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A NEW CONCEPT AND ALGORITHM TO TRANSFER BRITTLE AND ARBITRARY LOAD-SLIP CURVES INTO AN EFFECTIVE SHEAR RESISTANCE SUITABLE FOR EUROCODE 4

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This paper proposes a new concept and algorithm to transfer brittle and arbitrary load-slip curves into an effective shear resistance suitable for Eurocode 4. This algorithm is specifically for demountable shear connections of composite beams which do not exhibit ductile behaviour as required in EC4. The algorithm is validated with numerical finite element models which have been calibrated against experimental results. The algorithm extends the scope of the code to cover demountable shear connections: it allows the EC4 (EN 1994-1-1) rules remain applicable for the evaluation of the plastic bending resistance of composite beams with partial shear connection.

Keywords: composite beam, demountable shear connections, effective shear resistance

1. Introduction

1.1. The need for demountable and reusable structures

The building and construction sector accounted for about 39% of energy- and process-related CO_2 emissions in 2018 (GABC, 2019). About 11% out of those emissions were from the manufacture of building materials/products made of steel, cement and glass. Reuse of building materials and products, therefore, have a great potential to contribute to decarbonisation. In addition, the associated construction and demolition waste is identified as the largest waste stream in Europe which accounts for approximately 30% of all waste generated in the EU in volume and almost 50% of the world's waste. Considering that the building stock is anticipated to double by 2050 (GABC, 2019), sustainable building solutions targeting resource efficiency have to be promoted for carbon neutrality by 2050 and successful transition for Net Zero from a linear to a circular economy in line with the European Green Deal.

Steel-based composite structural systems are widely used owing to their structural benefits of enhanced load-bearing capacity and stiffness. However, in the current practice, a composite construction is not explicitly designed for deconstruction and re-use of building structural elements. For composite flooring systems, the composite action between the concrete floor slab and its supporting steel beam is achieved through permanently welded shear studs, which makes easy disassembling and re-use of structural elements impossible. With the introduction of novel and demountable shear connectors, both the concrete floor slab and the steel beam in a composite flooring structure can be potentially reclaimed and reused instead of the current practice of recycling, down-cycling or sent to landfill.

1.2. Demountable shear connectors: state of the art, load vs. slips behaviour and ductility requirements for shear connections in Eurocode 4

Driven by the need of sustainability in building constructions, various configurations of demountable shear connections utilizing bolts have been investigated and evaluated recently. Some most common demountable bolted shear connections found in literature are illustrated in Fig. 1. Although high-strength bolted shear connections were evaluated by Dallam (1968) and Marshall *et al.* (1971) nearly five decades ago. The relevant research on the fundamental behaviour of bolted connections and their demountability is very limited. For the evaluation of the performance of demountable shear connections, the main approaches to assess the shear resistance, slip capacity of the connectors, composite action and the behaviour of composite beams are standard push tests, beam tests and numerical simulations. The push tests have shown that

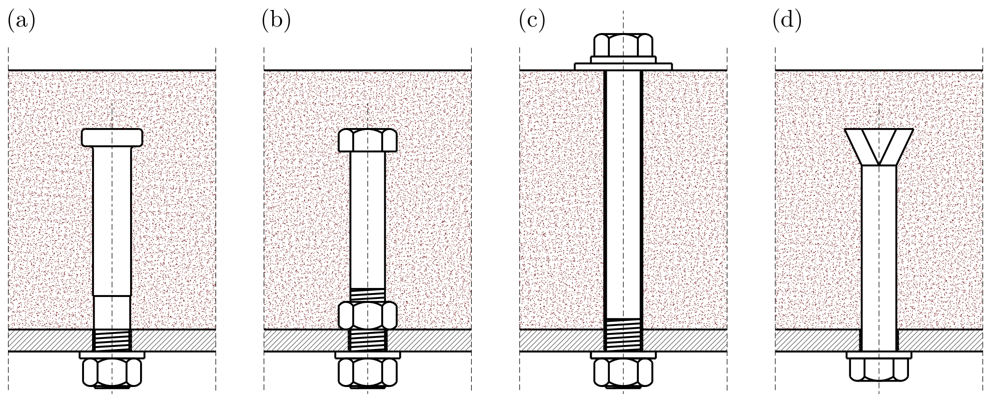


Fig. 1. Bolted shear connectors overview: (a) threaded studs, (b) encased bolts, (c) through bolts, (d) anchor bolts and blind bolts

