report unusual or unsafe cage behaviour. In this respect, cage deflection or any slow sway movement are two early warning signs of instability.

8(iv) This guidance recommends that the designer should undertake the following approach:

- study the structural form of the bars and consider assembly sequence (buildability).
- carry out a risk assessment to identify the key hazards and follow the principles of prevention by identifying and eliminating failure modes and ensuring stability at all stages in the life-cycle. The need for operatives entering the cage should also be eliminated if possible. If failure risks cannot be eliminated, then temporary measures should be designed and the risks clearly shown on drawings.
- justify the unaided stability of the cage at all stages in the life-cycle.
- if stability cannot be justified then design internal strengthening measures, or external stability measures to the cage.
- ensure inherent robustness and redundancy/alternative load paths to allow for tie stretch/failure.
- prepare an assembly/temporary works sequence which considers all stages in the life-cycle.
- some minimal internal bracing should always be included in cages (other than low risk cages which are considered to have inherent internal rigidity (see [2], Part 1, Figure 2 that shows a very low risk cage) and the desired base restraint conditions highlighted.
- the design output should indicate the anticipated deflected shape and set limits for any remedial action to be taken if these limits are exceeded.

8(v) Before carrying out a design the designer should receive a clear brief from the contractor, so that all parties fully understand the responsibilities, requirements and the forces that are to be considered. Good planning should identify:

- **Proposed layout**

  Position of joints both length and height with permanent works reinforcement drawings and schedules.

- **Construction method**

  Pre-fabricated or fixed in situ, limitations on lifting and preferred method of providing stability (including foundation options).

- **Site constraints**

  Environmental considerations including exposure to wind, physical restrictions due to site layout or working space and time of year the work is to take place.

8(vi) Designers should use engineering judgement to carry out analysis and design appropriate to the complexity and risk. The performance of a complex cage under load can be difficult to predict due to complex behaviour using a simplified structural analysis and more precise analysis is difficult and time consuming. There is also large variability in the construction due to differences between steel fixing techniques. The secondary effects caused by large deflection can also redistribute forces adding further complexity making it difficult to accurately predict realistic stresses in joints and members. Tied bar-to-bar connections, bar gaps and eccentricities give rise to second order (non-linear) effects. These need to be assessed when designing to limit state. The resultant of pulling components and shearing components needs to be considered when assessing the overall load on the ties at the bar-to-bar connections. Designers need relevant experience and should adopt a conservative approach with a high degree of redundancy. Robustness is the key to an effective and safe design.

8(vii) Complex analysis and design often cannot be justified (viz. not cost effective or timely) for a simple cage, where the designers costs could significantly outweigh the cost of any additional stability measures. Simplifying assumptions and design methodologies are often used in temporary works and these are moderated by adopting higher factors of safety or a conservative permissible design philosophy. This is particularly important when designing tied cages, given the variable nature of workmanship and non-engineered connections that may become loose when loads are reversed.

8(viii) Table 7 demonstrates two possible extremes:

Table 7: Design philosophies

3 m high x 10 m wide in-situ straight wall for a housing project on a green field site – where complex analysis and design would not be cost effective	Multiple 40 m long pre-fabricated diaphragm wall cages for major infrastructure project to be installed adjacent to live traffic where complex analysis and design is justified
• Simple hand calculations may suffice. • Consequences of failure are not severe. • Conservative assessment of impact and wind loading may be assessed by considering porosity of the cage. • On site testing of ties is not cost effective so conservative tie strengths are assumed. • Cage can be shown to be stable at all stages so additional temporary support measures are not required. • Generalised assembly sequence specified. • ‘Category 1’ design checking appropriate. • Minimal amount of on-site management and procedure required to manage the risks.	• Accurate assessment of cage weight and centre of gravity with splice details and lifting points required. • Finite element (FE) analysis may be viable. • Consequences of failure could be disastrous. • Comprehensive assessment of loads such as impact and wind • Tie testing regime established on site so less conservative tie strengths can be justified. • Numerous modes of failure identified. • Additional measures designed to provide stability and detailed assembly sequences specified. • ‘Category 3’ design check appropriate with peer review and external approval. • Significant amount of on-site management and procedure required to manage the risks.

8(ix) Temporarily supported cages subject to lateral loads are statically indeterminate structures. Determination of the resistance forces to lateral loads can be achieved by internal or external bracing, using established structural analysis procedures. The standing reinforcement cage can be idealised as a beam-column system, but the lack or rigidity in the cage complicates the analysis. It may not be practical to impose the requirement for structural analysis for all rebar cages and simple assessment or typical details may be appropriate for small rebar cages. Complicated or high-risk cages can be analysed a finite element method software package. 2D (assuming symmetrically placed braces/guys) or 3D analysis can be used to solve for the needed resistance forces in the selected internal or external support system. If the cage is assumed to be rigid, frame analysis may also be used.

8(x) The goal of the structural analysis is to determine the reaction forces at the temporary supports and at the connections. Understanding of the base condition of the structure is important in selection and design of the support system. Lap-spliced base connections (footing dowels tied to longitudinal bars) are idealised as pinned connections. Mechanically spliced base connections (with an approved mechanical rebar coupler) may be idealised as fixed. Pinned connections should be assumed if unspecified or unknown. It is common practice to perform the structural analysis based only on the gross geometry of the cage and constituent number and size of bars. Internal bracing added by a fabricator or rebar subcontractor is usually not accounted for and may improve the rigidity of the cage. Consequently, a conservative estimate of resistance forces needed in the support system may result.

8(xi) Composite action, or the transfer of shear between individual bars in the longitudinal direction, can increase the stability of a cage. The effective moment of inertia of a cross section with fully composite behaviour can be larger than that of individual bars. This document does not recommend relying upon composite action through ties between longitudinal and transverse bars, without the introduction of specific additionally designed measures such as z-bars (or similar). Complex modelling of each bar and tie is likely to be time consuming and may prove more expensive than the cost of providing any additional bracing bars. A simpler and more conservative model may be more efficient by considering the summed moments of inertia and areas of each individual longitudinal bars (i.e. transverse reinforcing and the ties do not provide any shear transfer and thus do not increase the stability of the cage).

8.1 Progressive deflection (P-Delta) and Joint deflection (P-Small Delta)

8.1.1 Except for simple and low risk cages (where cost and time cannot be justified for a complex analysis) the action of gravity on the deflected cage should be assessed by the designer. Any initial out-of-plumb causes the cage to lean over, the centre-of-gravity moves, gravity then acts on the deformed cage shape. This results in a progressive, creeping deformation, in turn causing more eccentricity and more deflection over time. Designers often call this ‘P-delta effect’. The cage reaches a point where the gravity action on the deformed cage causes excessive bending, exceeding the capacity of the bars or splice ties, at which point the cage collapses. The overall failure process may be over a significant period of time, i.e. the cage becomes increasingly less stable with time. This ‘P-delta effect’ is an important consideration when evaluating the stability of freestanding reinforcement cages, because under the action of gravity alone, it is likely to be the cause of a progressive ‘creeping’ collapse. Wind and impact loads may govern temporary stability, but they are not always present, unlike gravity which acts at every stage in the life-cycle of the cage. Site personnel often do not recognise the imminent danger of this ‘slow motion’ failure mechanism, incorrectly thinking that the cage is ‘a bit out of plumb’ and can be adjusted when the formwork is positioned.

8.1.2 This document recommends the following approach for designers:

- accurate evaluation of cage weight and theoretical centre of gravity at all key stages of assembly.

  NOTE: As a wall is assembled and more lacers are added, the height of the height of the centre of gravity increase which increases the susceptibility to P-delta effects.

- mark the theoretical centre of gravity on assembly sequence drawings and calculation check of elastic instability (Failure Mode 3) at each key assembly stage.
- allow for a basic out of plumb of at least 1:50 in the assembly process. Alternatively need to specify realistic allowable out of plumb on assembly sequence drawings.
- carry out second order analysis under gravity (large P-delta and joint deflection small P-delta).
- provide drawings with clear hazard warnings, describing expected deflection and unsafe lean out of plumb or deflection of cage (equally applicable to freestanding vertical cages, thick/tall base cages, and all cages being lifted).

8.1.3 When cage nodes (joints) distort this increases the deflection of the structure ('P-small delta'). Where the nodes of structural framing members tied with tying wire, the distortion at the nodes should be considered in the global deflection calculation (the overall magnitude from node displacements can be significant). Unless addressed through design, large cage deflections lead to buckling and bending failures.

8.2 Cage structure and deflection of truss-like structures

8.2.1 The structural form of most cages can be likened to parallel chord trusses, 2D-plane frame and 3D frames. Virtually all cages lack shear connection between the chords making them no more rigid than the sum of the individual bar stiffnesses. This is true of cages spaced with traditional chairs and u-bars. Designers can introduce z-shaped bars into the cage along strategic lines to stiffen the cage by introducing truss action. Figure 10 shows the basic terminology for a truss frame spanning between two supports. Similar terminology is used to describe the 'temporary works' structural framing members within cages. In large wall cages, wire-tied frames are typically spaced at 0.9 m to 1.2 m centres, with an upper limit of circa 1.8 m centres for moderate and smaller cages and loading. If welded, 'temporary works' frames are introduced which may be at greater centres, as determined by the designer.

8.2.2 The web elements comprise vertical post members and diagonal members. These space the parallel top and bottom chords. The posts do not contribute to stiffness unless their ends have a rigid moment connection to the chords. The diagonals contribute to truss stiffness and to be effective only require pinned connections at their joints to the chords which generally, are assumed to be continuous. Care must be taken to check that lapping bar discontinuities can transmit the axial loads and bending moments within the chord members. Where there is any doubt about this, a full-length bar can be incorporated into the frame, which can be an additional sacrificial 'temporary works' bar, making the temporary frame suitable for welding. It may also be possible to agree with the permanent works designer to substitute a full-length permanent works bar or a coupled connection at the location of strategic framing members.

NOTE: Permanent works bars should not be welded on site due to quality issues.

8.2.3 Excessive deflection increases the likelihood of progressive P-delta, bending and buckling failure. The risk of tie stretch and bar-to-bar connection failure increases with the magnitude of deflection. Truss deflection has two components:

- due to bending
- due to shear

$\Delta_{total} = \Delta_{bending} + \Delta_{shear}$ Equation 3

8.2.4 Shear stiffness normally governs the cage deformation behaviour. For this reason, composite inertia derived using the parallel axis theorem should not be used as the sole basis for assessing cage deflection behaviour. Cage shear stiffness depends on the form of 'web elements', and the relative movement of their connection to the chords. Shear deformation is governed by the axial stiffness of the diagonal web elements. The diagonals are less effective if any sliding occurs at their end connections to the chords. Where diagonals are fixed to chords with tying wire, some slip is likely. This increases the overall deflection of the cage and must be considered in the analysis.

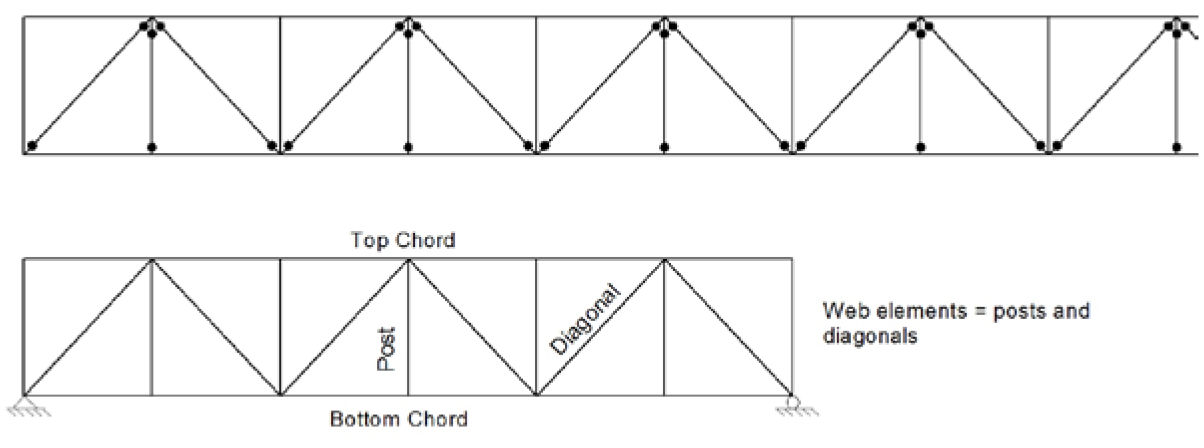


Figure 10: Truss terminology with cage orientated as a beam

NOTE: Lift and rotate wall cage from horizontal to vertical by introducing truss components to increase stiffness

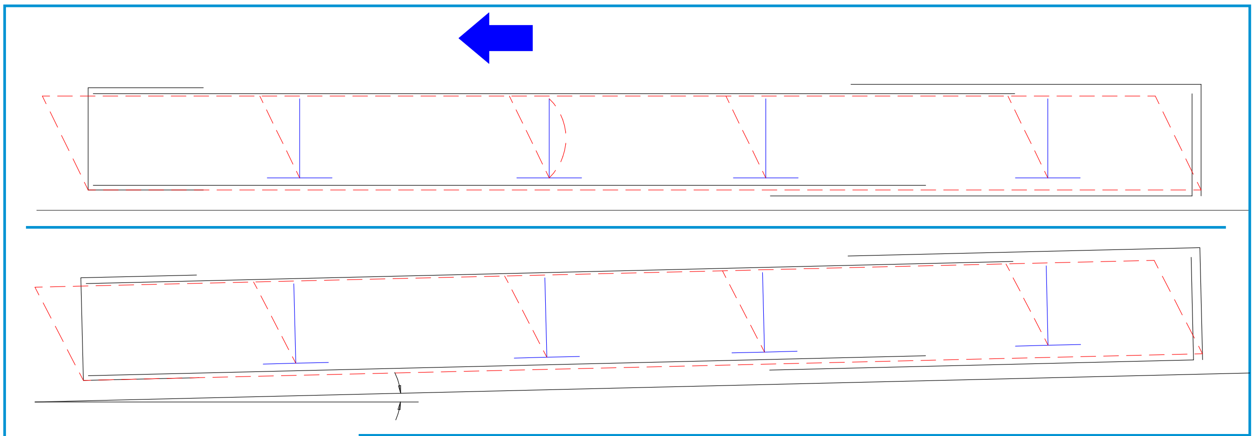


Figure 11: Sway effects and vertical buckling of chairs for horizontal and inclined mat

8.2.5 The stiffness is greatly affected by slippage occurring at the tied connection between bars. This is because the connection at these locations must be able to transfer forces between bars which are at an angle to each other – out of plane. The ties must carry a combination of (Figure 8(a)) pulling force normal to plane of the cruciform connection and (Figure 8(b)) tangential sliding parallel to plane of cruciform connection. Ideally the connection of the bars must be detailed so that separate sets of ties can take forces in separate directions.

NOTE: The connections are generally tying wire and hence the tying wire is being relied upon to transfer the horizontal and vertical forces.

8.2.6 The overall deflection is due to the axial shortening of compression members, lengthening of tension members and slip at member joints. Designers generally use a frame analysis software package to calculate member forces and deflection. Linear structural models assume that pinned or rigid member connections transmit forces at the nodes without relative movement. Tied bar-to-bar connections do not transmit load without some sliding, as it is necessary for the tie to go into tension to resist the connection load.

8.2.7 Example calculations are in Appendix I.

8.3 Horizontal cages ('mats') and chairs

NOTE: See Part 1, Figure 12

8.3.1 Horizontal cages typically comprise top and bottom longitudinal chord bars, with smaller diameter longitudinal side bar reinforcement enclosed with vertical shear links which are spaced at relatively close centres. A tied mat exhibits little truss behaviour due to the lack of shear rigidity.

8.3.2 The tied connections behave as pinned joints (rather than rigid with low stiffness and poor connection strength to chords) and can withstand little shear before sliding occurs under load. In a typical cage often the only web members are those introduced by the fixers on-site and these are normally in the form of light – u-shaped bars – used to space the mats apart. These form web post members, but due to their low stiffness, lack of end fixity (tending to be pin connections and are also prone to sliding) and large spacing within the cage, the spacers, shear links and chairs provide negligible resistance to shear deformation. Therefore, the cage stiffness tends to be no greater than the sum of the stiffness of the chord bars. So, for traditional tied cages:

$\sum I_{\text{chord bars}}$ Equation 4

8.3.3 Large/deep foundation, beam and slab cages, which are built in-situ, generally fail due to the insufficient support of the top mat (on chairs or similar supports), resulting in Failure Modes 3 and 5 and lateral instability. Sway and buckling can be caused by vertical loading from self-weight of bars, live loading, machinery, etc. and horizontal loading from: wind, accidental impact, out-of-plumb, inclined cages (even a small incline creates a notional horizontal load than can cause sway and collapse; see Figure 11), concreting pumping lines, landing/adjusting bundles of reinforcement bundles or un-rolling carpet mat. In deep sections (e.g. overall mat depth over 2.0 m) chairs may not be relied upon to prevent racking instability, unless z-bar bracing is used in both directions, however designers should justify their use for any deep section.

8.3.4 Fatalities have occurred because of sway failure when fixers have been working inside large base/beam cages. Operative entry inside any large cages should be avoided, designers should apply the principles of prevention and eliminate this hazard (where possible) by developing details such as temporary support within the cage, that maintain the structural integrity of the cage throughout the assembly sequence. Operative entry should only be permitted if stability is proven by calculation or suitable testing (allowing for horizontal and vertical effects) throughout all stages of assembly and safe access/egress/working area can be provided and emergency evacuation procedures are in place.

8.3.5 Chairs are required to maintain the depth of the section and should be sufficiently robust to support the weight of the top mat and any additional live loading and any temporary storage loads. The size of chairs required to support the top mat, is a function of the chair spacing (which depends on the size and strength of the top mat) and the weight of the top mat combined with the imposed load. Distribution steel running perpendicular to the lowest top mat bars, should be provided, as this prevents bars being suspended by tying wire and ensures all bars are bearing adequately onto the cover spacers. Figure 12 shows the standard bi-axially bent 'chair' from BS 8666, Shape Code 98 [16], which relies on the strut action of the vertical legs to support the applied loading and they can be susceptible to buckling/deformation. Often, smaller diameter bars are used (easier to bend/ adjust on site), they are installed by fixers, without calculation or engineering justification These small diameter bars also have poor resistance to sway (differential in plane movement of mats) and should not be relied upon to for lateral resistance to racking. Deep chairs can be particularly susceptible to buckling (Failure Mode 3) and sway from horizontal loads and they should not be considered for deep cages (over 2.0 m deep). There is a lack of understanding about how poor chairs are in preventing differential, in plane movement of mats, as is required to ensure that two mats can act together compositely. If they are used, then additional diagonal bracing is required between mid-points of chairs where maximum bending is likely to occur.

8.3.6 Shear links should not be relied upon to provide stability in the temporary condition, as they are effectively pinned and can still rack (unless the designer can design and detail otherwise).

8.3.7 Designers should consider the following aspects when designing 'chairs':

- Chairs should be designed so they adequately support the top mats of reinforcement and any additional applied vertical loads such as live loading, without excessive deflection of the top mat.
- Unless freestanding chairs are designed and used then inclined bracing bars should be provided for the erection of vertical chairs and they should not be removed. Safe locations for bundles of bars to be placed, should be at least two completed bays of steel chairs from an open end. Horizontal restraint bars in both directions are essential components to provide overall lateral stability to the steel cage. The restraint bars should be fixed to the main bars of the pile cap / slab and vertical bracing in both directions may also be necessary.

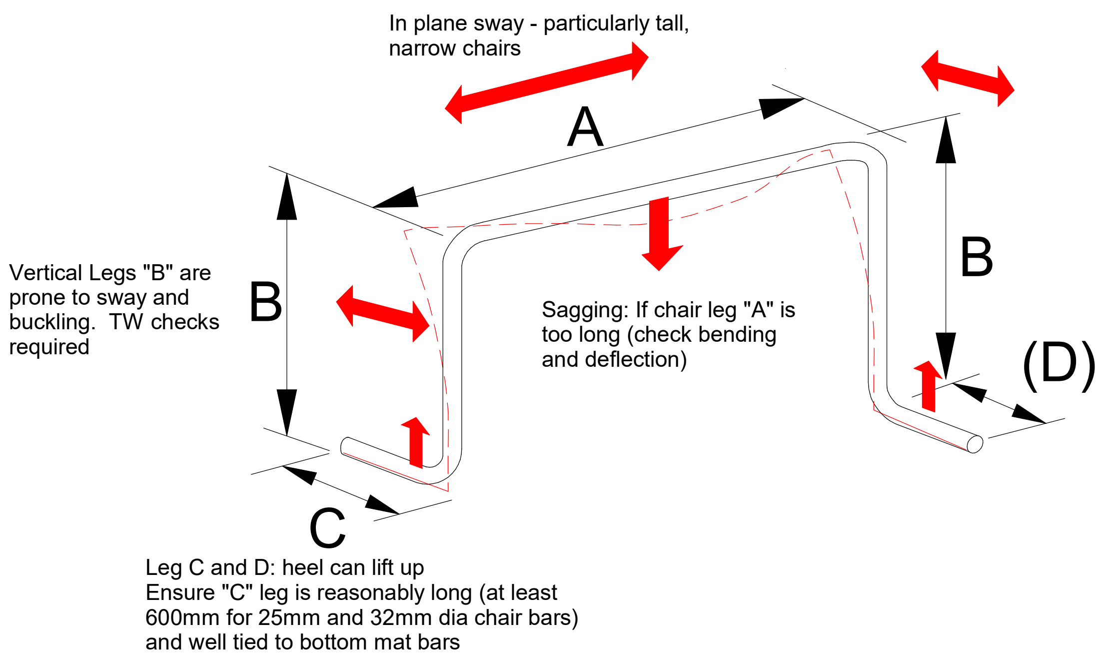


Figure 12: Failure Mode 3 (buckling), Failure Mode 5 (sway due to incline) and checks to be carried out on traditional chair supports.

- The ends of a horizontal slab or foundation cage can be designed to provide 'portal action' to resist sway and there should also be provision made for any possible on-site changes to details. This guidance recommends that any possible portal action of cage ends should not be relied upon to resist sway unless it is justified by calculation and /or testing and does not lead to congested detailing which is difficult to fix (could be better to introduce z-bars).
- Chairs should be designed for any applied horizontal loads with a minimum nominal horizontal load (see Section 5.4) and this should be applied to the top mat to give a lever arm. From Figure 12, the C and D dimensions should cover at least 2x the main bar spacing to give sufficient coverage across more than one bar.

8.3.8 Designers should be aware of the hazards associated with 'carpet mat' (rolls of reinforcement). They are a significant concentrated vertical load (especially when landed on timbers) and can cause buckling of chairs and when being 'unrolled' they exert horizontal dynamic forces which can also cause sway. This document recommends that the horizontal component should be calculated as 10% of the weight of the carpet mat.

8.3.9 Z-bars with suitable fixity should be introduced to limit sway especially for cages which exceed 1m thickness or if access for operatives into the cage is required. If the cage exceeds 2 m in depth, sacrificial structural steel members or scaffolding is recommended by this document and adequate foundations are required.

8.3.10 Table 8 and 9 are based on Shape Code 98, Grade 500 reinforcing steel with a load factor of 1.5. They are based on a vertical load causing bucking with separate horizontal support introduced into the cage to resist sway. For maintaining the separation of mats in thinner slabs, continuous wire chairs are useful. The edges of slabs and walls also need support close to the end of the wall or stop-end.

Table 8: Ultimate capacity of chairs per leg under vertical load, $P_{ULTIMATE}$ (kN)

Depth between mats (mm)	250	500	750	1000	1250	1500
H12 leg	12.7	3.4	X	X	X	X
H16 leg	36.8	10.6	4.9	X	X	X
H20 leg	79.4	25.2	11.7	6.7	X	X
H25 leg	Y	59.1	28.0	16.1	10.5	X
H32 leg	Y	Y	76.4	44.0	28.5	19.9

NOTE: Based on effective length equal to 1.5 times the mat spacing to allow for some applied moment

X indicates element is too slender; Y indicates a dimension that is too small to bend.

Table 9: Working capacity of chairs for pair of legs under vertical load, $P_{WORKING}$ (kN)

Depth between mats (mm)	250	500	750	1000	1250	1500
H12 leg	16.9	4.6	X	X	X	X
H16 leg	49.1	14.1	6.5	X	X	X
H20 leg	105.8	33.6	15.6	8.9	X	X
H25 leg	Y	78.8	37.3	21.5	14.0	X
H32 leg	Y	Y	101.9	58.7	38.0	26.5

NOTE: Based on Shape Code 98 with dimensions C and D = 500mm; B to suit cage and A to suit bending capacity of chairs under load applied from distribution bars (typically 150 to 500 mm))

Capacity is 2 x $P_{ULTIMATE}$ / 1.5

X indicates element is too slender; Y indicates a dimension that is too small to bend.

Some simple rules to follow:

- The applied vertical load to the top mat of a horizontal cage should be taken as a minimum of 0.75 kN/m^2 (for inspection and fixing) and unless specific loads are calculated for simple cages should be taken as a maximum of 5 kN/m^2 (for storage of light bars and general construction equipment).
- Traditional chairs should not be relied upon to resist sway and bracing bars (z-bracing) or end portal bars should be provided to prevent racking for horizontal cages. This should be done for all cages more than 1 m deep or if operative access into the cage cannot be avoided. Sway should be checked in both directions (transverse and longitudinally to the cage) and check for tension/compression discontinuity (lap failure) when transmitting loads to z-bars and or end-portal bars. The likelihood of slab cage instability increases in proportion to its depth, top mat weight and incline.
- The effective length of a chair strut is considered as 1.5 times the distance between the mats.
- If the height of the chairs exceeds 1 m then a buckling design check should be carried out and they should not be used if their height exceeds 2 m (steel sections or props should be used).
- The top horizontal section of the chair could fail due to a centrally placed point load from distribution bars. The bending moment needs to be considered in this section based upon the length (dimension A, Shape Code 98) and a moment of PL/8 for an encastre member with a mid-span point load (see Table 8 and 9).
- Chair centres should not exceed 50x the supported mat bar diameter to prevent excessive deflection of the top mat and should be staggered to ensure a row of chairs does not pick up a single bar (unless there is a specific tolerance requirement for the bars where the lever arm of the slab is critical).
- The chair feet (bottom horizontal) should be long enough to span 3 bars, with an allowance for the bend radius to the chair.
- Chairs should be stood on the uppermost of the bottom mats and they should be orientated to provide a robust load-path through the supported bars, lower mat and cover blocks. Tying wire in tension should not be relied upon to provide the principal load bearing solution.
- Additional chairs should be added beneath areas of load concentration (e.g. loading out areas) to help spread the load.
- When unrolling 'carpet mat' a dynamic horizontal component should be applied of 10% of the weight of the carpet mat to the top mat of the cage.
- All cages should be checked for a notional horizontal load (see Section 5.4).
- If a slab foundation/cage is on an incline there is a component of the vertical load acting horizontally. This component should be calculated but should not be less than a nominal 2½ % of the total vertical load.
- Closed links should not be used as top mat bars need to be 'threaded through' the closed links, which is difficult to do and can impose additional horizontal loads. Overlapping u-bars are an alternative as they allow the top longitudinal bars to be placed first and supported on chairs.

8.4 Kickers and starter bars

8.4.1 Starter bars extending from kickers should be long enough to ensure adequate bond length but also consideration should be given to applied loading in the temporary condition. Where possible, vertical bars which are being spliced to starter bars, should rest on kickers or the slab beneath. This is to prevent possible slippage of the ties which are supporting the weight of the cage above (see Section 7.4). Bar diameters may need to be increased to ensure stability of the cage above the starter bars from horizontal and vertical loading. Consideration should also be given to how the cage is connected to the starter bars so that sufficient support/resistance is provided at the connection.

8.4.2 Designers should be aware that on occasion sites may use 'kicker-less' construction, in which case the weight of the cage supported on wire ties alone which may be inadequate. This risk could be addressed by the designer by increasing the length of the bars, so they are directly supported by the slab beneath.

8.5 Vertical cages

8.5.1 Vertical cages (e.g. for walls and columns) normally consist of two separate faces of vertical and horizontal bars and tend to be slender, flexible structures with little rigidity and freestanding cantilevers being particularly prone to vertical buckling under their own self-weight (elastic instability (Failure Mode 3); see Figure 13). Vertical buckling of a unpropped cantilever cage results in a small side sway at the tip of the cantilever, it appears the cage is leaning to one side but is taking up a buckled shape (see Section 8.1, P-delta effects). The degree of base fixity, distribution of self-weight and stiffness affect the buckling parameters. Tied lap joints in the vertical bars becomes over-loaded and contribute to the overall failure mode. The risk of buckling increases if guy wires (especially with Tirfors) are used to provide restraint because the loads could be out of balance on either side of the cage and there is an induced compression from the inclined wire reactions.

8.5.2 The bars in each face may have different spacing and diameter depending on the design (asymmetric moments, corbels, earth retaining structures). The diameter of the vertical bar may even increase with height (on a bridge where the pier or abutment is integral with the deck). The faces of the reinforcement may be connected by traditionally tied u-spacer bars, stirrups, shear links or blast links which may appear to improve rigidity. Designers should consider if they can be relied upon as there is no specific evidence to justify this unless a bespoke design is carried out (see Section 8.6). Single face reinforcement is particularly vulnerable to instability as adjacent vertical bars do not behave compositely. This is a conclusion of full-scale testing carried out on behalf of the Health and Safety Executive [17], whereby: *"if a wall panel behaved compositely then significantly higher forces than those measured would be required to cause substantial deflection and hence it can be concluded that the cage does not behave compositely to any significant extent. Also, that wind gusts of speeds 4 to 7 m/sec (9 – 15mph) were capable of exerting forces on the cage which were significant in relation to its ability to resist side loading".*

8.5.3 Unless the bars are specifically designed (and the ties detailed) to create a trussing action, they do not improve rigidity and are effectively pinned at the ends and hence contribute little or nothing to the overall cage strength and each face should be considered separately (see Table 10 for freestanding heights and Section 8.6). Stability may be provided by external support as described elsewhere but if no external support is present, the reinforcement is cantilevering from the foundation. The strength of the cage in cantilever is due the moment of resistance of the bar and the axial load carrying capacity of the bar where it enters the foundation (this assumes that the lap joints have sufficient strength).

8.5.4 The ultimate elastic moment capacity depends upon the ultimate strength of the steel and the cross-sectional properties of the bar:

$$M = Z . F_y \qquad \text{Equation 5}$$

where:

Z = section modulus

F_y = ultimate tensile strength of steel

8.5.5 The axial compressive capacity depends on the height of the bar, the cross-sectional properties, the modulus of elasticity, the end conditions and the axial load applied to the bar. If the bar is sufficiently slender it fails by elastic instability and in this case the maximum stress the bar can sustain is significantly less than the yield stress of the material. Commonly wall reinforcement is fixed, starting with the verticals bars and then attaching the horizontal lacers working from bottom to top. This has the following effects:

- as more horizontal bars are fixed, the vertical load is increased.
- the height to the centroid of the self-weight increases.
- wind force increases as the area of bars increases and height to centroid of the wind force also increases.
- the wind moment increases as does the deflection.

