The ever changing moods of composite slabs

There has been significant interest recently in the vertical shear resistance of composite slabs. This is partly due to different values offered by manufacturers of products that are physically very similar. It has also been of interest because of the work that has been undertaken to evolve EN 1994 into its Generation 2 version (SCI has produced a so-called Eurocode Nugget that presents the revised rules for vertical shear resistance of slabs). In this article Graham Couchman takes a broader look at the work that has been done, and raises some practical issues for designers to consider. Composite slabs are also discussed in a more general context, in particular how their behaviour apparently changes depending on loading and other conditions.

Introduction

Various researchers, including those responsible for drafting the Generation 2 EN 1994 rules, are in agreement that the current Eurocode approach of only taking into account the vertical shear resistance of the concrete is conservative for composite slabs. It is worth noting that (one of) the reason(s) why EN 1994[1] only considers concrete resistance is because it refers 'back' to EN 1992[2] in order to comply with the Eurocode philosophy that content cannot be presented in more than one Eurocode, or Eurocode Part. Some researchers suggest the conservatism of the current EN 1994 approach is by a factor of four in some cases! A number of existing, non-European, national codes already add contribution from the decking. In France , designers adopt non-conflicting complementary information (NCCI)[3] that uses a clear first principles and apparently sensible approach, proven through use in practice over nearly a decade, to combine the:

- Concrete resistance (as given in the current EN 1994)
  - This takes into account the flanges of the decking as tensile reinforcement
- Shear buckling resistance of the decking webs (taken from EN 1993-1-3[4])

For this approach to be valid it is important that the decking is sufficiently anchored to be able to provide the necessary level of force. When the decking is continuous it will be fully anchored at the face of the support, and when discontinuous it is traditionally assumed that thru-deck welded studs provide a 'deemed to satisfy' level of anchorage (alternatively sufficient contact area is needed between the deck and concrete). Alongside a significantly more complex alternative model for certain situations, the 2022 draft of prEN 1994-1-1[5] provides a simple alternative that is, unsurprisingly, very similar to the French approach:

$$V_{v,Rd} = V_{c,Rd} + k_v V_{b,e,Rd}$$

The difference is that a factor k_v has been introduced, potentially to down rate the contribution from the decking. Three notes in the prEN suggest what value should be used by a designer, and although not stated in the draft document they provide alternative ways of achieving the same end result. The easiest of the three options to understand, and the one advocated for use by SCI, is Note 2:

> The value of k_v is to be taken as 0.5 when $V_{b,e,Rd}$ (the effective resistance) is considered as the design value of vertical shear resistance of the profiled steel sheeting $V_{b,e,Rd}$, unless the National Annex gives a different value.

When we appreciate that the three notes are alternatives, then it can be understood that this reduction factor is intended to be a simple and presumably conservative way of allowing for the combined effect of shear and moment, which Note 3 explicitly states should be considered together. The origin of this 50% reduction, and why it may be deemed relevant, are explained below.

The behaviour of composite slabs

Before looking in more depth at vertical shear resistance, it is worth considering how composite slabs are normally assumed to behave. The majority of such slabs are governed by the construction stage, namely the ability of the decking to support the wet weight of concrete and other construction loads. Deflection of the decking can be critical, to stop ponding of the concrete increasing self-weight. For this reason, decks are often designed to be continuous over at least one support, because of the resulting structural benefits (Figure 1).

At the 'normal stage' the concrete has hardened, and the decking acts as external tensile reinforcement when the slab is subject to sagging. This is achieved through the embossments and overall form of the deck, which assure structural interaction between concrete and steel by resisting interface slip (like the studs on a composite beam). The cross sectional area of the decking is large, and the lever arm large, so significant sagging resistance can be generated. The hogging resistance, where fabric typically provides the tensile component, is relatively much lower and in the interests of simplicity of design is neglected. The slabs are assumed to be simply supported, even when the decking and concrete are continuous at one or both ends.

▸26

Figure 1: Decking continuous over several bays (courtesy SMD)

▸24

Figure 2: A continuous floor plate awaiting concrete pouring. Rows of studs indicate the beam lines, and even with continuous concrete the slabs will be designed to be simply supported at these points (at ambient temperature)

The final 'stage' we consider is when the slab is subject to fire from below. The decking is totally exposed and loses much of its strength. To compensate for this strength loss, bars may be used in the troughs. Being insulated by a certain amount of concrete they remain cooler and so retain more strength. However, in the UK we normally avoid the use of bars, and despite its loss of strength do make an allowance for the decking. We also take into account the hogging resistance over continuous supports, which is relatively much more important than at ambient temperature because in hogging the tensile component, the fabric, remains 'cold'. The UK method is justified by a multitude of tests over many decades, as well as having a plausible mechanical model as described previously.

