MINIMUM DEGREE OF SHEAR CONNECTION RULES FOR UK CONSTRUCTION TO EUROCODE 4

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FOREWORD

Composite construction has proven popular because it combines structural efficiency with speed of construction to offer an economic solution for a wide range of building types. Applications include commercial, industrial and residential buildings. Composite beams are also an effective form of construction for bridges, but they are outside the scope of this publication.

The relevance of composite construction to the UK market has resulted in the relatively frequent development of new products. In particular decking profiles, used to form composite slabs, have evolved to allow them to span further between supporting beams. This evolution has seen a reduction in the volume, and therefore weight, of concrete needed. Whilst beneficial for the composite slabs, in some cases this reduction in concrete volume has had an adverse effect on shear stud resistances (compared to codified values).

This publication presents design resistances for shear studs when used in the presence of modern forms of decking. It includes rules for the minimum number of studs that are needed on a range of beams (the minimum degree of shear connection). In many cases this minimum is lower than would be required by EN 1994-1-1 (and indeed BS 5950-3.1 prior to its amendment in 2010).

The combination of less onerous requirements for minimum degree of shear connection, and lower stud resistances, allows many composite beams to be designed that would not satisfy the rules given in EN 1994-1-1.

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Both the technical report and this publication have been authored by Dr G. Couchman, assisted by Prof R. M. Lawson and Dr E. Aggelopoulos, all of SCI.

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SUMMARY

It is recognised that shear stud resistances as defined in current codes (BS 5950-3.1 as amended in 2010 gives significantly lower values than its previous version, and EN 1994-1-1 always gave lower values than the earlier BS 5950-3.1) are causing problems with the design of many composite beams. The reduced resistances are not a 'code error'; they reflect modern construction practice in which decking profiles have evolved to reduce the volume of concrete present.

This publication defines stud resistances that may be used in conjunction with design to EN 1994-1-1. They complement the values given in that code by including resistances that are compatible with different detailing options, and modern decking products, as used in the UK. New, more onerous limits on maximum stud spacing are given, although these will not normally affect design.

Minimum degree of connection rules are given to cover a range of scenarios, in particular propped or unpropped construction (the latter is not explicitly covered in either BS 5950-3.1 or EN 1994-1-1). Both transverse and parallel decking cases are covered as the deck orientation can have a significant impact on the required degree of shear connection. Consideration is given to beams that carry high levels of loading, as found in plant rooms, and beams that are only part utilised in bending (because their design is governed by serviceability considerations). The rules for part utilised beams are particularly important because they always give designers an option to use a 'larger' steel beam in order to obtain a valid design. Special consideration is also given to beams with regularly spaced, large circular web openings.

The lower bound minimum degree of shear connection of 40% that is specified in EN 1994-1-1 and BS 5950-3.1 is modified (as a function of a number of parameters), but there remains a need for an absolute limit to avoid 'shakedown' of the shear connection under repeated loading.

Because the minimum degree of connection rules could result in the application of fewer studs than EN 1994-1-1 would require, the resulting composite beams may be less stiff. Rules for how to take this into account when determining deflections are provided.

The rules given in this guide complement those given in EN 1994-1-1 by allowing the user who has greater knowledge to take into account more of the variables (that affect the requirements for shear connection) than are explicitly covered by the Eurocode. By so doing the beam design may be less conservative.

INTRODUCTION

1.1 The roles of shear connectors

Composite beams are efficient because they exploit the strengths of concrete in compression and steel in tension. They do this by enabling force transfer between the top flange of the steel beam and the concrete. This force transfer is achieved using shear connectors, normally welded headed studs, which are characterised by their ability to transfer force (their resistance), their stiffness, and their ability to accommodate slip between the steel and concrete.

Figure 1.1 shows the cross section of a typical composite beam, comprising a steel section, shear stud and width of concrete that can be mobilised (effective width). It also shows the stresses and forces that can be developed in the steel and concrete when subject to bending and structurally connected to each other by the stud. The force that is transferred between the steel and concrete may be limited by either the compressive resistance of the concrete flange (N_{cf}), the tensile resistance of the steel section (N_a), or the sum of the resistances of the shear studs (in the figure this is defined as N_c, equal to ηN_{cf}, where η is the degree of shear connection). When the force is limited by the shear studs the beam is said to have partial shear connection.

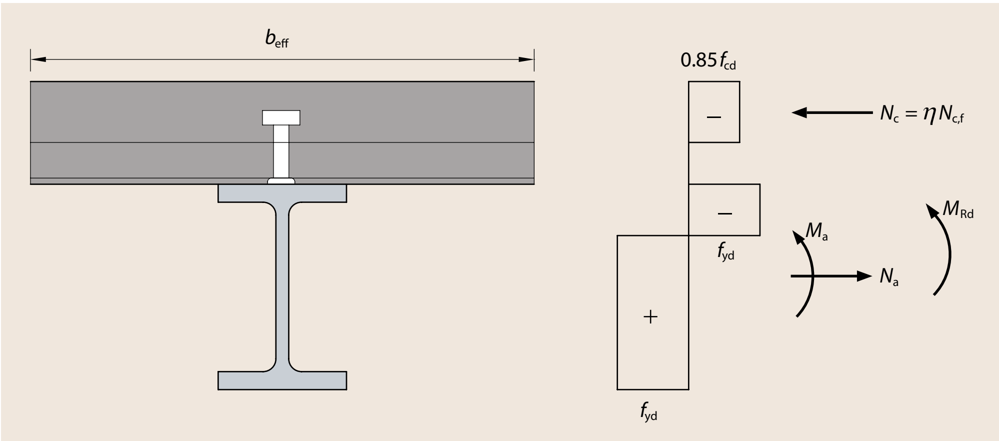
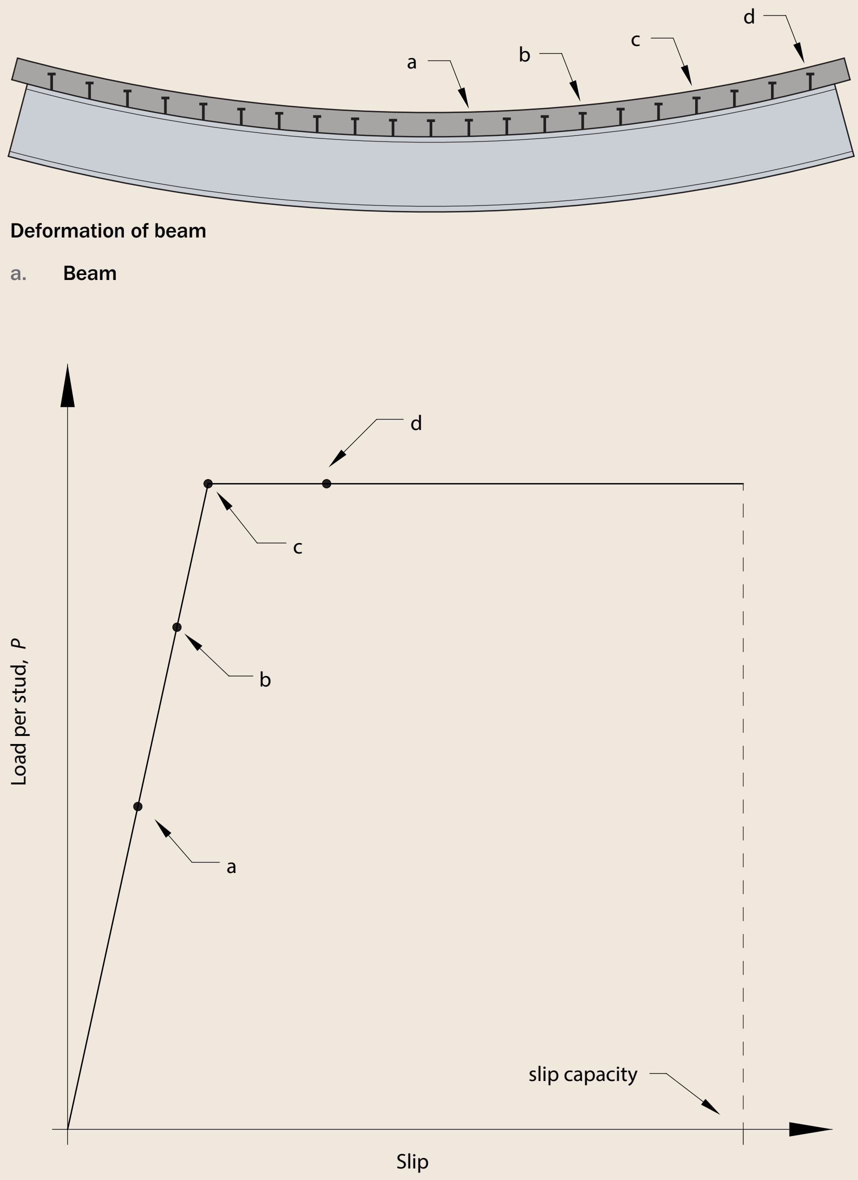