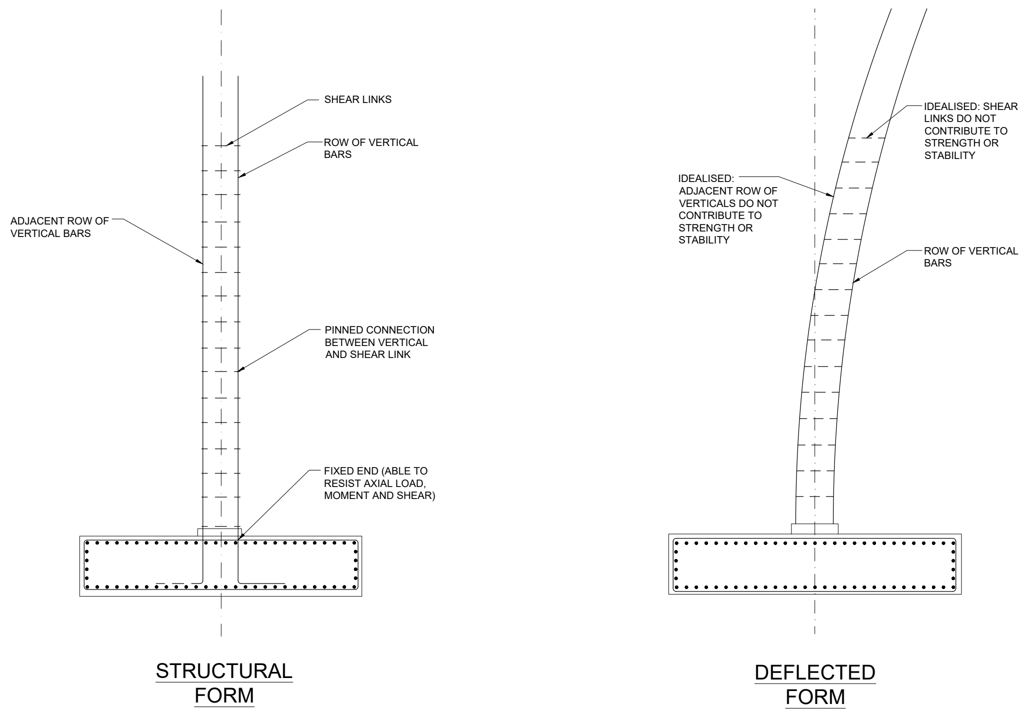


Figure 13: Wall reinforcement cantilevered from its foundation

- as the bar deflects further in the wind and the height to the centroid of the self-weight also increases, the moment due to the eccentricity of the self-weight increases.
- as the weight applied to the vertical bar increases, the utilization due to axial load increases and the capacity available to resist bending moment before collapse decreases. This reduces the wind load, notional horizontal load, or out-of-plumb which the wall can withstand before it becomes unstable.

8.5.6 These elements can fail by the shape not being maintained and by overturning if the connection to the starter bars is insufficiently robust. Maintaining shape is often problematic, as the stiffness of the element comes entirely from the connections between the bars and the links. Tying of the reinforcement becomes critical, particularly if the element is to be lifted. Pre-fabricated pile and diaphragm wall cages often have shaped templates within the cage and bars are welded to these to provide some additional integrity to the cage.

8.5.7 There may be discontinuity at lap positions, bending failure of bars, axial buckling, in plane racking (side sway). Strength of the bars in cantilever is due the moment of resistance and axial load carrying capacity of the bar where it enters the foundation (this assumes that the lap joints have sufficient strength). The failure mechanism for vertical members tends to be by the failure of the spacers between the faces leading to the mats separating and acting individually, causing a reduction in the section resisting overturning. Also, the ties between the starters and the cage can fail.

8.5.8 The presence of L-bars as starters or corbels at the top of the element (see Figure 14), introduces an eccentric load, significantly decreasing the stability of the element. They can induce elastic instability (buckling) and increase out-of-plane bending. Designers should consider the effect of combined buckling and bending (as well as second order effects due to eccentricity of loading) and develop a suitable construction method.

8.5.9 The strength of wall bars relies on effective length and elastic critical buckling. It is just as important as wind loading on the cage. The axial capacity of a bar depends on its height, cross sectional properties, modulus of elasticity, end conditions and axial load applied to the bar. If the bar is sufficiently slender (e.g. for a tall wall) it fails by elastic instability. In this case the maximum stress the column can sustain is less than the yield stress of the material.

8.5.10 The axial capacity of the bar is based on Roark [18]:

$$(p \times H) = K \pi^2 E I / L^2 \qquad \text{Equation 6}$$

where:

- axial capacity is defined as the load at which elastic instability occurs.
- K is given in Figure 15.
- for vertical wall reinforcement with uniform straight bar under and end load ‘P’ and uniformly distributed load ‘p’ over lower portion of the length
- applied load ‘P’ = 0 and weight of bars = ‘p’ and height distribution H/L = 1 gives K = 0.795 (a negative value for P / p x H means the end load is tensile):

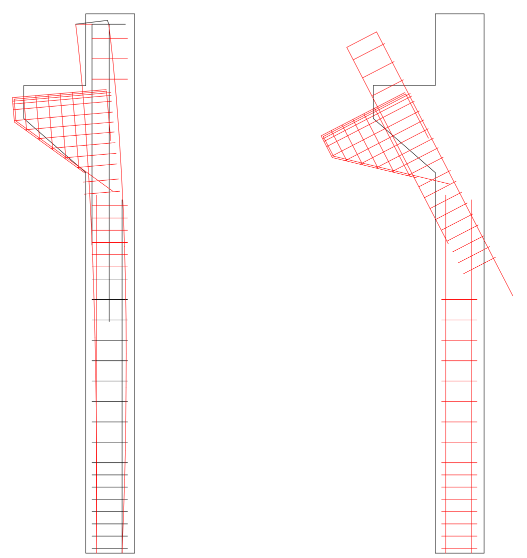


Figure 14: Corbels inducing instability

End conditions	Upper end free, lower end fixed			
a/l \ P/pa	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1
– 0.25		11.31	5.18	2.38
0.00	12.74	3.185	1.413	0.795
0.25	0.974	0.825	0.614	0.449
0.50	0.494	0.454	0.383	0.311
1.00	0.249	0.238	0.218	0.192

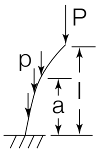


Figure 15: Roark (Table 15.1 .3a.)

8.5.11 For vertical wall reinforcement with lacers fixed all the way up to the top, l = 1

If the vertical load at the end of the bar is zero, then P = 0

Weight of bars is p and height of bars is H

Therefore: P / p x H = 0 / (p x H) = 0 and H / l = 1

This gives K = 0.795

This is determined by load distribution within the member and the end restraint conditions i.e. elastic cantilever fixed at one end with uniformly distributed axial load

Therefore, axial buckling capacity of bar = (p x H) = $0.795\,\pi^2\,E\,I / L^2$

8.5.12 These are 'ultimate' capacities so suitable factors of safety should be used (this guidance recommends a minimum of 2.0).

8.5.13 A deflection check should be carried out including second order P-delta effects (especially gravity acting on the deformed shape). A further check should be carried out to ensure the centre-of-gravity of the cage remains in the middle third of the cross section to prevent overturning. The distribution of weight throughout the cage should be accurately assessed or conservative assumptions made.

8.6 Vertical cages and horizontal mats connected with u-bar spacers

8.6.1 Where the u-bars are traditionally tied and spaced (used as spacers at 50D centres and not specifically designed otherwise), the cage should be analysed as two separate mats with pinned connections (Figure 16) as there is no evidence that any composite 'truss action' is achieved in practice. The flexural stiffness of the cage is equal to the sum of the bar stiffnesses.

$I_{cage} = \sum I_{vertical\ bars}$ Equation 7

8.6.2 In the case of a freestanding wall cage, the vertical bars are the structural members, acting as cantilevers. 'Lacing' the vertical bars together with the horizontal reinforcement does not increase the resistance to out-of-plane bending, buckling or in-plane sway. The horizontal bars are an additional vertical load acting on the vertical bars and attract additional wind load.

8.6.3 BS 7973 [13] is silent on chair requirements for wall cages greater than 400 mm thick and is geared to light wall reinforcement (fabric mesh and continuous 'vertical deck chairs' at 1000 mm centres). The explanatory notes below Figure 16 highlight that composite action cannot be assumed for traditional tied u-bar spacer chairs at 50D centres, of unspecified diameter and

Some simple rules to follow:

- Slender cages should be identified and checked with the maximum unsupported height of cage or the maximum unsupported interval between lateral tie in points specified.
- The maximum allowable deflection of a vertical cantilever - where second order effects (P-Delta and joint slippage) are included in the analysis is – L / 60.
- If a less accurate analysis is carried out (e.g. using simplifying assumptions; hand calculation; first order analysis without P-Delta effects) the maximum allowable deflection is – L / 100
- Designers should be aware that adding traditional u-bar spacers have little effect on increasing stability but adding z-bars can provide a trussing action providing adequate design is carried out and connections can be made.
- Designers can introduce the ability to fix corbel reinforcement without the reliance on long anchorage of bars into previous pours. Corbel reinforcement could be fixed at the soffit of the underside corbel, which provides a safer solution for the overall stability, helps with access provisions and thus improving accuracy of construction.
- Racking of a wall cage can be prevented by:
  - o cage restrained by tying against a stiff diaphragm (e.g. formwork).
  - o provision of additional sacrificial diagonal bracing bars – preferably on the inside to prevent compromising cover).
  - o provision of stiffened sections in face and or in plan of wall.
  - o external propping to the end of cages or tying to horizontal starter bars protruding from an adjoining concrete wall/permanent structure. This may not be suitable for long wall cages as they may buckle in the length of the cage in plan.

unspecified ties. Even if 20 mm diameter u-bars are provided in both directions at 50D centres in both directions, gives insufficient Vierendeel trussing action.

8.6.4 Vertically orientated u-bars can be used to enhance the overall rigidity of two separate faces of wall reinforcement by developing composite action (Figure 16(d)) and this can be used to enhance the temporary stability of the vertical wall cage. However, this would have to be justified by specific design calculations, with emphasis on the vertical u-bar to vertical cage bar connection. The moment generated should be within the capacity of the bar and the legs need to be adequately secured to the vertical wall bars to provide portal action.

8.6.5 The designer should consider the following:

- the structural form of the stiffening element is likely be a vertically orientated Vierendeel truss which can be assessed in a 2D frame analysis.
- to develop this form of truss action, u-bars tend to be large diameter (when compared to those used merely for spacing and sometimes taken as the same diameter as the main cage bars), to provide the necessary bending and axial rigidity.
- to act effectively as Vierendeel web elements, the u-bars are likely to be required at close centres (when compared to those used merely for spacing).
- for a freestanding cantilever wall, the shear and bending is larger toward the bottom of the wall and the u-bar spacing and distribution is likely to be more concentrated in this zone.
- the design of the connection between the u-bars and the wall leaf is critical. Fixed end moment connections are required between the web elements (u-bars) and the chords (vertical wall bars). Joint slip at laps in the chord lengths also needs to be considered.
- the designer needs to take account of any slippage and rotation (rotational stiffness) at the tied connections in the structural analysis, as they are likely to have a significant effect on the performance of the truss. Tied bar-to-bar connections, need careful consideration in the structural analysis (often this can be the limiting factor) as bar-to-bar movement and rotation can occur at relatively low load.
- the effects of larger bar diameter bending radii, and bar-to-bar eccentricity needs consideration, particularly where the connection is relatively weak (e.g. tying wire).

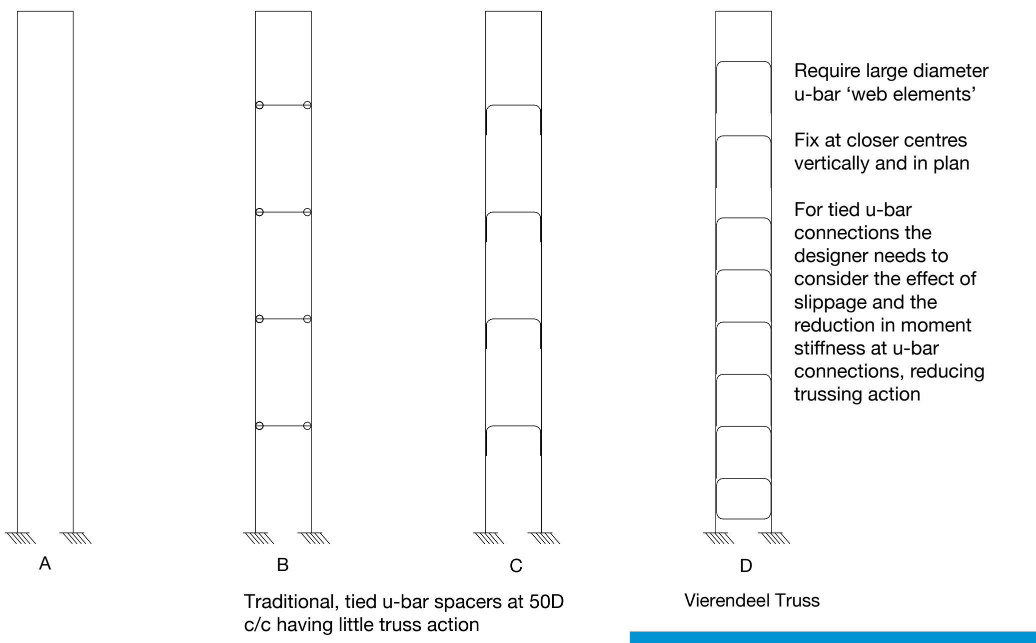


Figure 16: Freestanding wall cage with u-bars

Where: $EI_A = EI_B = EI_C$
A = as-detailed permanent rebar (temporary spacer bars to be added by contractor)
B = traditional spacer U bars tied horizontally (spaced 1.2 m x 1.5 m using a maximum 50D spacing)
C = raditional spacer U bars tied vertically (spaced 1.2 m x 1.5 m using a maximum 50D spacing)
D = composite action with specifically designed u-bars and ties to create Vierendeel truss

8.6.6 To reduce the risks associated with joint rotation and slippage at tied u-bar connections, sacrificial temporary works welded frames can be introduced, comprising of full height chord bars and welded u-bars. The welded temporary works member would be tied into the cage (with a significant number of splices at the starter bars). Designed welded bar connections should not be carried out on site, as a high degree of quality control and operative skill is required, and these are almost impossible to achieve in a typical site environment. If quality control procedures and workmanship are not implemented on site, there is a high risk of changing the metallurgy of the permanent works steel leading to brittle failure at small loads, which can render the bars useless.

Simple rule to follow:

- There is a perception that when two mats of large diameter reinforcing bars are joined together by traditionally tied and spaced vertical u-bars (see Figure 16(c)), they become significantly more stable. This perception is not correct, as connecting the two faces with tied u-bars does not increase bending resistance and the cage effectively behaves as two independent leaves and not as a truss. This is because:
  - (i) tied connections do not generate sufficient shear resistance.
  - (ii) the u-bar stiffness is small compared to the sum of the vertical bars.
  - (iii) tie stretch and tie location (offset by bend radius of the u-bars) leading to joint rotation.

To develop composite action of the two vertical faces a specific design would be required (see Figure 16(d)).

8.7 Walls with z-bar frames forming trusses

8.7.1 Figure 17 shows tied diagonal bars; trusses typically at 900 mm to 1200 mm centres, so as not to overload tied connections.

8.7.2 Tied diagonal 'truss' assumption: use the lesser of:

- 3 vertical bars mobilised at each truss chord (and check splice strength).
- Single vertical bar chord and stiffness of other bars.

8.7.3 Welded trusses which are manufactured off site and can be placed at greater centres based on span of lacers and strength of truss.

8.7.4 Wall buckling and bending can be assessed as follows:

$I = (I_{\text{truss 1 chord bar}} + \Sigma I_{\text{other bars}})$ over the width between the truss centres

or

$I = (I_{\text{virtual truss}})$ assuming 3 bar chords are mobilised at each z-bar frame set.

8.7.5 z, w or 'question mark' bars could all be used, and the principle is that these bars have legs that are spliced to the vertical wall bars. Assuming a minimum of 20 mm bar, then the bend radius needs to be considered to allow for a splice length between 400 mm to 700 mm.

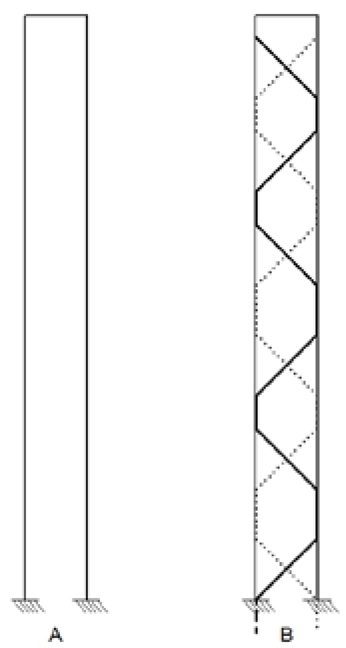
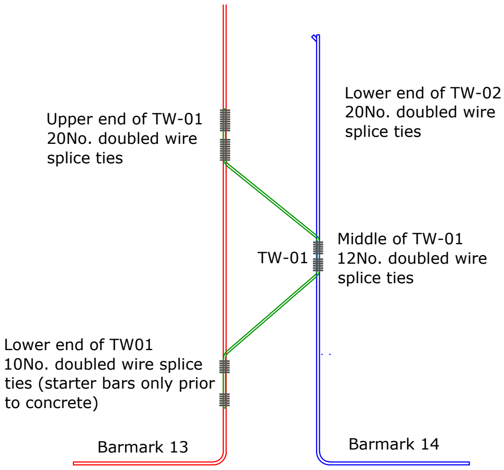


Figure 17: Walls with z-bar frames forming trusses

where: $EI_A < EI_B = EI_A + EI_{TRUSSES}$

NOTE: Highlighted is a Shape Code 46 (SC46) 'temporary works' stiffening bar, with multiple splice ties connecting opposing faces of the permanent works rebar to provide 'truss action'.



NOTE: To provide 'truss action' Barmark TW-01 (SC46) must be rigidly connected to both Barmarks 13 and 14. This is shown achieved using doubled wire, wrapped splice ties distributed along the parallel splice legs.

Figure 18: Walls with z-bar frames forming trussesforming trusses

8.7.6 In Figure 18 the splice tie arrangement looks excessive compared to a typical splice. However, it is required to carry significant load (sometimes approaching 3 tonnes). Under loading, it is important that ties do not stretch causing bars to become loose. The extra time and work involved in providing robust splice ties to diagonal bars is minimal compared to the consequence of failure.

9.0 Design of stability solutions

9(i) The temporary works solution concept is developed by studying the cage form, which enables the designer to identify weaknesses, discontinuities, potential failure modes and any other key risks. When these are understood, the designer can determine appropriate solutions which describe key load cases; load paths; type of framing members needed; cage and tying zones requiring design etc. Part 1, Section 10, of this guidance [2] highlighted possible stability solutions. Designers should consider the stability of the cage at every stage in its life-cycle, to determine the most critical condition and justify their choice of stability measures. Providing cages with support often presents a number of practical problems, e.g. finding suitable support points or obstructing the installation of formwork. Table 12 provides a summary of the options.

9(ii) This guidance recommends that designers consider stability solutions in the following order of preference:

(i) justify the cage is stable at all stages in its life-cycle.

(ii) if cage stability cannot be justified, then re-design the cage or amend assembly details (develop framing members, robust tying and positive load paths).

(iii) design engineered connections or additional sacrificial members/connections to provide stability.

(iv) design external support measures to provide stability.

9(iii) In addition to calculations, risk assessments and drawings, a designer should provide details of construction sequence (cage assembly plus details and installation / removal of temporary works) and details of any assumptions (plus how they are to be confirmed) and any on-site testing / verification. The designer should consider support to each of the bars and highlight any critical hold points introduced on site (when fixing should be halted until further defined means of temporary support has been introduced.

9(iv) Drawings should include information on the required size, type and strength of tying wire, tying patterns, bending schedule for any additional reinforcement, points and means of support, foundations and interface with follow-on works such as fixing shutters and concreting.

9.1 Justifying the cage Is stable

9.1.1 The starting point for any designer is to justify the stability of a cage (is inherently safe) without any additional measures. Any assessment must consider the loads, deflections, buckling and consequences of failure. If stability cannot be justified, then further measures should be designed to ensure safety. As mentioned previously the stability depends upon the height of the bars above kicker level, the spacing and diameter of the vertical bars. Double-face mats also become unstable above a certain height and require additional measures to ensure stability.

9.1.2 The construction sequence and method of working should ensure that the formwork follows the fixing of reinforcement as closely as possible. Wherever possible the fixing of reinforcement should generally commence or terminate at corners or return walls, which normally provide additional rigidity to the cage. If external temporary measures are required, then consideration should be given to the method of supporting the formwork which is subsequently installed.

9.1.3 A design check should be carried out on a cage if:

- the free-standing height of the cage is greater than the heights specified in Table 10 (see 'ASSUMPTIONS' and 'WARNING').
- the cage fails to meet 'normal custom and practice' as described in Table 11.
- the consequences of the cage collapsing are high (e.g. collapsing onto a railway).
- a relatively large or heavy pre-fabricated cage is to be lifted into position (determined by weight, shape and size by risk assessment) and specific lifting points and attachments are designed.
- the chairs in a slab / foundation cage are greater than 1m high.

9.1.4 Table 11 lists the characteristics of normal 'custom and practice' in the UK. Departure from these characteristics would tend to invalidate a reliance on experience as to the safe free-standing height of wall and column rebar. So, if the criteria in Table 11 are not met, the temporary stability should be given specific, engineering, consideration regardless of height.

9.2 Redesigning the cage or amending details

9.2.1 Minimising deflection is an important consideration and adding bars (or increasing size of existing vertical bars) increases cage stability and rigidity. This can also reduce prying and tensile forces in ties thereby increasing safety. A key skill for the designer is to identify where the addition of limited additional reinforcement makes the greatest difference to cage strength.

9.2.2 Stability may be achieved by:

- relying on robust tying may contribute to stability but should not be wholly relied upon.
- addition of extra internal bracing bars or increasing the diameter of the vertical bars.
- relying on an assembly sequence that ensures stability at all stages during assembly.
- design of an internal braced mattress (see Section 8.6 and 8.7).

Table 10 – Indicative limiting heights for stability of free-standing wall and column cages

Size of vertical bars	Maximum stable free-standing height of bars from base to highest point
12mm	2.4m
16mm	3.0m
20mm	3.5m
25mm	4.5m
32mm (and bigger)	5.0m

ASSUMPTIONS: *Basic wind speed 22 m/s; Altitude factor = 1.0 (assumed to be at sea level); Probability factor = 0.9; Topography factor = 1.0 (assumed to be flat terrain); Combined Exposure Factor between 1.5 and 2.0; Force coefficient = 1.2; lacers assumed at same centres as verticals with no laps for lacers; Yield of steel 500 N/mm^2; Density of steel 7850 kg/m^3*

WARNING: This Table is for guidance only and individual site circumstances should be assessed by a competent designer. The heights indicated are only appropriate in the London area and if free-standing heights exceed those shown, then there is significant risk of instability.

Readers should be aware that other parts of the UK are subject to higher wind speeds (which reduce the free-standing heights) and the addition of more lacer bars also reduces these heights.

Table 11 - Characteristics of normal ‘custom and practice’ for wall and column cages in UK
The cage is vertical and “cubic” in shape, with starter bars cast into a pile cap or robust slab.
The starter bars are not smaller in diameter than the vertical bars.
The starter bar laps are staggered.
Standard UK-type ‘nips’ are used by experienced steel fixers.
Tying conforms to BS 7973 Part 2; 1.6 mm dia. black annealed soft tying wire is used, with a minimum ultimate strength of 280 MPa. Specified ties and tying pattern.
The diameter of the lacers is not greater than the diameter of the vertical bars and spacing of lacers is not less than spacing of vertical bars.
The centre-to-centre spacing of the lacers is not less than the centre-to centre spacing of the verts.
The vertical bars are single bars – and at least 50 % are bearing onto the kicker and 50 % are full height with no intermediate laps.
There are no slab starters or other bars projecting horizontally, or other feature imposing an eccentric load or otherwise tending to weaken or destabilise the cage.
There is no abnormal high consequence should a failure occur.
Each vertical splice has 6 double wire splice ties (3 evenly distributed in outer third at each end of slice).
Every other bar intersection is tied.
A horizontal bar towards each end of the vertical splice zone is tied at every intersection with crown ties (doubled wire crown ties for 20 mm diameter bars and above).
Walls above the recommended free-standing heights must have additional support measures.

9.2.3 The placement of internal braces is dependent upon the height of the cage, the diameter of the bars and the experience of the fabricator. The use of internal braces varies in detail and location with two types of internal braces in common use: x-braces and square braces.

9.2.4 X-braces are normally made of 4 bars bent in a z-shape and welded to two inner rings at the ends of the bars. The braces are tied to the longitudinal bars and spaced at specified intervals along the length of the reinforcement cage. The x-braces have a single point in common in the centre of the brace where they are welded to each other.

9.2.5 Square braces are normally made of 8 bars, and they have three points in common with adjacent bars, two of which are close to the ends and on in the centre of the brace where they are welded to each other.

9.2.6 The design of internal braces involves standard structural frame analysis techniques. Good understanding of load path and reactions acting on the frame supports is required. Temporary support system designs should include proper placement of internal bracing at support and lift points of the reinforcement cage. Most cages with a height to breadth ratio of greater than 8 and reinforcement ratios of 1 % to 2 % percent are susceptible to instability and collapse see ASCE [19].

9.2.7 Shear link orientation can make a significant difference to their ability to resist differential movement between rebar mats. For all link types, resistance to relative movement perpendicular to the plane of the link is negligible because the connections at either end are effectively pinned with the leg at that location rotating within the tying wire. There is much better resistance to movement in the plane of the link (except for hoops – bends are better provided they have more than one tie).

9.2.8 ‘Question mark’ bars can be used to provide internal bracing by connecting separate mats together (see Figure 19 and 20). They are considered more efficient than u- and z-bars due to greater stiffness and more efficient for fixing (less steel and fewer ties). However structural use of tie wire is required.

NOTE: Question mark (or other similar bars) can be used to provide stiffness and resistance for out of plane stability, but consideration must also be given to in plane stability (In-plane side sway – Failure Mode 5, Section 7.5).

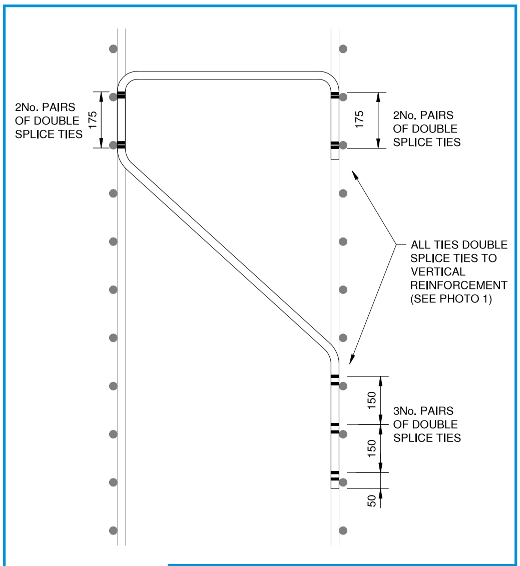


Figure 19: Tying details for 'question mark' bars

9.2.9 Additional temporary works reinforcement should be clearly marked on drawings by the designer, carefully scheduled as recommended in IStructE [20] and also using the notations for ties shown in Appendix F.

9.3 Independent Stability Measures

9.3(i) Designers should consider how these stability measures are to be installed and connected to the cage and how they are to be progressively removed, e.g. to allow formwork to be installed. When these measures are being progressively removed the cage may become unstable as it could merely be relying on its inherent stiffness, and any accidental load could easily result in the collapse of the cage. This document recommends that internal sacrificial measures are preferred where possible, as it allows for an easier sequence and can eliminate the need for operative access to remove external stability measures.

9.3.1 Installing one face of formwork

NOTE: See Part 1, Figure 15

9.3.1.1 A single face of formwork can be used to stabilise a cage being assembled in situ or a pre-fabricated cage being lifted into position with a crane. The formwork is installed and stabilised with inclined props (installed perpendicular to the formwork) which are anchored to a slab or to concrete kentlege blocks. Once the formwork is installed and aligned, the cage can be connected / tied to the formwork which then provides stability to the cage. The second face of formwork is then installed. The reaction from the inclined props create an uplift force. A check should be carried out to ensure the formwork is sufficiently heavy to resist the uplift, otherwise anchorage or additional kentledge is required.

9.3.1.2 In this condition the formwork and associated props should be designed for the following loading:

- wind loading (see Section 5.1) on the full face of the formwork and a probability factor of 0.9 being applied to the maximum calculated wind pressure. As the wind can potentially blow from any direction and the props are only on one side of the formwork, they should be designed for tensile and compressive loads (i.e. use 'push-pull' props) to allow access for work on the cage on the other side.
- overturning moment caused by eccentric projections, corbels etc from the cage. In the final condition prior to concreting, a minimum moment equivalent to a value of 2½ % of the total weight of the cage should be applied through the centroid, which allows for nominal out of plumb and eccentric loading. This may be increased to 5 % during the steel-fixing operation, as the out of plumb is likely to be more severe.

Figure 20: Use of internal 'question mark' bars and external props to provide stability

- each connection point from the cage to the formwork should be designed for a minimum of 2½ % of the total weight of the cage from above the connection point. This guidance recommends that any connection point should be designed for a minimum of 0.3 kN/m.
- accidental impact loading to be determined on a risk assessment basis (e.g. is it possible to enforce an exclusion zones to protect the props from accidental impact), considering the likelihood and consequences of failure (see Section 5.3).

9.3.1.3 Eventually both sides of the formwork need to be installed (unless single faced formwork is used e.g. a retaining wall cast against sheet piles) and they are designed for: the applied concrete pressure plus an overturning moment due to wind, plus the self-weight of access platform and live loading on the platform of 1.5kN/m^2 (see Formwork a Guide to Good Practice [9]). Adequate access and edge protection should be provided to the platform and should comply with BS EN 13374 [21]). The props should be checked for buckling under compressive loading (if on both sides of the formwork) or push-pull props (used in tension and compression) used if only on one side of the formwork. A minimum factor of safety on overturning of 1.5 should be applied to ensure the formwork remains stable during its life-cycle.

9.3.1.4 If a kentledge block is used, then it should be placed on level ground and be designed to prevent uplift (due to overturning of the cage leading to tension in the prop) and sliding. If the formwork props are anchored to kentledge blocks, then a minimum factor of safety of 1.5 should be applied to sliding. Kentledge blocks should be protected from possible water scour and undermining by excavations. Occasionally they may be dug into the ground to give greater resistance to compressive loads and tend to be known as thrust blocks.

9.3.2 Installing props to directly support the cage

NOTE: See Part 1, Figure 16

9.3.2.1 Props can be used to stabilise a cage being assembled in situ or a pre-fabricated cage being lifted into position with a crane. Props can be installed perpendicular to a wall cage to prevent overturning and buckling and at the end of a cage to prevent racking. Raking props create a reaction (tension or compression) and this should be considered by the designer. The props should be designed as described above for formwork. The props are generally installed at around two-thirds of the height of the cage with a designed connection to the cage and at the base (to a slab or kentlege block). The point loading is high at the connection and the design of this detail can be problematic and requires careful consideration. Spacing of pops should allow sufficient space for access for plant such as MEWPs and they may be on both sides of the cage (acting in tension or compression) or only on one side (acting in tension and compression so 'push-pull' props are used). They are ideally inclined at 45º to the horizontal but steeper angles may be required (but not more than 60º) where site space is limited. The prop angle causes a reaction into the vertical bars which needs to be considered. The prop centres suit the loading and the horizontal bending capacity for the lacer bars. This may become problematic where the cage has significant "box-outs". Props should be positioned to avoid becoming an obstruction to work progressing, as they may be prematurely removed. A permit system should be in place on site to prevent inadvertent removal of props by operatives and the operation should be supervised by a competent person.

