# Steel-concrete shear connection in composite structures – a key structural component for composite floor

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**Abstract**

A composite structural member is a member made of at least two parts with different materials, interconnected by a shear connection which allows to design the member as a single structural member. Composite members combining steel and concrete are the most common solutions met in practice and is the topic of the present paper. As reflected in the above definition, the shear connection plays a key role in the global behaviour of composite members, as the latter should limit the slip between the concrete part and the steel part but also to ensure the transfer of shear forces between the two materials to allow the composite member to act as a monolith structural element. The present paper summarises the general concept behind the design strategies for shear connection in steel-concrete composite beams, the code requirements and recent research outcomes allowing to extend the code requirements to new structural composite solutions such as shallow floors.

## 1 Introduction

A composite structure develops its bearing capacity through the activation of the collaboration of different materials exhibiting complementary mechanical properties. The nowadays most commonly used composite structure solutions combine steel and concrete. Indeed, although these materials are of different natures, they complement each other [1]:

- Concrete is resisting well to compression, while steel is better to sustain tensile forces;
- Steel members are sensitive to local and global instabilities such as plate buckling, flexural buckling, flexural-torsional buckling – the presence of concrete can limit or even avoid the occurrence of such instability phenomena;
- The concrete covering protects the steel from corrosion but also from fire thank to concrete's greater thermal inertia;
- Thanks to its ductility, steel provides composite construction with a very high deformation capacity.

Steel-concrete composite structures are covered by EN1994 normative documents, EN1994-1-1 [2] providing the general rules and rules for buildings. Within the latter document, a composite member is defined as "*a structural member with components of concrete and of structural or cold-formed steel, interconnected by shear connection so as to limit the longitudinal slip between concrete and steel and the separation of one component from the other*".

Through this definition, it is highlighted that composite member can only exist if an appropriate shear connection is ensured between the two materials, i.e. a shear connection that has sufficient strength and stiffness to enable the two materials to be designed as parts of a single structural member.

The present paper summarises the general concept behind the design strategies for shear connection in steel-concrete composite beams, focusing on the code requirements and recent research outcomes allowing to extend the code requirements to new structural composite solutions such as shallow floors. Based on this global overview, the present paper will conclude by highlighting the needs for further research development in the field.

## 2 Shear connection in steel-concrete composite beams

A steel-concrete composite beam exhibits three main parts:

- A steel profile;
- A concrete part, usually made of a collaborative concrete slab (with an effective width $b_{eff}$) connected to the upper part of the steel profile and;
- A connection, aiming at ensuring that both steel and concrete parts work together with a behaviour as close as possible to a monolith beam cross-section.

The steel profile can be made of hot-rolled double T-cross sections, built-up sections, cellular beams, trusses… The concrete part can be made of a reinforced concrete slab, a slab with precast components, composite slab combing reinforced concrete and steel sheets… Typical composite beam cross-sections are illustrated in Fig. 1. As can be seen on this figure, concrete can also be placed between the steel profile flanges; the main interest for such solutions is for fire scenarios, a significant part of the steel part being protected by the concrete in case of fire.

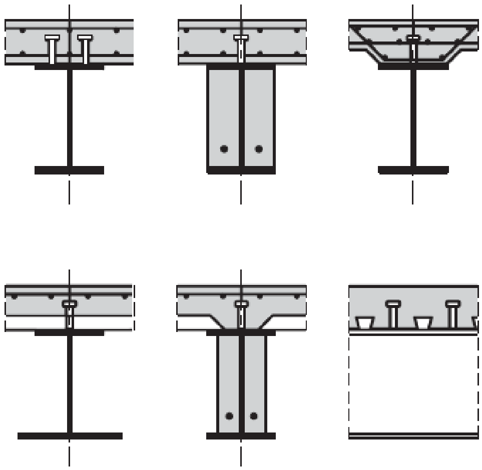


Fig. 1 Typical steel-concrete composite beam cross-section [2].

In a composite beam, the connection has to resist to the longitudinal shear forces developing at the interface between the steel and concrete parts. In steel-concrete composite beams, this connection is made of discrete connectors ensuring the transfer of shear forces and its spreading within the connected slab through the activation of a strut-and-tie behaviour. Within the present section, the behaviour of shear connectors will be first addressed and then, the design of a connection made of shear connectors according to EN1994-1-1 [2] will be discussed.