Figure 1.1 Composite beam cross section showing forces and plastic stress distribution for partial shear connection

As well as transferring force between the steel beam and concrete slab, the shear studs must limit the slip that occurs at the interface between these two elements as the beam bends. Studs do not have the infinite stiffness that would be needed to prevent slip, and so must have the ductility (slip capacity) to be able to accommodate whatever slip takes place. The more studs are present (the higher the degree of shear connection), the less slip. Figure 1.2 shows schematically a beam subject to bending, and the displacement of the slab relative to the steel beam (in particular the end slip). The studs near the beam ends are subject to the greatest amount of slip. The figure also shows a simplified (bi-linear) load-slip response for a shear stud with its three characteristics of initial stiffness, resistance, and slip capacity.



a. Beam

b. Shear connector load slip (idealised curve)

Figure 1.2 Composite beam showing slip experienced by the shear studs at the concrete-steel interface

Developments in decking products and UK construction practice have resulted in shear stud resistances being less than the values that were traditionally used in design, as presented in BS 5950-3.1 (prior to its amendment in 2010) [1]. Resistances given in EN 1994-1-1 [2] are lower than the pre-amendment BS 5950-3.1 values.

The lower stud resistances now presented in both codes have resulted in many composite beam designs (that were previously accepted) becoming impossible because the maximum number of studs that can be accommodated on a beam is often less than the number of studs needed to satisfy rules for minimum degree of shear connection.

The purpose of this publication is to provide designers in the UK with alternative rules, which can be used to complement those given in the Eurocode. The UK regulatory system allows a designer to use information that he/she feels is appropriate. Moreover, the Eurocodes recognise that they do not cover all applications and allow for the use of so-called non-contradictory complementary information (NCCI). Although ultimately it is the designer's responsibility to decide on the methods of design that are used to satisfy the Building Regulations, the rules given in this publication may be considered to complement those given in EN 1994-1-1 because:

- The shear stud resistances given in EN 1994-1-1 are associated with certain detailing requirements (a point that is often missed by designers). In particular, the code states that the 'lower level of mesh must be at least 30 mm below the head of the stud'. Although not stated, it may be assumed this only applies to solid slabs with two layers of mesh (numerous push tests have shown that neither the resistance nor the ductility of a shear stud are adversely affected when the mesh is less far below the head). This publication provides complementary guidance for when this detailing rule is not satisfied, and gives shear stud resistances for different detailing options.
- EN 1994-1-1 provides minimum degree of connection rules that are a function of steel grade, beam span, and asymmetry of the beam flanges. This publication introduces other variables such as whether the beam is propped or unpropped, the slip capacity of the studs (which is greater when they are placed in transverse trapezoidal decking than when in a solid slab or a slab with parallel decking), and the type of loading. Consideration is also given to beams with regularly spaced, large circular web openings (cellular beams), and beams that are only part utilised in bending. This publication therefore complements the EN 1994 rules by covering more alternatives than the simpler 'cover all' rules in the code. Complementary rules for maximum stud spacing are included.

1.2 Scope of this publication

This publication provides shear stud resistances and minimum degree of shear connection rules for the design of composite beams in buildings in accordance with EN 1994-1-1 and within the flowing scope:

- Downstand beams that are simply supported and internal (so the effective flange extends to either side of the beam).
- Beams not exceeding 22 m in span (except where a shorter span is specified in a particular Section of this document).

- Rolled or fabricated open cross sections that are doubly symmetric, or asymmetric (ratio of top:bottom flange areas up to 1:3 unless specified differently in a particular Section of this publication).
- Cross sections should be Class 1 or 2 (see Section 7 for comment on when Class 3 or 4 flanges may be treated as Class 2).
- Beams with solid webs, or with regularly spaced, large circular web openings
- Beams that are either propped or unpropped during construction (a detailed definition is given in the publication).
- Slabs that are either solid, or with trapezoidal and re-entrant decks within the scope of EN 1994-1-1, running either transverse or parallel to the beam.
- Nominal deck profiles not exceeding 80 mm in height (to the 'shoulder' of the decking).
- Shear studs of 19 mm diameter with an embedment of at least 35 mm into the solid concrete above the (shoulder of) the decking profile.
- Studs that have mesh placed either at nominal cover (assumed to be clear of the head of the stud) or below the head of the studs (by at least 10 mm).
- Nominal total slab depth not exceeding 180 mm (depth of concrete over the decking not exceeding 100 mm).
- Studs with a maximum longitudinal spacing as defined in Section 7 of this publication.

SHEAR STUD RESISTANCE AND SLIP CAPACITY

Although EN 1994-1-1 only gives shear resistances for studs with mesh below the head (indeed with a specific detailing requirement that the 'lower' mesh must be at least 30 mm below the head), the impact of mesh placed higher in the slab (at nominal cover) was investigated when developing the rules for BS 5950-3.1+A1:2010. Push tests on slabs with transverse trapezoidal decking, with a single layer of mesh at different 'heights', were used to inform the BS 5950 rules and (more-or-less) confirm the validity of the EN 1994 rules. That same empirical information can be used to develop complementary resistances for use with EN 1994 when the mesh is placed above the studs.

The tests only considered the resistance and slip capacity of studs placed either centrally or in a favourable position in transverse trapezoidal decking. Unfavourable stud positing should be avoided, and the behaviour of studs in solid slabs, with re-entrant decking, and with longitudinal trapezoidal decking is assumed to be consistent with codified rules.

In order to justify use of the rules for mesh placed below the heads of the studs, it would be possible to simply use a localised layer of mesh over the beam. This would need to extend an anchorage length beyond the potential transverse shear planes in-line with the edges of the beam flange. It could then also play the role of additional transverse reinforcement.