9.3.2.2 The designer needs to carefully consider:

- how the props are connected to both mats of the cage, how and when the props are removed to allow formwork to be installed and how the base of the props are to be fixed (foundations).
- reactions from props on the cage and provision of adequate foundations.
- accidental impact loading is determined on a risk assessment basis (e.g. is it possible to enforce exclusion zones to protect the props), considering the likelihood and consequences of failure (see Section 5.3).

9.3.2.3 Props should be designed for the relevant loadings (see Section 9.3.2).

9.3.3 Installing guy wires

NOTE: See Part 1, Figure 10

9.3.3.1 One of the most critical modes of failure is elastic bucking due to self-weight and effective length (Failure Mode 1). Hence the use of inclined guy wires to stabilise a wall increase the vertical load (compressive reaction from the wires) and brings it closer to buckling. Guy wires (or ropes for smaller cages) can be used to aid plumbing of a cage and to provide stability. The wires should be capable of supporting the lateral loads from the cage. Their use is not common in the UK (some contractors do not permit their use) when compared to other parts of the world where they are commonly used, e.g. North America.

9.3.3.2 Guy wires should be used with care and under supervision. Their positioning (generally towards the top of a cage) should be predetermined with designed connections and consideration given to load transfer (from wire reactions) through the cage. Sufficiently robust wire connection details to the cage may prove difficult to design. The wires should be carefully tensioned to remove slack and ensure a balance of forces, but site control measures are required to avoid over-tensioning. Collapses have occurred due to out of balance in wire tensions and the induced compression (reaction from the wire) can cause buckling failure (unless the wires can be installed horizontally).

9.3.3.3 Wires may be installed symmetrically about two sides of a wall cage, or all four sides for a column cage or in a "wagon wheel" arrangement for large and complex cages. They are ideally inclined at 45° to the horizontal but steeper angles may be required (not more than 60º) where site space is limited. Supports should be positioned to suit the loading and the horizontal bending capacity for the lacer bars (this may become problematic where the cage has significant 'box-outs'). For very tall cages (generally over 9 m), multiple levels of wires may be used. This document recommends that all the longitudinal bars can be used to resist the bending moment, but only some of the vertical bars should be used for transfer of axial loads from a brace or guy wires assuming four braces or guy wires (one in each direction) – the designer should exercise engineering judgement in determining how many vertical bars can be utilised.

9.3.3.4 If kentledge blocks are used, they should be managed and designed (see Section 9.3.1).

9.3.3.5 Guy wires need to be removed during shutter installation, which may cause the cage to become unstable and careful thought should be given to the sequencing to prevent collapse of the cage. This document does not recommend the use of hydraulic "Tirfors" to tension the guy wires and hand "Tirfors" should be used with care as any out of balance during tensioning may be difficult to control.

9.3.3.6 Professor Ahmad M. Itani and his team at The University of Nevada, Reno have carried out extensive studies on the stability of cages with the use of guy wires (see [48] and Bibliography).

9.3.3.7 For cages supported by guy wires, the following general procedure is recommended:

- Set the reinforcement cage with crane.
- Attach guy wires to anchor blocks and reinforcement cage. Guy wires should be attached to both longitudinal bars and hoops.
- Carefully remove the slack from the wires, whilst avoiding excessive pre-tension.
- Slack the crane and rigging (but not the guy wires) and verify cage is stable by shaking/bumping/pushing.
- If cage shows no indications of instability, remove the crane. If unstable, leave the crane attached until more bracing/ reinforcement can be installed.
- Install reflective tape or flags on guy wire system to improve visibility for crane operators and other crews.
- Provide sequence for removing wires and installing formwork.
- Cage should be checked and monitored until formwork has been installed.

9.3.3.8 A permit system should be in place to prevent inadvertent removal of wires by operatives and the operation should be supervised by a competent person. This document recommends that exclusion zones are enforced around guy wires as the possibility of accidental impact loading should be avoided.

9.3.4 Installing scaffolding

NOTE: See Part 1, Figure 17

9.3.4.1 A scaffold can be used to stabilise a cage being assembled in situ or a pre-fabricated cage being lifted into position with a crane. The scaffold should generally be on both sides of the cage (which can make lifting the cage and formwork into position more difficult), should be robust and free-standing.

9.3.4.2 The scaffold should be designed to provide sufficient stability to the cage and should be in accordance with scaffold design standards (with handrails and toe-boards) NASC TG20:21 [22] for tube and fitting scaffolds or manufacturers technical information for system scaffolds. The scaffold should also be designed for:

- overturning moment from the cage (due to wind, eccentricity, notional horizontal load, etc.) (see Section 9.3.1, 5.2 and 5.4). The wind loading applied to the scaffold from the cage is greater than for a scaffold alone (cage is likely to be less permeable than a scaffold unless the scaffold is sheeted).
- storage of reinforcement on the scaffold as required by site.
- live loading of 1.5 kN/m^2 for fixing bars, formwork and concreting operations.
- allow formwork to be installed and removed (sequence to ensure cage connections to the scaffold can be safely removed to allow formwork to be installed) and formwork props (if they are used).

- buttressing or kentledge may be required to provide sufficient overall stability to the scaffold. Alternatively, if a robust slab is available beneath the scaffold, it may be anchored into the slab (e.g. using ring bolts).
- accidental impact load (see Section 5.3) depending on risk assessment and consequences of failure.
- connection points from the cage to the scaffold should be designed (see Section 9.3.1).

9.3.4.3 The overall factors of safety on overturning and sliding should not be less than 1.5.

9.3.4.4 For deep slab reinforcement, sacrificial scaffold supports, in the form of a birdcage may be used to provide support to the top mat and any additional live loading and storage. The birdcage is generally diagonally braced to provide lateral stability.

9.3.4.5 Cage stability should also be justified when the restraint provided by the scaffold is removed to allow formwork to be installed. Accidental impact loading on the cage from the formwork installation should also be considered (see Section 5.3).

9.3.5 Installing sacrificial or removable posts / trusses

NOTE: See Part 1, Figure 18

9.3.5.1 Are generally used to stabilise a cage being assembled in situ and three common solutions can be used (with permission from the permanent works designer for sacrificial options):

- Structural steel sections;
- Welded pre-fabricated trusses made from reinforcing bars;
- Removable external frames comprising proprietary components (soldiers).

9.3.5.2 These options are designed to provide sufficient stability to the cage during fixing until the formwork is installed. They are designed for the appropriate loadings (see Section 9.3.1) with a minimum overall factor of safety on overturning of 1.5.

9.3.5.3 These options should be positioned to avoid box outs and congested parts of the cage. All are installed at predetermined spacing and act as ‘cantilevered wind posts’ to stabilise the cage. Steel sections and pre-fabricated trusses should be contained within the overall thickness of the cage (they are generally sacrificial) and allow clear access for the bars to be fixed at height from MEWPs. Either option can be cast into a base slab. With pre-fabricated trusses the lowest diagonal can be heavily loaded and should extend sufficiently so it can be cast into the base slab so that truss action can be achieved. Robust tying or welding of chord members at lapping splices and at diagonals is crucial. If the diagonal connections with vertical bars are poor, then little if any truss action is achieved and the front and rear mats behave independently and could result in instability. The arrangement and strength capacity of laps in the vertical chord bars needs to be designed to resist the truss member forces. Steel sections can also be driven into the ground below if the slab is not adequate (or if construction a deep base with only blinding concrete beneath), however permission from permanent works designer is required as it may pass through insulation and membranes. If pre-fabricated trusses are used, they can also be connected to the starter bars, but this detail needs careful consideration.

9.3.5.4 Sacrificial truss girders are installed within the thickness of a wall at designed centres to provide stability against lateral loads and to prevent buckling under self-weight. Lateral loads such as wind are transferred horizontally into the trusses. The trusses behave like a pin jointed truss where tension and compression forces can only develop with bending and shear assumed to be negligible. The truss is designed assuming a certain porosity of reinforcement depending on number of layers and bar diameters. Trusses are generally manufactured off site, transported and then lifted into position. the vertical bars are welded to the starter bars with an 8mm continuous fillet weld. Sufficient fixity needs to be achieved at base slab / foundation level for it to act as a free cantilever. An alternative solution could be for the vertical bars to be fixed into precast sockets into the slab/foundation. Effectiveness of the truss system could be questionable for tall and slender walls due to slenderness and the lack of inertia. The capacity of wall to span horizontally between trusses also needs to be checked. The truss is a space frame, with four corner verticals and zig-zag shear elements welded between. The truss could be pre-fabricated into the cage, acting as a temporary chair, and the whole rigid lot lifted into place. Then, while still on the hook, the vertical members of the truss could be welded to the starter bars, and the spreader beam released remotely. This method allows the cage to be stabilised relatively easily and allow steel fixers to work efficiently (large sections of wall cages can be assembled quickly on site to be stable) and away from the operation to install the following formwork.

9.3.5.5 External frames are often installed on one side to allow access for fixing on the other side and may be fixed to a slab or kentledge used for stability and removed and re-used. these support frames can be assembled from proprietary components or from purpose made fabricated steelwork. They generally would also incorporate access and a working platform. They should be designed for the loadings stated above (for scaffolding) and may be buttressed, have added kentledge or be anchored into a slab. For long walls these frames may need to be moved from one location to the next and so the designer should provide adequate lifting points.

10.0 Pre-fabricating and transporting cages

10.1 Prefabrication of cages is common and can improve safety and quality. Onsite prefabrication requires a sufficiently large area for storage of bars, assembly and storage of completed cages. Offsite prefabrication is preferred due to space limitations on site and once assembled they are then transported to site before installed. Transport restriction limits the size of cages than can economically and easily be transported to site and large cages need to be assembled in sections and spliced together on site. On site cages are often be stacked on top of each other for storage. Perhaps the most common cages to prefabricate are cages for foundations such as piles and diaphragm walls but column and wall cages are also regularly pre-fabricated.

10.2 Cages tend to be pre-fabricated in the horizontal plane (to eliminate the need for work at height) at ground level and once completed they may need to be rotated into the vertical plane and lifted into position (this tends to be the cages for piles and diaphragm wall cages).

10.3 Offsite pre-fabricated cages require special consideration to ensure stability during assembly, transportation, lifting and positioning in their final position. Designed and purpose made fabrication frames can be used to support a cage during assembly. These frames should be positioned on a sound and level surface and are often used for cages which are a difficult shape. For circular or oval cages then stiffener rings are used to form and maintain the outline shape.

10.4 During stacking, lifting, moving and transporting cages vertical dynamic loads can be generated. These dynamic loads can typically be between 10 % to 25 % of the self-weight of the object being lifted (see Section 5.3) and from BS 5975: 2019, Section 17.4.3.4 [4].

Table 12 – Summary of stability measures

	Propping the cage	Using formwork to support the cage	Specifically designed truss diagonal bracing (stiffening)	Using robust free-standing scaffold	Sacrificial or removable / re-usable wind posts	Additional bracing bars or guy wires (if used correctly)	Additional couplers or mechanical clips
Out-of-plane bending *Failure Mode 1*	X	X	X	X	X	X	
Bending induced by discontinuities *Failure Mode 2*	X	X		X		X	X
Vertical buckling followed by bending *Failure Mode 3*	X	X	X	X	X		
Vertical discontinuity sliding and buckling *Failure Mode 4*			X				X
In plane side sway *Failure Mode 5*	X	X	X (façade bracing)	X	X	X	

10.5 Particular attention should be paid to cantilever 'flying' bar ends, where prying forces, load reversal and dynamic loads can be induced (causing oscillation), which could cause ties to stretch and failure, leading to a loss of cage integrity. it is estimated that the natural frequency of 25 mm cantilever bar ends is 9 to 11 Hertz. If transport causes resonance at this frequency and the vibration is not damped, then the theoretical deflection is approximately 145 mm (which would not be acceptable). Under these conditions it would be necessary to restrain the bar ends or otherwise damp the motion of the bars.

10.6 The whole cage is also subject to vibration and dynamic loading from the delivery vehicle acceleration, deceleration and cornering. This document recommends that designers also consider the incline of the road and allow an additional 5 % in addition to dynamic and cornering loads.

10.7 Cages may also be stacked on top of each other to make transportation cost effective (also stacking on site is common due to space restrictions) and may deform under vertical loading. These effects may cause the whole cage to deform, become unstable or individual bars or other pre-fitted items (e.g. tubes for sonic logging or base grouting in piles) to become deformed or completely detaching and may cause damage to pre-fitted cover blocks.

10.8 Designers should consider these effects to make adequate provision to prevent cages deforming or becoming unstable and should consider the need for adequate packing and stacking of cages to prevent damage during stacking and transportation (some consultation with contractor and hauliers should be encouraged). Figure 21 shows that the load path through bars capable of taking compressive forces from tensioning straps (used to secure the load). In Figure 21 the packs (generally timber) span across the links and should be as close as possible to the vertical legs of the links as possible.

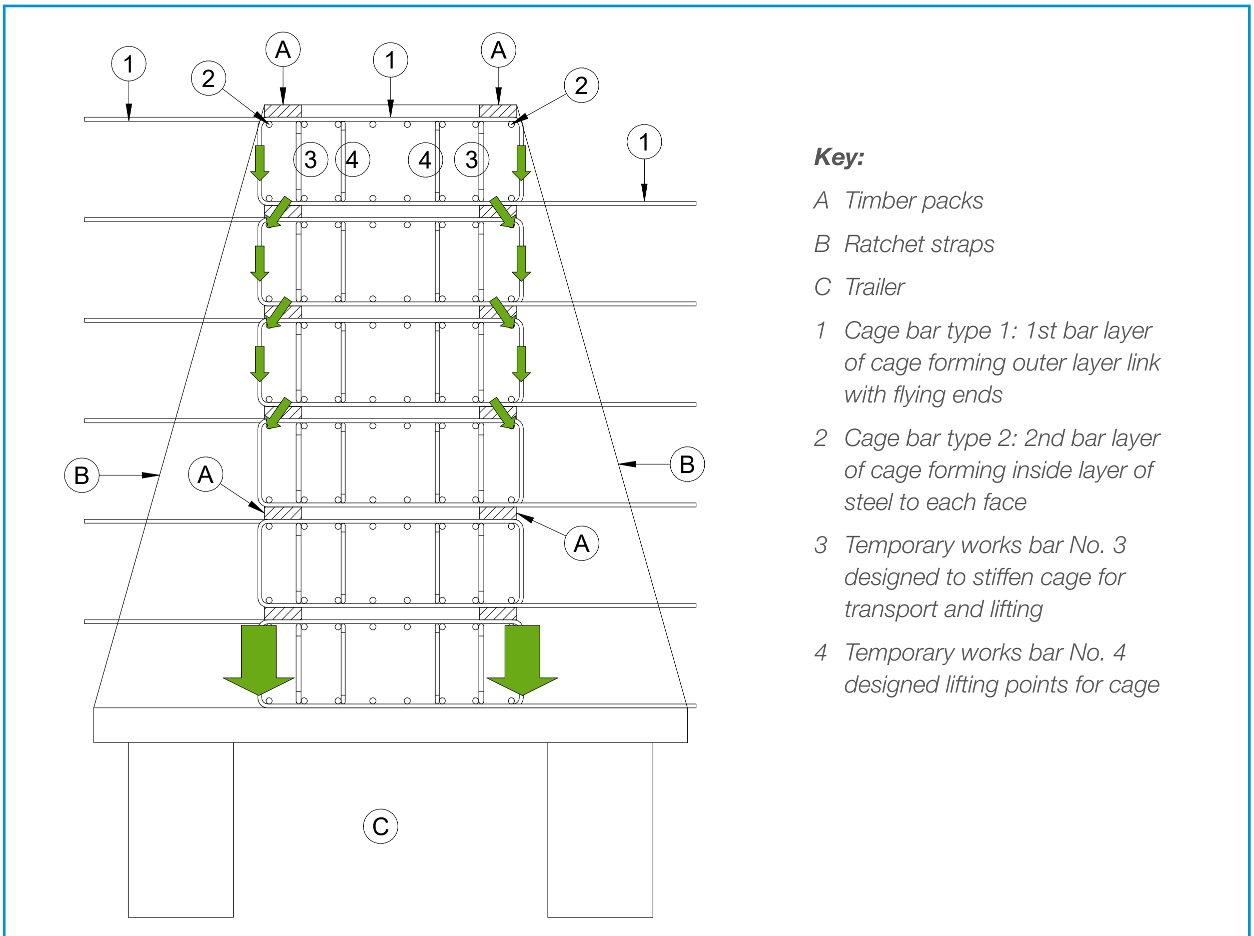


Figure 21 - Overall image of packing and stacking of cages for transportation

NOTES: Temporary works design requires packs as indicated. These packs span across the top of all the outer links (bar No.1). The packs must be as close to the vertical legs of links (bar No.1) as possible.

The arrows indicate the compression load path through the packs to the vertical leg of cage link bar No. 1. No central pack is used as, in this example. this may overload the cages.

10.9 The maximum height to which pre-fabricated cages can be stacked is 3 m to comply with standard vehicle height limit. However, as the stack height reduces the load stability increases. The stack needs to be restrained by strapping to the vehicle trailer. Straps should ideally bear onto longitudinal packs and should be arranged so as not to put undue stress on corners of the cage. The risk of toppling is greatest just before staps are tensioned and when straps are removed (and hence risk of injury to operatives), uneven ground beneath the transport vehicle exacerbates the problem. Consideration should be given to the use of specifically designed cradles to provide lateral stability of the cages, plus improve speed and safety, by allowing loading and off-loading in a single lift (cradle is to be designed for lifting).

10.10 Figure 22 shows the correct and incorrect use of packing.

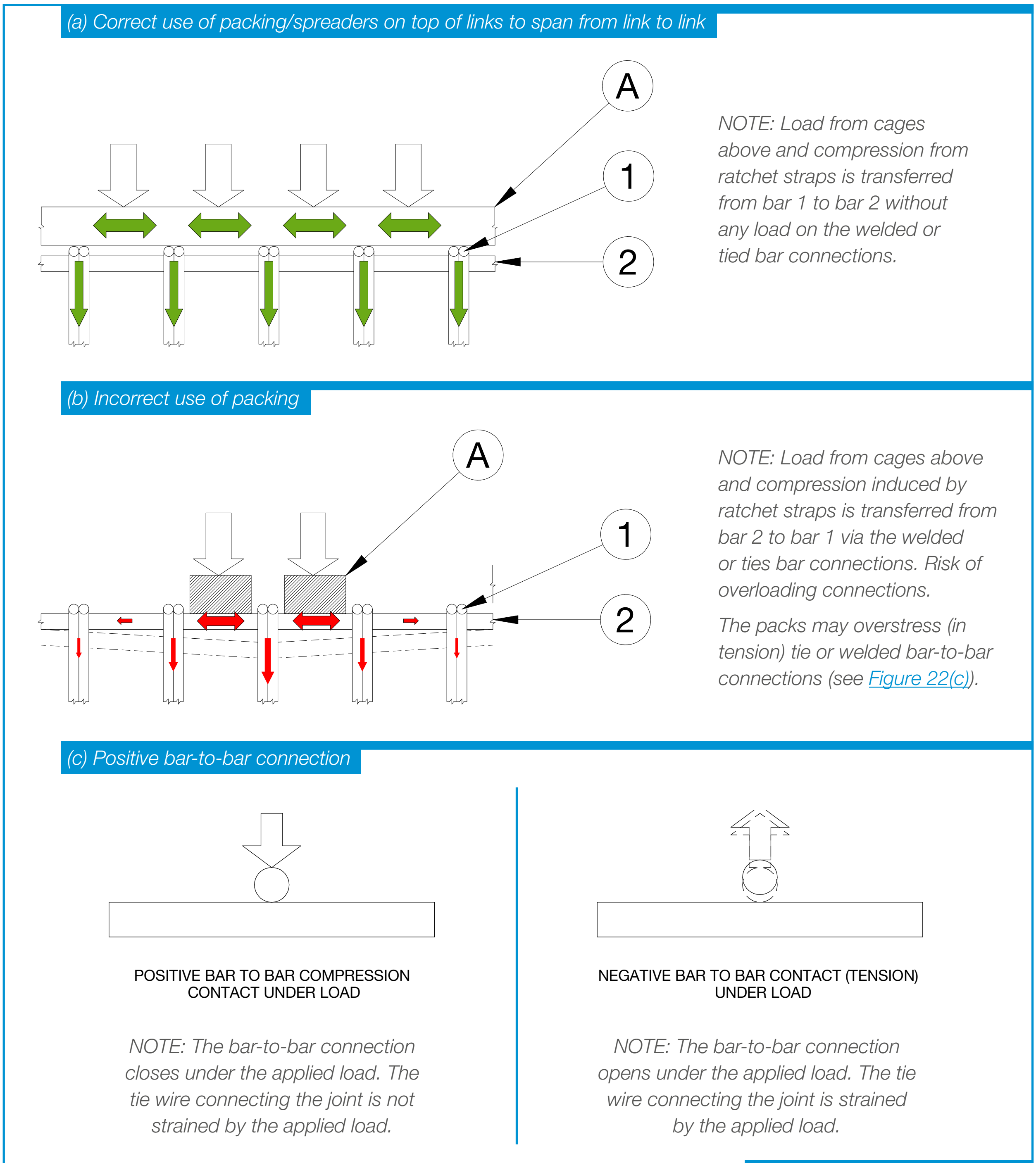


Figure 22 – Close up of packing

Some simple rules to follow:

- During transportation, dynamic effects can be large, unless the loads are adequately restrained for uneven road surfaces. Based on Department for Transport [23], the load restraint system should be sufficient to withstand an applied loading caused by accelerations of not less than:
  - (i) Forward, 1.0 x g and Backward, 0.5 x g (for braking and acceleration respectively)
  - (ii) Sideways, 0.5 x g (for cornering)
  - (iii) For overturning, 0.2 x g
- Particular attention should be given to cantilever ends of bars which can oscillate unless they are adequately restrained.
- Over-tightening of chains or ratchet straps should be avoided as this could cause damage (crushing) to the cages. This can often govern the design of chairs for cages, especially when cages are being stacked. Chairs should be aligned with timber supports so that there is a continuous 'positive' support (i.e. avoid putting ties and weld in tension with all joints in compression and positive bar-to-bar connection).

Designers should:

- be responsible for ensuring/designing all suitable measures to ensure the cage is sufficiently robust and stable to be transported, stacked, lifted and turned into its final position. A contractual agreement should be reached as early as possible to define responsibility for the design, testing, certification and provision of lifting points and lifting frames.
- specify how many cages can be stacked on top of each other and where packing and strapping should be located.
- specify that suppliers/haulage companies should pre-sling the cage as requested by the contractor to allow for easy unloading without climbing onto the back of delivery vehicles. Alternatively, smaller or loose items may be delivered on pallets to allow for offloading with forks.
- consider that confinement cages/cradles are often used for transportation, but they are not suitable for lifting unless specifically designed for this purpose as a lifting frame.
- consider that transportation should allow for dynamic loads due to sudden acceleration, breaking or cornering, to ensure stability of the cage as a whole and to prevent the load from falling off the vehicle. Also care should be taken as cages can move during transportation which could make them unstable un-stable during unloading when the restraining straps are removed.

10.11 The Federation of Piling Specialists [24] and [25], have further useful information specific to piling operations.

10.12 CIRIA Special Publication 118 [15], Sections 7 and 8 has some useful information on supply delivery, handling and storage of reinforcement.

10.13 Construction Industry Council, Hong Kong [26] – has guidance for bored piles.

11.0 Rotating, lifting and installing pre-fabricated cages

NOTE: See Part 1, Figures 9, 10, 13 and 14

11.1 The requirements for the lifting and stability are defined in Lifting Operations and Lifting Equipment Regulations (LOLER) [27] and the associated Approved Code of Practice [28].

- All lifting operations shall be properly planned by a competent person. A lift plan should be prepared to ensure appropriate lifting equipment is being used.
- Lifting equipment is of adequate strength and stability for each load.
- Every part of a load and anything attached to it and used in lifting is of adequate strength.

11.2 The provisions need to be considered in parallel with the Management of Health and Safety at Work Regulations [29] and the Provision and Use of Work Equipment Regulations [30] There are no parts of LOLER that are specific to the lifting of reinforcement.

11.3 All lifting attachments should be designed robustly by calculation to BS EN 13155, Appendix A [31] and should allow the lifting attachments to be attached and detached safely. A high factor of safety is used (typically 5) for the design of lifting attachments and the connection points to the cage itself (e.g. welds), unless specific control measures are in place to ensure that unplanned loads (e.g. due to unequal length of chains or slings) cannot develop. The lifting accessories should be attached to parts of a cage that can withstand the high load concentrations without failing. These points must also be able to redistribute load through the cage.

11.4 A lower factor of safety may be justified when lifting small/light cages directly from the bars (factor applied to the design of the bars), however it is the ties which are most likely to fail during lifting and a high factor of safety should be used on the ties as mentioned previously in this document.

11.5 During turning and/or lifting, a cage does not generally fail due to excessive stresses in the bars but due to excessive deflection. If cage instability or failure is considered an issue, then designers should eliminate the risks by designing adequate measures. The following hazards can occur:

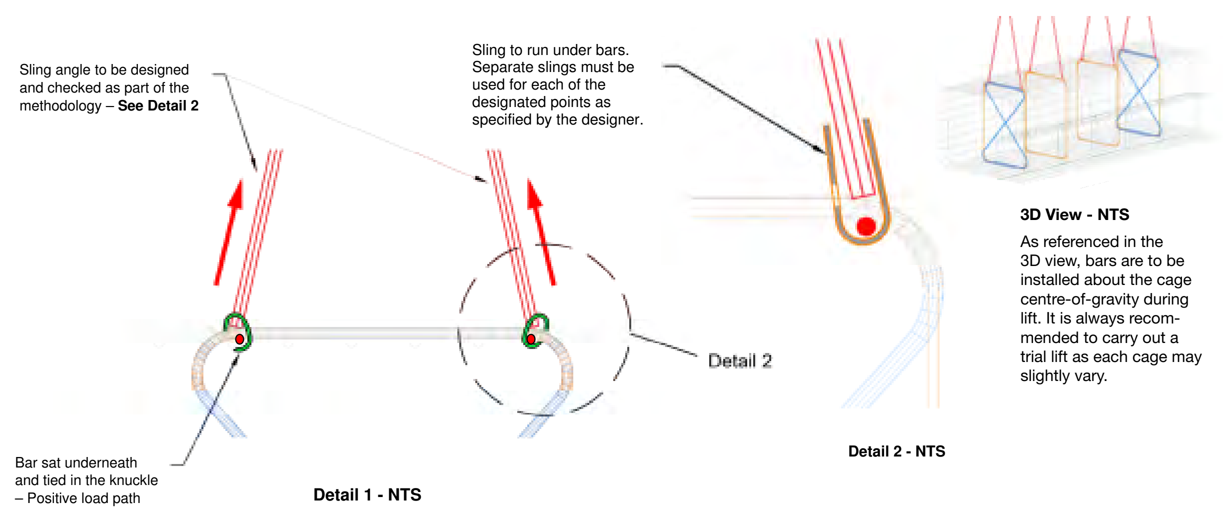


Figure 23: Example of positive load path principle (captive bar for lifting low risk cages)

- failure of the lifting machinery (particularly foundation failure).
- failure of the lifting equipment or lifting points (uneven distribution of load - the load could be focussed on some of the lifting points with others taking no load – they become slack) or slinging error.
- inadequate load path from the lifting points due to workmanship errors (gaps between bar-to-bar connections and difficulty of achieving robust bar-to-bar cruciform connections.
- axial buckling due to compression caused by the reaction from inclined lifting attachment.
- bending failure with scissoring action at laps or excessive deflection of the cage (lack of stiffness).
- tied joints along the face nearest the lifting points undergo large forces and could fail suddenly.
- during rotation, the joints between the longitudinal and transverse bars undergo movement and forces which causes the bars to slide or shear.
- dynamic effects during moving, rotation and lifting.
- the cage is accidentally struck or landed unevenly, inducing bending or torsion into critical connections especially if they have only been designed for direct shear/ tension.
- failure of laps or splices or the connection to the starter bars.

11.6 Small cages in a low-risk environment, can be lifted by slinging from bars or from simple lifting points, providing the following design checks have been carried out:

- a cage should not be lifted from the uppermost (or outermost) layer of reinforcement. Slings or chains should be placed on captive bars (bars within the cage, see Figure 23 and 1.0, Terminology) which should be checked to ensure they are adequate in bending and shear.
- the captive bar to u-bar/link connection (tied or welded) is adequate.
- u-bar/link is adequate in bending, shear and tension.
- when Shape Code 51 closed links are formed, there is a bar overlap (knuckle lapping point) and adequate tying at the overlap is required to prevent the link from opening. If two u-bars are used to form a link, then they could part if the tying is inadequate.
- small pile cages should be lifted from the main bars and not the spiral.
- lifting points are attached with double ties and they should be either slash, slash and ring, hairpin, hairpin and ring or crown.
- horizontal component from inclined slings or chains do not cause bars to buckle.

Figure 24: Using a temporary jig

11.7 Turning and lifting a large/long/heavy cage into place is one of the most high-risk activities carried out on a project and should be properly planned, to identify and eliminate where possible the inherent hazards and potential risks. Tag lines should always be used to prevent the cage from swinging uncontrollably. During lifting and turning there can be large changes in internal cage forces which could cause a cage to become unstable, deform/deflect excessively, lifting points could fail or components could become detached and fall. If a cage is permitted to sag or deform excessively, individual bars could yield, which affects structural performance and could affect cover. The designer (as part of their CDM buildability assessment) should design any additional stiffening bars or lifting support frame (see [2], Part 1, Figure 13) to prevent sagging and deformation. These need to be added to the overall weight that is to be lifted. Cages could also drag on the ground during rotation and lifting potentially causing damage to the cage. If possible, the cage should be assembled in the same alignment as it is eventually placed so that it does not have to be tilted or turned. This is not always possible (e.g. pile cages which are assembled in the horizontal plane but then lifted, rotated and installed in the vertical plane). This can involve assembling the cage in a temporary jig that is set at the correct angle (see Figure 24).

11.8 Tilting a cage is critical both for the internal strength of the cage and for the lifting equipment (including the lifting points). Large wall cage lifts, particularly piles and diaphragm wall cages, are often undertaken as tandem lifts so that the cage is not touching the ground when it is rotated, this is a specialist and high-risk operation. The rigging and execution of such lifts requires a large amount of space, is complex and involves lifting equipment that accommodates the change in lifting angles (this can involve pulleys to allow rotation; see Figure 25). Sliding of the cage along the ground as it is tilted should be avoided and prevented with ties, if necessary. The design of lifting points to facilitate rotation in reinforcement cages is complex and specialist design is necessary to consider the number and location of lifting points. Careful consideration also should be given to how the chains or slings are detached from the cage without undue risk to operatives.

11.9 The total weight of cage to be lifted should include all bars (including laps, splices, ties etc) and should be calculated from the bar bending schedule or taken from analysis programme. For simplicity (unless accurate calculations are carried out) this document recommends that an additional 7.5% of the cage weight is added to allow for tying wire, welds and typical temporary works strengthening measures and bar cutting and bending tolerances. The dynamic effects should be considered depending on control measures in BS 5975: 2019, Clause 17.4.3.4 [4] and Section 5 (depending on mechanical or manual control and dynamic effects during lifting, could typically be between 10 % to 25 % and up to 33 % in certain circumstances).

11.10 This guidance recommends a factor of safety of 5 for welding connections, where there is a high concentration of load during lifting.