### 2.1 Shear connectors

A shear connector can be classified in two main categories according to their deformation capacity: ductile ones and non-ductile ones – see Fig. 2. This classification is strongly influencing the design approach to be adopted for the connection. If ductile connectors are used, a plastic design of the connection can be targeted, accounting for a plastic redistribution of forces between the shear connectors. If non-ductile connectors are used, an elastic design of the connection has to be adopted.

According to EN1994-1-1 [2], a connector can be assumed as ductile if $\delta_{uk}$ is bigger or equal to 6mm (see Fig. 2). Standard push test procedures are defined in Annex B of EN1994-1-1 to characterize the shear connector behaviour.

This definition of ductility for connectors is quite questionable as the provided criterion only imposes to reach a minimum absolute value of deformation for the connectors. However, in case of flexible connector, such a level of deformation could be reached while remaining in the elastic domain, i.e. without activating any plasticity, what does not correspond to the notion of ductility as defined in EN1998 which corresponds to the ability of a structure or parts of it to sustain large deformations beyond the yield point without breaking. The criterion for the classification of connectors as ductile ones has been revised and improved for the next generation of EN1994; this will be discussed in the next Section.

Different solutions of shear connectors exist on the market, but the most common one is the headed shear stud connector illustrated in Fig. 3. Headed shear studs are welded to the top plate of the steel profile using a specific stud welding gun, based on arc butt welding [3]. Headed shear studs are the only connector explicitly covered in EN1994-1-1 [2]. According to the latter, a headed shear stud can be assumed as ductile if:

(i) its nominal diameter $d$ is not less than 16mm and not greater than 25mm and;

(ii) its overall height $h_{sc}$ is not less than 4 times its diameter $d$.

These rules are really useful for practice as, through geometrical checks, it allows the design engineer to select the appropriate design approach (elastic or plastic) without requiring any characterization experimental tests.

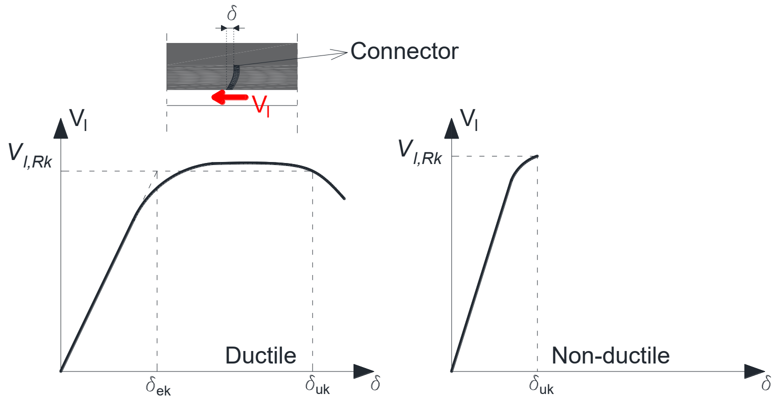



Fig. 2 Behaviour law of ductile and non-ductile shear connectors [2].

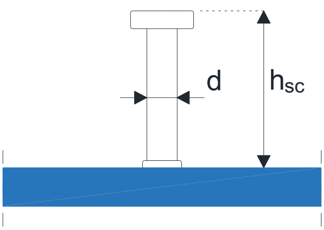



Fig. 3 Headed shear stud connector.

EN1994-1-1 [2] also provides rules to characterize the resistance of headed shear studs, expressed as $P_{Rd}$. When embedded in a reinforced concrete slab, the latter can be computed as the minimum of two expressions:

- $P_{Rd,1} = \frac{0{,}8 f_u \pi d^2/4}{\gamma_v}$
- $P_{Rd,2} = \frac{0{,}29 \alpha d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_v}$

$\rightarrow P_{Rd} = min\left(P_{Rd,1}; P_{Rd,2}\right)$

with $\gamma_v$, the partial safety factor (recommended value = 1,25); $f_u$, the specified ultimate tensile strength of the stud material (not greater than 500MPa); $f_{ck}$, the characteristic cylinder compressive strength of the concrete (not less than 1750kg/m³); $E_{cm}$, the secant modulus of elasticity of concrete and: $\alpha$, a parameter depending on the $h_{sc}/d$ ratio (see EN1994-1-1[2]).