So the decking apparently goes from being continuous, to simple span, and back to continuous when we are considering the behaviour of the composite slab subject to fire. The concrete goes from having no continuity over internal supports to having full continuity. But nothing physical changes!

A problem?

Even though a slab may be assumed to be simply supported, if it is continuous over internal supports it will attract hogging moment. As noted above this condition applies to the majority of composite slabs constructed in the UK. That moment will certainly be lower than one determined assuming elastic behaviour and uniform stiffness, because the slab in hogging will be less stiff and therefore shed moment into the span. Drawing an analogy with beams and semi-continuous design, the slab in hogging will be 'partial strength', i.e. have a moment resistance that is significantly lower than that of the slab in sagging. It might therefore be sensible, and certainly not unconservative, to assume that the section in hogging reaches its ultimate resistance, the concrete is cracked, the deck plastified, we get rotation, and moment is shed. The slab in hogging is then rotating as a plastic hinge.

The moment resistance in hogging is a combination of:

- Compression in the lower parts of concrete acting as a couple with tensile reinforcement in the upper part of the slab
- The moment resistance of the decking

So, in theory at least, one might imagine that the decking is working at full capacity in bending, even if it is assumed in design to be acting like a pin.

If we then turn to EN 1993-1-3[4] to see how a deck behaves in combined bending and shear (and axial force) we find this:

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right)\left(\frac{2V_{Ed}}{V_{w,Rd}} - 1\right)^2 \leq 1.0$$

Where:

N_{Ed} is the imposed axial force
N_{Rd} is the design resistance of the cross section for uniform tension or compression
$M_{y,Ed}$ is the imposed moment
$M_{y,Rd}$ is the design moment resistance of the cross-section
V_{Ed} is the imposed shear force
$V_{w,Rd}$ is the design shear resistance of the web
$M_{f,Rd}$ is the moment resistance of a cross section comprising the effective area of the flanges alone
$M_{pl,Rd}$ is the plastic moment resistance of the cross-section

Already apparent from this formula, the same clause nevertheless emphasises that 'no reduction due to shear force need not be done' (sic) provided that (the applied shear is no more than 50% of the shear resistance). It is understood this clause is the origin of the 0.5 suggested in Note 2 of the prEN clause stated previously.

However, we are not interested in how much moment resistance remains in the presence of shear, we are interested in how much shear resistance remains in the presence of (unwanted, unneeded but nevertheless present) moment. It is informative to try some numbers in Equation 6.27:

- Assume that the flanges contribute 80% of the bending resistance of the complete deck
- Assume that the applied moment is 90% of the moment resistance
- Then to satisfy:

$$0.9 + 0.2\left(\frac{2V_{Ed}}{V_{W,Rd}} - 1\right)^2 \leq 1.0$$

- Requires that $V_{Ed} \leq 0.85\ V_{W,Rd}$

So even when the moment is at 90% capacity, we still retain 85% of the shear resistance. This is reassuring, and suggests that the value of 0.5 for the factor k_v proposed by prEN 1994-1-1 may be conservative. What that value does do, however, is provide reassurance that no matter what the (unidentified) moment may be, the section will be able to support the combination of actions. Moreover, using 0.5 will still lead to a significant increase in shear resistance compared to current practice, and avoid it governing in all but extremely unusual cases. Searching for a better result, that might be more difficult to justify, therefore seems rather pointless.

Conclusions

UK practice for composite slab design is another of those methods where pragmatism and engineering judgement are adopted. We make assumptions that simplify the design process, and produce 'the right end result', even though they cannot be physically correct. But in order to exploit safely the benefits of the proposed new Eurocode rules for the shear resistance of composite slabs, it is necessary to revisit the traditional pragmatism. This article has shown that the traditional approach can be combined with the new rules, even though the latter may need to be conservatively applied through the use of a factor that reduces the shear resistance of the decking (as recommended by the new code itself). In many situations the extra resistance provided by the decking will not be needed, but it may be helpful when considering relatively narrow strips of slab supporting a concentrated load. ■

References

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