11.11 The position of lifting points, number of attachments and slinging method is governed by the cage load and cage stiffness distribution. For cages with uniform weight distribution the lifting points are often positioned at 0.2 L in from each end of the cage. On a uniform distributed cage load the cantilever end and mid span deflections can be made equal by setting the lifting points 0.274 L either side of the centre of gravity. For non-uniform load distribution where the cage is to remain horizontal, the slings are distributed equidistant from the centre of gravity.

Figure 25: Complex lift of diaphragm wall cage (Courtesy: Malachy Ryan)

NOTE: Designers should be aware that in this example the majority of the weight of the cage is supported by the lower lifting points and only when the cage is near vertical is the load transferred to the upper lifting points.

11.12 During lifting, the self-weight of the cage hangs from the lifting points (and lifting accessories) which are points of high load concentration which could cause ties to stretch and fail and these ties are relied upon to prevent individual bars from falling out of the cage. Hence it is critical that there are sufficient ties to provide secondary load paths through these non-engineered ties. Lifting accessories should be designed, tested and certified in accordance with LOLER [27] to ensure they do not fail catastrophically (see Figure 26).

11.13 Long pile and diaphragm wall cages are often pre-fabricated in sections and spliced together, so designers should ensure that splices are adequately designed. (See Section 6 for guidance on ties). Designers should also consider the effect of horizontal reactions from inclined lifting chains or slings which may cause the cage to buckle (see [2], Part 1, Figure 10).

11.14 Special consideration should be given to pile cages which are installed into concreted piles. The cages may be inserted with the aid of a cage vibrator and the cage should be sufficiently robust to withstand the vibration. Designers should specialist advice from piling specialist.

NOTE: If designing to Eurocodes then partial load factors and workmanship factors may need to be increased beyond those usually adopted for 'static' permanent works.

11.15 The British Constructional Steelwork Association [32] has additional guidance although not specific to lifting of cages.

11.16 Federation of Piling Specialists [24] has further guidance on splicing and couplers, also see Section 13.

Figure 26: Lifting cage

Some simple rules to follow:

Designers should:

- engage with the site team and encourage input, promote understanding of risks and practical issues to develop a solution.
- consider site constraints and buildability (e.g. spaces for cranes) to determine how the cage is to be lifted and turned safely, including how lifting attachments are removed. This should include the provision of any necessary internal stiffening to prevent cage failure through excessive deformation.
- provide the total weight and centre of gravity (top heavy cages rotate if lifted from below the centre of gravity so lifting points should be above the centre of gravity) of any cages that requires mechanical assistance to be lifted into position and design the necessary lifting points to ensure the cage remains stable (does not deflect/deform excessively) during lifting.
- for complex / heavy large cages - designers should review contractors lift plans / methodology to ensure cage deflections are within allowable limits to ensure ties do not break or deform.
- localised forces from lifting slings and chains should be assessed.
- not rely on ties alone to lift heavy cages – positive connections should be designed.
- limit the number of ties in tension, ensure robust tying, good tie patterns and alternative load paths through the cage. If the strength of tied joints cannot be justified (ties may stretch or fail) for highly stressed nodes then couplers, bulldog grips or welded connections should be used to prevent failure.
- if necessary, specify/design lifting beams to ensure loads are evenly distributed and at an angle perpendicular to the cage. Lifting frames may also be used to support the whole cage. Consideration should be given to all stages during the lifting and turning process.
- on site welding should be avoided. Welded connections should be designed, they should be CARES compliant and consider settlement during lifting and turning.
- identify the deflected shape expected and allowable deflection/limiting values on drawings so the site team is clear on what constitutes adverse cage behaviour and identify what intervention may be required (e.g. stop work, evacuate area, report to designer).
- ensure the cage remains stable and does not unduly deform/deflect/buckle during rotation and lifting.
- provide additional stiffening (to prevent racking during lifting) in the form of stiffening rings (e.g. for piles), welded z-bars may be used to create truss action, inclined bars, u-bars, etc.
- provide additional diagonal bracing and laps to increase stiffness and strength and to prevent racking when the cage is suspended.
- consider the position of laps and splices to ensure they do not slip excessively or fail (noting that tied laps can move around 25 mm before failure).
- provide dedicated “pick-up” bars which can transfer all the cage loading into the lifting equipment.
- consider any reactions (induced compression could cause failure mode 3) from inclined chains or slings.
- use a conservative design approach with appropriately high factors of safety (see Section 6.2.1, 6.2.2 and Flowchart 1 for appropriate factors of safety in Methods A and B) applied to cage lifting connection points and that these points should be capable of re-distributing load throughout the cage.
- the diameter, number and distribution of spanning bars should be reviewed and the variation in stiffness along the cage calculated. In a beam, the spanning bars are the longitudinal bars. In a 2D mat or 3D mattress, the longitudinal and transverse steel distribution should be reviewed, and the stiffness variation considered in both directions.

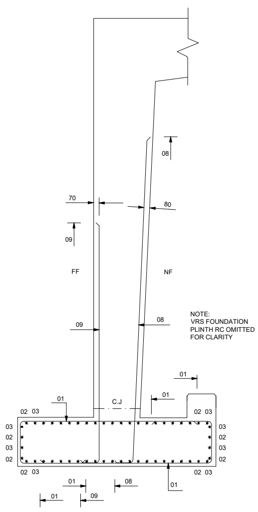
Some simple rules to follow:

The site team should:

- ensure all lifting of cages complies with LOLER and ACOP with lift plan being provided and all lifting equipment appropriately tested and certified and avoid lifting over people (exclusion zone).
- lifting operations should be carried out by competent personnel.
- cage weights should be noted on the cage label / delivery ticket. It should be possible for operatives to identify the weight and sling the cage without climbing onto the delivery vehicle on onto stacked cages.
- soft slings should be used for lifting large cages and these should comply with EN 1492-1 and -2 [33]. These slings should not be damaged and identifiable and the SWL noted on the sling.
- cages should not be lifted from a single horizontal bar – no matter how well tied.
- for large and complex cages always carry out a trial lift (should be defined as a hold point), to verify that the cage behaves as expected. This should be witnessed by the designer (could be remotely using video).
- any welding should be quality assured to ensure the correct weld size and quality.
- an initial “test lift” (lift the cage a short distance above the ground) should be carried out and inspect for loose items or excessive deflection/ deformation which may indicate a cage which has not been assembled correctly.
- monitor the cage during lifting as small deflections / deformation are a sign of adequate robustness. Long cages should not be allowed to ‘drag’ along the ground when being turned.
- be aware that if a cage is lifted and moved by excavator on rough terrain, then it is subject to vibration and can be prone to failure by the spacing between the upper and lower mats not being maintained – this type of movement should be avoided / done carefully.
- cages should be inspected by a competent person, prior to lifting (to ensure loose objects cannot fall out), tagged to indicate they are safe to lift, ensure the area is clear (cage cannot snag during lifting) and a permit to lift system adopted. If a cage is to be lifted several times, then it should be re-inspected (for damage, excessive movement, tie stretch, etc.) every time.
- ensure cages are adequately connected to the starter bars (and any other temporary stability measures provided) before it is released from the lifting machinery.
- cages should not be lifted during bad weather (e.g. high winds or poor visibility) and tag lines should be used.

12.0 Integral bridges

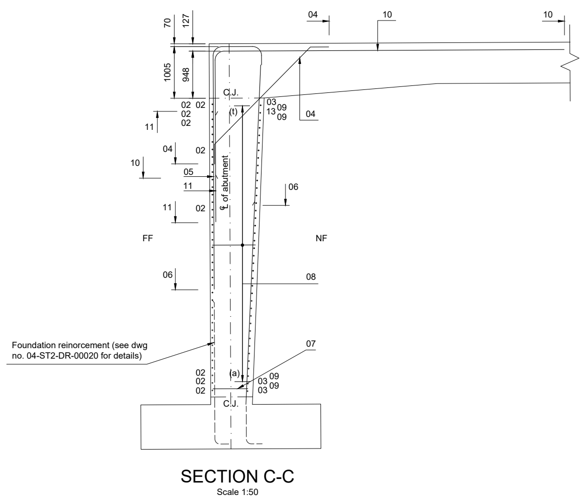
(a) Example of reinforcement that would require significant temporary worksbridge deck with over-hanging reinforcement



Plinth level

B32 inclined starter bar projecting 5 m above kicker, weight 38 kg per bar

b) Example of reinforcement that would require significant temporary worksbridge deck with over-hanging reinforcement



Top of abutment

B40 bar 9.2 m long projecting horizontally 6.9 m, weight per bar 91 kg

Figure 27: Example of poor detailing of integral bridge deck with over-hanging reinforcement

Table 13: Integral bridge detailing problems

Detailing Problem	Safety consequence on site (Hazard)	Solution
Abutment/pier base Anchorage length requirement for wall starters cast into base pour	• Excessive length of reinforcement projecting from base pour leading to instability	• Replace the excessive length of projecting reinforcement with a coupler. • The length of leg supporting the starter should be a minimum of one-third the height. • Support the starter bars with purpose designed temporary works.
Abutment/pier wall Diameter and density of reinforcing bars increasing with height	• Top heavy reinforcement cage leading to instability	• Use same diameter and density of reinforcement from the base of the wall to the top. This will increase the strength of the reinforcement to support its self-weight without buckling. • Support the wall bars with purpose designed temporary works.
Abutment/pier wall Inclined face	• Reinforcement leaning over by design	• If this is only for aesthetic reasons, can the reinforcement be detailed vertically? • If this is a requirement of the design, then temporary support will (almost certainly) be required. If this is provided by fixing the shutter first, the wall will need to be fixed from one side. Consider detailing the verticals to be closest to the concrete face.
Abutment/pier wall L-bars with long horizontal anchorage into deck located at top of wall	• Support of vertical weight of bar attached part way up wall, problem fixing accurately. • Eccentric load applied to top of wall leading to instability	• Form a construction joint in concrete directly below where reinforcement is located to provide support and reduce length of reinforcement subject to loading. • Replace the length reinforcement of projecting horizontally with a coupler.

12.1 Integral bridges are a form of bridge construction where there are no expansion joints. This has many advantages for the whole life cost of the structure, greatly reducing the hazards and costs associated with maintenance. The Highways Authority has been promoting the design of integral bridges since the 1980s. It is now a requirement that all bridges with a skew angle of up to 30 degrees and length of up to 60 m shall be designed as integral bridge structures (see HE CD350 [34]). This design results in large moments, shears and forces being formed at the joint between the bridge deck and pier/abutment.

12.2 To resist the tensions and compressions developed, there needs to be a large amount of steel reinforcement at these joints with long anchorages into the deck and pier/abutment. Integral bridge cages are more unstable, being top heavy with small diameter U bars at the top linking the rebar mats together. If poorly detailed (see Figure 27) this can lead to problems for the fixers and require temporary works (see Table 13). However, it may be possible to detail out these problems. If purpose designed temporary works are needed to support the reinforcement, the hazard and costs resulting from the temporary works may be greater than eliminating the original hazard by better detailing.

13.0 Splicing vertical cage sections together

13.1 Where large cages for deep foundation piles or diaphragm walls need to be joined together on site, they are typically connected vertically over the pile/wall bore as the cage is lowered in. Splicing of cages has the potential to cause significant instability issues and subsequent injuries, but various advances have been made to mechanically splice cages. Some systems simply lock together as the individual parts of the cage are positioned; others require some physical intervention. Ensuring that the systems are aligned and installed correctly so that the cages fit together with minimal risk and effort is critical. It is important that the cage joining system is designed for the permanent and temporary conditions. There are a number of proprietary splicing systems available, which have been developed to make the cage joining process as safe and quick as possible. The key safety issue is to avoid placing hands into the cage which eliminates potential accidents if the cage moves during the splicing operation (either by the cage trapped over the pile bore moving or the cage supported by the crane). Preferred systems should be an integral part of the cages or, if separate, connect from outside the cage only without the need to insert fasteners or tools inside the cage. Splices need to provide adequate laps to the bars for the permanent design case and they also need to be able to support the weight of the cage below the splice. The contractor should specify how the cage is to be constructed and the design should confirm the temporary and permanent design of the splice connection. Care should be taken when constructing piles with low level cut-off and a sacrificial cage and main cage needs to be able to support the weight of the cage below. Manufacturer's guidance for cage splicing needs to be followed carefully. Particularly with respect to how any separate fixings are installed and tightened, the minimum number for the load and the minimum number for spacing.

13.2 Some common systems which are available. An extract from FPS [24] states:

- **Wire rope u-clips / Bulldog grips**

  Primarily designed for the termination of steel wire ropes as stated in BS EN 13411-5: 2003 [35]. Their use should be assessed by a competent person considering appropriate factors of safety (see Section 15).

- **Zip splice**

  Has been tested to proof loads over 1700 kg and have a recommended SWL of 3.5 kN.

- **Quick splice**

  A series of clamping devices are required to connect splice bands of the male and female sections. They are commonly used in piling industry and SWLs range from 20 kN and 28 kN (depending on size) are specified by supplied based on testing at low torques (to represent hand tightening).

- **Safe Splice**

  Uses a wrench to drive bolts through a set of pre welded plates. The SWLs range from 20 kN to 170 kN (depending on size).

- **Superlatch**

  A relatively recent product which should be matched to the diameter of the bars. The SWLs range from 6 kN to 90 kN (depending on type/size).

- **Couplers**

  Commonly used since the introduction of BS EN 1997 [36] which does not allow the splicing of H50 bars in any other way. Should be CARES approved with various types are available from various manufacturers and any couplers used for splicing must be a positional coupler with full tensile capacity as it is not possible to rotate the bar inside the cage to connect them to the couplers.

- **Fish Plates**

  Only used to splice diaphragm wall cages which utilises two aligned plates which are bolted together. The steel frame design which positions the plate, all corresponding welding and bolts should be designed by a competent person.

14.0 Welding of bars and cages

14.1 *IStructE, Section 5.5 [37] has useful information on welding rebar. "On-site welding of reinforcement should be avoided wherever possible. However, where it is deemed necessary, the technical guidance described in BS 8548 [38] should be satisfied to produce acceptable welds. The contract administrator should be responsible for ensuring the qualification of weld test procedures and the qualification and testing of welders. The contract administrator should clearly identify any design requirement, including temporary works design, and who is responsible for the design. In the UK, semi-structural welding of reinforcement should only be carried out by firms that have achieved certification to CARES' [39]. Tack welding on site should not be permitted, without special approval. Tack welding of reinforcement should only be carried out by firms that have achieved certification to CARES' [39].*

14.2 Welding of rebar is an alternative to tying, subject to client approval. Most UK specifications do not permit in-situ welding of permanent works reinforcement. This is because it is easy to damage and weaken high yield steel bars during the weld process. If site welding in unavoidable, then weldable bars are to be used and the work undertaken by competent welders under supervision. Welding of rebar should comply with BS EN ISO 17660-2 [40] and should only be carried out in a controlled environment in factories compliant with the relevant CARES approvals for welding rebar, by suitably trained, experienced and certified welders.

14.3 Some clients, e.g. Network Rail, have their own specific requirements, e.g. Network Rail Standard NR/L2/CIV/140/1700N and 1700C [41].

1. *Welding General 12/14: welding reinforcement other than steel fabric reinforcement shall not be incorporated in the permanent works unless permitted in contract specific Appendix 17/4. When required, welding of reinforcement bars shall comply with the requirements of clause 3.2.5 of BS EN 1992-1-1* [12], *shall be carried out in accordance with BS EN 17660* [40] *and be subject to the demonstration of the satisfactory performance of trial joints. The contractor shall demonstrate that at each location the fatigue life, durability and other properties of the member are not adversely affected by the proposal. Welding of reinforcement shall not be carried out for reinforcement subject to variable loading, or where epoxy coated reinforcement is used. Site welding of stainless-steel reinforcement bars shall not be permitted.*
2. *Strength of Structural Welded Joints 12/14: the strength of all structural welded joints shall be assessed following tests on trial joints to establish the minimum specified mechanical properties of the joint. Tests shall be carried out by an independent testing body appropriately accredited as described in clause 105. The employer's representative shall be provided with the following information for acceptance prior to welding commencing:*
   a. *Written welding procedures to BS EN ISO 17660-1* [40], *approved by an independent testing authority.*
   b. *Certificates for each welder to be provided by an independent testing authority appropriate to each weld type and procedure.*

14.4 Welding of laps or bar intersections adds stiffness and, by consideration of their location added robustness, but any welding should be quality assured to ensure strength and to avoid adverse effects on the reinforcement itself. Welding is mentioned in the National Standard for Concrete Specification [42]. Clause 6.1.2.3 states: *only firms that have achieved certification to CARES SRC Appendix 10* [43], *or equivalent, shall be permitted to supply pre-assembled fabrications.* There is a similar requirement for tack welds. However, the CARES scheme does not apply to site operations (see Part 6 of the CARES data) and hence if welding is to be implemented on site the contract should spell out alternative measures to ensure adequate standards.

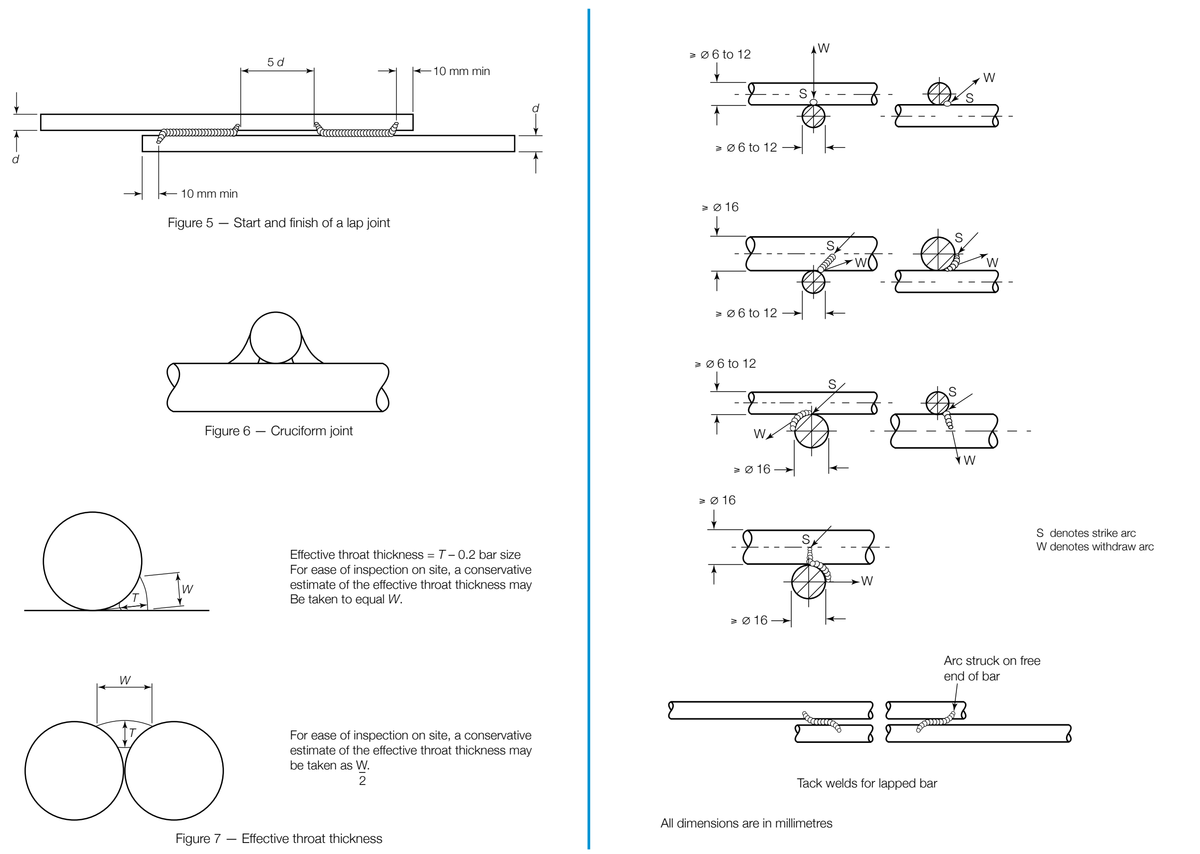


Figure 28 BS7123 Semi-structural welds

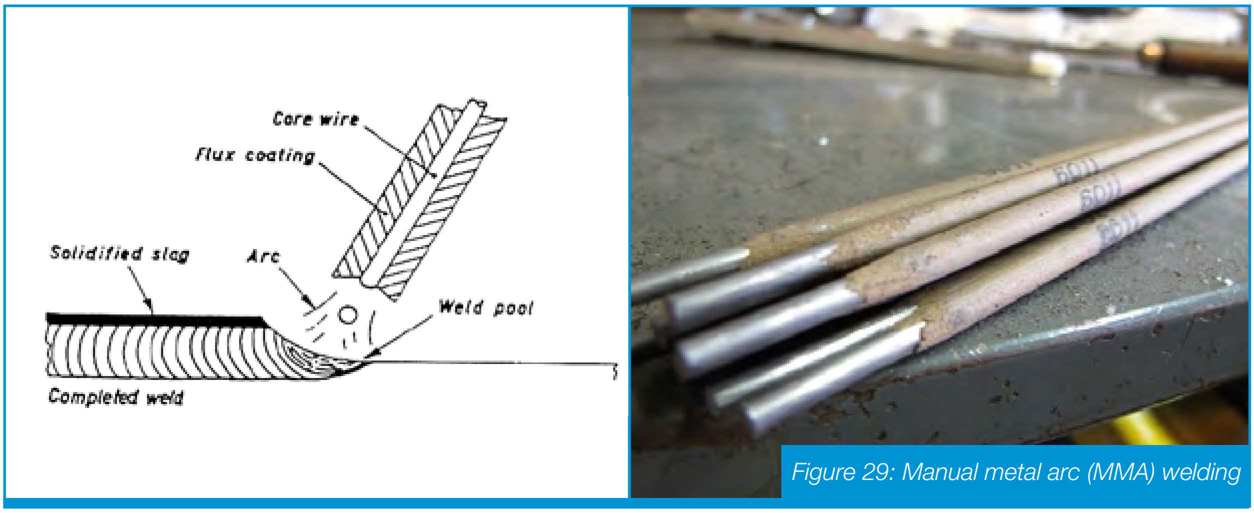


Figure 29: Manual metal arc (MMA) welding

Advantages – small diameter rods give good access into difficult areas, all welding positions possible, can be easily carried out on site and can be used on any type of joint.

Disadvantages – short electrode which requires frequent replacement and the slag needs removing

14.5 Welding of reinforcing bars is an alternative to tying for highly stressed connections and should be subject to client approval. The purpose is to increase stiffness and strength by ensuring bars are adequately joined, for lifting, to aid stability or to rigidly fix components such as instrumentation, pipework, brackets etc. Welding should comply with the British Standard for the welding of reinforcing BS EN ISO 17660-2 [40], it gives guidance on procedures, approvals, acceptable imperfections etc. CARES Guide to Reinforcing Steels – Part 6 [44], also provides useful information.

14.6 A high degree of skill is required to weld rebar. There is a high risk of changing the metallurgy of the permanent works steel, rendering it useless, if the proper welding quality controls are not implemented effectively (brittle failure at minimal load). It is recommended that all welding of reinforcement is undertaken in workshop conditions to ensure quality and be subject to appropriate quality control measures.

14.7 Welds should be designed, specified and the work carried out by competent operatives. A visual inspection for all welds should be carried out to ensure compliance, quality and that they

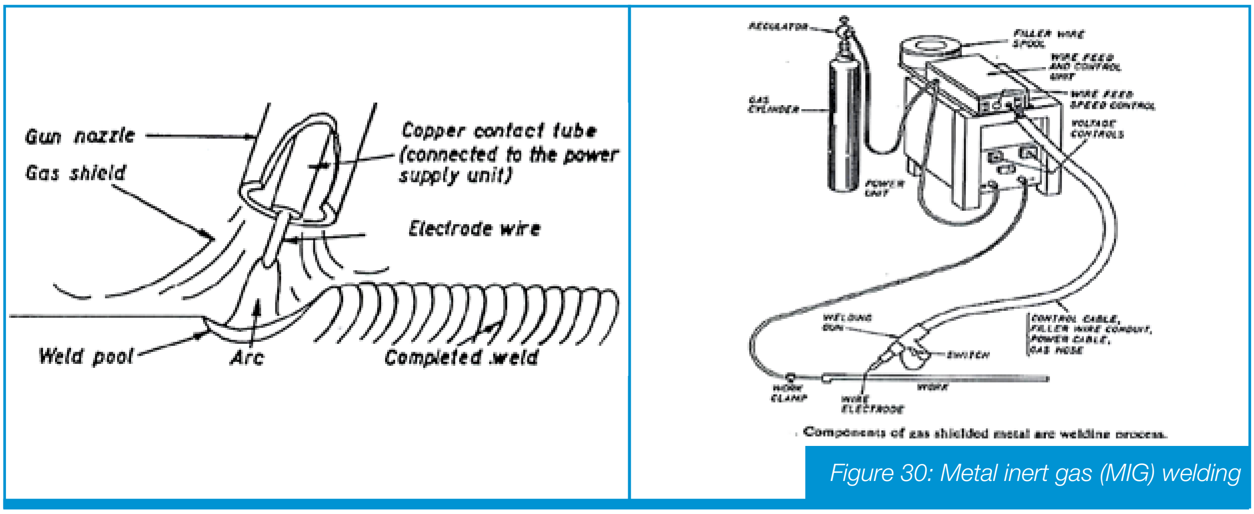


Figure 30: Metal inert gas (MIG) welding

Advantages – continuous welding process as uses a long wire rather than rods, no slag and automatic arc control.

Disadvantages – size of the nozzle means poor access to difficult areas, gas shield must not be blown away so it is much more difficult to do on site and it is not easy to weld in all positions.

are free from defects. Further non-destructive testing (NDT) may be deemed necessary for critical items. This should be specified by the designer. Welding produces extremely hot surfaces and splatter with potential for fire and injury from molten metals.

14.8 BS 7123 [45] recommends that tack welds are only used for locating purposes and not for carrying the full tensile strength of the bar. The throat thickness should not be less than 4 mm and a minimum length of 25 mm. The bars should be preheated before tack welding. Tack welds for cruciform joints used to locate bars in made up assemblies should be built up, so the throat thickness is at least 1/3 of the size of the smaller bar or 6mm (whichever is the greater).

14.9 Figure 28 shows semi-structural welds. Figure 29 and 30 show MMA and MIG welding. Figure 31 shows weld defects. Figure 32 is an extract from BS 7123, showing weld defects. Appendix G shows some poor welding workmanship.

14.10 Common weld defects:

- Incomplete penetration or excessive penetration
- Undercutting
- Excessive spatter
- Porosity
- Cracking
- Lack of fusion
- Stray flash

15.0 Issues related to using 'u-clips' and 'Bulldog' grips

15.1 Where connections are highly stressed the bars may be clamped together using "wire rope u-clips / bulldog type grips", at laps to achieve a higher strength joint. They may also be used an alternative to welding particularly where welding could be difficult to carry out (hot works / access) or the effects of welding are considered detrimental. However, the use of grips could be expensive and can be difficult to justify their use.

15.2 U-clips / bulldog grips are commonly used for the termination of steel wire ropes to form a "loop or eye" and the rated capacity is based on squashing the rope – see BS EN 13411-5 [46]. This cannot be done with bars as the grips can merely keep the bars in close proximity, by friction and allow some slippage until the ribs on the bars engage. There is a large variation in the dimensions of the ribs and the theoretical load capacity is variable. The standard does allow for: *"other suitable uses which have been assessed by a competent person considering appropriate factors of safety".*

15.3 Some issues for designers to consider:

a) Clips/grips are not certified for any load capacity. The torque for tightening is often unspecified and often torque wrenches are not used (resulting in under or over tightening and possible damage).

b) Clips/grips rely on friction and the available friction depends on the orientation of the bar, i.e. whether the ribs are being mobilised or not.

c) Clips/grips come in different sizes and provided by different suppliers, with the possibility that incorrect ones could be used on site.

d) Clips/grip should be avoided where possible, as the primary system for connecting cages together; better to use couplers or proprietary systems instead. They may be justified as a secondary system.

e) Installing clips/grips on site, may require operative hands going inside the cage and this should be avoided if possible.

f) The saddles of clips/grips are designed to work with "soft" wire rope. When used on rigid bars, the brittle saddles can rupture during cage lifting.

15.4 This document recommends that clips/grips are used with caution and testing is always carried out, for each individual site, with a factor of safety of 3 applied on the initial slip load. Test results from one site should not be used for another site.

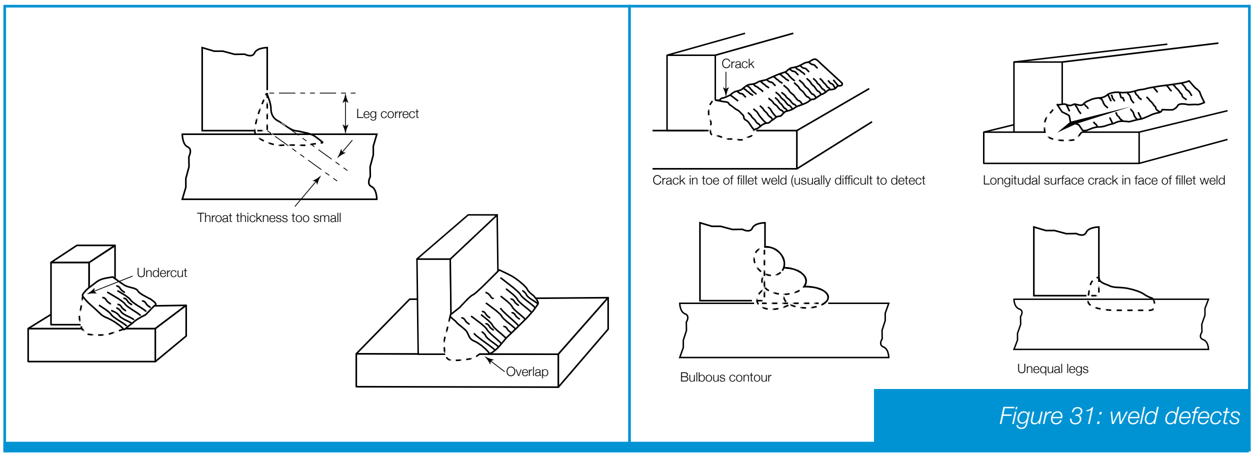


Figure 31: weld defects

Imperfection type	Permitted maximum	
	Procedure approval and Welder approval (visual and macro-examination)	Production welding (visual examination)
a) Cracks	Not permitted	Not permitted
b) Lack of root fusion* Lack of side fusion Lack of inter-run fusion	Not permitted	Not applicable
c) Lack of root penetration*	* Not permitted	Not applicable
d) Undercut	Depth not to exceed 1 mm	Depth not to exceed 1 mm
e) Excess weld metal	Weld metal to blend smoothly with the parent metal	Weld metal to blend smoothly with the parent metal
f) Overlap	Not permitted	Not permitted

**Applies to butt joints only.*

Figure 32: From BS 7123

15.5 A recent addition to the market is purpose made clips specifically for lifting and fixing most combinations of bars. These have been fully tested and the manufacturers provide SWLs (see Ischebeck Inform RECO Clamps, www.informuk.co.uk [47]).