2.1 Slip capacity

When trapezoidal decking is placed transverse to the beam, full scale beam tests and push tests have shown that the shear connection can achieve at least 10 mm slip capacity. EN 1994 assumes this figure to be 6 mm [3], which is conservative.

When decking is parallel to the beam the studs may be assumed to achieve 6 mm slip capacity. There is no test evidence to suggest greater slip can be achieved.

The slip capacity that can be achieved significantly affects the minimum degree of shear connection that can be used in design (see Section 5).

2.2 Stud resistance

2.2.1 In a solid slab

According to EN 1994-1-1, 6.6.3.1 the design resistance of a shear stud in a solid slab is the lesser of the values for P_{Rd} given by two equations, one of which represents failure of the stud itself (a 'steel failure'), and the other failure of the surrounding concrete.

$$P_{Rd} = \frac{0.8 f_u \pi d^2 / 4}{\gamma_v}$$

$$P_{Rd} = \frac{0.29 \alpha d^2 \sqrt{(f_{ck} E_{cm})}}{\gamma_v}$$

Where:

α may be taken as 1.0 for 19 mm diameter studs with a length before welding of at least 100 mm.

γ_v is the partial factor, taken as 1.25 according to the UK National Annex.

d is the diameter of the shank of the stud.

f_{ck} is the characteristic cylinder strength of the concrete.

f_u is the ultimate tensile strength of the stud material, but not greater than 500 N/mm^2.

E_{cm} is the secant modulus of elasticity of the concrete.

2.2.2 With transverse decking

When the stud is placed in the trough of a deck, rather than in a solid slab, the solid slab resistance (as defined above) is reduced using a factor k_t for decking placed transverse to the beam.

From EN 1994-1-1, 6.6.4.2(1), which applies when mesh is present below the head of the studs (this is implicit from the detailing rule given in 6.6.5.1 and shown in Figure 6.14 of EN 1994-1-1, although the detailing is different from UK practice and the need for a value of 30 mm could be argued against):

$$k_t = \frac{0.7}{\sqrt{n_r}} \frac{b_0}{h_p} \left(\frac{h_{sc}}{h_p} - 1 \right)$$

Where:

n_r is the number of studs in a deck trough. Note that no more than two studs may be used.

h_{sc} is the as-welded height of the stud (this is unclear in EN 1994-1-1 but recommended by SCI).

h_p is defined in EN 1994-1-1 as the overall depth of the decking. When the decking has a small re-entrant shape at the top of the upper flange, it may be taken as the depth (height) to the shoulder of the decking.

b_0 is the mean trough width for trapezoidal decks, and the minimum trough width for re-entrant decks.

The code includes some absolute limits to the value of k_t (see Table 6.2). An extract, covering common UK practice, is given in Table 2.1 below.

STUDS PER TROUGH n_r	THICKNESS t OF SHEET (mm)	THROUGH DECK WELDED STUDS < 20 mm DIAMETER
1	$\leq$ 1.0	0.85
	>1.0	1.00
2	$\leq$ 1.0	0.70
	>1.0	0.80

Table 2.1 Absolute limits on k_t according to EN 1994-1-1

According to test data as reflected in document NCCI PN001a-GB [4], when double studs are present, the values from EN 1994 may be unconservative. In this case, additional factors are introduced as follows:

- When mesh is placed below the heads of the studs an additional multiplication factor k_{mod} of 0.9 should be applied.
- When mesh is placed at nominal cover (assumed to mean above the head given typical slab geometries) the values derived from EN 1994 should be reduced using an additional multiplication factor k_{mod} of 0.7.

No further reduction is necessary when single studs are used, even if mesh is placed at nominal cover.

2.2.3 With parallel decking

When the stud is placed in the trough of a deck, rather than in a solid slab, the solid slab resistance (as defined above) is reduced using a factor k_l. The behaviour of a stud in the trough of parallel decking is similar to that in a solid slab, with the greatest forces around the base of the stud (the behaviour in transverse decking is fundamentally different). This means that the height of the mesh is not a significant variable and may be ignored.

EN 1994-1-1, 6.6.4.1(2) defines k_l as follows:

$$k_t = 0.6\frac{b_0}{h_p}\left(\frac{h_{sc}}{h_p} - 1\right) \leq 1.0$$

Variables are as defined above.

DEFINITION OF UNPROPPED CONSTRUCTION

Section 4 of this publication considers how rules for minimum degree of shear connection are affected by a number of variables. One of the most important is whether the beam is propped or unpropped during construction. Before considering these rules, it is important to be clear how unpropped construction is defined, and why:

- The rules here only concern cases where there is no temporary support (propping) of the decking. The beams themselves may be propped or unpropped.
- In an unpropped situation, because dead load is applied to the steel beam alone, at a time when the concrete has negligible strength, the dead load applies no force to the shear studs. None of their slip capacity is therefore used under this dead load condition.
- The benefit to be had from unpropped construction (in terms of less onerous rules for minimum degree of shear connection) therefore reduces as the imposed load increases as a proportion of the total load on the beam. Note that here ‘imposed load’ is taken to be all loads other than the self-weight of the beam and slab. This is an important concept:
  - The beam will be ‘sized’ for the total load on it, whether dead or imposed.
  - The minimum degree of connection to be satisfied will vary depending on what proportion of that load is imposed. In the (hypothetical) extreme, if all the load was imposed then the requirements for unpropped and propped construction would be the same (because all the load would be applied to a propped beam only after the props had been removed).
  - Previous guidance from SCI has defined minimum degree of shear connection limits for unpropped construction that only apply to beams subject to a factored imposed UDL of not greater than 9 kN/m^2. In this publication that definition is complemented as follows:
    - When loading other than just uniform loading (UDL) is present (meaning the 9 kN/m^2 check cannot be applied), as an alternative the moment due to factored imposed load should not exceed 70% of the moment due to total factored loading.
    - Specific minimum degree of shear connection requirements are given for so-called heavily loaded beams, as would be found in plant rooms. When these rules are applied, the definition of unpropped construction is modified accordingly (see Section 5).

It is important that these limits are not exceeded because the finite element analyses that were used to model this complex behaviour assumed certain levels of imposed loading. The rules developed should not be used beyond these limits.

MINIMUM DEGREE OF SHEAR CONNECTION

4.1 Why specify a minimum degree?

When a beam is designed with full shear connection it means that there are sufficient shear connectors present to either fully exploit the steel section in tension or, as is more often the case, fully exploit the concrete slab in compression. A reduced number of shear connectors may be used, giving so-called partial shear connection, when less force is required to be transferred between the steel and concrete to achieve the necessary composite beam moment resistance.

However, it is important to recognise why a minimum degree of shear connection is required. It is a resistance check that is used to ensure there are sufficient studs present on a beam. 'Sufficient' has traditionally been taken as meaning the number of studs needed to provide a collective stiffness to limit the slip between steel and concrete elements to a certain amount. So it is a resistance check to indirectly check stiffness, and this lack of transparency means care must be taken when adapting the rules for different cases.