The term $P_{Rd,1}$ corresponds to the resistance of the embedded headed stud in shear while the term $P_{Rd,2}$ corresponds to the resistance of the concrete crushing in the close vicinity the headed stud.

If headed studs are used to connect steel profiles with composite slabs, the so-computed resistance $P_{Rd}$ has to be reduced through the use of a reduction coefficient, depending on the geometry and the orientation of the composite sheet ribs with the beam axis (transverse or longitudinal), as specified in EN1994-1-1 [2].

## 2.2 Shear connection

If no relative displacement occurs at the interface between the steel profile and the concrete, the longitudinal shear force per unit length $v_{Ed}$ can be expressed as follows:

$$v_{Ed} = \frac{V_{Ed}.S}{I_c}$$

with $V_{Ed}$, the vertical shear force; $S$, the static moment of the profile according to the bending neutral axis and; $I_c$, the bending inertia of the homogenised composite cross-section.

As worked example, the distribution of the longitudinal shear force per unit length for a simply supported composite beam subjected to a uniformly distributed load q is illustrated in Fig. 4. For such a loading condition, the total longitudinal shear force to be supported by the connection from an external support to the mid-span of the beam corresponds to the area below the diagram showing the evolution of the longitudinal shear force per unit length $v_{Ed}$ along the beam:

$$V_{l,Ed} = \frac{v_{max}.L/2}{2} = v_{max}.\frac{L}{4} = M_{Ed}.\frac{S}{I_c}$$

$V_{l,Ed}$ also corresponds to the resulting normal force $N_c$ present in the slab at mid-span of the composite beam under $M_{Ed}$.

In order to obtain the number of connectors $n$ to be placed along half of the length of the beam to support the longitudinal shear force associated to $M_{Ed}$, $V_{l,Ed}$ has to be divided by the resistance of one connector. If headed shear studs are used to connect a steel profile to a reinforced concrete slab:

$$n = \frac{V_{l,Ed}}{P_{Rd}} = \frac{N_c}{P_{Rd}}$$

As illustrated in Fig. 4, in elastic domain, the shear connectors have to be distributed along the length of the beam in order to support equivalent shear forces (represented by equal areas in the longitudinal shear force per unit length diagram), which means that, for the considered worked example, this distribution will not be uniform, the distance between the connectors being smaller close to the external support than at mid-span.

This elastic procedure is valid, whatever the composite beam cross-section class is.

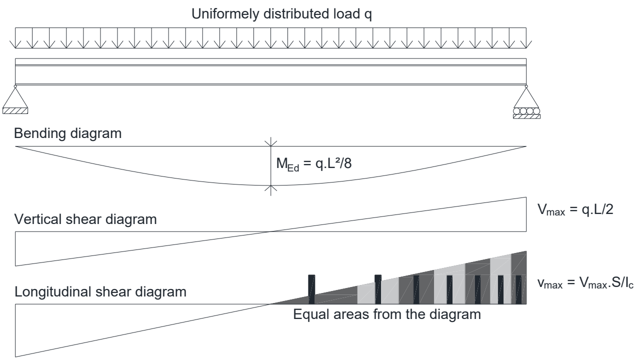



Fig. 4 Distribution of the longitudinal shear forces in a composite beam in elastic domain.

However, a uniform distribution of the connectors through a plastic verification of the connection can be targeted if the composite beam cross-section is at least of Class 2 and if ductile connectors are used. Indeed, in such a case, plastic redistributions between the connectors can be activated. For the worked example, if a uniform distribution of ductile connectors is used, it means that:

- at the beginning of the loading, i.e. in elastic domain, the connectors close to the external supports will be more loaded than the ones close to mid-span;
- if the applied load continues to increase, the connectors close to the external supports will reach their plastic resistance while the other ones will remain in the elastic domain – at this stage, as the connectors are ductile, the connectors which reached their plastic resistance will deform while maintaining the supported load as equal to their plastic resistance;
- then, if the applied load continues to increase, the other connectors will also reach their plastic resistance and start to plastically deform – if the connectors are sufficiently ductile, the process stops when all the connectors have reached their plastic resistance.

When possible, the use of ductile connectors is always recommended as it simplifies the execution of composite beams but also provides the composite beams with ductility and deformation capacity, key properties in terms of robustness of the designed solution.