16.0 Recommendations for further research

16.1 The following recommendations are made for further research:

a) Temporary Works Forum (TWf) should establish an industry steering group to provide some cohesion for research and the next generation of this guidance.

b) Bars within cages and the whole cage could resonate under wind loading (and earthquakes in some parts of the world) and this could be an additional mode/ cause of failure. There is no specific research on this subject.

c) The stability of cages made from plastic/ epoxy-coated and GRP reinforcing bars should be investigated to determine behaviour. Similarly, with epoxy coated tying wire.

d) Examine the effects of mechanical connectors (e.g. u-bolts, threaded rod with plate, wire rope connectors) on the stiffness and strength of a cage.

e) Further testing of ties required as there is a wide variation in strength. University of Nevada Report CCEER10-07 [48] found that experienced fixers typically produce 18 % stronger connections than inexperienced fixers. The industry should strive towards better consistency of tying practice through training and site control measures.

f) Testing required to determine wind effects on cages with respect to shielding and wind reduction factors based on bar sizes and spacing density.

g) Further investigation is required to determine best ways to mitigate the effects of accidental loading (if accidental impact cannot be eliminated). Many cages can collapse suddenly under a relatively small accidental impact load but if designed and constructed robustly then the cage may withstand this loading, or any potential collapse may be more gradual.

h) Research is required to determine the effect of ‘number of twists’ on tie wire.

i) Review of new products for bar and splice connection.

j) Testing is required to determine if vortex excitation can occur in cages and what are the potential effects.

k) Those involved in the design, management and tying of cages should be made aware of the practical and theoretical applications of this guide. Education and training of those involved with cages (in particular, fixers) should also be updated to include the recommendations of this guidance.

l) A handheld, mobile tie tester should be developed so that it can be used to test in-situ ties on cages and as a training aid for fixers to develop a better understanding of “what good looks like”.

m) Further testing should be carried out using different types of tying wire and different ties and a more rigorous analysis of all test results undertaken.

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Useful websites

British Standards Institution (BSI)
https://shop.bsigroup.com

Construction Industry Training Board (CITB)
https://www.citb.co.uk

Health and Safety Executive (HSE)
https://www.hse.gov.uk/

National Access & Scaffolding Confederation (NASC)
https://nasc.org.uk/

Temporary Works Forum (TWf)
https://www.twforum.org.uk

Appendix A - Summary of results from recent testing by the Temporary Works Forum (TWf), Morgan Sindall Infrastructure via Programme and Project Partners PPP (Sellafield) and historic tests carried out by others

Analysis of results for Robust Structural Ties - Method B (see Section 6.2.2)

TWf testing

A series of tests (Tests A, B and C), using bars of varying diameter and double wire ties, were carried out on two separate occasions at two locations. All the bars used in the testing were high yield deformed B500B. The bars and tie wire were procured from BRC. A bespoke testing rig was developed by TWf, and partner organisations, and this is shown in Appendix B along with a summary of the testing procedure.

1. **Preliminary tests** - On 20th June 2022 at Swantest Ltd in Erith, South-East, London a preliminary series of 90 tests were undertaken. These used 12 mm, 20 mm and 32 mm bars and 1.6 mm black annealed tying wire. The purpose of these tests was to determine whether the test equipment was sufficiently stiff and tom provide an overall 'proof of concept'. During these tests an initial pre-load of 0.1 kN was applied to remove any "slack" from the system. The system was then "zeroed" and the load applied. These trials were successful.
2. **Main test programme** - Between 5th and 9th September 2022 at Staht Ltd. in Stourbridge, West Midlands a series of over 400 tests were carried out by Morgan Sindall Infrastructure. These were carried out on bars ranging from 16 mm to 40 mm diameter, using 1.6 mm black annealed as well as 1.2 mm stainless steel wire. The loading applied was either a steady load to failure or cyclically, i.e. loading then unloading of 0.5 kN intervals to failure. With these tests a pre-load was not applied (the system was set up to be 'hand tight' to remove any slack) to ensure that load-versus-displacement at very low strain could be measured. These tests were successful and observations were made relating to the mode of failure.

The data from both sets of testing is available at https://www.twforum.org.uk/resources/rebar-tie-testing

Executive summary

From a combined total of circa 480 separate tests the results have been analysed to prepare the recommendations set out within this Appendix. The main observation is that the typical failure mode of the 1.6mm black annealed wire and 1.2 mm stainless steel wire differ and this affects the range of failure for each wire.

The black annealed wire typically failed by breaking outside the area that had been tied and cut after a minimum of 3.5 twists for ≤25 mm bars, increasing to 4 twists ≥32 mm bars.

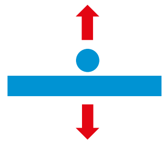
The stainless-steel wire typically failed by unravelling after a minimum of 4 twists but no more than 5 twists, irrespective of bar diameter and combination.

These observations have thus informed the guidance on the minimum number of turns associated with each respective tie wire type and bar.

Furthermore, the respective data set from each round of testing shows a large variation within the deformation due to the randomness of bar-to-bar versus bar-to-tie arrangement. These variables take cognisance of the ribs on the bar, which was observed to dramatically affect the failure value of a tie (in particular for Test Type C).

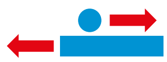
The average failure loads presented in **Appendix A** are considered to provide a conservative approach in generating the 'SWL' of each tie for each respective quality control combination (and are broadly consistent with historic data).

Appendix A – *continued*

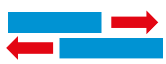


Cruciform normal pulling (Test Type A)	**Tie Types** Doubled Wire Crown Tie Doubled Wire Hairpin Tie Doubled Wire Looped Hairpin Tie		**SWL and usage condition:** All load types, BUT must never hang a load directly from a tied bar	
Wire type	Wire Dia. (mm)	Average Failure Load (tie disintegration) (kN)	SWL (even load over multiple ties and good site quality control) (kN)	SWL (load on one tie and poor site quality control) (kN)
Soft Black Annealed	1.6	3.38	0.9	0.35
	1.4	2.57	0.6*	0.3*
	1.2	1.90	0.5*	0.25*
Stainless Steel	1.2	3.2	0.85	0.35
Movement limit assumption:			$0.073D_{av}$	

** Corrigendum, January 2023*



Cruciform Tangential Sliding (Test Type B)	**Tie Types** Doubled Wire Crown Tie Doubled Wire Hairpin Tie Doubled Wire Looped Hairpin Tie		**SWL and usage condition:** All load types, BUT must never hang a load directly from a tied bar	
Wire type	Wire Dia. (mm)	Average Failure Load (tie disintegration) (kN)	SWL (even load over multiple ties and good site quality control) (kN)	SWL (load on one tie and poor site quality control) (kN)
Soft Black Annealed	1.6	3.12	0.78	0.35
	1.4	2.39	0.6	0.3
	1.2	1.76	0.44	0.22
Stainless Steel	1.2	3.02	0.76	0.35
Sliding displacement assumption for small p-delta analysis			$0.63D_{av}$ (typically 10 to 13 mm)	



Splice tie Sliding (Test Type C)	**Tie Types** Doubled Wire, Wrapped Splice Tie		**SWL and usage condition:** All load types, BUT must never hang a load directly from a tied bar	
Wire type	Wire Dia. (mm)	Average Failure Load (tie disintegration) (kN)	SWL (even load over multiple ties and good site quality control) (kN)	SWL (load on one tie and poor site quality control) (kN)
Soft Black Annealed	1.6	2.8	0.7	0.35
	1.4	2.14	0.54	0.27
	1.2	1.58	0.4	0.2
Stainless Steel	1.2	3.0	0.75	0.35
Sliding displacement assumption for small p-delta analysis			Average, 10 to 13 mm	

Appendix A – *continued*

Notes for the tables:

- D_{av} is average bar diameter of the two bars in contact. The maximum permitted difference in bar diameter is two standard sizes (e.g. 40 mm to 25 mm; 32 mm to 20 mm; 25 mm to 16 mm; 20 mm to 12 mm). Some values are pro-rata those of 1.6 mm soft black annealed wires and shown in italics.
- The 'average failure loads' recommended are, conservatively, based on 90% of the appropriate test results to allow for site conditions; as opposed to laboratory conditions.
- The 'safe working loads' are based on a factor of safety of four (even load over multiple ties and good site quality control), with a 50% reduction to allow for any ineffective ties (load on one tie and poor site quality control) (see Sections 6.3 and 6.4).
- Any recommendations for displacement and/or movement are based on the test results and the average distance and height between bar ribs and are made in order to prevent excessive deformation of the overall cage.
- There are two tables for Cruciform Tangential Sliding (Test Type B) as there is significantly more displacement (compared with Tests A and C) before the tie takes up load.
- Appendix F shows different types of tie.
- 'Good site quality control' is assumed to be the following: 'good quality ties' carried out by experienced fixers with all ties visually inspected (and testing carried out, see Section 6.2.2.1 and Appendix B) before each load condition / cycle and fixers can carry out any remedial work between load cycles. The load is also assumed to be distributed equally over multiple ties.
- 'Poor site quality control' is assumed to be the following: tying carried out by inexperienced fixers, ties are likely to work loose due to repeated load cycles, without inspection / re-inspection and no remedial work can be carried between load cycles. The load is applied to one (or two) tie without any opportunity for load re-distribution.

NOTE: A single load carrying tie is more vulnerable and is statistically more likely to have a lower failure load than a large group of ties.

Appendix B – Summary specification for assembly of testing apparatus and carrying out tie testing

B.1 Bespoke testing apparatus was developed by the TWf and partner organisations with the aim to standardise the testing of reinforcement ties (see Figures B1 to B.3).Designer and/ or Third-Parties need to ensure that the consideration for critical temporary works is clearly defined within the pre-construction information, outline method statement and/or the temporary works pre-construction schedule.

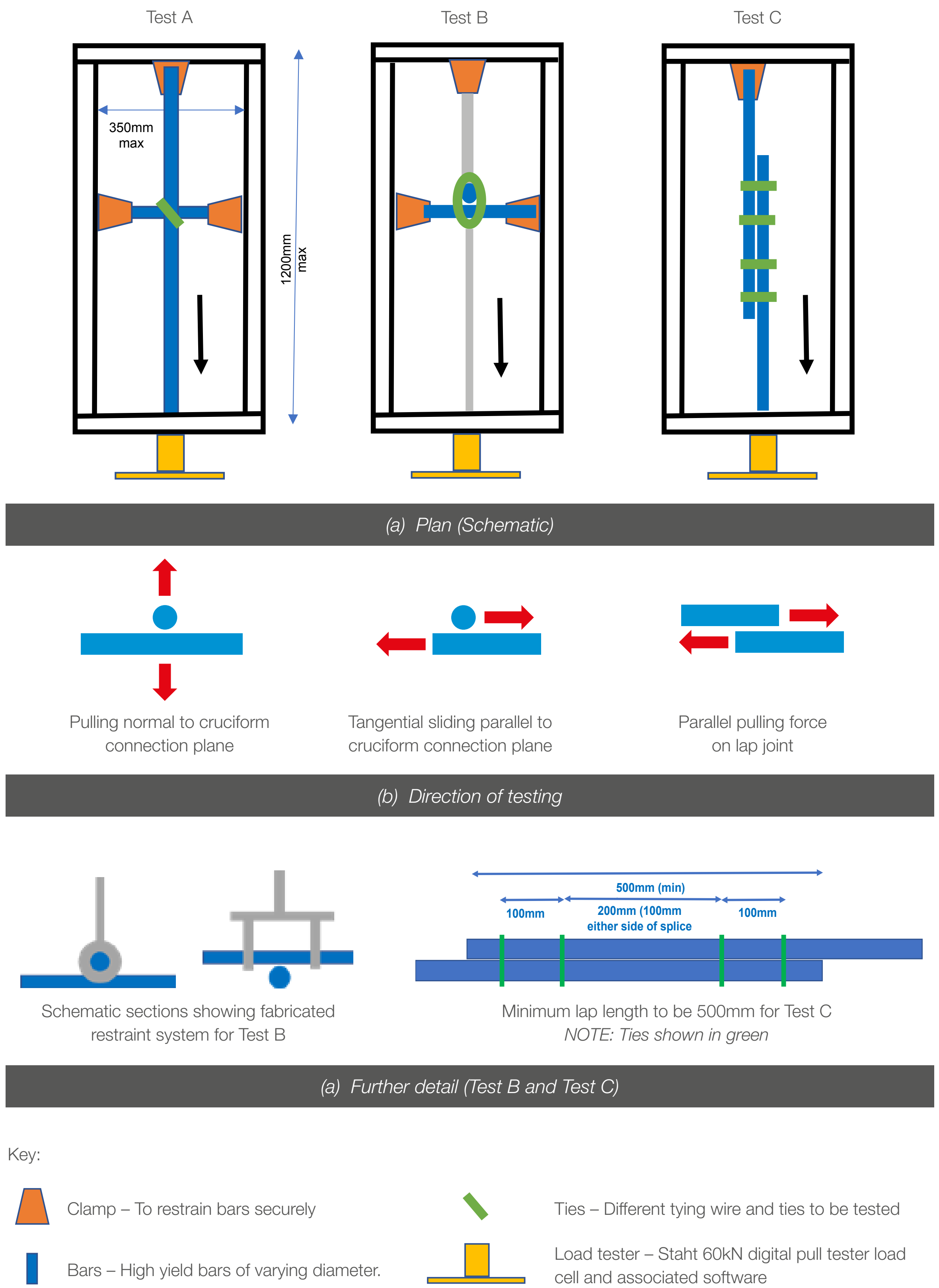
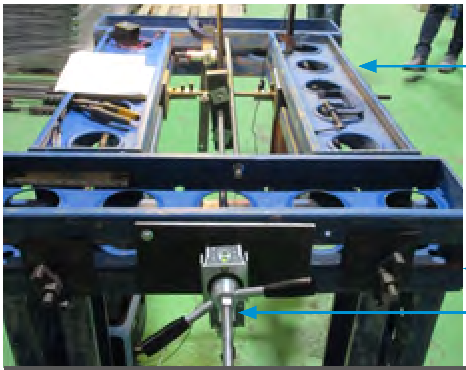


Figure B.1 – Test apparatus and set-up (schematic)

Appendix B – *continued*



Frame and stand made from proprietary soldiers (e.g. RMD or similar), which can be bolted together with proprietary corner backets or tied together with ties.

Proprietary ties to secure frame.

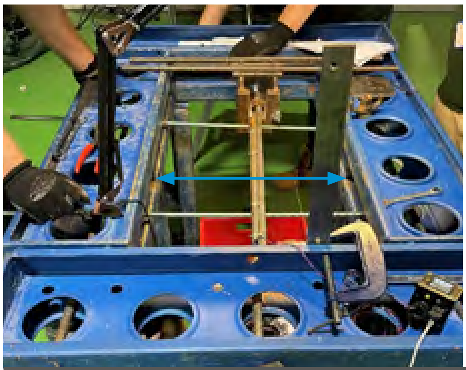
Pull tester and load application handle.

(a) Assembled testing apparatus (Test Type B arrangement)

Bar diameters can be varied.

Ties and tying wire to be tested can be varied.

(b) Close up of bar arrangement for Type A test



Distance between side soldiers to be kept to a minimum (typically 250mm to 350mm), ensuring there is sufficient space for tying wire.

If the distance is too large, then the reinforcing bar (especially smaller diameters) will bend during testing of Type A and B.

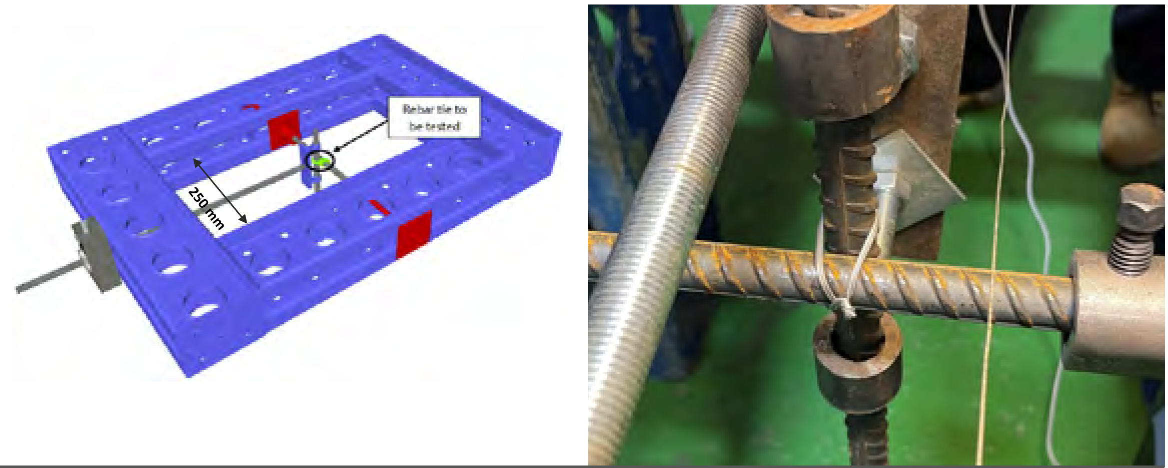
(c) Close up of bar arrangement for Type C test

Draw string sensor and pressure transducer.

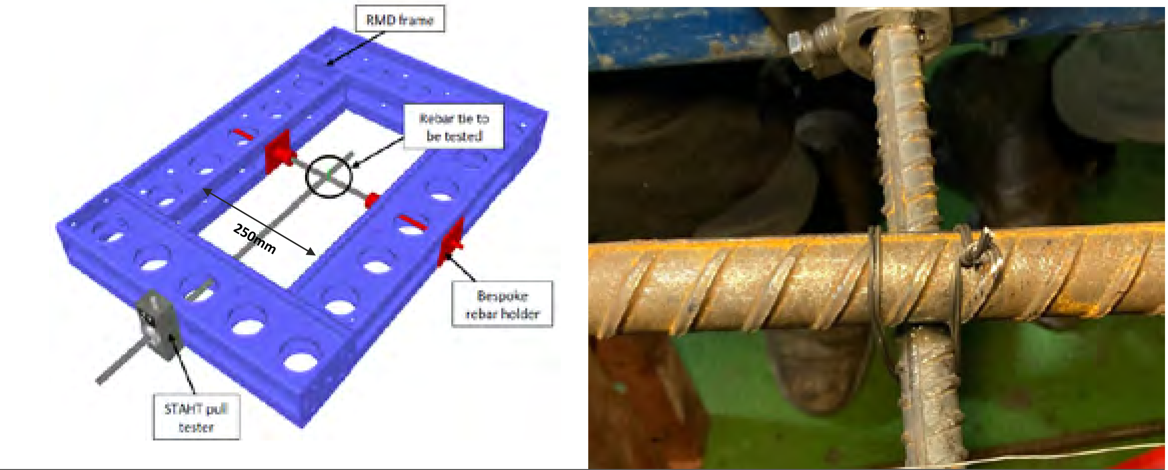
(d) Close up of draw string sensor and pressure transducer

Figure B.2 – Assembled tests apparatus

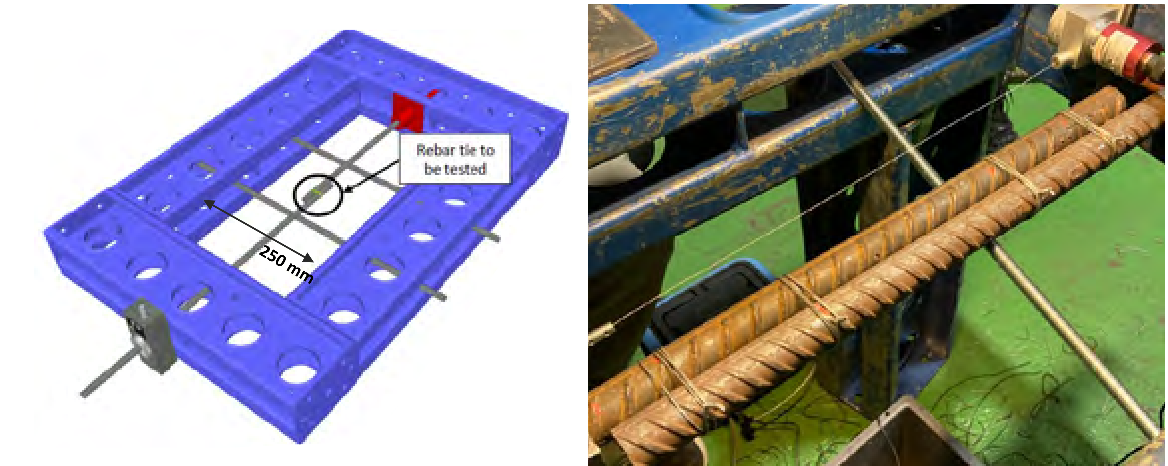
Appendix B – *continued*



(a) Test A



(b) Test B



(c) Test C

Figure B.3 - Tie Tests A, B and C (also showing a typical tie to be tested)

Appendix B – *continued*

Methodology to determine typical tie strength

B.2 The frame and stand should be assembled securely using proprietary soldiers (e.g. RMD "Superslim" or similar) as shown in Figures B.1 to B.3. The frame can be bolted together using proprietary corner brackets or tied together with tie rods (e.g. Dywidag or similar with spreader plates and wing nuts) to ensure it cannot move or distort during testing. The gap between the side soldiers should be kept large enough to allow tying (minimum 250mm) but not more than 350mm to prevent the reinforcing bars deflecting significantly during testing.

NOTE: Video and additional photographs showing the apparatus being assembled - and the tie testing sequences - are available from the TWf at https://www.twforum.org.uk/resources/rebar-tie-testing

B.3 It is recommended that bars from 12mm to 40mm diameter be used. The two bars used in the test can be the same diameter or of different diameters. When testing bars of different diameters, the two bars should not differ by more than two standard bar diameters (e.g. 12mm to 20mm or 25mm to 40mm). Any type of tying wire can be used, and – for structural ties – a suitable type of doubled wire tie should be tested.

B.4 Three different tests – named A, B and C – should be carried out (see Figures B.1 and B.3).

B.5 A Staht 60kN digital pull test load cell (with associated software) is used to apply the tensile load by turning the load application handle manually. The small hydraulic cylinder allows the load application to be controlled and is connected directly to a reinforcing bar. The handle which applies the pulling force should be turned steadily at 900 per second (i.e. a full turn every 4 seconds). A draw string sensor and pressure transducer is connected to the Staht tester to monitor load versus displacement.

B.6 The tying wire diameter should be confirmed with a micrometer and the wire checked for kinks, damage, grease, oil, dirt, etc. The wire strength should also be confirmed.

B.7 The bar type should be confirmed, and each bar checked for oil, grease, dirt, etc. When carrying the testing any length of bar with manufacturers markings should be avoided.

B.8 The bars should be positioned in the testing apparatus and tied together with tying wire. Various fabricated brackets or couplers can be used to secure the bars to the frame (see TWf website).

B.9 The ties should be hand tied using 'standard nips'. The number of twists on the tying wire should be as per the recommendations in this guidance (see Section 6.0 and Figure 15). If the wire snaps during tying, then the tie should be replaced. The whole system should be set up to be 'hand tight' to remove any slack before the tensile load is applied.

B.10 A single double wire tie is used for Tests A and B (typically double wire crown or double wire hairpin). Four ties should be used for Test C (bars spliced together, see Figure B.1(c)) to prevent 'scissoring' during testing. Additional anti-scissoring bars may also be used (see Figure B.3(c)).

B.11 The bar diameter(s), type of wire, number and type of tie(s) should be recorded.

B.12 The load should be applied steadily (by turning the loading handle, as described) until 'failure'. Failure is where either (i) the wire snaps; or, (ii) unravels.

NOTE: It is preferable for the wire to snap. If unravelling occurs, then more twists may be required on the tie wire.

B.13 Cyclic loading can also be applied as follows:

a. apply a load of 0.5kN (at a rate of 1 handle turn every 4 seconds) then unload;

b. apply a load of 1.0kN (at a rate of 1 handle turn every 4 seconds) then unload;

c. repeat the loading in increasing increments of 0.5kN, then unloading, until failure.

B.14 Load and displacement should be measured continually with time, and a graph plotted. Photographs and filming are recommended for record purposes.

B.15 Tests A, B and C can be carried out in any sequence.

B.16 The mode of failure (e.g. wire unravelling or snapping or – for Test C – the bars sliding over the ribs) should be noted, in addition to any other relevant points pertinent to each test.

Appendix C – Simplified checklist for designers

C.1 Designers should:

- be satisfied they have the skills, knowledge and experience and organisational capabilities.
- identify how the cage is to be constructed, e.g. in-situ, pre-fabricated on site and lifted into position or pre-fabricated off site and transported before being lifted into position.
- consider the position of laps, splices, construction joints and weights of bars to be handled.
- consider the use of specialist measures such as couplers and welding.
- consider the scale and complexity of the work as this determines the complexity of the analysis and if tie testing is viable.
- if tie testing is carried out, be satisfied with the testing procedures and consider the results.
- identify tall and slender cages or deep / inclined mats or cages with corbels / overhangs which could be prone to instability.
- identify loads and carry out analysis to justify the stability of the cage.
- specify maximum unsupported heights or maximum unsupported intervals between lateral supports.
- if the cage stability cannot be justified, then discuss options with the contractor.
- ensure that responsibility for various items has been agreed, an adequate design brief has been provided and the category of design check agreed.
- if the cage stability cannot be justified, then follow the 'principles of prevention' to design out the hazards and provide measures to ensure stability (e.g. redesign the cage, provide additional sacrificial bars or provide external support to suit the contractors preferred method of working).
- ensure relevant residual risks are clearly highlighted.
- ensure starter bars and kickers and detailed in the bases rather than walls / columns.
- avoid (if possible) specifying bars at very close spacing which may be difficult to tie, prevent concrete passing through or being adequately compacted.
- ensure that any additional sacrificial bars (added for stability or stiffness) do not compromise cover.
- determine whether ties are non-structural positional ties or structural robust ties:
  - For structural robust ties establish whether 'Method A' or 'Method B' is to be used for tie capacity (see Section 6).
  - For Method B ensure appropriate design experience is available, ensure appropriate testing is carried out to justify tie strengths and consideration is given to effects of increased displacement at tie positions.
- ensure "safety in numbers" for ties and provide alternative load paths to allow for ineffective ties (in particular for structural robust ties); ensure that appropriate ties and number of ties have been specified.
- for deep mats or mats on an incline, check that there are an adequate number / size of chairs and whether racking failure been considered.
- for long cages (e.g. for diaphragm walls or deep piles) that are generally rotated from horizontal to vertical plane when being lifted, ensure that consideration been given to temporary stiffeners to prevent buckling during lifting.
- provide an assembly sequence which considers easy buildability and safety of operatives. (The assembly sequence should consider the whole life-cycle including the removal of any external temporary support measures to allow the formwork to be installed.)
- ensure drawings are clear and easy to read with bars shown in a way that allows operatives to understand their spacing, position and orientation.
- ensure laps, cuts and bends have been adequately allowed for on schedules and drawings.
- for cages which are to be lifted, provide the weight, position of centre of gravity, design for lifting points and anticipated deflections during lifting or rotating.
- for cages which are to be stacked and/or transported, consider stability and the correct use of packing and strapping.
- manage effectively any on site change requests from the contractor.

C.2 PAS 8811:2017, Figure 1 [49] – herein, Figure C.1 - shows that the Client, Principal Designer and/ or Third-Parties need to ensure that the consideration for critical temporary works is clearly defined within the pre-construction information, outline method statement and/or the temporary works pre-construction schedule.

C.3 This means an upfront cost to the Client to review the relationship between anticipated temporary works and the permanent works on more complex projects. Many consider that the responsibility for temporary works lies with the contractor only, but this is not the case. Value-engineering – with the aim of cost efficiency and/ or material saving (in particular reinforcement, by a reduction in bar diameters as a design matures) - has the propensity to result in significant risk and a cost burden to others during the construction phase.

C.4 If the consideration for significant temporary works is led by the Client/ Principal Designer or Third Party within the pre-construction information phase - when the Principal Contractor or Specialist sub-contractor is able to refine the detail as part of their readiness for operational delivery – a significant front-end risk can be more easily reduced and communicated. (Also, see [50].)

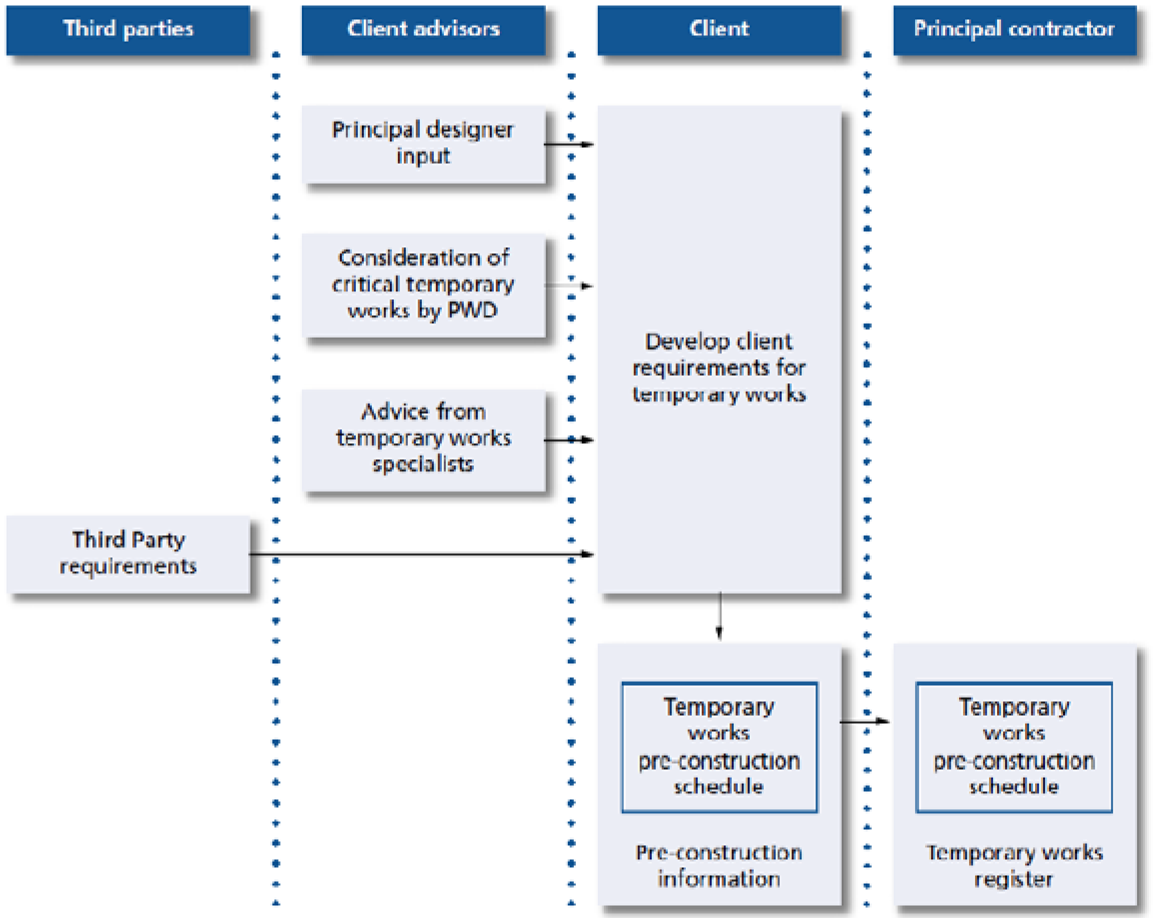


Figure C.1 - PAS 8811:2017, Figure 1, Pre-construction flowchart

Appendix D – Simplified checklist for site

D.1 Site inspections by a competent person should be carried out to ensure that:

- correct assembly sequences are being followed;
- the correct bars and ties are being used;
- they are installed to an acceptable standard;
- ties do not work loose or deteriorate during the cage life-cycle;
- any temporary works measures are in place.

D.2 This should be done:

- progressively, throughout assembly;
- prior to any moving or lifting;
- after lifting (landing) and prior to release of crane;
- after a load event that could affect stability or safety (e.g. after high wind or accidental impact).

