# Minimum degree of shear connection in composite beams, according to Eurocode 4 and other guidance

In this article Graham Couchman of SCI and former chairman of CEN/TC250/SC4 (the Eurocode 4 committee), considers why we have rules for minimum degree of shear connection, and what implications the upcoming changes to Eurocode 4 have for current UK practice. The rules are very much related to the resistance of shear connectors (hereafter simply referred to as studs), which are also changing – or maybe not?

## Introduction

The shear connection between a steel beam and the slab it supports ensures that force can be transferred from the steel to the concrete. That is how a humble steel beam can become twice as strong and three times as stiff when connected structurally to the floor slab (the slab would have been present anyway, even if not structurally connected).

Each stud can transfer an indicative 50 kN to 80 kN, depending on the slab details (presence of deck etc), with its resistance readily determined using relevant guidance. Full shear connection is achieved when the number of studs is sufficient to transfer enough force to either fully utilise the concrete in compression, or the steel beam in tension. In buildings the former normally governs. If fewer studs are used the degree of shear connection is the sum of their resistances divided by this maximum force, and the beam resistance is determined using this lower level of force. However, studs have a limited range of slip (movement) over which they can transfer their assumed resistance, from about 1 mm to in excess of 6 mm, again depending on the details of the slab (Figure 1). They also have a finite stiffness, with an upper bound of about 100 kN per mm in a solid slab. This stiffness is not readily calculable, or indeed quantifiable in any other practical way by a designer. The purpose of a minimum degree of shear connection is to ensure that the collective stiffness of the studs on a given beam is enough to ensure that the greatest slip, which occurs at the beam ends (for a beam subject to UDL we have a symmetric situation with zero slip at mid-span), does not exceed the slip at which the stud resistance starts to drop off. Because the stiffness of the studs is not known by designers, the rules allow them to make this verification indirectly by considering the resistance of the studs, which is known (i.e. there is an assumed relationship between stud stiffness and strength).

Generation 2 EN 1994-1-1[1] (hereafter referred to as prEN 1994-1-1 to differentiate from the current EN 1994-1-1) makes this all clear in 8.6.3.3(1) of the 2023 draft by including wording that states that 'either the maximum calculated slip should not exceed the capacity....., or the degree of shear connection shall comply [with the appropriate minimum value]'. This is something SCI has been doing for years, using numerical modelling to predict the level of slip in beams that failed to comply with the minimum degree rules, often because somebody on site left out half the studs!

It is worth noting that for beams with transverse decking the minimum degree is often a critical check. It is not physically possible to place studs closer than in every trough (so at about 300 mm centres). Adding more than two per trough is not permissible according to Eurocode 4 and indeed will add very little in typical cases where a concrete failure surface passing over the studs governs (Figure 1). So, if two studs per trough will not transfer enough force to satisfy the limit the design will not just have a lower resistance, it simply cannot be made to satisfy the code.

## The evolution of codified limits and other guidance

BS 5950-3.1[2] included very simple rules for determining both stud resistance and minimum degree of shear connection. The rules only considered the influence of a limited number of variables. EN 1994-1-1[3] includes rules for minimum degree that is only assumed to vary as a function of the steel grade and span of the beam, plus any asymmetry of the steel cross-section, despite the fact that other variables may well be relevant, most obviously:

Figure 1: Deformation (slip) of a 19 mm diameter shear stud in transverse decking at failure (courtesy University of Luxembourg)

- the slip capacity of the studs (tests have shown that in excess of 10 mm can be achieved when studs are placed in decking with ribs running transversely with respect to the beam)
- whether the beam is propped or unpropped during construction.
- how much the beam is utilised under design loading (once the steel starts to plastify and loose stiffness the amount of slip, which is related to the curvature of the cross-section, increases disproportionately, so if a beam is not required to be fully utilised the number of studs needed to control slip drops significantly).