As part of the study leading up to this publication an additional definition of 'sufficient' was considered, namely the number of studs needed to ensure that the shear connection remains elastic under serviceability (SLS) levels of loading. A danger of this criterion not being satisfied would be that, under the unlikely event of repeated loading up to service levels, a 'shakedown' of the shear connection would occur (leading to cumulative and irreversible beam deflections).

4.2 Variables that affect the minimum degree of shear connection

EN 1994-1-1 recognises that the minimum degree of shear connection needed to maintain slip at the steel-concrete interface to an acceptable level is influenced by three parameters:

- Beam span.
- Steel grade.
- Symmetry of the steel beam (asymmetric means the flanges are not of equal area).

However, a number of other variables also affect the slip, and are considered in this publication. Comment on their relevance is given below. The impact of each variable was quantified using extensive finite element (FE) studies, supported by work undertaken by a number of independent researchers and validated using several beam tests. Other important variables include:

- Type and orientation of decking,
  - Trapezoidal or re-entrant shape.
  - Ribs transverse or parallel to the beam axis.
- Beams that are propped or unpropped during construction.
- Beams with a solid web or regularly spaced, large circular web openings.
- The nature of loading,
  - Uniformly distributed loading (UDL), point loads, combination of load types.
- The level of utilisation of the beam in bending,
  - A beam that is governed by serviceability requirements will be only part utilised in bending.

4.2.1 Type and orientation of decking

EN 1994-1-1 recognises that shear stud resistance in a solid slab may be governed either by failure of the stud itself, or failure of the surrounding concrete (EN 1994-1-1, 6.6.3.1 Equations 6.18 and 6.19). The shear resistance of a stud in the presence of profiled decking is defined as its solid slab resistance reduced using a factor that is a function of the deck and stud geometry, and the deck orientation (EN 1994-1-1, 6.6.4.1(2) Equations 6.22 and 6.23). The slip capacity of through deck welded headed studs is assumed to be 6 mm, regardless of the details of the slab around them.

This approach hides the fact that there are some significant differences in behaviour – in a solid slab the stud compresses concrete near the base of the stud, whereas in a composite slab formed on transverse decking the peak compression is nearer the head of the stud, in the region of the stiff concrete above the decking. Beam and push tests undertaken since EN 1994-1-1 was developed have shown that one of the main differences when trapezoidal decking is used, with the troughs running transverse to the beam axis, is that slip in excess of 10 mm can be achieved. This greater deformation capacity means that fewer studs are needed to maintain the interface slip at an acceptable level (so the minimum degree of connection can be reduced).

The behaviour of a composite slab with parallel decking is similar to that of a solid slab (but with a reduced volume of concrete 'ahead' of the studs). It is worth noting that the number of studs to be considered when defining the degree of connection (η) when parallel decking is present is open to some debate. Traditionally it has been taken as the number of studs between an end support and the point of maximum applied moment (i.e. the point where maximum moment resistance is needed). However some interpret EN 1994 as saying that it is the number of studs over the whole length of beam, meaning that when point loads are present the studs 'in-board' of the loads can be taken into account when calculating η. Finite element (FE) analyses carried out to validate this assumption suggest that, although the studs on the intermediate part of a beam (between point loads) do contribute, they are not fully effective. In the absence of further evidence it is therefore recommended that only the shear connectors from the end of a simply supported span up to the point of maximum moment are (conservatively) considered in design.

There is currently no evidence to suggest that studs in re-entrant decking, or parallel trapezoidal decking, can achieve more than 6 mm slip. Should future research show that a greater slip capacity can be achieved in some circumstances, then this could easily be taken into account with appropriate application of the rules given in Section 5 of this publication.

4.2.2 Beam propped or unpropped

When a beam is unpropped (see Section 3 for a definition of unpropped) during construction the dead loads do not result in any deformation of the shear studs, because at the time of their application the concrete has negligible strength and so 'flows' around the studs rather than exerting force against them. This means that slip requirements are less than in a propped beam (although the higher strains that result in the bare steel section carrying the construction load negate this benefit to some extent). The net beneficial impact of unpropped construction is something that could be exploited for many beams, given it is by far the most common form of construction. However the behaviour of unpropped beams is significantly more complex to model (and replicate in a lab), and all current code rules adopt the more conservative approach of using the same rules (for propped construction) to cover both cases.

4.2.3 Presence of regular large web openings

When a regular series of large circular openings is present in a beam web, less strain is required in the beam flanges to approach the beam's moment resistance (as there is no need to mobilise the 'missing' central part of the web). This benefit reduces as the asymmetry of the beam increases (bottom flange becomes bigger relative to the top flange) and the web therefore makes a reduced contribution to the resistance. These lower levels of strain, even given a coincident change in neutral axis position, equate to less slip at the concrete to steel interface. Another unique feature of beams with regular large web openings is that, because the regions where holes are present have considerably less resistance than the 'solid' regions, the latter are only stressed to a level considerably below their capability (effectively these regions are 'part utilised in bending', as considered in Section 4.2.5 and shown to be highly beneficial).

4.2.4 Nature of loading

In most cases the nature of the loading will be linked to the orientation of the decking. Heavy point loads would often result from incoming secondary beams, and the beam under consideration would have parallel decking spanning between these secondary beams. Discussion on the influence of parallel decking is given in Section 4.2.1.

Studies have shown that when a composite beam is subject to point loads (instead of, or in addition to, UDL) this imposes less onerous demands on the shear connection stiffness. The minimum degree of shear connection required becomes less severe as we move from a beam with UDL, to a beam with point loads at 1/3 span positions, to a beam with a single point load at mid-span.

The above observations, though encouraging for beams with parallel decking and different types of loading, do not justify the provision of an alternative set of rules for minimum degree of shear connection for these cases. The avoidance of an alternative set will also facilitate ease of use of the rules by practitioners.

4.2.5 Level of utilisation of the beam in bending

The elastic-plastic behaviour of steel means that as the plastic resistance of a beam is approached (at ULS) the strains in the extreme fibres increase disproportionately. A typical solid web composite beam at 95% of its moment resistance will only experience three to five times yield strain in the bottom flange. The shear studs show similar non-linear behaviour. Together these phenomena mean that slip increases rapidly as the full composite beam moment resistance is approached.

When a beam is not fully utilised in bending, for example because it is governed by serviceability considerations, ultimate slip demands at the steel to concrete interface reduce significantly. Reducing the minimum degree of shear connection requirements as a function of beam utilisation is comparable to the existing common practice of designing the beam assuming a lower yield stress than is actually present, which is a simplified way of limiting utilisation.

Because at serviceability levels of loading there is significantly less non-linear behaviour (of the steel and shear studs), the impact of part utilisation in bending on the shear connection needed to keep the shear connection elastic is less noticeable. A simple linear relationship can be seen in the rules given in Section 5 of this publication.

DESIGN RULES FOR MINIMUM DEGREE OF SHEAR CONNECTION

Though clearly some of the variables that permit relaxation of requirements for minimum degree of connection could be coincident (for example a part utilised beam is also likely to be unpropped), parameters that permit relaxation **should not be combined except where explicitly stated** (because the FE and other studies used to justify the rules have insufficient scope).

The rules given below are based on those given in BS 5950-3.1+A1:2010, EN 1994-1-1 and NCCI document PN002a-GB [5] (although with some variations and additions).

All rules are related to the use of 19 mm through deck welded headed studs, with a length after welding of not less than 95 mm. They therefore cover standard UK building practice.