D.3 Ties should be visually inspected with particular attention being paid to areas that are deemed critical, e.g. for lifting or connections to starter bars, where additional physical inspections should be carried out. Periodic inspections should be carried out especially after “loading events” (e.g. between repetitive lifting) to ensure ties have not worked loose or deteriorated and if necessary appropriate remedial action taken.

- Visual inspection:
  - Correct wire is being used, correct number and type of ties at the correct locations.
  - Correct number of “carrier bars” at correct centres and correct tie pattern (i.e. at every intersection).
  - They are sufficiently tight to ensure no visible gaps between bars.
  - There are sufficient twists.
- Physical inspection:
  - When walking over a flat mat (on boards) use body weight to check for loose bars.
  - For wall cages can try to move bars by hand to check if they are not loose.
  - Using a gloved finger individual ties should be “waggled” (i.e. application of around 5kg of hand force) to check for excessive movement.

D.4 Useful checks include:

- Has the stability of the cage been checked at all stages in its life-cycle? Have maximum free-standing heights been provided (if applicable) and have any additional temporary works measures been designed?
- Has an assembly sequence been provided and is it being adhered to?

  NOTE: The sequence should consider easy buildability and safety of operatives. The assembly sequence should consider the whole life-cycle including the removal of any external temporary support measures to allow the formwork to be installed.
- Is the working area safe and clear of obstructions?
- Has consideration been given to how bundles of bars of pre-fabricated cages are offloaded and stored on site?
- Has manual handling and access for work at height been adequately considered?
- Has consideration been given to safety issues with operatives walking on mats?

  NOTE: Boards should be provided, which spread the load and prevent deformation of the horizontal bars and supporting chairs.
- Are the bars (bent using correct formers in accordance with BS 8666), laps and spacing correct with the right cover?

NOTE: There should be correct orientation of bars and number of layers. No unauthorised cutting of bars or application of heat, bars are clean so concrete can adhere properly.

- Has the cage been assembled to an acceptable / agreed tolerance?
- Have any additional temporary works bars been installed and tied correctly?
- Are the type and frequency of ties correct?

  NOTE: Ensure ties have been installed to an acceptable standard (workmanship complies with an agreed standard). Ties are correctly tensioned with sufficient twist projecting from the tie.
- Do splices have the correct lap length, appropriate ties and appropriate lap stagger?

- Have any mechanical couplers been installed correctly (i.e. fully engaged and tightened as per manufacturers' instructions)? Similarly, for any grips / clips.
- Have any box outs, formers, instrumentation, etc. been correctly and securely installed?
- If welding is being used, has it been carried out by an appropriately-skilled welder to an approved procedure? Do welds comply with the design and are they the correct size and length?
- Once complete, has the whole cage been checked to ensure that it has retained the design shape (viz. correct dimensions and bars have not kinked or been bent out of shape) and any excessive deformation or distress reported by the PC's TWC/TWC to the designer.
- Have appropriate temporary works (i.e. additional bars or external support measures) been installed correctly?
- Have concrete foundations fully cured?
- Have any on site modifications have been communicated to the designer by the PC's TWC/TWC and approval received?
- If a cage is being transported, have it been checked to ensure they can be stacked and are sufficiently robust for transport? Has load stability and security been considered during transport?
- If a cage is being lifted by crane, have lifting points been designed, installed correctly, tested and certified? Is LOLER being followed? Has a plan been produced by an Appointed Person (AP) and complied with? Is all lifting equipment as per the lift plan and certified? Is the crane the same as that specified in the lift plan?
- Is there adequate supervision for lifting operations and, if possible, has an exclusion zone been established and enforced?
- Have the crane foundations been designed and checked?

  NOTE: Ensure the area around the lifting operation is clear of hazards that could cause the cage to snag during the lift.
- Before lifting, has the cage been inspected for loose items which could fall out during lifting?

  NOTE: For anything other than very low risk / light cages, a permit to lift should be provided.
- Before lifting, check that the wind speed is below any limit imposed in the lift plan and that an exclusion zone has been set up (if possible) and is being enforced.
- Before the chains / strops are released, is the cage stable and have and additional temporary works measures been installed correctly? How are the chains / strops to be removed safely?
- After lifting, has an inspection been carried out to check the cage for any damage or distress?
- Has consideration been given to tensioning and removing any guy wires?
- Has consideration been given to adequate foundations for props and guy wires?
- Are measures in place to prevent / limit the effects of any possible accidental impact?

D.4 The Institution of Structural Engineers' Standard Methods of Detailing Structural Concrete (4th Edition) [20] has some useful checklists:

- Checklist of information to be provided by designer (box 1, p7);
- Construction information to be coordinated between designer, contractor and detailer (box 2, p7);
- Checklist for detailer (p37);
- Procedure for checking reinforcement drawings and schedules (p41).

Appendix E – Principles of prevention for designers

E.1 The general principles of prevention are a requirement of the Management of Health and Safety at Work Regulations 1999 [29] and provide a framework to identify and implement measures to control risks on a construction project. Good design considers 'safe by design' from the outset and ensures that hazards are identified and eliminated wherever possible.

E.2 The general principles of prevention from L153, Appendix 1 [46] are to:

(a) avoid risks (e.g. by eliminating hazards at source);

(b) evaluate the risks which cannot be avoided (and a structured approach should be taken);

(c) combat the risks at source (and this requires the control measures to be close to the danger point and to be effective in reducing it);

(d) adapt the work to the individual (especially regarding the design of workplaces, the choice of work equipment and the choice of working and production methods, etc.);

(e) adapt to technical progress (e.g. keeping informed about and using the latest technical knowledge);

(f) replace the dangerous by the non-dangerous or the less dangerous (viz. substitution);

(g) develop a coherent overall prevention policy which covers technology, organisation of work, working conditions, social relationships and the influence of factors relating to the working environment (viz. the whole safety system needs to be considered: the individual, the task, the plant and equipment);

(h) give collective protective measures priority over individual protective measures (as these can eliminate risks to more than one person and have major advantages over individual protective measures); and

(i) give appropriate instructions to employees (so they know how to perform the work safely).

E.3 For designers – whether permanent works designers or temporary works designers – the principles can be visualised as shown in Figure E.1.

NOTE: The 'Eliminate, Isolate and Minimise' approach illustrated can also be referred to as 'Eliminate, Reduce, Inform (and Control)' ('ERIC').

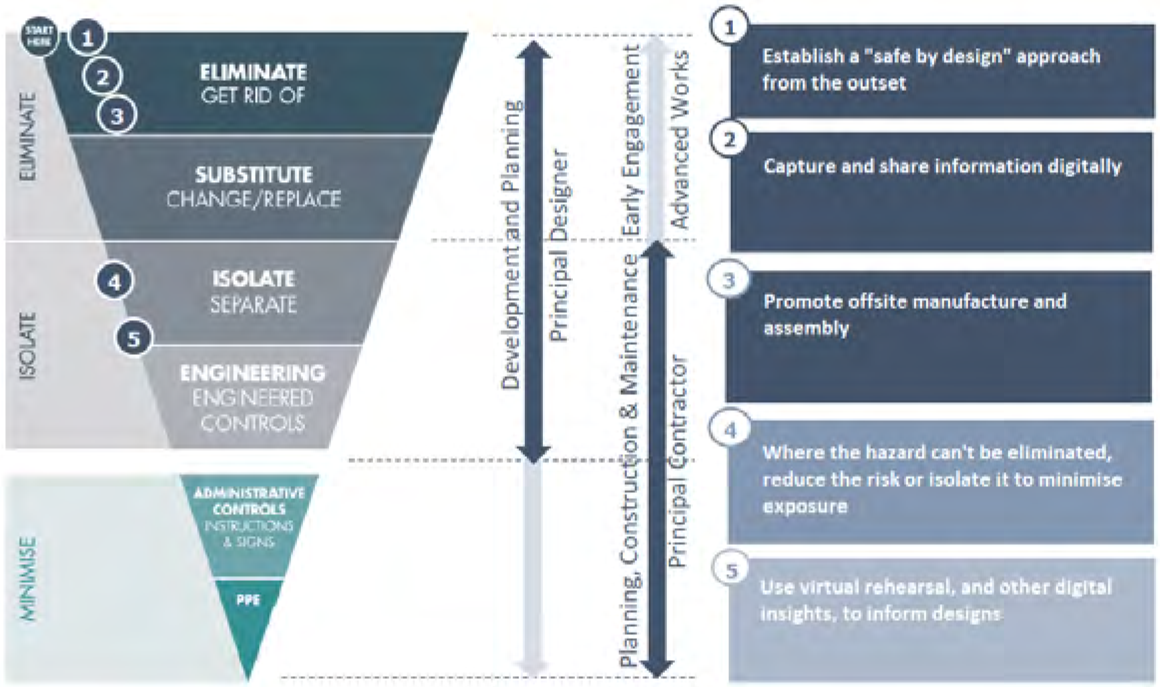
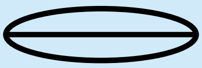
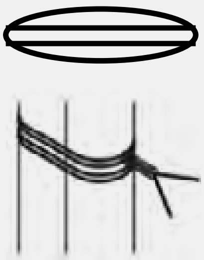
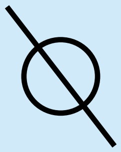
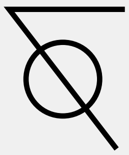
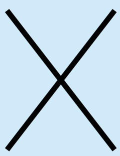


Figure E.1 – A visualisation of the general principles of prevention

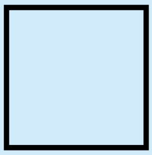
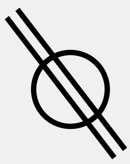
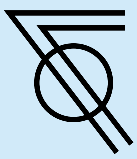
Appendix F – Tie symbols, abbreviations and typical uses

Drawing symbol	Tie name, description and typical use	Abbreviation
	Single **W**ire **S**plice **Typical use:** In-situ fixing, to splice horizontal lapping bars up to 25mm and possibly 32mm dia. Might also be used as an 'infill' splice tie to vertical laps on up to 20mm dia. vertical bar laps on small in-situ cages. Good for splicing small diameter bars. **Function:** Strictly quality only – to keep bars in place during placement and compaction of concrete. No semi-structural function.	**SWS**
	**D**oubled **W**ire **S**plice **Typical use:** In-situ fixing to splice larger diameter (>=25mm) horizontal lapping bars. Used for in-situ splicing vertical laps supporting 150mm to 250mm wide strip of vertical weight. **Function:** Can be used for quality purposes to keep larger spliced bars (horizontal and vertical) in place during concrete compaction. Also used as a robust tie for smaller diameter vertical bar splices and large diameter bar splices on non-framing bars. Has a semi structural function.	**DWS**
	**S**ingle **W**ire, **W**rapped Splice **Typical use:** Vertical lapping splice, e.g. starter bar splice. The single wire double wrapped splice is suitable for small diameter bars and short walls (e.g. 12mm or 16mm diameter circa 2-3m high). **Function:** Can be used for quality purposes to keep spliced bars in place during placement and compaction of concrete. Not considered to be a semi-structural tie connection as it is single wire.	**SWW**
	**D**oubled **W**ire, **W**rapped Splice **Typical use:** Vertical lapping splice, e.g. starter bar splice, particularly large diameter bars; designated framing members, z-bar laps and locations where scissoring is anticipated. **Function:** Semi-structural tie for robust tying of framing members and vertical splice of e.g. heavier wall cages.	**DWW**

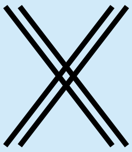
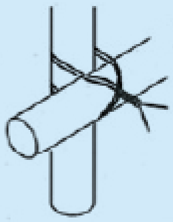
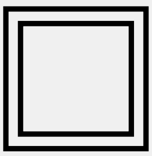
Appendix F – Tie symbols, abbreviations and typical uses – *continued*

Drawing symbol	Tie name, description and typical use	Abbreviation
	**S**ingle Wire **S**lash **Typical use:** Basic cruciform connection horizontal and vertical bars and elements – as an infill tie. Any diameter bar – for infill tying but more effective for small diameter bars. **Function:** Quality purpose to keep bars in place during concrete placement. No semi-structural function.	**SS**
	**S**ingle Wire **R**ing-Slash **Typical use:** This is a variation of the slash tie for cruciform connection, particularly with horizontal lacers onto vertical bars in walls or horizontal bar connections in slabs where sliding movement of one bar is to be resisted relative to the other bar. Any diameter bar but more effective for small diameter bars up to 20mm. The purpose of the loop is to form an 'anchor point' on the static bar to help resist sliding of the connected bar. The loop is tied so the connected bar slides away from the loop and this part of the tie goes into tension. For example, if a horizontal lacer bar is expected to slide down a static vertical bar, the loop must be above the horizontal lacer. **Function:** Quality purpose to keep bars in place during concrete placement. No semi-structural function.	**SR**
	**S**ingle Wire **C**rown **Typical use:** Tight cruciform connection of horizontal and vertical small and moderate diameter bars (<=20mm) and elements. Good for positioning 'set' bars, e.g. corner of beam and column links and where there is an element of spring in bars being connected. The single wire crown tie will be used in light weight cages with small/medium diameter bars. Can also be used on larger diameter bars as an infill tie. **Function:** Quality purpose to set key bars accurately in place. Not considered to have a semi-structural function as it is single wire. Slightly better at maintaining cage shape than, e.g. a slash tie.	**SC**

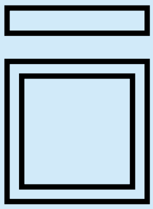
Appendix F – Tie symbols, abbreviations and typical uses – *continued*

Drawing symbol	Tie name, description and typical use	Abbreviation
	**S**ingle Wire **H**airpin **Typical use:** Tight cruciform connection of horizontal and vertical small and moderate diameter bars (<=20mm) and elements. Good for positioning 'set' bars, e.g. corner of beam and column links. The single wire hairpin tie will be used in light weight cages with small/medium diameter bars. Can also be used on larger diameter bars as an infill tie. **Function:** Quality purpose to set key bars accurately in place. Not considered to have a semi-structural function as single wire. Slightly better at maintaining cage shape than, e.g. a slash tie. Hairpin ties are good for direct pulling and shearing resistance at cruciform joints. They do not provide any side clamping action and are therefore less desirable than crown ties and when forming a cruciform tie at a splice location (e.g. horizontal bar secured to vertical starter bar splice zone).	**SH**
	**D**oubled Wire **S**lash **Typical use:** Basic cruciform connection horizontal and vertical bars and elements – as an infill tie to large cages and larger diameter bars. Used as an infill tie to secure bars in prefabricated cages. **Function:** Quality purpose to keep large diameter bars in place during concrete placement. Has some semi-structural function in sliding and direct pulling. Due to simplicity of form, develops quite good clamping action both normal and tangential to bars so can be used for cruciform tie at splice locations. Easy to form.	**DS**
	**D**oubled wire **R**ing Slash **Typical use:** Simple cruciform connection for horizontal and vertical bars as an infill tie to large cages and larger diameter bars. Used as an infill tie to secure larger diameter bars in prefabricated cages. The purpose of the loop is to form an 'anchor point' on the static bar to help resist sliding of the connected bar. The loop is tied so the connected bar slides away from the loop and this part of the tie goes into tension. For example, if a horizontal lacer bar is expected to slide down a static vertical bar, the loop must be above the horizontal lacer. **Function:** Quality purpose to keep large diameter bars in place during concrete placement. Has some semi-structural function in sliding and direct pulling. Due to simplicity of form, develops quite good clamping action both normal and tangential to bars so can be used for cruciform tie at splice locations. Easy to form.	**DR**

Appendix F – Tie symbols, abbreviations and typical uses – *continued*

Drawing symbol	Tie name, description and typical use	Abbreviation
 	**D**oubled Wire **C**rown **Typical use:** Fixing large diameter bars where weight of bar is to be supported by ties. To close gaps between springing bars. Tying prefabricated assemblies. Tying horizontal and vertical set bars and pick-up (lifting framing members). Corner 'link knuckle' bars to beam and column cages. In zones where there are concentrations of force in cages – for example, at the connection of push pull props – in order to spread loads into the cage. Tying horizontal lacer bars across z-bars and other framing members to 'contain' out of plane forces. Tying of face bracing reinforcement at bar intersections. Tying of horizontal lacer set bars positioned toward the top and bottom of lapping splice zones – to resist scissoring. **Function:** Semi-structural cruciform connection. Has good resistance to normal pulling forces, e.g. where bars are springing apart. Tangential sliding resistance is good after some initial movement (circa 4 to 5mm for 20mm-plus diameter bars) to engage the tie. The form of this tie also enables an element of side clamping making it suitable for cruciform connections in bar lapping zones. The pulling resistance at cruciform connections can help to resist scissoring effects.	**DC**
	**D**oubled Wire **H**airpin **Typical use:** Fixing large diameter bars where weight of bar is to be supported by ties. Tying prefabricated assemblies. Tying horizontal and vertical set bars and pick-up (lifting framing members). Corner 'link knuckle' bars to beam and column cages. In zones where there are concentrations of force in cages – for example, at the connection of push pull props – in order to spread loads into the cage. Tying horizontal lacer bars across z-bar zones and other framing members to 'contain' out of plane forces. Tying of face bracing reinforcement at bar intersections. Lacer set bars tied toward the top and bottom of lapping splice zones. **Function:** Semi-structural cruciform connection. Has good resistance to normal pulling forces. Tangential sliding resistance is good – requiring less sliding movement than a crown tie to engage resistance. The form of this tie does not provide any side clamping which might be desirable when forming a cruciform connection at a splice location. The pulling resistance at cruciform connections can help to resist scissoring effects in contained bars.	**DH**

Appendix F – Tie symbols, abbreviations and typical uses – *continued*

Drawing symbol	Tie name, description and typical use	Abbreviation
	**D**oubled Wire Looped (or ring) **H**airpin This is a variation of the hairpin tie. The purpose of the loop is to form an anchor point on the static bar to help resist sliding of the connected bar. The 'loop' is tied so the connected bar slides away from the loop so this part of the tie goes into tension. For example, if a horizontal lacer bar is expected to slide down a static vertical bar, the loop must be above the horizontal lacer. Tests indicate that more initial movement needs to occur to engage the tie, compared to a normal hairpin tie. This is thought to be because when the tie is formed, the wire strands are less likely to be uniformly tensioned and there is reduced clamping force from the tying process as a result. A small initial sliding movement, typically 3mm, is required to engage the tie. The looped hairpin does not appear to be stronger than the standard hairpin tie, but it might tolerate more movement and may have some redundancy under high strain. More specific testing is required to fully understand the benefits of the loop for this tie. **Typical use:** As for standard doubled wire hairpin tie (DH) – but where a load is hung from the tie. **Function:** As for standard doubled wire hairpin tie (DH).	**SH**

Summary:

Single wire ties are suitable for small-to-medium size diameter bars and for larger bars where the function of the tie is simply to prevent displacement during pouring.

Doubled wire ties are used for large diameter bars (ties at larger centres) and for all tied bar connections having a semi-structural function where an engineered connection (welded, bolted, etc.) is not possible.

Appendix G – Examples of poor workmanship

Insufficient number of drop chains for the size of the cage, inclined drop chains (should be vertical to avoid reactions into the cage), incorrect attachment points and visible deflection of the cage

Figure G.1 - Example 1, Poor lifting

(a) Insufficient weld to one of the bars so the bars are not effective joined

(b) A poorly executed weld

Figure G.2 - Example 2, Poor welds

Courtesy: Nick Cook

Appendix G – Examples of poor workmanship

(a) Ineffective tie due to insufficient twists

(b) Ineffective tie due to overtightening causing the tie to break

(c) Ineffective tie which is too loose

(d) Ineffective tie which is too loose and which has insufficient twists

Figure G.3 - Example 3, Ineffective ties

Appendix H – Case studies

H.1 Examples of rebar failure and cage collapse (primarily in the UK) - known to members of the Temporary Works Forum (TWf) – provide a wide range of causes for cages in their interim state.

H.2 Names and locations have been removed, but examples include:

- operatives being injured whilst working inside a cage which collapsed.
- cantilever wall cage collapsed in high winds causing damage to site machinery.
- changes in agreed assembly sequences led to a cage toppling over.
- failure of lifting equipment and failure of tying wire holding several cages together during lifting which caused several cages to fall into an exclusion zone.
- over-tensioning / out of balance tension in guy wires pulling cages over.
- incorrect assumption that a freestanding cage was stable without engineering justification.
- operative killed when 80t cage collapsed in strong winds as inadequate lateral support was provided.
- to install formwork, the props supporting the cage were being removed by operatives and the cage collapsed due to lack of consideration of the sequence of work.
- slinger signaller failed to connect lifting slings to the correct lifting points on a cage, resulting in a mesh panel detaching during the lift and falling some 30m into a shaft.
- inadequate planning and site control measures allowed props (which were providing temporary stability to a cage) to be removed in an uncontrolled manner to allow formwork to be installed. When the props were removed the cage became unstable and collapsed.
- lack of active and ongoing supervision leading to cage collapse.
- lack of rigging and temporary works drawings (and a reliance on verbal instructions).
- low levels of lighting on site.
- lack of clarity on responsibilities.
- the permanent works design of the rebar cage was adequate but did not consider it being erected in a free- standing manner.
- the cage had been left effectively free-standing as all that was supporting it was some tying wire tied back to the buttressed scaffold (the scaffold was provided for access only).
- rebar stability not considered in planning construction methodology.
- lack of experience of the TWC in controlling the overall temporary works process.
- the support of the rebar had not been included in the temporary works schedule and therefore no temporary works design had been completed or implemented learning from previous rebar incidents had not been properly distributed.
- coordination of adjacent trades, scaffolder and steel fixer did not raise any previous concerns.
- designers engaged to review all rebar on site for stability during construction phase and to ensure any residual risks are designed out or clearly indicated on the construction drawings.
- all findings to be fed back into parent companies.
- following the collapse of a slender wall a series of vertical trusses were introduced.
- large rebar cage for deep slab collapsed with fixers inside, with the failure described as a “racking movement”.
- flaws in planning, management and monitoring.

H.3 All those involved in cage assembly, transport, lifting etc and especially designers should be made aware of these various incidents to better understand the hazards and thereby they can determine appropriate solutions.

Appendix I – Example calculations

Job Number	Task	Sheet	of	Rev.	Date
999999	001	1	23	P04	27/06/2022

RICHTER

Customer: TWf
Job: Rebar Stability — By: SM/MD
Description: Base Slab — Checked: N/A

Reference	Calculations	Output

Introduction

Detailed design of pre-fabricated support cages for the top mat of a base slab. The support cages will be fabricated from welded reinforcing bar in a factory then transported to site.

The base slab is for a 30m diameter shaft and has and overall depth of 4.0m.

The support cages shall be placed end to end to provide a series of lines of support at 3.0m centres. Each cage shall be 1.5m wide and 4.0m long.

The following design situations will be considered
(i) in service, supporting the top mat and construction loads
(ii) during lifting at factory and at site
(iii) during transport on HGV

References

BS 5975:2019 Temporary works procedures and permissble stress design of falsework

BS 449-2:1969 Use of structural steel in building

BS 4449:2016 Steel for the Reinforcement of Concrete

BS 8666:2020 Scheduling of reinforcement for concrete

Steel Designer's Manual 7th Edition

Assumptions

loads:
• 40% allowance for laps in permanent reinforcement mat
• wind may be ignored

the cage will be fixed to the permanent reinforcement, top and bottom mats, using nominal hit and miss staggered slash ties and these are considered adequate for stability by inspection

lifting:
• slinging points shall be at the inboard links at 'fifth' points
• slings for lifting will be at no more than 30° to the vertical
• dynamic enhancement for lifting may be taken to be 25%

rebar guide 10 — worst case horizontal force during transport will be decelaration due to braking which shall be taken to be a maximum of 1.00g

design:
• permissible bending and shear stresses provided in BS 449 for grade 55 steel are acceptable for reinforcement of all diameters
• axial compressive permissible stress derived in accordance with BS449 Appendix B using yield strength provided in BS 4449
• permissible stresses for welds provided in BS449 for grade 43 steel are adopted for all welded connections to accommodate use of commonly available weld rods
• modulus of elasticity may be taken to be as provided in BS 449 App B, E = 210 MN/mm^2
• for the purposes of analysis, frames may be treated as pinned
• for the purposes of design, welded joints may be considered to provide full restraint for position and rotation *

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	2	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

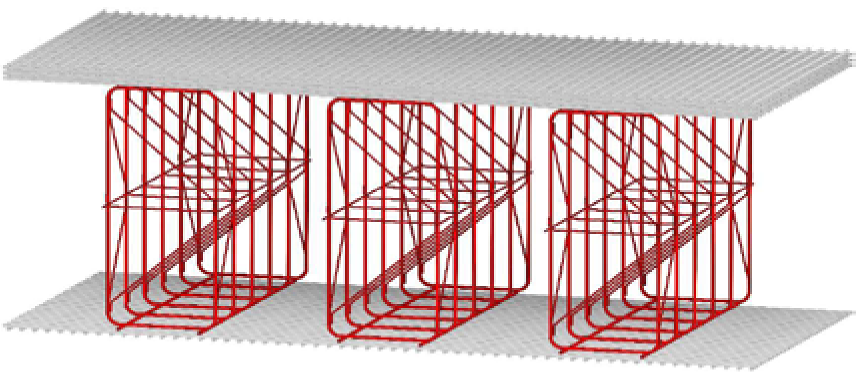
* CAUTION

Full restraint is only considered applicable in this example due to the use of fully welded joints, the size and stiffness of individual bars, the specific configuration of the bars and the minimal deformation under load.

In this particular instance all joints have significant fixity against rotation in plane and about bar axes due to continuity of bar and/or welds

The end fixity in solutions using smaller more flexible individual bars, different configurations and/or experiencing greater deformation may require assumption of reduced fixity at joints.

Sketch Detail 1 - General Arrangement 3D View



Key:-
support cages - red
permanent reinforcement - grey

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	3	23	P04	27/06/2022

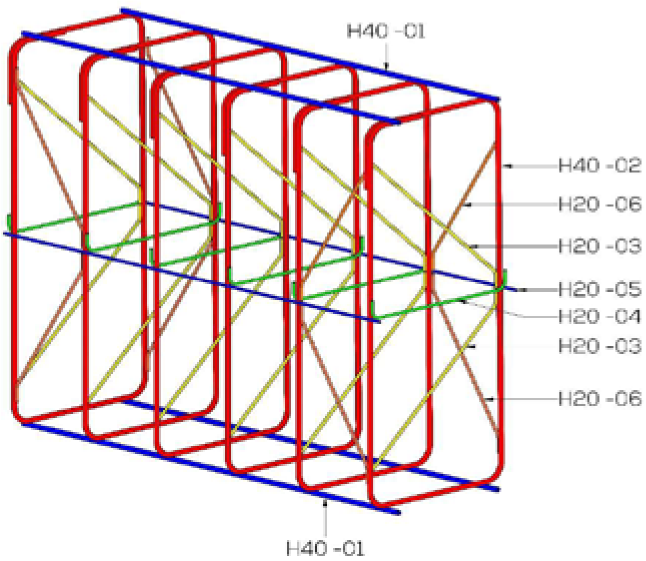
Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

Sketch Detail 2 - Support Cage 3D View



Key:-
Longitudinal bars (b/mk 01 & 05) - blue
Links (b/mk 02) - red
Transverse ties/struts (b/mk 03) - yellow
Transverse bars (b/mk 04) - green
Longitudinal ties/struts (b/mk 06) - orange

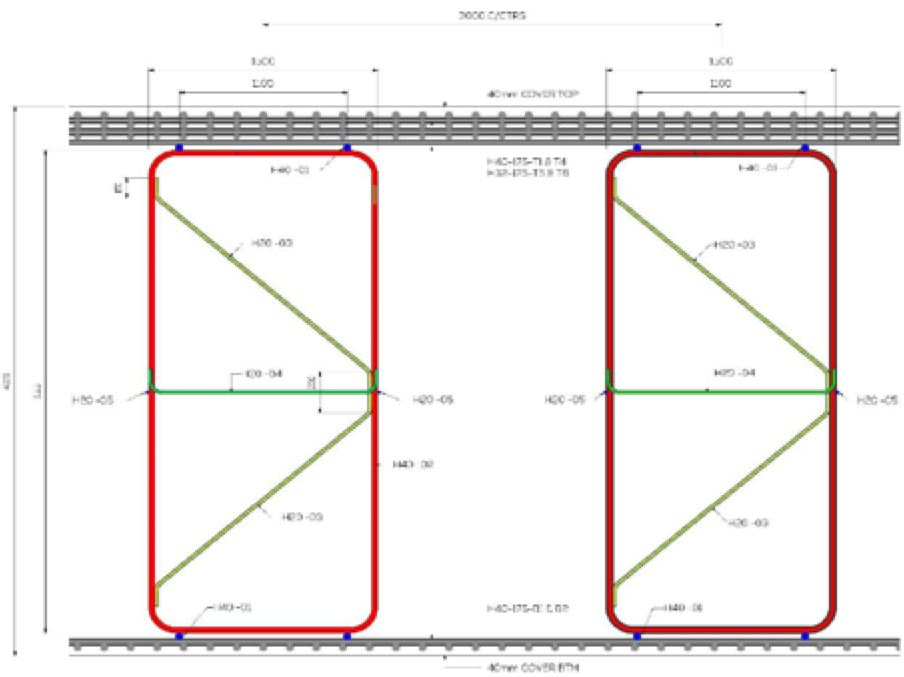
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	001	4	23	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Base Slab	Checked	N/A

Reference	Calculations	Output

Sketch Detail 3 - General Arrangement Cross Section



Key:-
Longitudinal bars (b/mk 01 & 05) - blue
Links (b/mk 02) - red
Transverse ties/struts (b/mk 03) - yellow
Transverse bars (b/mk 04) - green
Longitudinal ties/struts (b/mk 06) - orange
permanent reinforcement - grey

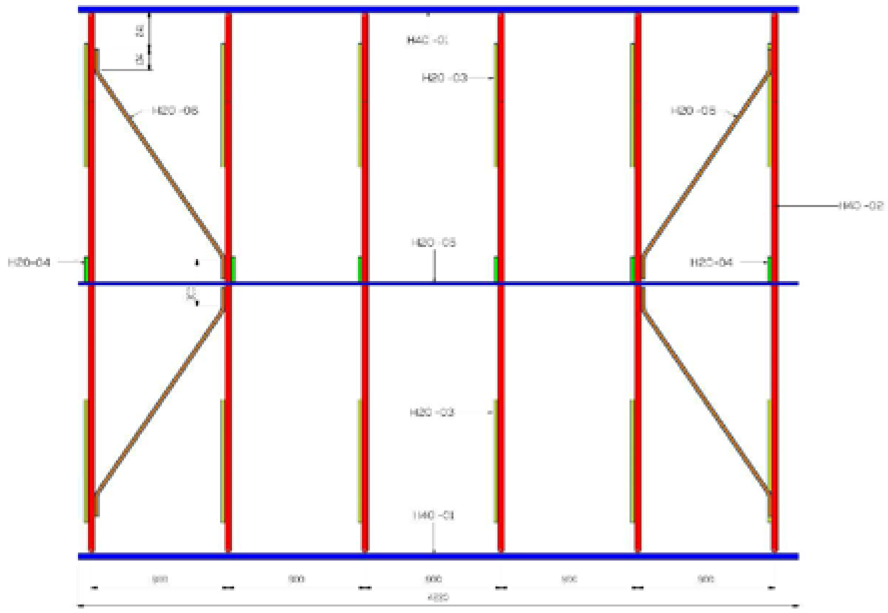
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	001	5	23	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Base Slab	Checked	N/A