If Class 1 or Class 2 beam cross-sections and ductile connectors are used, the design process of the shear connection can be simplified by referring to the notion of degree of connection $\eta$ defined as follows:

$$\eta = \frac{n}{n_f} = \frac{N_c}{N_{c,f}}$$

with $n_f$, the number of connectors required to reach the plastic bending resistance of the composite cross-section under consideration and; $N_{c,f}$, the normal force in the slab when the plastic bending resistance of the cross-section is reached. The link between $n_f$ and $N_{c,f}$ is as follows in case of headed shear studs:

$$n_f = \frac{N_{c,f}}{P_{Rd}}$$

The value of $N_{c,f}$ depends on the position of the plastic neutral axis when the composite cross-section is fully yielded. For the worked example:

- $N_{c,f} = N_{pl,a} = A_a . f_{yd}$ if the plastic neutral axis is in the slab (represented in Fig. 5)
- $N_{c,f} = h_c . b_{eff} . 0{,}85 . f_{cd}$ if the plastic neutral axis is in the steel profile

with $A_a$, the steel profile cross-section area; $f_{yd}$, the design elastic strength of the profile steel; $h_c$, the height of the collaborative concrete slab; $b_{eff}$, the effective width of the collaborative concrete slab and; $f_{cd}$, the design elastic compressive strength of the slab concrete.

Accordingly, the value of $N_{c,f}$ can be easily computed on the basis of the knowledge of the geometrical and mechanical properties of the composite beam under consideration. When the number of connectors placed at the interface between the steel profile and the concrete slab is equal or higher than $N_{c,f}$, the connection is identified as a "complete shear connection" while, when this number is smaller than $N_{c,f}$, the connection is identified as a "partial shear connection".

So, knowing the value of $n_f$ and of $M_{Ed}$, it is possible to predict the required degree of connection $\eta$ and so, the number of required connectors $n$ to support $M_{Ed}$ using the graph reported in Fig. 5 proposed in EN1994-1-1 [2] without computing the applied longitudinal shear forces at the interface between the steel profile and the concrete graph.

On this graph, it can be seen that the relation between the bending resistance of the composite beam cross-section and the degree of connection is reflected by a non-linear curve ABC, but the latter can be simplified considering the linear relationship AC. So, based on the knowledge of $M_{Ed}$, it is possible to predict the required degree of connection $\eta$ to support $M_{Ed}$ using this linear simplification as illustrated in Fig. 5:

$$\eta = \frac{M_{Ed} - M_{pl,a,Rd}}{M_{pl} - M_{pl,a,Rd}}$$

with $M_{pl,a,Rd}$, the plastic bending resistance of the steel profile cross-section alone and; $M_{pl}$, the plastic bending resistance of the composite beam cross-section.

As the connectors are ductile, the latter can be placed uniformly along the beam length.

According to EN1994-1-1 [2], the degree of connection should never be smaller than a certain limit $\eta_{min}$ for sake of ductility of the connection. Indeed, if the degree of connection is very small, the number of connectors $n$ to be placed along the beam will be limited and so, the required deformation capacity at the level of the connectors will be higher than the available one, i.e. 6mm as previously stated. For steel profiles with equal flanges, the required minimum degree of connection can be computed as follows [2]:

- $L_e \leq 25m$: $\eta_{lim} = 1 - \left(\frac{355}{f_{yk}}\right).(0{,}75 - 0{,}03.L_e)$ and $\eta_{lim} \geq 0{,}4$
- $L_e > 25m$: $\eta_{lim} = 1$

with $L_e$, the distance (in meters) between points with bending moments equal to 0 (equal to the length of the beam for the worked example) and; $f_{yk}$, the characteristic elastic strength of the profile steel.