EN 1994-1-1 also imposes an absolute minimum of 40% connection, although the reasons why are not obvious or indeed logical (a limit on maximum spacing of studs ensures other effects, such as vertical separation of the slab and steel, will not occur, and effectively sets a minimum level of shear connection). The example below is taken from 6.6.1.2(1) to illustrate the current EN 1994-1-1 approach for symmetric beams:

- For an effective span $L_e$ not exceeding 25 m:

$$\eta \geq 1 - \left(\frac{355}{f_y}\right)(0.75 - 0.03L_e)$$

But $\eta \geq 0.4$

Where $f_y$ is the yield strength of the steel

- For spans in excess of 25 m:

$\eta \geq 1.0$

▸26

▸24 Given the often critical and 'show stopping' nature of the rules for minimum degree of connection, as well as their obvious simplicity in terms of variables considered, some time ago at SCI we undertook an extensive range of numerical modelling to see how many studs were needed to limit the slip for different beams. This led to the rules presented in SCI's publication P405[4]. For the first time all the relevant variables, including those noted above, were taken into account. The presentation is a series of equations of a form similar to those presented in EN 1994-1-1, but with different values to cover different design situations. This more comprehensive and explicit approach allowed massive reductions in the minimum degree limits, as can be seen from Figure 2 (these curves are for a symmetric section, and show the influence of slip capacity and whether the beam is 80% or 100% utilised in bending). The P405 rules are incorporated in many current examples of design software, highlighting just how important this work was in facilitating economic beam design.

The rules that are currently included in prEN 1994-1-1 (due for publication by BSI in the next year or so) move the previous code approach very much in the direction of P405, although the rules for minimum degree are simplified and more conservative. This is for two reasons as explained below.

Firstly, P405 uses many pages to give different equations to cover different situations (propped vs unpropped etc), whereas it would not be possible for a design code to treat a single subject in this way. As a result, the rules are more succinctly presented in prEN 1994-1-1, possibly making them appear more complicated but at the same time including some simplification (and simplification is almost always achieved at the price of conservatism).

Secondly, rules given in international standards like the Eurocodes must always satisfy everybody involved, and whilst one might tolerate some excess conservatism, acceptance of something considered to be unconservative will not happen. As experts from different nations have different traditions and views on the benefits of economy vs safety, it is inevitable that the results will appear excessively conservative for some.

The extracts below are taken from the 2023 draft to illustrate the prEN 1994-1-1 approach (clause numbers are unlikely to change in the version to be published by BSI). The previous Eurocode equations are reproduced in 8.6.3.3(3) for symmetric and asymmetric sections, with the exception that the previous variable $\eta$ is now defined as $\eta_0$.

In 8.6.3.3(2) various modification factors are applied to this 'basic' minimum degree $\eta_0$, that adjust the value to take into account the effects of

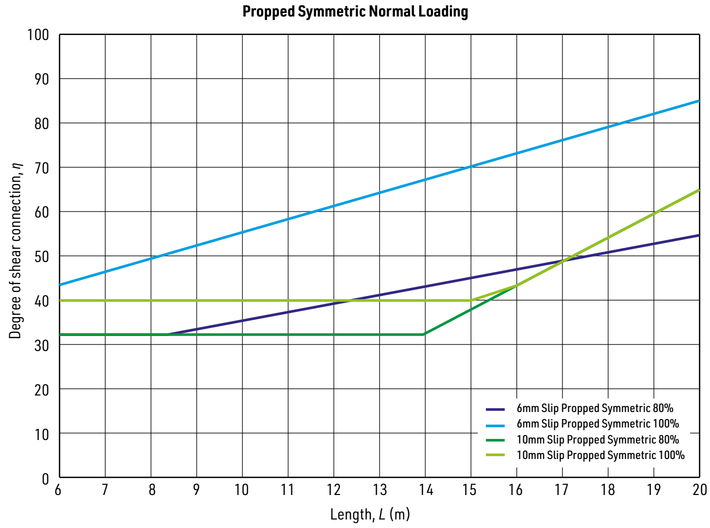


Figure 2: Minimum degree of shear connection vs span, according to the rules given in P405 (EN 1994-1-1 would only consider 6 mm slip and 100% utilisation, so is represented by the upper curve)

part utilisation ($\rho_m$) and method of construction ($k_{up}$). As can be seen from the definitions below, both these variables have absolute limits that, similar to the traditional 40% lower bound, appear illogical given they relate to physical phenomena that have no discontinuities (there is no physical change in behaviour at certain spans, as the curves in Figure 2 suggest – the kinks are due to these absolute limits). Whilst they will ensure stud spacings are reasonable, they have the effect of limiting the benefits to be had from considering these variables. Extracts from 8.6.3.3(2) are given below:

$$\eta \geq \eta_0 \rho_m^2 k_{up} \geq \eta_{min}$$

$$\rho_m = \frac{M_{Ed}}{(0.95 M_{Rd(\eta)})}$$

But $0.8 \leq \rho_m \leq 1.0$

Where:

$M_{Ed}$ is the applied moment

$M_{Rd(\eta)}$ is the moment resistance of the composite section with degree of shear connection $\eta$

When the steel section is propped during construction $k_{up} = 1.0$

When unpropped:

$$k_{up} = (1 - \rho_{up})$$

$$\rho_{up} = \frac{M_{a,Ed}}{M_{Pl,Rd}} \leq 0.15 \text{ when } \frac{M_{Ed}}{M_{Rd(\eta)}} \leq 0.95 \text{ otherwise } \rho_{up} = 0.0$$

$M_{a,Ed}$ is the moment applied to the steel section

$M_{Pl,Ed}$ is the moment resistance of the composite section assuming 100% shear connection

Absolute limits are also given in this clause:

$\eta_{min} = 0.4$ for studs in Ductility Category D2

$\eta_{min} = 0.3$ for studs in Ductility Category D3

The references to Ductility Category relate to studs with 6 mm slip capacity (D2) and 10 mm (D3). Studs in transverse trapezoidal decking will be D3, which relates this work to the P405 rules.

All very fascinating you may say, but what does it mean for design in the UK? SCI's recommendation would be that you carry on using the rules in P405, so no change! The P405 rules may reasonably be considered to be non-conflicting and complementary (NCCI), looking at the subject (or at least presenting outcomes) in more detail, which is why more accurate results can be obtained. The fact that Eurocode 4 has gone in a similar direction validates the work done by SCI a decade ago. The P405 guidance also addresses the prEN 1994-1-1 allowance to ignore the code rules for minimum degree if control of slip has been demonstrated in some other way (it's just that the designer is not doing this explicitly for themselves, SCI did it for them), which is part of a general Eurocode philosophy that the code rules should not prevent an expert designer doing something better.

### And what of stud shear resistance?

As noted above, although they are used to limit slip (which is a function of stud stiffness) the rules for verifying minimum degree of shear connection rely on stud resistance as an input. It is therefore worth noting that prEN 1994-1-1 provides different ways of determining stud resistance, partly related to scope of application. When decking is present the traditional approach of reducing the resistance in a solid slab using a k factor can still be used, but the scope of slabs for which this can be applied has now been revised and will exclude much typical UK practice (for example requiring an extra embedment length for the stud above the deck). An alternative approach is given in an informative annex, but as well as scope issues the method is complicated and more conservative than traditional UK practice.

It is worth noting that the reasons for current UK practice now being excluded and/or appearing (relatively) unconservative are because the new work is based on a mechanical model, which has been shown to be excessively conservative. This was the price paid for developing a model that deals with a multitude of variables but needed to be simple enough to understand. SCI alumnus and current Eurocode 4 Chairman Prof Stephen Hicks at the University of Warwick has given further comment on this approach, including noting that it is 'unreliable'[5]. It is highly likely that when a UK National Annex for prEN 1994-1-1 is produced it will state this annex should not be used. Thankfully testing can be used as an alternative, and SCI's position is to exploit this rule to justify carrying on using the values we have been using for the past decade (and potentially use better values coming from the Warwick work in due course).

### Conclusions

The second generation of Eurocodes will bring widespread change to the current rules. However, for composite beams the rules related to shear connection effectively endorse previous guidance produced by SCI, which provide more accurate results and it is recommended can still be used as NCCI, so there is no need to change current practice.

### References


1. prEN 1994-1-1 *Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings*. CEN, 2023 (not publicly available)
2. BS 5950-3.1:1990+A.1:2010 *Structural use of steelwork in building –Part 3: Design in composite construction –Section 3.1 Code of practice for design of simple and continuous composite beams*. BSI
3. BE EN 1994-1-1:2004 (incorporating corrigendum April 2009) *Eurocode 4: Design of composite steel and concrete structures –Part 1-1: General rules and rules for buildings*. BSI
4. Couchman G *Minimum degree of shear connection rules for UK construction to Eurocode 4*. P405. SCI, 2015
5. Degtyarev VV, Hicks SJ *Shear resistance of welded studs in deck slab ribs transverse to beams*, 2023, Engineering Structures, 294