The minimum degree of connection rules given below, which concern limiting the slip at the concrete-steel interface, **must** be applied in conjunction with the detailing rules given in Section 7 for maximum longitudinal shear connector spacing (which prevent vertical separation and lateral movement of the beam flange).

The impact of the degree of shear connection on the flexural stiffness of the beam (and therefore its deflection), **must** be considered using the rules given in Section 6 of this publication.

5.1 Rules for symmetric beams

5.1.1 Normal loading

Normal loading is defined as unfactored imposed load not exceeding 6 kN/m^2 (assumed to be 9 kN/m^2 when factored).

Slip capacity limited to 6 mm

This represents the general case. These rules may be applied to all types of decking, regardless of orientation, and to all types of symmetric beam, propped or unpropped (with some conservatism in many cases). Note that the requirements may be reduced when a beam is part utilised in bending.

$$\eta \geq [1-\left(\frac{355}{f_y}\right)(0.75-0.03L)].[\frac{M_{Ed}}{M_{Rd}}]^2 \qquad \text{but } \eta \geq [0.40].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.28$$

η is the degree of shear connection.

f_y is the yield strength of the steel beam.

L is the beam span.

M_{Ed} is the design bending moment (due to factored loading).

M_{Rd} is the design resistance of the composite beam (allowing for any partial shear connection).

This is the same requirement as presented in EN 1994-1-1, 6.6.1.2, except the Eurocode does not permit relaxation for a beam that is part utilised in bending.

Note that this requirement, and those that follow, is shown graphically in Appendix A as degree of shear connection versus beam span.

Slip capacity limited to 10 mm

These rules apply to cases as defined above except the decking must be trapezoidal and transverse to the axis of the beam.

$$\eta \geq 1-\left(\frac{355}{f_y}\right)(1.433-0.054L) \quad \text{but } \eta \geq [0.40].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.28$$

5.1.2 Heavy loading

For plant rooms the unfactored imposed loading could be as high as 8 kN/m^2 (assumed to be 12 kN/m^2 when factored), which is here defined as 'heavy loading'. Specific rules have not been determined for loads exceeding this value (noting that the equations below are a little more onerous than those in Section 5.1.1, it can be concluded that it would be unconservative to use the EN 1994-1-1 rules when loading is heavier than 'normal').

Slip capacity limited to 6 mm

These rules may be applied to all types of decking, regardless of orientation, and to all types of symmetric beam. The beams may be propped or unpropped. Note that the requirements may be reduced when a beam is part utilised in bending:

For $L_e \leq 18$
$$\eta \geq [1-\left(\frac{355}{f_y}\right)(0.855-0.048L)].[\frac{M_{Ed}}{M_{Rd}}]^2 \quad \text{but } \eta \geq [0.40].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.28$$

Slip capacity limited to 10 mm

These rules apply to cases as defined above except the decking must be trapezoidal and transverse to the axis of the beam:

For $L_e \leq 18$
$$\eta \geq 1-\left(\frac{355}{f_y}\right)(1.577-0.072L) \quad \text{but } \eta \geq [0.40].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.28$$

5.2 Rules for asymmetric beams

It is recommended that the following rules are only used for 'normal loading', as defined above. Specific rules have not been developed for asymmetric beams subject to 'heavy loading'.

These rules are applicable to beams with a bottom flange having up to three times the area of the top flange (asymmetry 1:3). For lower levels of asymmetry it is acceptable to linearly interpolate between the limits given by these rules and the corresponding limits for symmetric beams.

Slip capacity limited to 6 mm

This represents the general case. These rules may be applied to all types of decking, regardless of orientation. The beams may be propped or unpropped. Note that the requirements may be reduced when a beam is part utilised in bending:

For $L_e \leq 20$ $\quad \eta \geq [1 - \left(\frac{355}{f_y}\right)(0.30 - 0.015L)].[\frac{M_{Ed}}{M_{Rd}}]^2$ but $\eta \geq [0.55].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.39$

For $L_e > 20$ $\quad \eta = 1.0$

Slip capacity limited to 10 mm

These rules apply to cases as defined above except the decking must be trapezoidal and transverse to the axis of the beam.

$\eta \geq 1 - \left(\frac{355}{f_y}\right)(0.435 - 0.021L)$ and $\eta \geq [0.55].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.39$

5.3 Alternative rules for unpropped symmetric beams

5.3.1 Normal loading

Slip capacity limited to 6 mm

These rules apply when the decking is re-entrant, or trapezoidal orientated parallel to the beam axis.

Provided the definition of 'unpropped' as given in Section 3 is satisfied:

$\eta \geq [1 - \left(\frac{355}{f_y}\right)(0.802 - 0.029L)].[\frac{M_{Ed}}{M_{Rd}}]^2$ but $\eta \geq [0.30].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.25$

Slip capacity limited to 10 mm

These rules apply when the decking is trapezoidal and transverse to the beam axis.

Provided the definition of 'unpropped' as given in Section 3 is satisfied:

$$\eta \geq 1 - \left(\frac{355}{f_y}\right)(2.019 - 0.070L) \quad \text{and } \eta \geq [0.30].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.25$$

5.3.2 Heavy loading

Slip capacity limited to 6 mm

For (factored) imposed UDLs between 9 kN/m^2 and 12 kN/m^2, the minimum degree of shear connection may be taken as:

$$\eta \geq [1 - \left(\frac{355}{f_y}\right)(0.833 - 0.034L)].[\frac{M_{Ed}}{M_{Rd}}]^2 \quad \text{and } \eta \geq [0.30].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.25$$

Slip capacity limited to 10 mm

These rules apply when the decking is trapezoidal and transverse to the beam axis.

For (factored) imposed UDLs between 9 kN/m^2 and 12 kN/m^2, the minimum degree of shear connection may be taken as:

$$\eta \geq 1 - \left(\frac{355}{f_y}\right)(2.048 - 0.081L) \quad \text{and } \eta \geq [0.30].[M_{Ed}/M_{Rd}] \text{ and } \eta \geq 0.25$$

5.4 Alternative rules for unpropped asymmetric beams

It is recommended that the following rules are only used for 'normal loading', as defined above. Specific rules have not been developed for asymmetric beams subject to 'heavy loading'.

These rules are applicable to beams with a bottom flange having up to three times the area of the top flange (asymmetry 1:3). For lower levels of asymmetry it is acceptable to linearly interpolate between the limits given by these rules and the corresponding limits for symmetric beams.

Slip capacity limited to 6 mm

These rules apply when the decking is re-entrant, or trapezoidal orientated parallel to the beam axis.

Provided the definition of ‘unpropped’ as given in Section 3 is satisfied:

For $L_e \leq 20$ $\eta \geq [1 - \left(\frac{355}{f_y}\right)(0.322 - 0.014L)].[\frac{M_{Ed}}{M_{Rd}}]^2$ but $\eta \geq [0.42].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.30$

For $L_e > 20$ $\eta = 1.0$

Slip capacity limited to 10 mm

These rules apply when the decking is trapezoidal and transverse to the beam axis.