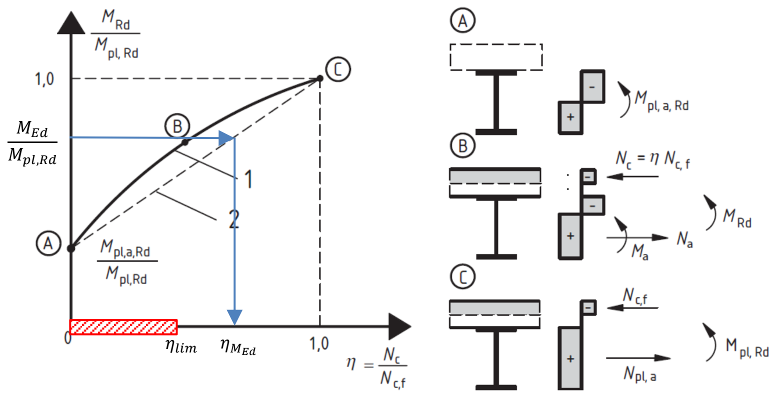



Fig. 5 Relation between the bending resistance $M_{Rd}$ of the composite beam cross-section and the degree of connection [2].

## 3 Next generation of Eurocode

In the previous section, the characterisation of connectors and the design of connections as presently recommended in EN1994-1-1 [2] have been described. However, as mentioned here above, the criterion provided for the classification of a connector as ductile is quite questionable, reason why this criterion has been revised and improved for the next generation of Eurocode 4, as reflected in prEN1994-1-1 document [4], on the basis of recent researches developed at European level [5].

In prEN1994-1-1 [4], three ductility categories are now defined for connectors: D1, D2 and D3 as reflected in Table 1. As can be observed, a criterion is now also included on the characteristic elastic slip $\delta_{ek}$, corresponding to the elastic deformation of the connector when the characteristic resistance of the latter is reached (see Fig. 2), in order to limit the contribution coming from the elastic deformation of the connectors to the value of $\delta_{uk}$ (see Fig. 2). Only connectors included in ductility category D2 and D3 are considered as ductile, with a sufficient deformation capacity to allow for a plastic design of the connection and a uniform distribution of connectors along the length for Class 1 or Class 2 composite beam cross-sections. Headed shear studs connecting steel profiles to composite slabs can be assumed to be at least of ductility category D2. For the classification of connectors and, in particular of headed studs, in ductility category D3, no specific rules are provided; the realisation of push tests in agreement with Annex B of prEN1994-1-1[4] is required, which can be seen as a brake on the use of such connectors.

Thanks to the improvement of the ductility classification criteria for connectors, it was also possible to consider reduced values for the required minimum degree of connection $\eta_{min}$ as defined in the previous Section. Accordingly, a new formula is proposed in prEN1994-1 [4] for the computation of a new $\eta_{min,new}$ as follows:

$$\eta_{min,new} = \eta_{min}\rho_m^2 k_{up} \geq \eta_{lim}$$

with:

- $\eta_{min}$, the degree of connection calculated according to the rules reported in Section 2.2;
- $\rho_m$, a reduction coefficient accounting for the loading ratio of the beam in terms of bending: $\rho_m = M_{Ed}/\left(0{,}95 M_{Rd}(\eta)\right) \in [0{,}8; 1{,}0]$ with $M_{Ed}$, the design bending moment and $M_{Rd}(\eta)$ the design moment resistance for the considered degree of connection $\eta$;
- $k_{up}$, a coefficient depending on the execution method (propped or unpropped);
- $\eta_{lim}$, an absolute value of minimum degree of connection taken as equal to 0,4 for ductility category D2 and 0,3 for ductility category D3.

The possibility of considering smaller degree of connection is of great interest for the practitioners as it allows to reduce the number of connectors to be placed along the beam and so to optimise the composite beam solution in terms of performance and costs.

Table 1 Ductility categories for shear connectors according to prEN1994-1-1 [4]

| Ductility category | Criterion on the characteristic elastic slip $\delta_{ek}$ | Criterion on the characteristic slip at ULS (Ultimate Limit State) $\delta_{uk}$ |
|---|---|---|
| D1 | - | - |
| D2 | $\delta_{ek} \leq \delta_{ek,lim}$* | 6mm $\leq \delta_{uk} < 10mm$ |
| D3 | | $\delta_{uk} \geq 10mm$ |

* Recommended value for $\delta_{ek,lim}$: 2,5mm

## 4 Specificities of shallow floor

The previous sections were dedicated to "classical" steel-concrete composite beam solutions, i.e. a steel profile with the upper plate connected to a concrete or composite slab.

However, for some years, new optimised integrated composite beam solutions, identified as shallow floors, have been developed and proposed on the market, reason why the next generation of Eurocode also includes design recommendations for such solutions.