bolted shear connectors, such as those machined from studs as shown in Fig. 1a, have higher slip capacity but relatively lower stiffness compared to welded studs (Lam and Dai, 2013), although an additional nut above the beam flange can improve stiffness of the bolted connectors. Nevertheless, good demountability of a flooring system using such studs and reusability of steel beam and floor slabs were demonstrated by a full-scale composite beam test by comparing the first use with the second one (Lam *et al.*, 2021). Other studies investigated the effect of geometry (e.g. size of the collar and threads) of such studs (Rehman *et al.*, 2016) and the use of ultra high performance concrete (Wang *et al.*, 2017). Moynihan and Alwood (2014) performed bending tests on composite beams using M20 bolts as illustrated in Fig. 1b and found that the tested 5 m and 10 m span beams performed similarly to comparable beams using welded shear studs. The beams were loaded up to service loads, then unloaded, disassembled and reassembled again for final failure tests to demonstrate good demountability and reusability of the system. Lee and Bradford (2013) and Ataei *et al.* (2016) conducted tests on high-strength friction grip bolts, Fig. 1c, and found that the full interaction between a steel flange and concrete slab can be achieved until the forces exceeds the friction resistance. Liu *et al.* (2017) conducted further research and recommended to use fewer bolts with larger diameter rather than smaller diameter bolts at smaller spacings for the same degree of shear connection in composite beams. Suwaed and Karavasilis (2017) used through-bolts to form a novel demountable shear connection, and the bolt clearance was grouted after installation of shear connectors. Nijgh *et al.* (2019) investigated resin-injected bolt-coupler shear connectors to reduce the effect of bolt clearance and to optimize the beneficial effect of composite action. Pathirana *et al.* (2016) and Uy *et al.* (2017) investigated the use of blind bolts as shear connectors. Such connectors have no problem with tolerances, however, might have a relatively low strength.

Certain types of bolted shear connections exhibit load-slip behaviour that is significantly different from that of headed studs. Especially, their stiffness could be lower owing to that the tolerances required in bolt holes affect the slips of shear connection. For example, the demountable shear connection shown in Fig. 2a has highly nonlinear and monotonic increasing behaviour; the load-slip curve can be best represented by a multilinear curve as illustrated in Fig. 2b, and the curve cannot be idealised as a standard rigid-ductile curve used for headed studs. Figure 2c illustrates the load-slip curve (CEN, 2018) which is implied in Eurocode 4 for welded studs. Push tests show that the shear resistance of a headed stud usually reaches its ultimate value PR at around 1-2 mm relative slip. Then, the slip continues until a minimum characteristic slip value of 6 mm for the studs to be classified as ductile connectors which is required in EN 1994-1-1 (CEN, 2004). The Eurocode 4, EN 1994-1-1, assumes a rigid-plastic load-slip curve for ductile headed studs in the calculation of plastic moment resistance of composite sections with partial or full shear connection. The level of horizontal plateau represents shear resistance of the connection. It is assumed that each shear connector of a composite beam undergoes a slip that is sufficiently large to activate the full shear capacity P_R of the connector. As a result, the design procedure of steel-concrete composite beams is relatively simple because determination of the occurring slip values for each shear connector is not needed. The shear force of each connector is always assumed as P_R when the plastic moment resistance is reached. Therefore, the sum of shear resistance of the connectors within the shear length (distance between the position of the maximum bending moment and supports in the case of a simply supported beam) can be expressed as the compression force N_c in the concrete deck, i.e., $N_c = nP_R \leqslant N_{c,f}$, where n is the number of shear connectors and $N_{c,f}$ is the maximum possible compression force in the concrete deck. Finally, the plastic moment capacity $M_{pl,\eta}$ can be calculated on the basis of equilibrium equations.