Provided the definition of ‘unpropped’ as given in Section 3 is satisfied:

$\eta \geq 1 - \left(\frac{355}{f_y}\right)(0.434 - 0.011L)$ and $\eta \geq [0.42].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.30$

5.5 Alternative rules for beams with large web openings

When a composite beam with regularly spaced, large circular web openings is fully utilised, it is possible to reduce the minimum degree of shear connection required to limit slip at the ULS (so long as the beam is assumed to be fully utilised). It is not possible to relax the requirement associated with keeping the shear connector behaviour elastic at SLS (see example below).

A beam is considered to have large web openings if the depth of the opening is not less than 60% of the depth of the web. When this limit is not satisfied the beam should be treated as having a solid web. These rules must only be applied to beams with regular openings throughout the span (a beam with localised openings should be treated as a beam with a solid web).

The beneficial impact of web openings on the minimum degree of shear connection is similar whether the beam is propped or unpropped during construction. Values provided by the relevant rules given above for solid web beams may be reduced using a factor:

- Symmetric section (1:1) 0.60
- Max asymmetric (1:3) 0.90
- Lesser asymmetry interpolate

For example, a propped symmetric beam with 6 mm slip capacity and solid web requires the following minimum degree of shear connection (from Section 5.1.1):

- To satisfy ULS slip: $\eta \geq [1 - \left(\frac{355}{f_y}\right)(0.75 - 0.03L)].[\frac{M_{Ed}}{M_{Rd}}]^2$
- And to ensure SLS slip is acceptable: $\eta \geq [0.40].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.28$

In the presence of regular large web openings these requirements would become:

- To satisfy ULS slip: $\eta \geq [1 - \left(\frac{355}{f_y}\right)(0.75 - 0.03L)].[0.6]$
- And to ensure SLS slip is acceptable: $\eta \geq [0.40].[M_{Ed}/M_{Rd}]$ and $\eta \geq 0.28$

Note that it is not currently possible to combine the beneficial effects on the shear connection (needed to limit ULS slip) of part utilisation with those of having web openings. When a beam with web openings is only part utilised the rules given above to allow for this effect in solid web beams may be conservatively used (without further reduction).

DEFLECTION CALCULATIONS

According to EN 1994-1-1, 7.3.1(4), provided the degree of shear connection is greater than certain limits then the influence of slip at the steel-concrete interface on beam deflection (i.e. composite beam stiffness) can be ignored. If the degree of shear connection limits given in Section 5 of this publication are used, and they give a lower degree of connection than would be provided following EN 1994-1-1 (or, conservatively, even if they don't), then the effects of incomplete interaction should be considered when calculating the deflections of the beam in its composite state.

The effect of partial interaction on the deflection of the composite beam may be determined as follows, using rules taken from BS 5950-3.1:

For propped construction:

$$\delta = \delta_c + 0.5(1 - \eta)(\delta_s - \delta_c)$$

For unpropped construction:

$$\delta = \delta_c + 0.3(1 - \eta)(\delta_s - \delta_c)$$

where:

δ_s is the deflection for the serviceability loads acting on the steel beam alone.

δ_c is the deflection of a composite beam with full shear connection for the same loading. This can be determined using the second moment of area of the composite beam calculated using BS 5950-3.1, B3.

Creep and shrinkage may be accounted for by using an appropriate value of modular ratio, in accordance with EN 1994-1-1, 5.4.2.2(11).

MAXIMUM LONGITUDINAL STUD SPACING

The minimum degree of connection rules given in Section 5 of this publication must be used in conjunction with appropriate detailing to limit the maximum longitudinal stud spacing.

Hicks [6] has previously suggested that the maximum spacing should not be greater than 450 mm. With transverse decking this equates to a need to have a stud in every trough. Note that these limitations are more onerous than those currently given in EN 1994-1-1, which are recognised as being too lenient.

EN 1994-1-1, 6.6.5.5 (2) imposes additional requirements when a compression flange that would otherwise be Class 3 or 4 is considered to be Class 2 because of restraint from the shear connectors. In relevant circumstances this clause should be respected.

REFERENCES

[1] BS 5950-3.1:1990+A:2010.
Structural use of steelwork in buildings. Design in composite construction. Code of practice for design of simple and continuous composite beams.
BSI, 2010 (Superseded).

[2] BS EN 1994-1-1:2004.
Eurocode 4: Design of composite steel and concrete structures. General rules and rules for buildings.
BSI, 2005.

[3] Johnson, R.P.
Designers' Guide to Eurocode 4: Design of Composite Steel and Concrete Structures, Second Edition.
ICE Publishing, 2011.

[4] PN001a-GB.
Resistance of headed stud shear connectors in transverse sheeting.
Available from: www.steel-ncci.com.
SCI, 2010.

[5] PN002a-GB.
Modified limitation on partial shear connection in beams for buildings.
Available from: www.steel-ncci.com.
SCI, 2010.

[6] Hicks, S.
Strength and ductility of headed stud connectors welded in modern profiled steel sheeting,
The Structural Engineer, Volume 85, Issue 10.
The Insitution of Structural Engineers, 2007.