Reference	Calculations	Output

<u>Sketch Detail 4 - Support Cage Long Section</u>



Key:-
Longitudinal bars (b/mk 01 & 05) - blue
Links (b/mk 02) - red
Transverse ties/struts (b/mk 03) - yellow
Transverse bars (b/mk 04) - green
Longitudinal ties/struts (b/mk 06) - orange

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	6	23	P04	27/06/2022

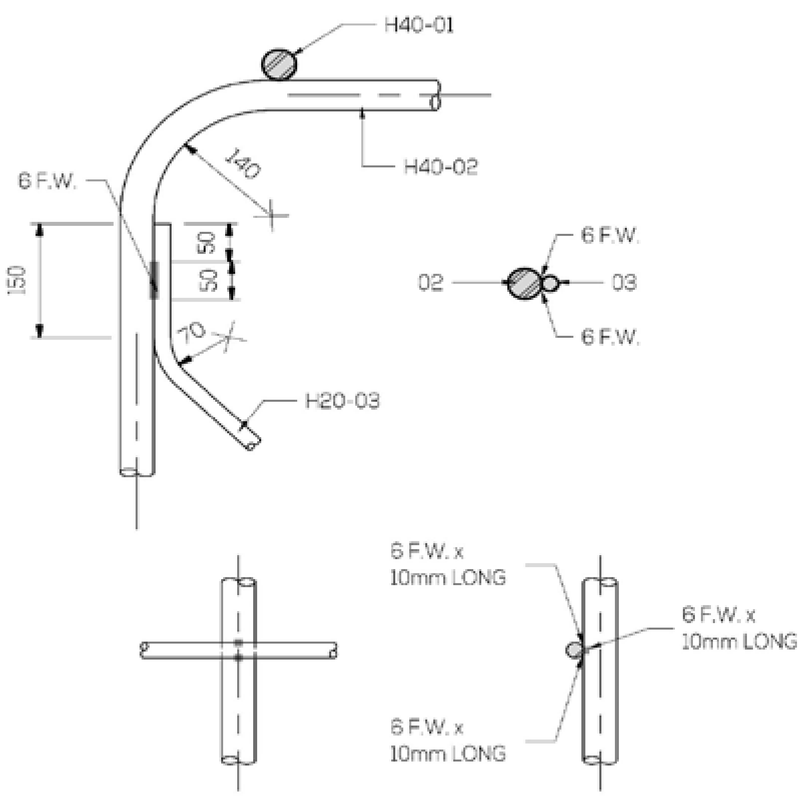
Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

Sketch Detail 5 - Welds



Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	7	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

Loads

Rebar Guide 5.0 — **Top mat self weight**

4 layers H40 @ 175 c/c (T1-T4) + 2 layers H32 @ 175 c/c (T5 & T6)

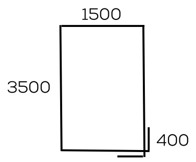
assuming 40% laps

BS4449 Table 7 — top mat UDL, w_{mat} = 1.4 x (4x9.86 + 2x6.31) / 0.175
= 418 kg/m²
= 4.10 kN/m²

Rebar Guide 5.0 — **Cage self weight**

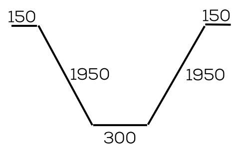
approximate lengths of bent bars,

b/mk 02,
shape code 51



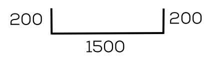
L = 10250

b/mk 03,
shape code 46



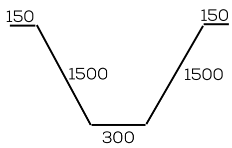
L = 4500

b/mk 04,
shape code 21



L = 1800

b/mk 06,
shape code 46



L = 3600

BS4449 Tb7

b/mk	size	quant	bar length m	total length m	weight kg/m	total weight kg
01	H40	4	4.20	16.8	9.86	165.65
02	H40	6	10.25	61.5	9.86	606.39
03	H20	6	4.50	27.0	2.46	66.42
04	H20	6	1.80	10.8	2.46	26.57
05	H20	2	4.20	8.4	2.46	20.66
06	H20	4	3.60	14.4	2.46	35.42
					TOTAL	921.11 kg

support cage self weight, W_{cage} = 9.04 kN

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	8	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability | By: SM/MD

Description: Base Slab | Checked: N/A

Reference	Calculations	Output
Rebar Guide 5.2	**Construction load**	
BS5975 17.4.3.1	take live load for operatives and small equipment to be, $q = 1.5$ kN/m²	
Rebar Guide 5.4	**Notional horizontal load**	
BS5975 19.2.9.1	notional horizontal load to be taken as 2.5% of applied vertical loads	
	Braking load	
	take braking load during transport to be 1.0g i.e. 100% of self weight	

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	9	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output
	Top Mat Spanning	
	check spanning bars of top mat to carry self weight and construction load spanning between rider bars, considering width supported by a single bar and load sharing between layers T2, T4 & T6	
bar spacing $s = 0.175$ m	UDL, $w = (w_{mat} + q).s$ $= (4.10 + 1.50) \times 0.175$ $= 0.98$ kN/m	
	span, $L = 1.90$ m	
	bar diameters T1 $D_2 = 40$ mm T2 $D_4 = 40$ mm T6 $D_6 = 32$ mm	
	Bending	
	Maximum applied bending moment $M = wL^2/8$ $= (0.98 \times 1.90^2)/8$ $= 0.442$ kNm	
	Section modulus $z = \pi(D_2^3+D_4^3+D_6^3)/32$ $= (\pi \times 40^3 + 40^3 + 32^3)/32$ $= 15783$ mm³	
	Applied bending stress $f_b = M/z$ $= (0.442 \times 10^6)/15783$ $= 28.0$ N/mm²	
BS 449 Tb2	Permissible bending stress $p_b = 280$ N/mm²	$f_b < p_b$ PASS
	Shear	
	Maximum applied shear $V = wL/2$ $= (0.98 \times 1.90)/2$ $= 0.93$ kN	
	Section area $A = \pi D_6^2/4$ $= (\pi \times 32^2)/4$ $= 804$ mm³	
	Applied shear stress $f_q = 1.5V/A$ $= 1.5 \times 0.93 \times 10^3/804$ $= 1.74$ N/mm²	
BS 449 Tb10	Permissible maximum shear stress $p_q = 195$ N/mm²	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	001	10	23	P04	27/06/2022	

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Base Slab	Checked	N/A

Reference	Calculations		Output
	Deflection		
	Moment of inertia	$I = \pi(D_2^4+D_4^4+D_6^4)/64$ $= \pi \times (40^4 + 40^4 + 32^4) / 64$ $= 302799\ mm^4$	
	Modulus of elasticity	$E = 210\ MN/mm^2$	
	Total deflection	$\delta = (5/384).wL^4/EI$ $= (5/384) \times 0.98 \times (1900^4)/(210000 \times 302799)$ $= 2.6\ mm$	
	Limiting deflection	$\delta_{max} = L/200$ $= 1900/200$ $= 9.50\ mm$	$\delta < \delta_{max}$ PASS
	Dead load deflection	$\delta_{dead} = \delta\ w_{mat} / (w_{mat} + q)$ $= 2.6 \times 4.10 / (4.10 + 1.50)$ $= 1.9\ mm$	$\delta_{dead} < 5mm$ PASS

Appendix I – Example calculations – *continued*

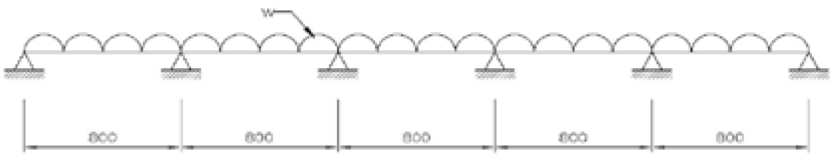
Job Number	Task	Sheet	of	Rev.	Date
999999	001	11	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output
	<u>Bar Mark 01 Rider Bar In Service</u>	



Reference	Calculations		Output
cage spacing $s = 3.000$ m	UDL,	$w = (w_{mat} + q).s/2$ $= (4.10 + 1.50) \times 3.000/2$ $= 8.40$ kN/m	
	span,	$L = 0.80$ m	
	bar diameter	$D = 40$ mm	
	Bending		
	Maximum applied bending moment	$M = wL^2/8$ $= (8.40 \times 0.80^2)/8$ $= 0.672$ kNm	
	Section modulus	$Z = \pi D^3/32$ $= \pi \times 40^3/32$ $= 6283$ mm³	
	Applied bending stress	$f_b = M/Z$ $= (0.672 \times 10^6)/6283$ $= 107.0$ N/mm²	
BS 449 Tb2	Permissible bending stress	$p_b = 280$ N/mm²	$f_b < p_b$ PASS
	Shear		
taking 25% for continuity	Maximum applied shear	$V = 1.25\ wL/2$ $= 1.25 \times (8.40 \times 0.80)/2$ $= 4.20$ kN	
	Section area	$A = \pi D^2/4$ $= (\pi \times 40^2)/4$ $= 1257$ mm³	
	Applied shear stress	$f_q = 1.5V/A$ $= 1.5 \times 4.20 \times 10^3/1257$ $= 5.01$ N/mm²	
BS 449 Tb10	Permissible maximum shear stress	$p_q = 195$ N/mm²	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	12	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output
	Reaction	
taking 25% for continuity	Maximum reaction $R = 1.25\,wL = 1.25 \times 8.40 \times 0.80 = 8.40$ kN	
	Deflection	
	Moment of inertia $I = \pi D^4/64 = \pi \times 40^4 / 64 = 125664\ \text{mm}^4$	
	Modulus of elasticity $E = 210\ \text{MN/mm}^2$	
	Total deflection $\delta = (5/384).wL^4/EI = (5/384) \times 8.40 \times (800^4)/(210000 \times 125664) = 1.7$ mm	
	Limiting deflection $\delta_{max} = L/200 = 800/200 = 4.00$ mm	$\delta < \delta_{max}$ PASS
	Dead load deflection $\delta_{dead} = d\, w_{mat} / (w_{mat} + q) = 1.7 \times 4.10 / (4.10 + 1.50) = 1.2$ mm	$\delta_{dead} < 5$mm PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	13	23	P04	27/06/2022

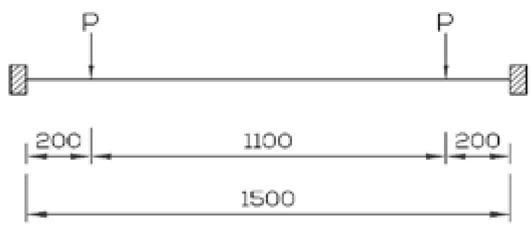
Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

<u>Bar Mark 02 Transom In Service</u>



Reference	Calculations		Output
b/mk 01 member reaction	point load,	$P = 8.40$ kN	
	span,	$L = 1.50$ m	
	offset from support,	$a = 0.20$ m	
	bar diameter	$D = 40$ mm	
	Bending		
	Maximum applied bending moment	$M = Pa.(L-a)/L$ $= 8.40 \times 0.20 \times (1.50 - 0.20) / 1.50$ $= 1.46$ kNm	
	Section modulus	$z = \pi D^3/32$ $= \pi \times 40^3 /32$ $= 6283\ mm^3$	
	Applied bending stress	$f_b = M/z$ $= (1.456 \times 10^6)/6283$ $= 231.8\ N/mm^2$	
BS 449 Tb2	Permissible bending stress	$p_b = 280\ N/mm^2$	$f_b < p_b$ PASS
	Shear		
	Maximum applied shear	$V = P$ $= 8.40$ kN	
	Section area	$A = \pi D^2/4$ $= (\pi \times 40^2)/4$ $= 1257\ mm^3$	
	Applied shear stress	$f_q = 1.5V/A$ $= 1.5 \times 8.40 \times 10^3/1257$ $= 10.03\ N/mm^2$	
BS 449 Tb10	Permissible maximum shear stress	$p_q = 195\ N/mm^2$	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	14	23	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Base Slab	Checked	N/A

Reference	Calculations	Output
	Deflection	
	Moment of inertia $I = \pi D^4/64$ $= \pi \times 40^4 / 64$ $= 125664\ mm^4$	
	Modulus of elasticity $E = 210\ MN/mm^2$	
	Total deflection $\delta = \alpha.PL^3/6EI$ $= 0.011 \times 8401 \times 1500^3/(6 \times 210000 \times 125664)$ $= 2.0\ mm$	
	where $\alpha = 3a^2/4L^2-(a/L)^3$ $= (3 \times 200^2/4 \times 1500^2)-(200/1500)^3$ $= 0.011$	
	Limiting deflection $\delta_{max} = L/200$ $= 1500/200$ $= 7.5\ mm$	$\delta < \delta_{max}$ PASS
	Dead load deflection $\delta_{dead} = d\ w_{mat} / (w_{mat} + q)$ $= 2.0 \times 4.10 / (4.10 + 1.50)$ $= 1.4\ mm$	$\delta_{dead} < 5mm$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	15	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations			Output
	<u>Bar Mark 02 Leg In Service</u>			
braced at mid point	length,	L	$= 1.77\ m$	
	bar diameter	D	$= 40\ mm$	
	Axial compression			
b/mk 02 transom reaction	axial force,	F_c	$= 8.40\ kN$	
	Section area	A	$= \pi D^2/4$ $= (\pi \times 40^2)/4$ $= 1257\ mm^3$	
	Applied axial compressive stress	f_c	$= F_c/A$ $= 8.40 \times 10^3/1257$ $= 6.7\ N/mm^2$	
BS449 cl 31	effective length	L_e	$= 0.7\ L$ $= 0.7 \times 1770$ $= 1239\ mm$	
	radius of gyration	r	$= D/4$ $= 40/4$ $= 10\ mm$	
	slenderness	λ	$= L_e/r$ $= 1239/10$ $= 124$	
BS 449 App B	min yield stress for reinforcing bars	Y_s	$= 500\ N/mm^2$	
	Young's modulus for reinforcing bars	E	$= 210\ MN/mm^2$	
	Euler critical stress	C_0	$= \pi^2 E/\lambda^2$ $= (\pi^2 \times 210000)/123.9^2$ $= 135.0\ N/mm^2$	
		η	$= 0.3(\lambda/100)^2$ $= 0.3(123.9/100)^2$ $= 0.46$	
		F	$= (Y_s+(\eta+1)C_0)/2$ $= (500 + (0.46+1) \times 135.0) / 2$ $= 348.6\ N/mm^2$	
	permissible axial compressive stress	p_c	$= (F-\sqrt{(F^2-Y_s C_0)})/1.7$ $= (348.6 - \sqrt{(348.60^2-500.0 \times 135.0)})/1.7$ $= 68.3\ N/mm^2$	$f_c < p_c$ PASS
	Bending			
	by inspection applied and permissible bending stresses are as determined for the b/mk 02 transom element, therefore accepted, no calculation necessary			

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	16	23	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Base Slab	Checked	N/A

Reference	Calculations	Output
	Combined axial compression & bending	
	Applied axial compressive stress f_c = 6.7 N/mm²	
	permissible axial compressive stress p_c = 68.3 N/mm²	
b/mk 02 transom bending	Applied bending stress f_b = 231.8 N/mm²	
	Permissible bending stress p_b = 280.0 N/mm²	
	combined check $(f_c / p_c) + (f_b / p_b)$ = (6.7 / 68.35) + (231.8 / 280.0) = 0.926	< 1.00 PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	17	23	P04	27/06/2022

Customer: TWf

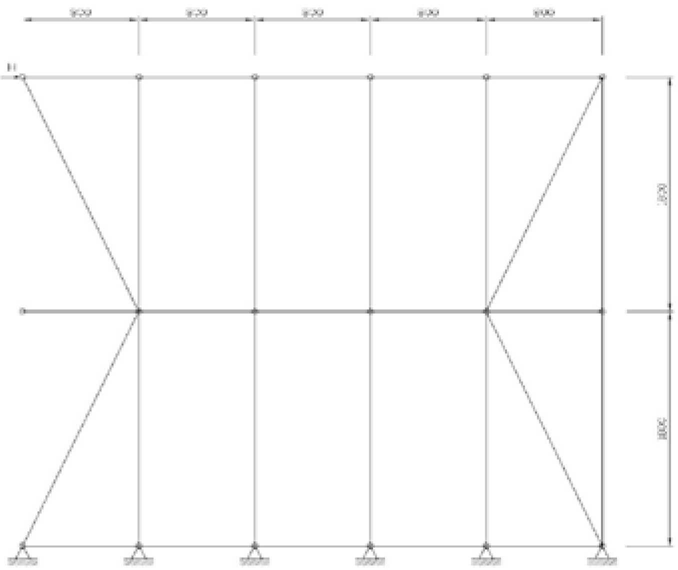
Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output

<u>Bar Mark 03 & 06 Diagonal Ties</u>

consider longitudinal tie b/mk06 to be worst case



vertical span $z = 1.80$ m

horizontal span $x = 0.80$ m

length $L = \sqrt{(z^2+x^2)}$
$= \sqrt{(1.80^2 + 0.80^2)}$
$= 1.97$ m

angle from horizontal $\theta = \tan^{-1}(z/x)$
$= \tan^{-1}(1.80/0.80)$
$= 66.0°$

bar diameter $D = 20$ mm

number of braces $n = 2$

Notional horizontal force

cage spacing $s = 3.00$ m
cage length $l = 4.00$ m

vertical load on cage $F_v = ((w_{mat} + q).s.l)+W_{cage}$
$= ((4.10 + 1.50) \times 3.00 \times 4.00) + 9.04$
$= 76.24$ kN

Notional horizontal load on cage $H_{n'} = 0.025\ F_v$
$= 0.025 \times 76.24$
$= 1.91$ KN

Transport / braking force

braking factor $a = 1.00$

horizontal load $H_{brake} = a\ W_{cage}$
$= 1.00 \times 9.04$
$= 9.04$ KN

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	18	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations		Output
	Tension		
	the horizontal force due to braking is greater than the notional horizontal force		
	horizontal force	$H = 9.04$ KN	
	axial force, per brace	$F_t = (H/\cos\theta) / n$ $= (9.04/\cos 66.0) / 2$ $= 11.12$ kN	
	Section area	$A = \pi D^2/4$ $= (\pi \times 20^2)/4$ $= 314$ mm³	
	Applied axial compressive stress	$f_c = F_c/A$ $= 11.12 \times 10^3/314$ $= 35.4$ N/mm²	
BS 449 Tb 19	Allowable tensile stress	$p_t = 265$ N/mm²	$f_t < p_t$ PASS
	<u>Bar Mark 04 & 05 Horizontal Ties</u> by inspection the applied axial tensile stresses are less than those determined for b/mk 03 and b/mk 06, therefore accepted and no further calculation necessary		

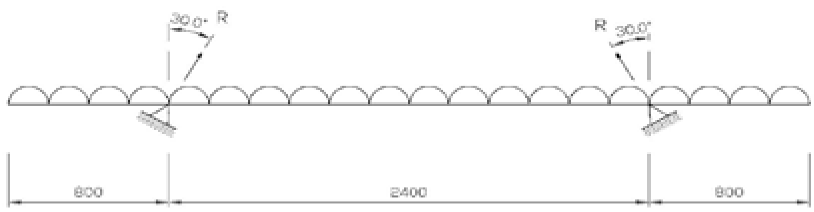
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	19	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output
	Bar Mark 01 Rider Bar Lifting	
4 leg sling with 2 legs each side		
dynamic enhancement factor $a = 1.25$ cage length $l = 4.00$ m	UDL, per rider bar $w = a.(W_{cage}/l)/2$ $= 1.25 \times (9.04 / 4.00) / 2$ $= 1.41$ kN/m	
	span, $L = 2.40$ m	
	bar diameter $D = 40$ mm	
	Bending	
	Maximum applied bending moment $M = wL^2/8$ $= (1.41 \times 2.40^2)/8$ $= 1.017$ kNm	
	Section modulus $Z = \pi D^3/32$ $= \pi \times 40^3/32$ $= 6283$ mm³	
	Applied bending stress $f_b = M/Z$ $= (1.017 \times 10^6)/6283$ $= 161.8$ N/mm²	
BS 449 Tb2	Permissible bending stress $p_b = 280$ N/mm²	$f_b < p_b$ PASS
	Shear	
	Maximum applied shear $V = wL/2$ $= 1.41 \times 2.40/2$ $= 1.69$ kN	
	Section area $A = \pi D^2/4$ $= (\pi \times 40^2)/4$ $= 1257$ mm³	
	Applied shear stress $f_q = 1.5V/A$ $= 1.5 \times 1.69 \times 10^3/1257$ $= 2.02$ N/mm²	
BS 449 Tb10	Permissible maximum shear stress $p_q = 195$ N/mm²	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	20	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations		Output
	Axial compression		
	maximum sling angle	$\theta = 30.0°$	
	axial force,	$F_c = a.(W_{cage}/2).\tan\theta$ $= 1.25 \times (9.04)/2) \times \tan 30.0°$ $= 3.26$ kN	
	Section area	$A = \pi D^2/4$ $= (\pi \times 40^2)/4$ $= 1257$ mm^3	
	Applied axial compressive stress	$f_c = F_c/A$ $= 3.26 \times 10^3/1257$ $= 2.6$ N/mm^2	
BS449 cl 31	effective length	$L_e = 0.7\,L$ $= 0.7 \times 2400$ $= 1680$ mm	
	radius of gyration	$r = D/4$ $= 40/4$ $= 10$ mm	
	slenderness	$\lambda = L_e/r$ $= 1680/10$ $= 168$	
BS 449 App B	min yield stress for reinforcing bars	$Y_s = 500$ N/mm^2	
	Young's modulus for reinforcing bars	$E = 210$ MN/mm^2	
	Euler critical stress	$C_0 = \pi^2 E/\lambda^2$ $= (\pi^2 \times 210000)/168.0^2$ $= 73.4$ N/mm^2	
		$\eta = 0.3(\lambda/100)^2$ $= 0.3 \times (168.0/100)^2$ $= 0.85$	
		$F = (Y_s+(\eta+1)C_0)/2$ $= (500 + (0.85+1) \times 73.4) / 2$ $= 317.8$ N/mm^2	
	permissible axial compressive stress	$p_c = (F-\sqrt{(F^2-Y_sC_0)})/1.7$ $= (317.8 - \sqrt{(317.81^2-500.0 \times 73.4)})/1.7$ $= 37.8$ N/mm^2	$f_c < p_c$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	21	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations	Output
	Combined axial compression & bending	
	Applied axial compressive stress f_c = 2.6 N/mm²	
	permissible axial compressive stress p_c = 37.8 N/mm²	
	Applied bending stress f_b = 161.8 N/mm²	
	Permissible bending stress p_b = 280.0 N/mm²	
	combined check $(f_c / p_c) + (f_b / p_b)$ = (2.6 / 37.80) + (161.8 / 280.0) = 0.646	< 1.00 PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	22	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations		Output
	<u>Diagonal tie connection welds</u>		
	consider b/mk 06 longitudinal ties to acting in tension under braking load as a worst case		
sheet 15	number of welds	$n = 2$	
sheet 15	brace angle from horizontal	$\theta = 66.0°$	
	transverse force per weld	$F_T = H_{brake} / n$ $= 9.04 / 2$ $= 4.52$ kN	
	length of weld	$L_w = 2 \times 50$ $= 100$ mm	
	elastic modulus of weld	$Z_w = (2 \times 50^2)/6$ $= 833$ mm²	
	weld eccentricity	$e = 75$ mm	
	transverse force/length	$f_T = F_T/L_w + F_Te/Z$ $= 4.52/100 + 4.52 \times 75/833$ $= 0.452$ kN/mm	
	longitudinal force per weld	$F_L = F_T\tan\theta$ $= 4.52 \times \tan 66$ $= 10.17$ KN	
	longitudinal force/length	$f_L = F_L/L_w$ $= 10.17 / 100$ $= 0.102$ kN/mm	
	resultant force/length	$f_R = \sqrt{(f_L^2 + f_T^2)}$ $= \sqrt{(0.102^2 + 0.452^2)}$ $= 0.463$ kN/mm	
BS 449 cl53.a.(ii)	permissible weld stress	$P_w = 125$ N/mm²	
	Leg length	$s = 6$ mm	
	permissible force / length	$p_w = 0.7sP_w$ $= 0.7 \times 6 \times 125 / 1000$ $= 0.53$ kN/mm	$f_R < p_w$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	001	23	23	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Base Slab — Checked: N/A

Reference	Calculations		Output
	<u>Horizontal tie connection welds</u>		
	consider b/mk 05 longitudinal tie under braking load as a worst case, ignore weld transverse to force		
	number of welds	$n = 2$	
	longitudinal force per weld	$F_L = H_{brake} / n$ $= 9.04 / 2$ $= 4.52$ kN	
	length of weld	$L_w = 2 \times 10$ $= 20$ mm	
	longitudinal force/length	$f_L = F_L/L_w$ $= 4.52 / 20$ $= 0.113$ kN/mm	
BS 449 cl53.a.(ii)	permissible weld stress	$P_w = 125$ N/mm²	
	Leg length	$s = 6$ mm	
	permissible force / length	$p_w = 0.7sP_w$ $= 0.7 \times 6 \times 125 / 1000$ $= 0.53$ kN/mm	$f_L < p_w$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	RICHTER
999999	002	1	21	P04	27/06/2022	

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output

Introduction

Detailed design of pre-fabricated support trusses and stability for bridge abutment wall reinforcement. The support trusses will be fabricated from welded reinforcing bar in a factory then transported to site for incorporation into the wall panel.

The wall reinforcement will be formed in discrete panels fixed in the horizontal position, with the lacer bars fixed directly onto the trusses using tying wire. top mat is supported fully by the trusses. Standard format chairs, shape code 98, and will be used to stabilise the trusses and top mat.

Upon completion, the panels will be turned to a vertical position, lifted into place and the now vertical trussed chords welded fixed to sacrificial starter bars. The sacrificial starter bars shall be standard L bars detailed with the appropriate minimum lap length for the bar diameter.

Any in-situ in-plane sway due to maximum wind or accidental impact will be resisted by tube and coupling lacing and bracing which is removed under controlled conditions (working wind) when the formwork is installed. These may be designed and detailed using appropriate methods covered by other publications and will not be considered in this example.

The the wall height is 9200 mm including a 100 mm high kicker. Correspondingly the trusses will be a nominal 8800 mm long/high with 8 bays of 1100 mm length/height.

The wall is 1200 mm thick with H32 vertical bars and H25 lacer bars giving a nominal dimension between chords of 1000mm. Wall lacers will be positioned in layer 2.

The nominal panel width will be 6000 mm with trusses at 2000 mm centres. Vertical bars will be a single length. Lacers will be connected using splice bars in-situ, with 50 diameter laps.

The following design situations will be considered:
(i) Turning - consider panel in initial horizontal position acting as a beam with self weight simply supported (by ground at one end and by lifting chains at the other).
(ii) In service - consider the panel in the final vertical position with all verts tied to starters acting as a cantilever resiting wind load in each direction.

References

BS 5975:2019 Temporary works procedures and permissble stress design of falsework

BS 449-2:1969 Use of structural steel in building

BS 4449:2016 Steel for the Reinforcement of Concrete

BS 8666:2020 Scheduling of reinforcement for concrete

Steel Designer's Manual 7th Edition

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	001	2	23	P04	27/06/2022	[redacted]

Customer: TWf

Job: Rebar Stability By: SM/MD

Description: Base Slab Checked: N/A

Reference	Calculations	Output

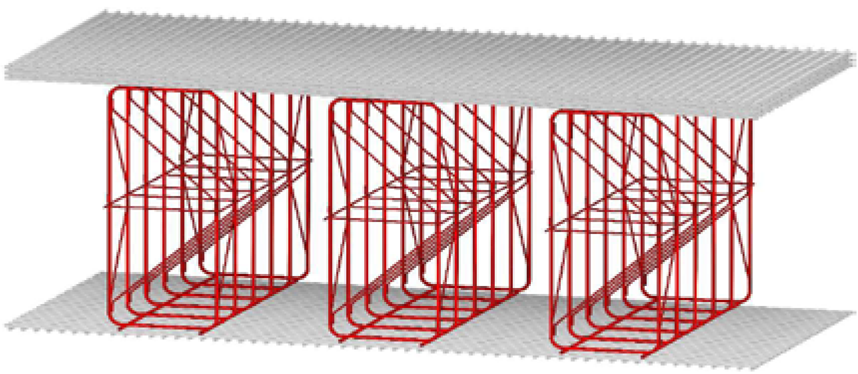
* CAUTION

Full restraint is only considered applicable in this example due to the use of fully welded joints, the size and stiffness of individual bars, the specific configuration of the bars and the minimal deformation under load.

In this particular instance all joints have significant fixity against rotation in plane and about bar axes due to continuity of bar and/or welds

The end fixity in solutions using smaller more flexible individual bars, different configurations and/or experiencing greater deformation may require assumption of reduced fixity at joints.