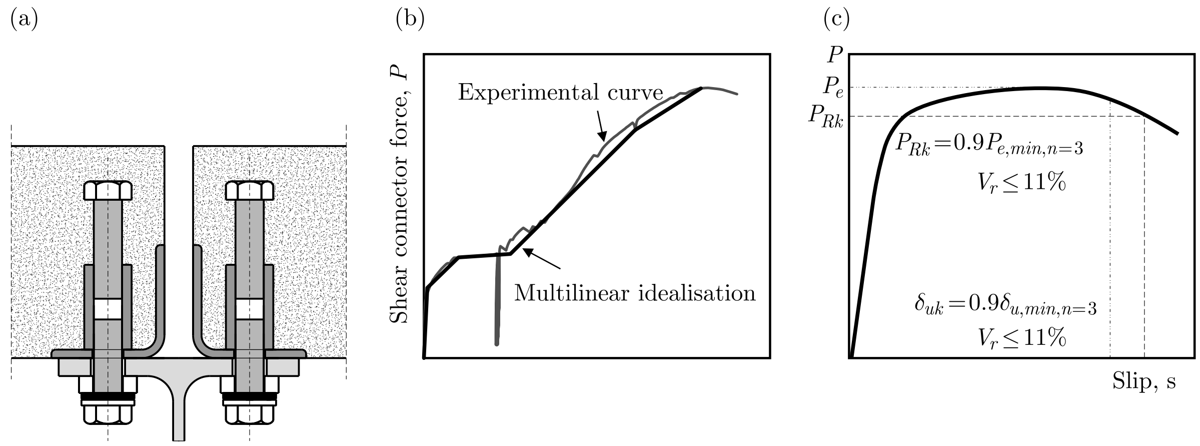


Fig. 2. An example of a demountable shear connector: (a) illustration image, (b) multilinear load-slip curve, and (c) load-slip curve implied in Eurocode 4 for welded studs (CEN, 2018)

The described procedure for the evaluation of plastic moment resistance of composite beams with partial shear connection cannot be used when those types of demountable shear connections, shown in Fig. 2, are applied. Instead of plastic resistance, the code requires a fully elastic design for such connections, and an equidistant spacing of connectors is not allowed. However, full-scale beam tests (Kozma, 2020) showed that composite beams with such demountable shear connections (with partial shear connection) are able to develop plasticity, and to reach their maximum moment beyond their elastic limit. The results indicate that the elastic design neglects a significant plastic reserve and, therefore, leads to an uneconomic design. This may hinder the practical application of composite beams that use novel and demountable shear connections with flexible or multilinear behaviour. Therefore, a new algorithm has been proposed and developed to obtain an effective shear resistance $P_{R,eff}$ which should fulfil the following requirements:

(i) to assess the compression force N_c developed in the concrete deck at the mid-span and the resulting bending moment resistance $M_{pl,\eta}$ accurately,
(ii) to ensure that the end slip of the composite beam does not exceed the limit value (for example 6 mm).

Within the frame of RFCS (Research Fund for Coal and Steel) research project REDUCE (grant No. 710040, 2016), various systems of demountable shear connections using high strength bolts have been developed and tested by standard push tests and beam tests. The bolted shear connectors presented in Fig. 3a had high resistances, and the shear load from push tests had monotonous increasing behaviour during the increase of slip displacements, as shown in Fig. 3b. Shear fracture of bolts, which was brittle failure, governed the failure of the tested demountable connections, however, the majority of connections had more than 6 mm slip capacity. The algorithm presented in the following Sections is proposed and evaluated based on the results from these connections.