A composite shallow floor is defined in prEN1994-1-1 [4] as a steel section partially encased in a concrete slab and acting compositely with the latter. The slab is supported on the bottom flange of the steel beam. The steel section may be hot rolled or welded from plates, with an open or a closed cross-section. Examples of typical shallow floor cross-sections are represented in Fig. 6. Shallow floor presents several advantages amongst which high bearing capacity for compact dimensions allowing a reduction of the global storey height in buildings and a good performance in case of fire.

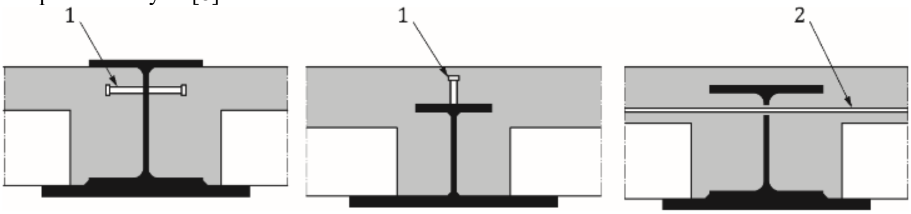
For most of the solutions represented in Fig. 6, it can be observed that the connection between the steel part and the concrete part is ensured through the use of headed shear stud connectors. The latter can be designed referring to the design rules described in the previous sections, including the possibility of considering partial shear connection.

For some other solutions, the connection between the steel part and the concrete part can be ensured through the use of transverse rebars, acting as connectors, embedded in the concrete and passing through holes implemented in the web(s) of the steel part [6]. The characterisation of such transverse rebar connectors is not covered by EN1994-1-1 [2] but is now covered in the next generation of Eurocodes, in particular in Annex I of prEN1994-1-1 [4]. According to the latter, the resistance of a transverse rebar acting as a connector can be predicted using the following formula:

$$P_{Rd,rebar} = \frac{\pi\phi^2}{4}\frac{f_{sk}}{\sqrt{3}}\frac{1}{\gamma_v}$$

with $\phi$, the diameter of the transverse rebar and; $f_{sk}$, the characteristic yield strength of the transverse rebar. For the application of this formula, it is required to satisfy some constructive impositions specified in prEN1994-1-1 [4].

Such a specific shear connecting solution is presented in Fig. 7 for a shallow floor known as the DELTABEAM® solution. The use of such connecting solution allows to avoid the use of welded connectors and so, to optimize the execution phase from a time and cost perspective. For this solution, the use of transverse rebars as connector allows (i) to activate the transverse rebars in shear but also (ii) to activate concrete dowels representing the mobilized concrete cylinders passing through the holes in the web of the Delta steel beam [6], [7]. Both contribution can be added up to predict the global resistance of the connection [6]. The efficiency of such connections in DELTABEAM® solution has been demonstrated experimentally in [8].




**Key**

1 Headed studs

2 Transverse bar

Fig. 6 Examples of typical shallow floor cross-sections [4].

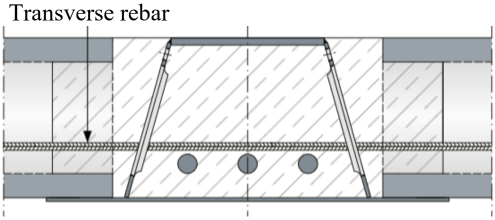



Fig. 7 Example of shear connection using transverse rebars – the DELTABEAM® solution [9].

## 5 Conclusions

Steel-concrete composite solutions present many advantages from a technical and economic point of view, reason why the use of such solutions in civil engineering is widely spreading, in particular as floor solutions in buildings. The connection between the steel part and the concrete part is identified as a key component without which composite solutions cannot exist. Within the present paper, a global overview of the normative recommendations for the design of such connection has been realized, highlighting the new possibilities offered by the next generation of Eurocodes. Particular attention has also been paid to the design of the connection of shallow floors, innovative and promising technical solution targeting high bearing capacities with limited dimensions.

Even if the next generation of Eurocodes will bring significant improvements, in particular for what concerns the classification of connectors in terms of ductility, the consideration of the highest ductility category still requires the use of push out tests to determine the deformation capacity of the connectors. In the future, practice-oriented criteria should be provided for the classification of typical connector solutions such as headed shear studs and transverse rebars to avoid the need for experimental tests.

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