Sketch Detail 1 - General Arrangement 3D View



Key:-
support cages - red
permanent reinforcement - grey

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	3	21	P04	27/06/2022	

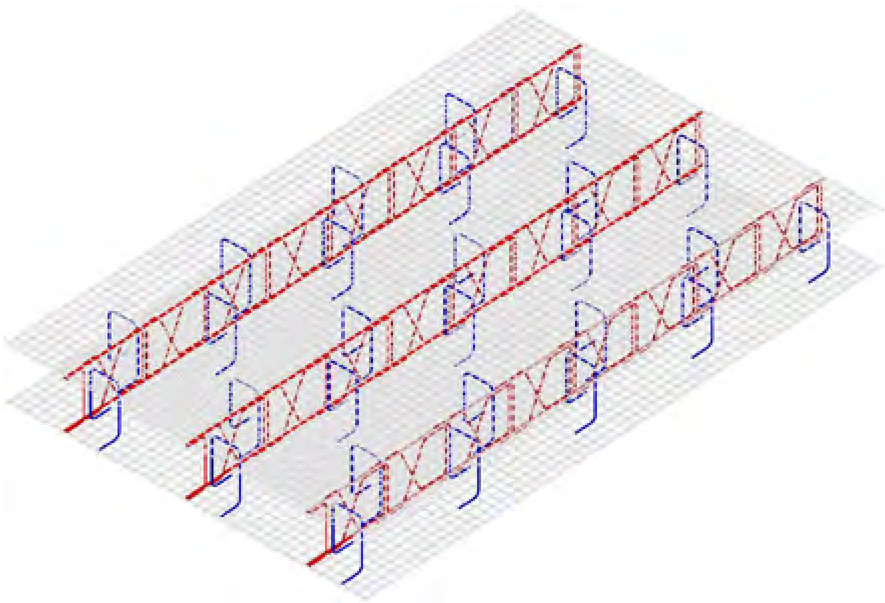
Customer TWf

Job Rebar Stability By SM/MD

Description Wall Checked N/A

Reference	Calculations	Output

Sketch detail 1 - General Arrangement Horizontal Position 3D View



Key:-
support trusses - red
chairs - blue
permanent reinforcement - grey

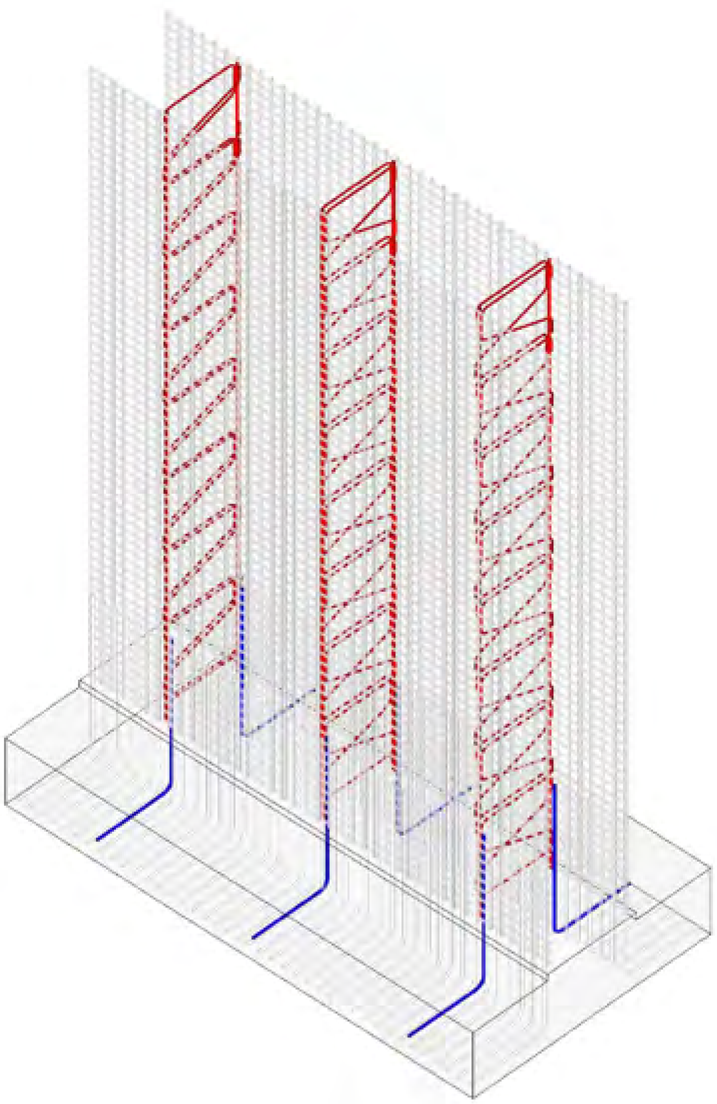
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	4	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output

Sketch detail 2 - General Arrangement Vertical Position 3D View



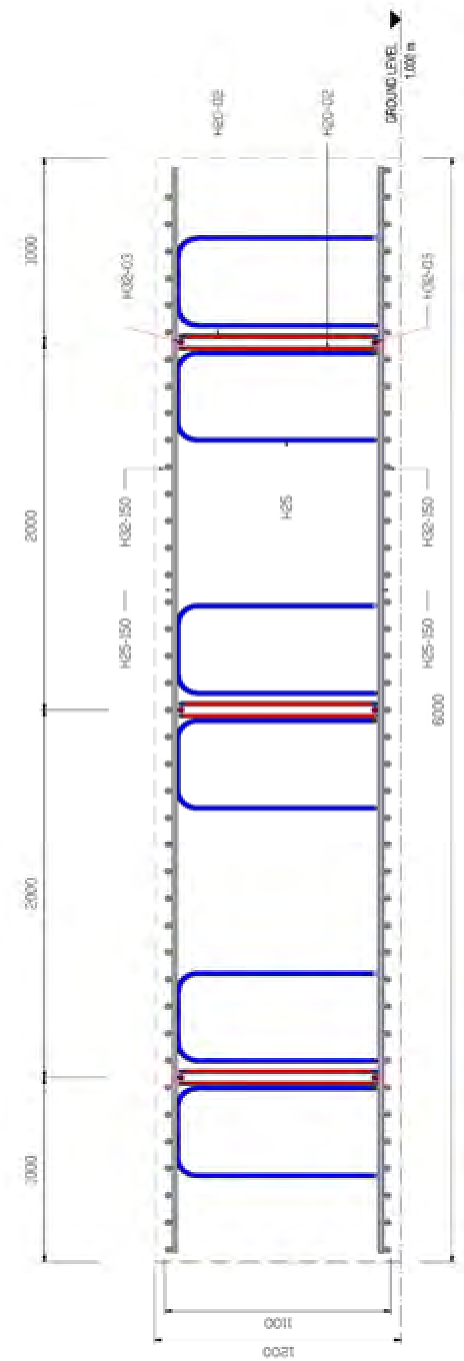
Key:-
support trusses - red
sacrificial starter bars - blue
permanent reinforcement - grey

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	5	21	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Sketch detail 3 - General Arrangement Horizontal Posistion Cross section	



Key:-
support trusses - red
chairs - blue
permanent reinforcement - grey

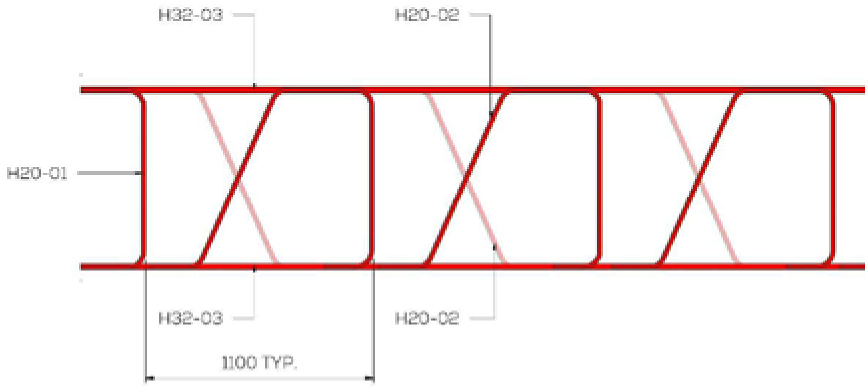
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	6	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output

Sketch detail 3 - Support Truss Elevation

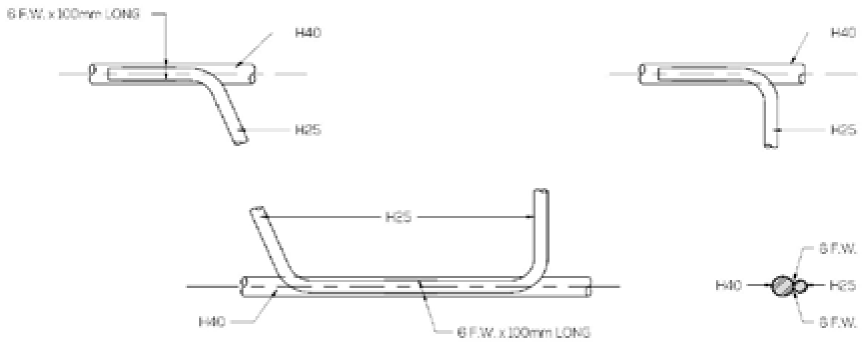


Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	7	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Sketch Detail 5 - Welds	



Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	8	21	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	<u>Loads</u>	
Rebar Guide 5.0	reinforcement self weight	
	verts H32 @ 150 c/c each face + lacers H25 @ 150 c/c each face	
BS4449 Table 7	UDL, w_{reinf} = 2 x (6.31 + 3.85) / 0.150 = 135.5 kg/m² = 1.33 kN/m²	
	width of panel per truss B = 2.0 m	
	line load on truss $w_{truss} = w_{reinf}\,B$ = 1.33 x 2.0 = 2.66 kN/m	
Rebar Guide 5.2	**Construction load**	
BS5975 17.4.3.1	take live load for operatives and small equipment to be,	
	q_{con} = 1.5 kN/m²	
BS5975	**Wind load**	
Fig4	Basic wind velocity $v_{b,map}$ = 22.0 m/s	
Fig5	Topography factor T_{wind} = 1.00	
	Site altitude A = 100.0 m	
cl17.5.1.3 (3)	Wind factor $S_{wind} = T_{wind}\,v_{b,map}\,(1 + A/1000)$ = 1.00 x 22.0 x (1 + 100.0 / 1000) = 24.20 m/s	
Fig6	height $z - h_{dis}$ = 9.0 m	
T15	Combined exposure factor $c_e(z)c_{e,T}$ = 1.93	
cl17.5.1.3 (2)	Peak velocity pressure $q_p = 0.613 \times 0.7 c_e(z) c_{e,T} S_{wind}^2$ = 0.613 x 0.7 x 1.93 x 24.20² = 485 N/m²	
cl17.5.1.11	structural factor $c_s c_d$ = 1.00	
cl17.5.1.12	force coefficient c_f = 1.20	
cl17.5.1.14	shielding factor η = 1.00	
cl17.5.1.10 (6)	maximum wind pressure $q_{W,max} = c_s c_d\,c_f\,q_p\,\eta$ = 1.00 x 1.20 x 485 x 1.00 = 582 N/m² = 0.58 kN/m²	
	width of panel per truss B = 2.0 m	
	line load on truss $q_{truss} = q_p\,B$ = 0.58 x 2.0 = 1.16 kN/m	

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	9	21	P04	27/06/2022	[redacted]

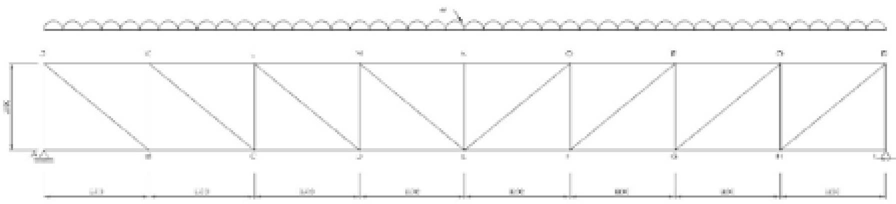
Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Notional horizontal load	
	width of panel $B_{panel} = 6.0$ m	
	width of panel per truss $L_{panel} = 9.2$ m	
	panel self weight $W_{panel} = w_{reinf}\, B_{panel}\, L_{panel} = 1.33 \times 6.0 \times 9.2 = 73.37$ kN	
cl 5.4.1(b)	notional horizontal load $H_{nonl} = 0.025\, W_{panel} = 0.025 \times 73.4 = 1.83$ kN	
	Accidental Impact load	
	for panels lifted under close control, consider possible transverse impact between ends of panels	
cl 5.3.2	impact load $H_{accl} = 0.1\, W_{panel} / 2 = 0.10 \times 73.4 / 2 = 3.67$ kN	
	NOTE:- Both the notional horizontal load and the accidental impact load are less than the wind load. Wind load shall be taken to govern.	
	<u>Chairs</u>	
	take spacing to be maximum 50 bar diameters	
	horizontal spacing $s_h = 1.00$ m	
	vertical spacing $s_v = 1.00$ m	
table 9	working load on chair $P_{working} = (w_{reinf} + q_{con})\, s_h\, s_v = (1.33 + 1.50) \times 1.00 \times 1.00 = 2.83$ kN	use H20 chairs (8.9kN working capacity)

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	[redacted]
999999	002	10	21	P04	27/06/2022	

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	<u>Truss Member Forces</u>	
	Turning	
		
	overall span — $L = 8.80$ m	
	bay width — $b = 1.10$ m	
	truss height — $h = 1.00$ m	
	tie angle from horizontal — $\theta = \tan^{-1}(h / b) = \tan^{-1}(1.00 / 1.10) = 42.3°$	
	conservatively simplifying,	
sheet 6 25% dynamic enhancement	max bending moment — $M = 1.25\, w_{truss}\, L^2 / 8 = 1.25 \times 2.66 \times 8.8^2 / 8 = 32.17$ kNm	
	max axial force in chords (top compression, bottom tension) — $N_{chord} = M/h = 32.17 / 1.00 = 32.17$ kN	
sheet 6 25% dynamic enhancement	max shear — $V = 1.25\, w_{truss}\, L / 2 = 1.25 \times 2.66 \times 8.80 / 2 = 14.62$ kN	
	max axial force in struts (compression) — $N_{strut} = V = 14.62$ kN	
	max axial force in ties (tension) — $N_{tie} = V / \sin\theta = 14.6 / \sin 42.3° = 21.7$ kN	

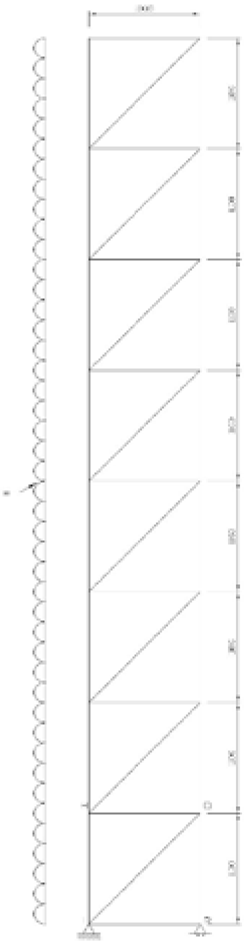
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	11	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output

In Service



overall span L = 8.80 m

bay width b = 1.10 m

truss height h = 1.00 m

tie angle from horizontal $\theta = \tan^{-1}(h / b)$

$= \tan^{-1}(1.00 / 1.10)$

$= 42.3°$

Appendix I – Example calculations – *continued*

Customer	TWf	[redacted]	
Job	Rebar Stability		
Description	Wall	Checked	N/A

Reference	Calculations	Output
	conservatively simplifying,	
	max bending moment $M = q_{truss} L^2 / 2$ $= 1.16 \times 8.8^2 / 2$ $= 45.07$ kNm	
	max axial force in chords (windward tension, leeward compression) $N_{chord} = M/h$ $= 45.07 / 1.00$ $= 45.07$ kN	
	max shear $V = q_{truss} L$ $= 1.16 \times 8.80$ $= 10.24$ kN	
	max axial force in struts (compression) $N_{strut} = V$ $= 10.24$ kN	
	max axial force in ties (tension) $N_{tie} = V / \sin\theta$ $= 10.2 / \sin 42.3°$ $= 15.2$ kN	

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	13	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations		Output
	<u>Top Chord - Turning</u>		
	length,	$L = 1.10$ m	
	bar diameter	$D = 32$ mm	
	line load from top mat	$w = w_{truss} / 2$ $= 2.66 / 2$ $= 1.33$ kN/m	
	Axial compression		
sheet 8, N_{chord}	axial force,	$F_c = 32.2$ kN	
	cross-sectional area	$A = \pi D^2/4$ $= (\pi \times 32^2/4)$ $= 804$ mm²	
	compressive axial stress	$f_c = F_c / A$ $= (32.2 \times 10^3) / 804$ $= 40.0$ N/mm²	
fully restrained both ends	Effective length of member	$L_e = 0.7\,L$ $= 0.7 \times 1100$ $= 770$ mm	
	Radius of gyration	$r_y = D/4$ $= 32/4$ $= 8$ mm	
	Slenderness	$\lambda = L_e/r$ $= 770/8$ $= 96$	
BS 449 App B	min yield stress for reinforcing bars	$Y_s = 500$ N/mm²	
	Young's Modulus for reinforcing bars	$E = 210000$ N/mm²	
	Euler critical stress	$C_0 = \pi^2 E/\lambda^2$ $= (\pi^2 \times 210000)/96.3^2$ $= 223.7$ N/mm²	
		$\eta = 0.3(\lambda/100)^2$ $= 0.3 \times (96/100)^2$ $= 0.278$	
		$F = (Y_s+(\eta+1)C_0)/2$ $= (500 + (0.28+1) \times 223.7) / 2$ $= 393.0$ N/mm²	
	permissible axial compressive stress	$p_c = (F-\sqrt{(F^2-Y_sC_0)})/1.7$ $= (393.0 - \sqrt{(392.95^2 - 500.0 \times 223.7)})/1.7$ $= 109.8$ N/mm²	$f_c < p_c$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	14	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Bending	
	Maximum applied bending moment $M = wL^2/8 = (1.33 \times 1.10^2)/8 = 0.201$ kNm	
	Section modulus $z = \pi D^3/32 = \pi \times 32^3 / 32 = 3217$ mm³	
	Applied bending stress $f_b = M/z = (0.201 \times 10^6)/3217 = 62.5$ N/mm²	
BS 449 Tb2	Permissible bending stress $p_b = 280$ N/mm²	$f_b < p_b$ PASS
	Combined axial compression & bending	
	Applied axial compressive stress $f_c = 40.0$ N/mm² =	
	permissible axial compressive stress $p_c = 109.8$ N/mm²	
	Applied bending stress $f_b = 62.5$ N/mm²	
	Permissible bending stress $p_b = 280.0$ N/mm²	
	combined check $(f_c / p_c) + (f_b / p_b) = (40.0 / 109.81) + (62.5 / 280.0) = 0.587$	< 1.00 PASS
	Shear	
	Maximum applied shear $V = wL/2 = (1.33 \times 1.10)/2 = 0.73$ kN	
	Section area $A = \pi D^2 / 4 = (\pi \times 32^2) / 4 = 804$ mm³	
	Applied shear stress $f_q = 1.5V/A = 1.5 \times 0.73 \times 10^3/804 = 1.36$ N/mm²	
BS 449 Tb10	Permissible maximum shear stress $p_q = 195$ N/mm²	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	15	21	P04	27/06/2022	[redacted]

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Wall — Checked: N/A

Reference	Calculations			Output
	<u>Top Chord - In Service</u>			
	length,	L	$= 1.10$ m	
	bar diameter	D	$= 32$ mm	
sheet 7, q_{truss}	line load	w	$= 1.16$ kN/m	
	Axial compression			
sheet 9, N_{chord}	axial force,	F_c	$= 45.1$ kN	
	cross-sectional area	A	$= \pi D^2/4$ $= (\pi \times 32^2/4)$ $= 804$ mm²	
	compressive axial stress	f_c	$= F_c / A$ $= (45.1 \times 10^3) / 804$ $= 56.0$ N/mm²	
fully restrained both ends	Effective length of member	L_e	$= 0.7\,L$ $= 0.7 \times 1100$ $= 770$ mm	
	Radius of gyration	r_y	$= D/4$ $= 32/4$ $= 8$ mm	
	Slenderness	λ	$= L_e/r$ $= 770/8$ $= 96$	
BS 449 App B	min yield stress for reinforcing bars	Y_s	$= 500$ N/mm²	
	Young's Modulus for reinforcing bars	E	$= 210000$ N/mm²	
	Euler critical stress	C_0	$= \pi^2 E/\lambda^2$ $= (\pi^2 \times 210000)/96.3^2$ $= 223.7$ N/mm²	
		η	$= 0.3(\lambda/100)^2$ $= 0.3 \times (96/100)^2$ $= 0.278$	
		F	$= (Y_s+(\eta+1)C_0)/2$ $= (500 + (0.28+1) \times 223.7) / 2$ $= 393.0$ N/mm²	
	permissible axial compressive stress	p_c	$= (F-\sqrt{(F^2-Y_sC_0)})/1.7$ $= (393.0 - \sqrt{(392.95^2 - 500.0 \times 223.7)})/1.7$ $= 109.8$ N/mm²	$f_c < p_c$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	16	21	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Bending	
	Maximum applied bending moment $M = wL^2/8 = (1.16 \times 1.10^2)/8 = 0.176$ kNm	
	Section modulus $z = \pi D^3/32 = \pi \times 32^3 / 32 = 3217$ mm³	
	Applied bending stress $f_b = M/z = (0.176 \times 10^6)/3217 = 54.7$ N/mm²	
BS 449 Tb2	Permissible bending stress $p_b = 280$ N/mm²	$f_b < p_b$ PASS
	Combined axial compression & bending	
	Applied axial compressive stress $f_c = 56.0$ N/mm²	
	permissible axial compressive stress $p_c = 109.8$ N/mm²	
	Applied bending stress $f_b = 54.7$ N/mm²	
	Permissible bending stress $p_b = 280.0$ N/mm²	
	combined check $(f_c / p_c) + (f_b / p_b) = (56.0 / 109.81) + (54.7 / 280.0) = 0.706$	< 1.00 PASS
	Shear	
	Maximum applied shear $V = wL/2 = (1.16 \times 1.10)/2 = 0.64$ kN	
	Section area $A = \pi D^2 / 4 = (\pi \times 32^2) / 4 = 804$ mm³	
	Applied shear stress $f_q = 1.5V/A = 1.5 \times 0.64 \times 10^3/804 = 1.19$ N/mm²	
BS 449 Tb10	Permissible maximum shear stress $p_q = 195$ N/mm²	$f_q < p_q$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	17	21	P04	27/06/2022

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output

<u>Deflection Checks</u>

Young's Modulus for reinforcing bars $E = 210000\ \text{N/mm}^2$

chord bar diameter $D = 32\ \text{mm}$

chord bar area
$$A = \pi D^2 / 4 = \pi \times 32^2 / 4 = 804\ \text{mm}^2$$

chord bar MOI
$$I = \pi D^4 / 64 = \pi \times 32^4 / 64 = 51472\ \text{mm}^4$$

distance between chords
$$h_{truss} = h - D = 1000 - 32 = 968\ \text{mm}$$

//el axis theorum — truss MOI
$$I_{truss} = 2A(h_{truss}/2)^2 + 2I = 2 \times 804 \times (968 / 2)^2 + 2 \times 51472 = 376902651\ \text{mm}^4$$

Turning

deflection
$$\delta = (5/384).w_{truss}L^4/EI_{truss} = (5/384) \times 2.66 \times 8800^4 / (210000 \times 376902651) = 2.62\ \text{mm}$$

span / deflection ratio $= L / 3355$ — << L/100 PASS

In Service

deflection
$$\delta = q_{truss}L^4/8EI_{truss} = 1.16 \times 8800^4 / (8 \times 210000 \times 376902651) = 11.02\ \text{mm}$$

span / deflection ratio $= L / 798$ — << L/100 PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	18	21	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Wall — Checked: N/A

Reference	Calculations	Output
	Struts	
	check axial compression only, by inspection Turning case controls	
	length, $L = 1.00$ m	
	bar diameter $D = 20$ mm	
	Axial compression	
sheet 8, N_{strut}	axial force, $F_c = 14.6$ kN	
2nr legs, 1nr each side of truss	Cross-sectional area $A = 2\,(\pi D^2 / 4) = 2 \times (\pi \times 20^2 / 4) = 628$ mm²	
	Maximum applied axial stress $f_c = F_c / A = (14.6 \times 10^3) / 628 = 23.3$ N/mm²	
fully restrained both ends	Effective length of member $L_e = 0.7\,L = 0.7 \times 1000 = 700$ mm	
	Radius of gyration $r_y = D/4 = 20/4 = 5$ mm	
	Slenderness $\lambda = L_e/r = 700/5 = 140$	
BS 449 App B	min yield stress for reinforcing bars $Y_s = 500$ N/mm²	
	Young's Modulus for reinforcing bars $E = 210000$ N/mm²	
	Euler critical stress $C_0 = \pi^2 E/\lambda^2 = (\pi^2 \times 210000)/140.0^2 = 105.7$ N/mm²	
	$\eta = 0.3(\lambda/100)^2 = 0.3 \times (140/100)^2 = 0.588$	
	$F = (Y_s+(\eta+1)C_0)/2 = (500 + (0.59+1) \times 105.7) / 2 = 334.0$ N/mm²	
	permissible axial compressive stress $p_c = (F-\sqrt{(F^2-Y_sC_0)})/1.7 = (334.0 - \sqrt{(333.96^2 - 500.0 \times 105.7)})/1.7 = 54.0$ N/mm²	$f_c < p_c$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	19	21	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations	Output
	Ties	
	check axial tension only, by inspection Turning case controls	
	bar diameter $D = 20$ mm	
	Axial Tension	
sheet 8, N_{tie}	axial force, $F_t = 21.7$ kN	
	Cross-sectional area $A = \pi D^2/4 = (\pi \times 20^2/4) = 314$ mm²	
	Maximum applied axial stress $f_t = F_c / A = (21.7 \times 10^3) / 314 = 69.2$ N/mm²	
BS 449 Tb 19	Allowable tensile stress $p_t = 265$ N/mm²	$f_t < p_t$ PASS

Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date
999999	002	20	21	P04	27/06/2022

Customer: TWf

Job: Rebar Stability — By: SM/MD

Description: Wall — Checked: N/A

Reference	Calculations		Output
	<u>Starter connection welds</u>		
4nr legs, 2nr each side of chord / starter	length of weld	$L_w = 2 \times (2 \times 100)$ $= 400$ mm	
	transverse force per weld	$F_T = w_{truss} L_{panel}$ $= 2.66 \times 9.20$ $= 24.46$ kN	
	transverse force/length	$f_T = F_T/L_w$ $= 24.46 / 400$ $= 0.061$ kN/mm	
sheet 9, N_{chord}	longitudinal force per weld	$F_L = 45.07$ kN	
	longitudinal force/length	$f_L = F_L/L_w$ $= 45.07 / 400$ $= 0.113$ kN/mm	
	resultant force/length	$f_R = \sqrt{(f_L^2 + f_T^2)}$ $= \sqrt{(0.113^2 + 0.061^2)}$ $= 0.128$ kN/mm	
BS 449 cl53.a.(ii) for commonly available weld rods	permissible weld stress	$P_w = 125$ N/mm²	
	Leg length	$s = 6$ mm	
	permissible force / length	$p_w = 0.7sP_w$ $= 0.7 \times 6 \times 125 / 1000$ $= 0.53$ kN/mm	$f_R < p_w$ PASS
	<u>Strut connection welds</u>		
	connection between ties and chords, by inspection Turning controls		
sheet 8, N_{strut}	transverse force per weld	$F_T = 14.62$ kN	
2nr legs, 1nr each side of truss	length of weld	$L_w = 4 \times 100$ $= 400$ mm	
	elastic modulus of weld	$Z_w = (4 \times 100^2)/6$ $= 6667$ mm²	
	weld eccentricity	$e = 100$ mm	
	transverse force/length	$f_T = F_T/L_w + F_Te/Z$ $= 14.62/400 + 14.62 \times 100/6667$ $= 0.256$ kN/mm	
BS 449 cl53.a.(ii) for commonly available weld rods	permissible weld stress	$P_w = 125$ N/mm²	
	Leg length	$s = 6$ mm	
	permissible force / length	$p_w = 0.7sP_w$ $= 0.7 \times 6 \times 125 / 1000$ $= 0.53$ kN/mm	$f_T < p_w$ PASS

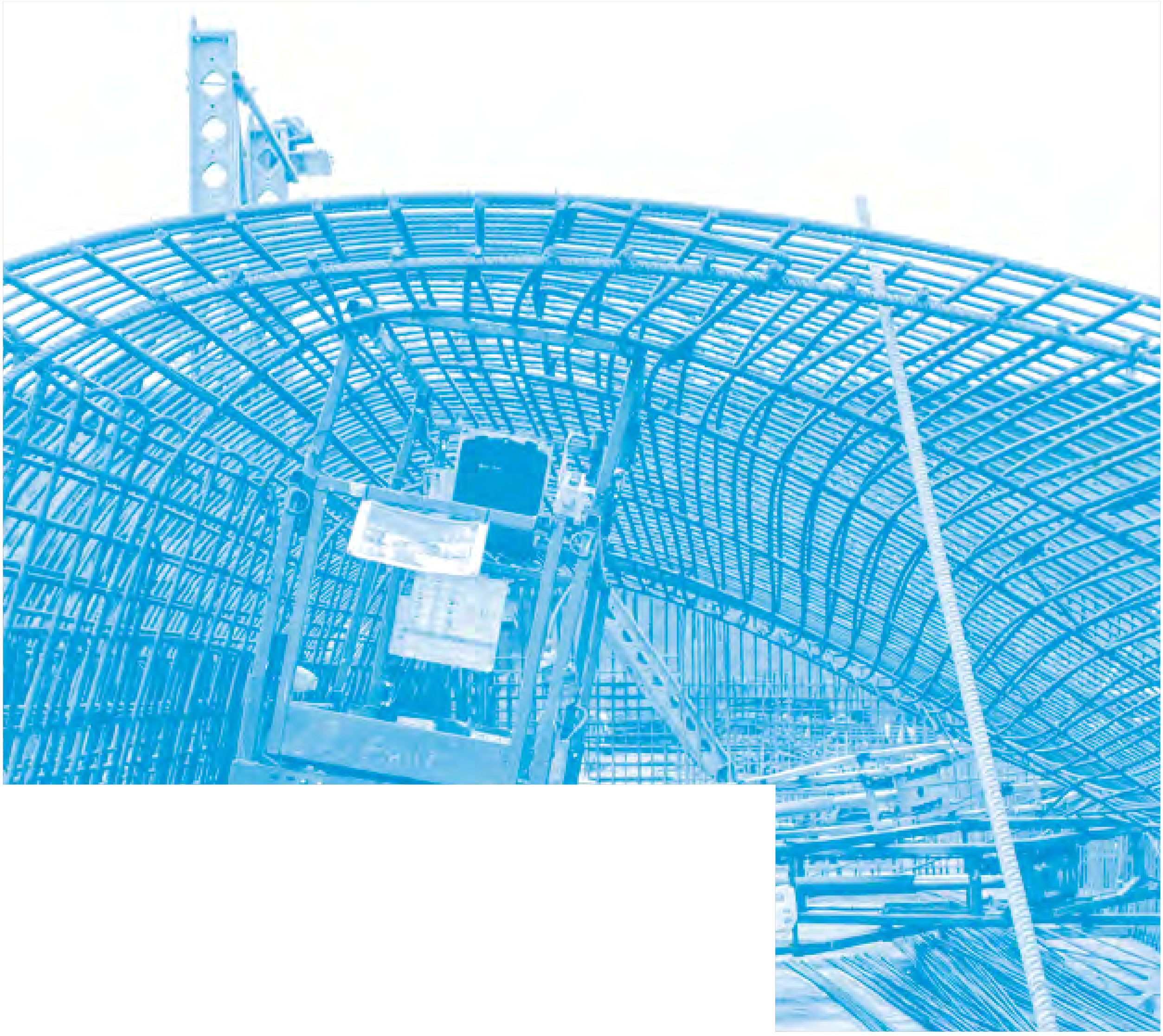
Appendix I – Example calculations – *continued*

Job Number	Task	Sheet	of	Rev.	Date	
999999	002	21	21	P04	27/06/2022	[redacted]

Customer	TWf		
Job	Rebar Stability	By	SM/MD
Description	Wall	Checked	N/A

Reference	Calculations		Output
	Tie connection welds		
	connection between ties and chords, by inspection Turning controls		
sheet 8	angle between members	$\theta = 42.3°$	
sheet 8, N_{strut}	transverse force per weld	$F_T = 14.62$ kN	
	length of weld	$L_w = 2 \times 100$ $= 200$ mm	
	elastic modulus of weld	$Z_w = (2 \times 100^2)/6$ $= 3333$ mm²	
	weld eccentricity	$e = 100$ mm	
	transverse force/length	$f_T = F_T/L_w + F_T e/Z$ $= 14.62/200 + 14.62 \times 100/3333$ $= 0.512$ kN/mm	
	longitudinal force per weld	$F_L = F_T \tan\theta$ $= 14.62 \times \tan 42.3$ $= 13.29$ KN	
	longitudinal force/length	$f_L = F_L/L_w$ $= 13.29 / 200$ $= 0.066$ kN/mm	
	resultant force/length	$f_R = \sqrt{(f_L^2 + f_T^2)}$ $= \sqrt{(0.066^2 + 0.512^2)}$ $= 0.516$ kN/mm	
BS 449 cl53.a.(ii) for commonly available weld rods	permissible weld stress	$P_w = 125$ N/mm²	
	Leg length	$s = 6$ mm	
	permissible force / length	$p_w = 0.7sP_w$ $= 0.7 \times 6 \times 125 / 1000$ $= 0.53$ kN/mm	$f_R < p_w$ PASS
	Truss to Lacer Tying Wire Connection		
	provide sufficient crown ties between truss chords and lacers to support self weight of lacers and verts, in sevice case controls		
	assume double crown ties at every chord-lacer intersection		
	verts H32 @ 150 c/c + lacers H25 @ 150 c/c		
	load per tie	$F_L = (6.31 \times 0.15 \times (2.00/0.15)) + 3.85 \times 2.00$ $= 20.3$ kg/m² $= 0.20$ kN/m²	
cl 6.2.1.2	SWL for tie	$P_L = 0.35$ kN	$F_L < P_L$

Notes:



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