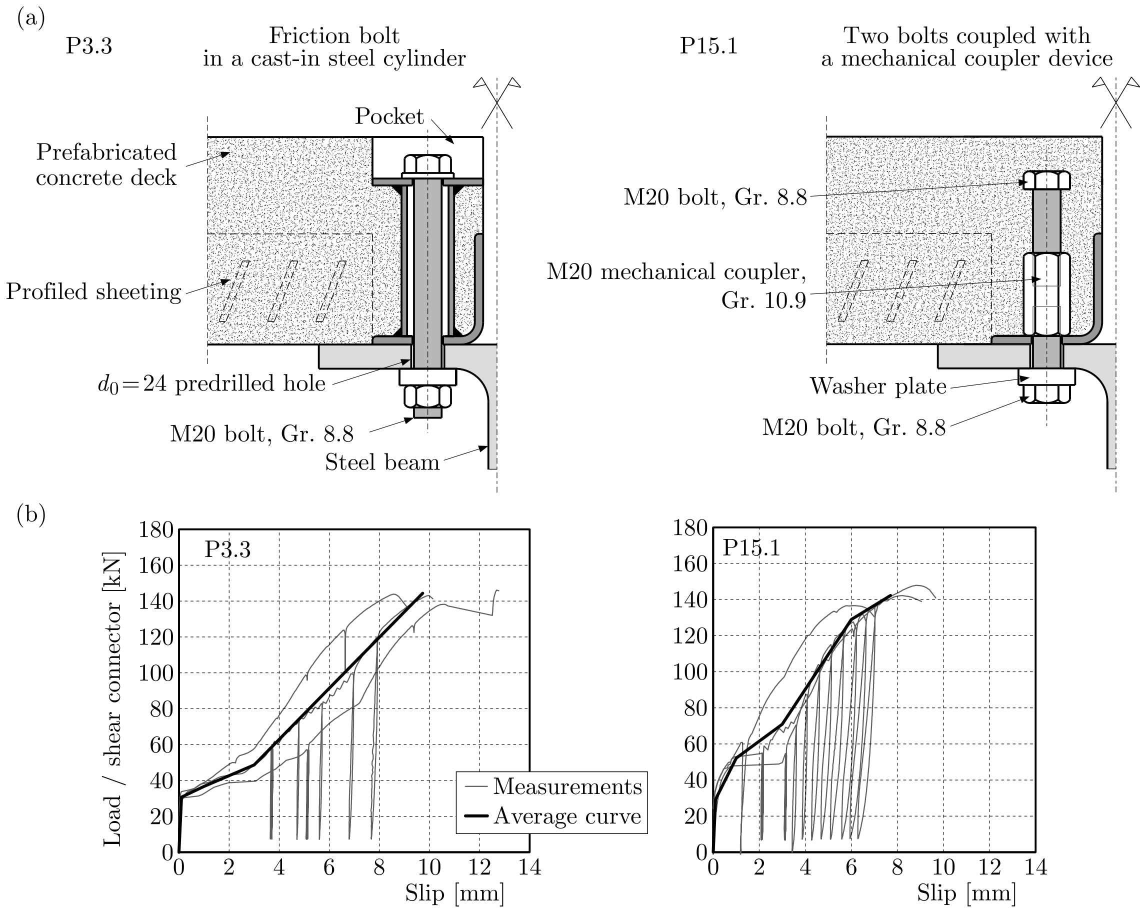


Fig. 3. Investigated demountable shear connectors: (a) section of System P3.3 and System P15.1, (b) load-slip curves from push tests

2. Analytical approach to the moment resistance based on the effective shear resistance $P_{R,eff}$

This Section presents an analytical calculation method for the evaluation of plastic moment resistance of composite beams considering load vs. slip relationships of demountable shear connections which has not been covered yet by the current version of Eurocode 4, EN 1994-1-1 (CEN, 2004).