CREDITS

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APPENDIX A

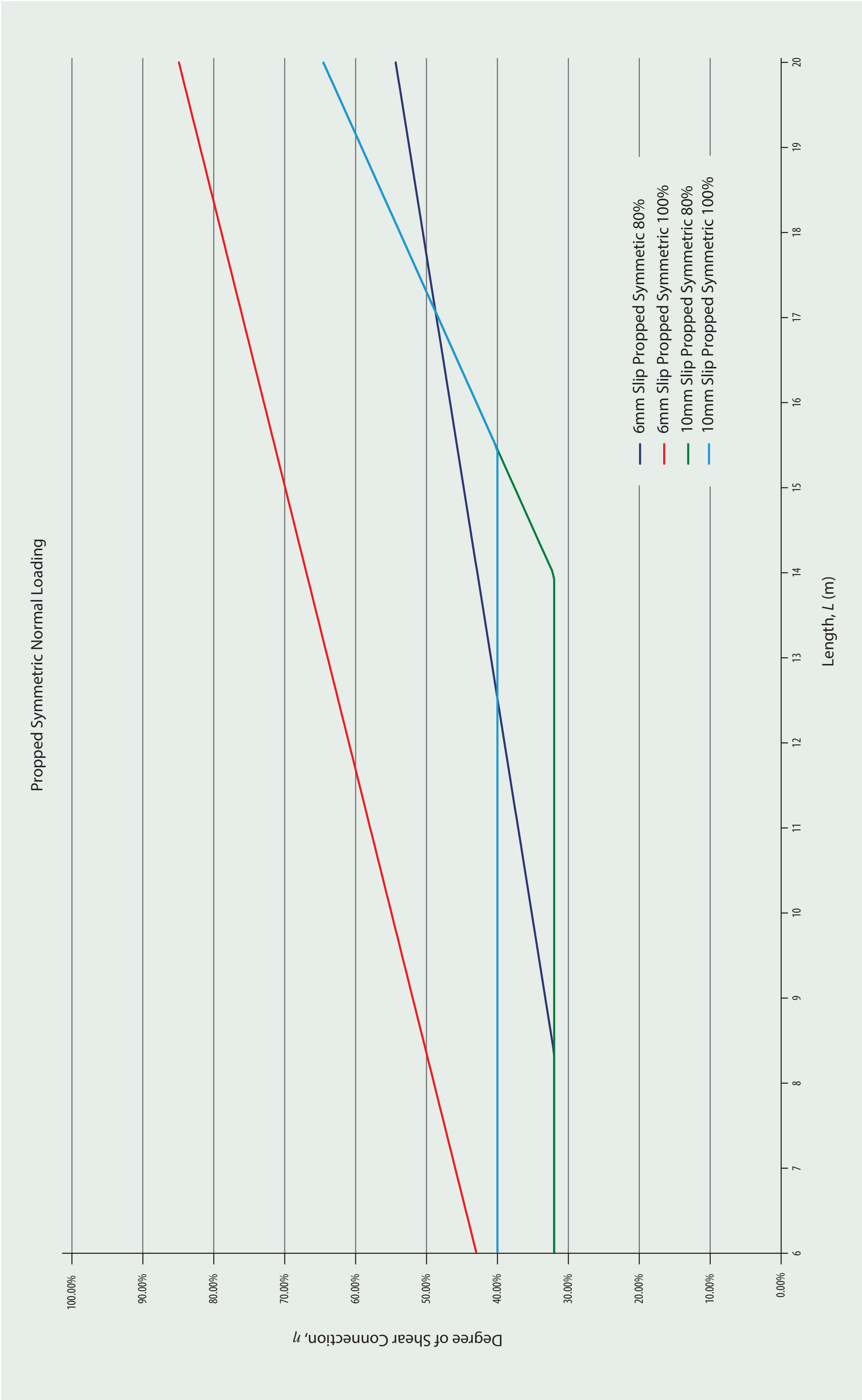

Figure A.1 Minimum degree of shear connection vs span for propped symmetric beams (normal loading). Utilisation in bending either 100% or 80%

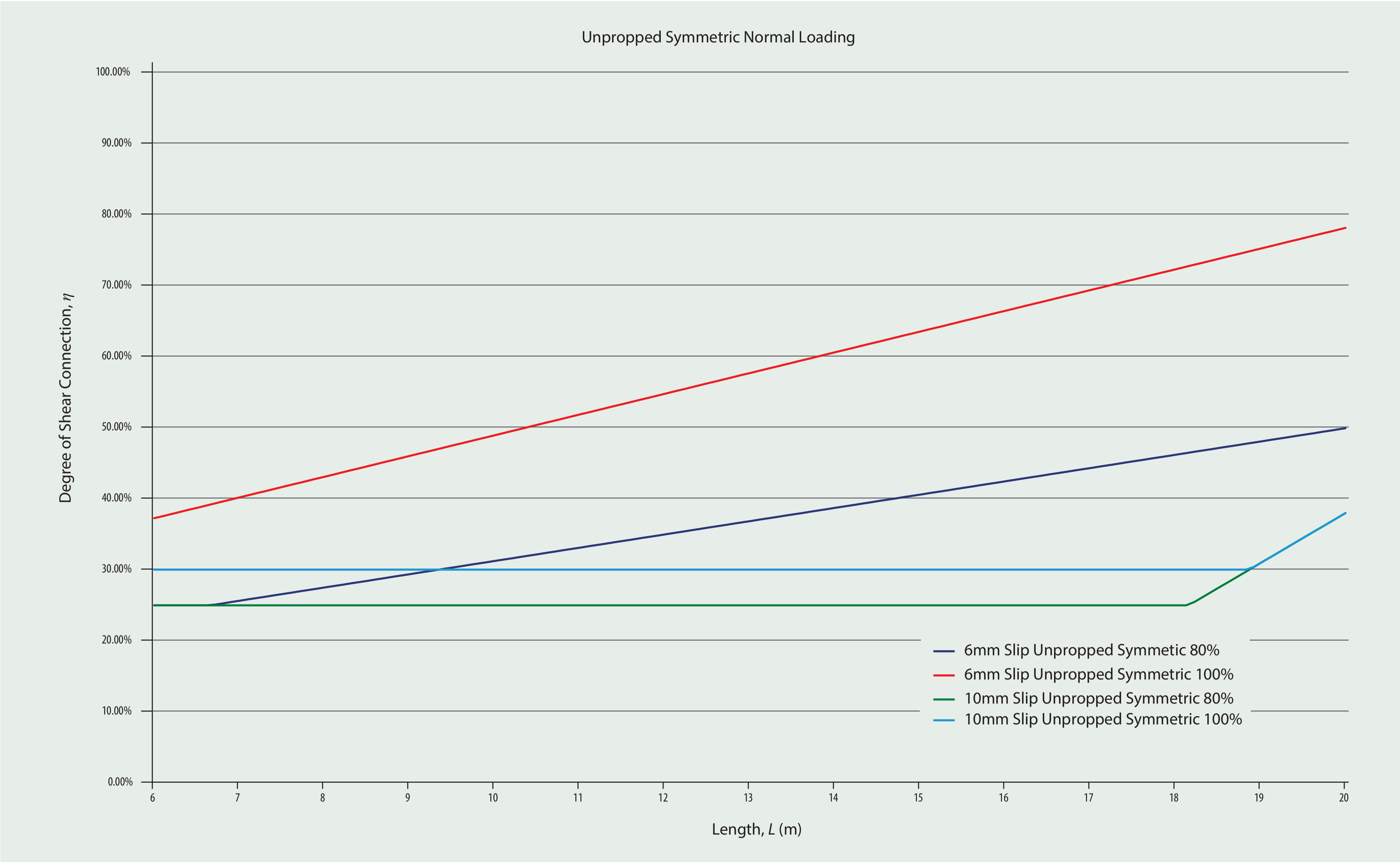

Figure A.2 Minimum degree of shear connection vs span for unpropped symmetric beams (normal loading). Utilisation in bending either 100% or 80%

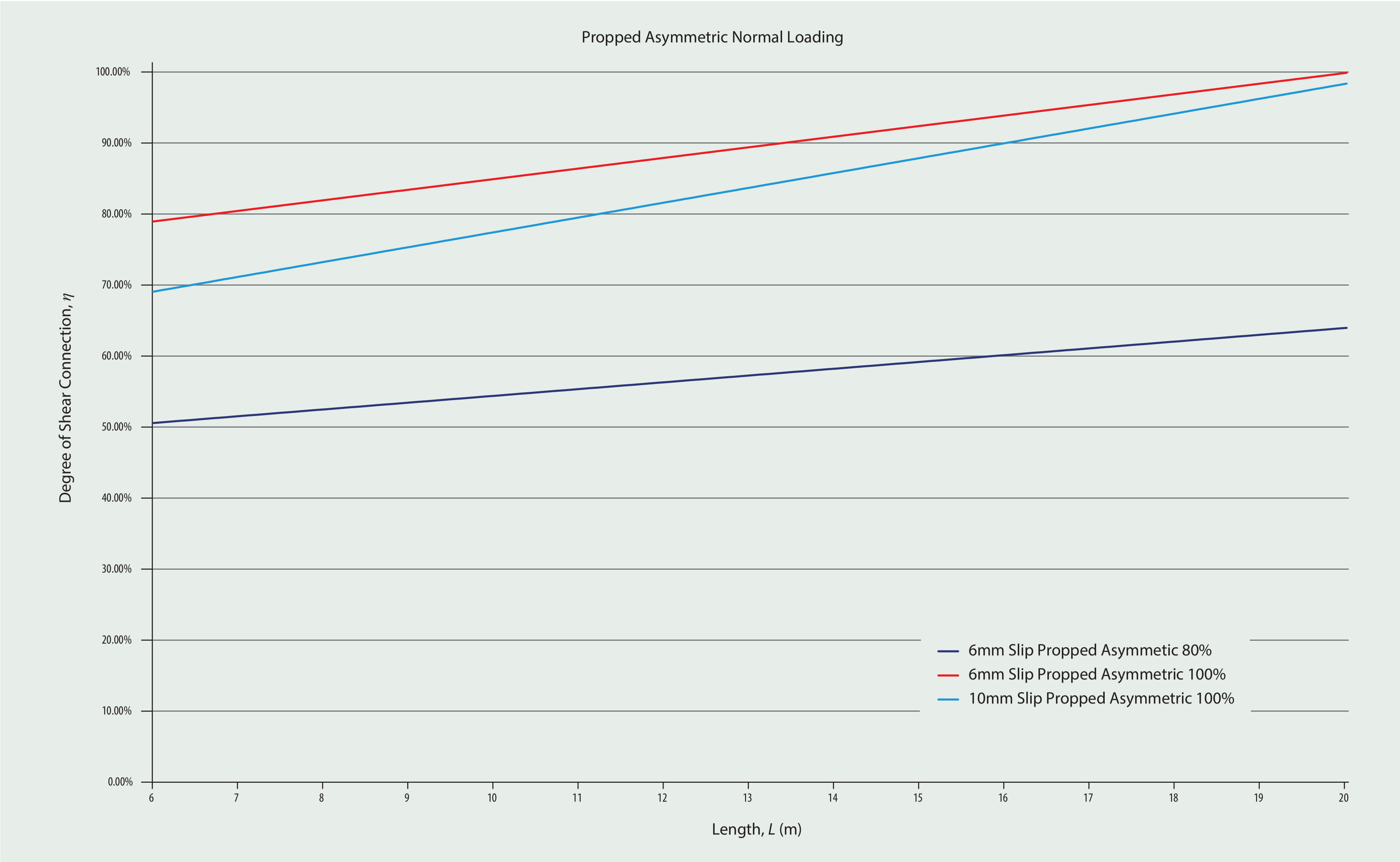

Figure A.3 Minimum degree of shear connection vs span for propped asymmetric (1:3) beams (normal loading). Utilisation in bending either 100% or 80%

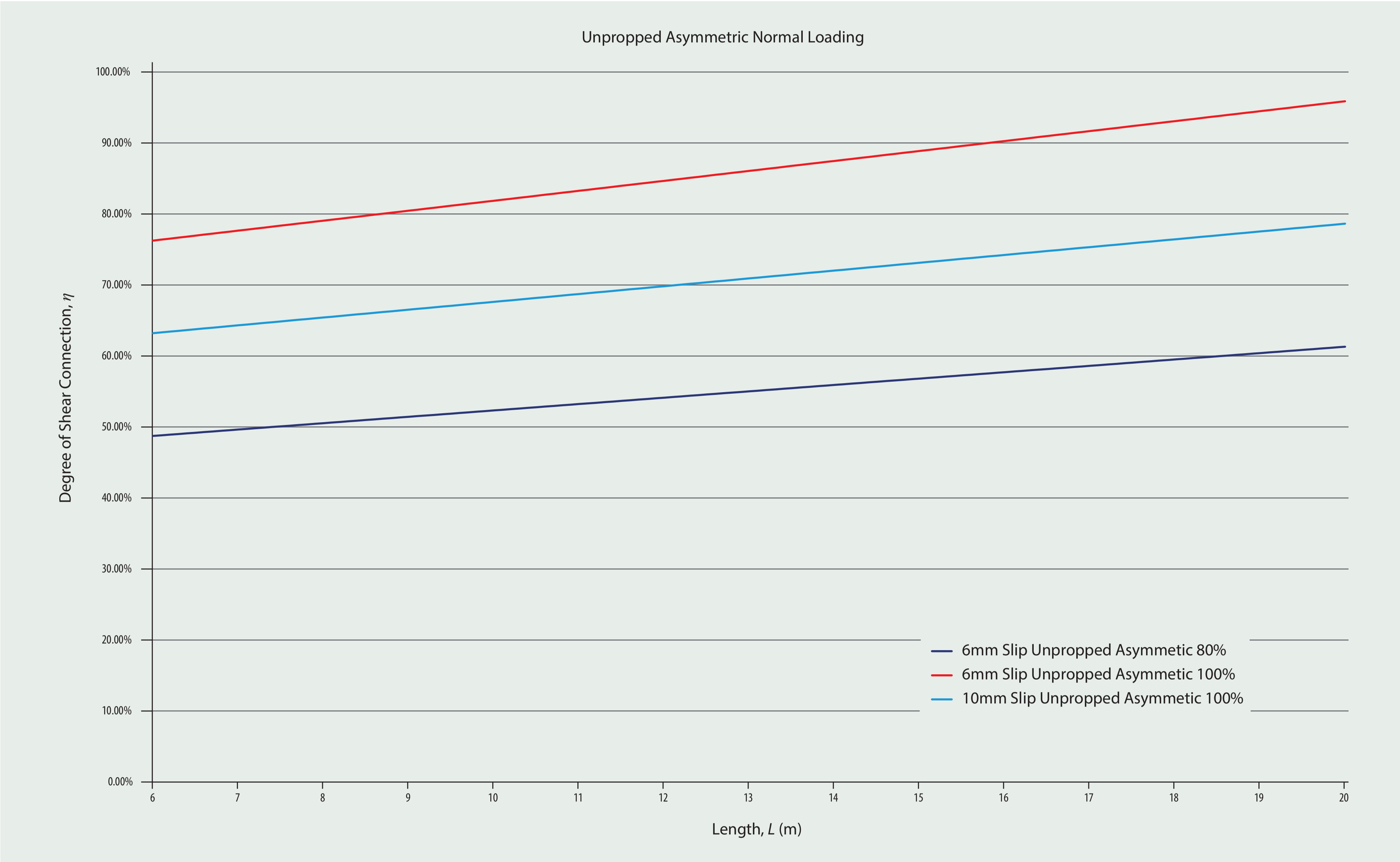

Figure A.4 Minimum degree of shear connection vs span for unpropped asymmetric (1:3) beams (normal loading). Utilisation in bending either 100% or 80%

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MINIMUM DEGREE OF SHEAR CONNECTION RULES FOR UK CONSTRUCTION TO EUROCODE 4

Developments in decking products and UK construction practice have, in some cases, resulted in shear stud resistances dropping below the values that were traditionally used in design. Lower stud resistances can result in composite beam designs (that were previously possible) becoming impossible, not because insufficient force can be transferred between steel and concrete to generate the necessary moment resistance, but because the maximum number of studs that can be accommodated on a beam is often less than the number of studs needed to satisfy rules for minimum degree of shear connection.

EN 1994-1-1 takes explicit account of three variables that affect minimum degree of shear connection – namely beam span, steel grade, and any asymmetry of the steel section. In this publication a number of other variables are also considered, including the type and orientation of decking, whether or not the steel beam is unpropped during construction, the presence of regular large web openings, and the utilisation in bending of the composite beam. In many cases, consideration of this broader range of variables results in less onerous requirements for the minimum degree, thereby enabling composite solutions that according to the code would be inadmissible.

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