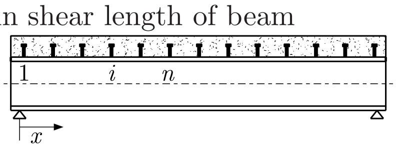
2.1. Basic concept and algorithm

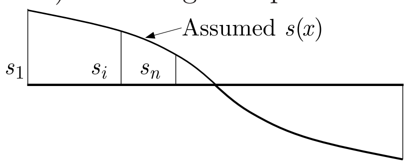
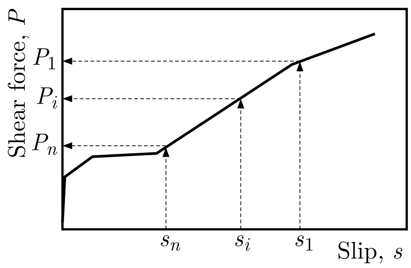
The compression force developed in the concrete deck of a composite beam N_c depends on the force that shear connectors can transfer. This compression force N_c is needed for the calculation of moment resistance of the composite beam. When the load vs. slip relationship is idealised as rigid-plastic, it is not necessary to know the occurring slip at each shear connector for the calculation of moment resistance. However, with load-slip curves of demountable shear connections as illustrated in Fig. 2b and Fig. 3a,b, the slips at each connector are needed to know the shear force that each connector transfers when the plastic moment resistance of a composite beam is reached. The determination of shear forces in the connectors along beam length depends on (i) the distance from the connectors within the shear span to the supports, and (ii) the respective occurring slip. In summary, the following parameters are required for the calculation of moment resistance:

i. end slip value s_1, and
ii. slip distribution along beam length $s(x)$.

With these two parameters and the distance of connectors, the occurring slip s_i at each shear connector can be defined. Knowing the load-slip relationship of the shear connections, the shear forces P_i at each shear connector can be then determined. Considering the flexibility of the shear connection, a parameter k_{flex} is defined and an effective shear connection resistance $P_{R,eff}$ is introduced based on the sum of shear forces P_i. On that basis, the compression force N_c in the concrete deck is equal to the sum of shear forces of connectors $nP_{R,eff}$. The plastic stress distribution can be then determined from N_c. The plastic moment resistance $M_{pl,\eta}$ can be then calculated from the equilibrium equations for the partial shear connection. A general and a simplified algorithm describing procedures for the compression force N_c considering the effective shear resistance of nonlinear demountable shear connections are proposed and outlined in Table 1.

Table 1. The general and simplified algorithm considering effective shear resistance of nonlinear demountable shear connection

Step	General algorithm	Simplified algorithm
1	Select (i) shear connectors distribution, (ii) number of shear connections n placed within shear length of beam 	Assume (i) shear connectors distribution as uniformly distributed, (ii) number of reference points $n = 6$

2	Assume (iii) slip distribution function $s(x)$, (iv) end slip s_1, and determine slip values s_i $(i > 1)$ according to slip distribution  	Assume (iii) cosinus slip distribution function, (iv) end slip of $s_1 = 6$ mm, and determine slip values s_2 to s_6 according to cosine function
3	Determine shear forces P_i on basis of slip values s_i and chosen load-slip curve: $s_i \to P_i$  	<u>Define design load-slip curve</u> (in accordance with EN 1994-1-1, Annex B2, from at least 3 norminally identic tests) (i) check that coefficient of variation CV (deviation from mean value) of ultimate shear force P_{ult} out of tests is not greater than 10%, (ii) determine shear forces P_i for each test curve on basis of slip values s_i, where $s_1 = 6$ mm and P_1 is force at 6 mm slip: $s_i \to P_i$, (iii) find for each slip s_i the minimum occurring shear force $\min P_i$, (iv) analyse for each step i, from 1 to 6 $P_{i,k} = 0.9 \cdot \min P_i$ $P_{i,d} = P_{i,k}/(\text{partial factor of } 1.25)$ (v) create design load-slip curve $P_{i,d}$ vs. s_i
4	Determine average shear force P_{av} for given shear connector in specific situation $P_{av} = \frac{1}{n}\sum_{i=1}^{n} P_i$	Determine average design shear force $P_{av,d}$ for given shear connector in specific situation $P_{av,d} = \frac{1}{6}\sum_{i=1}^{6} P_{i,d}$
5	Determine k_{flex} specific to given shear connection and specific situation $k_{flex} = \frac{P_{av}}{P_1}$	Determine $k_{flex,d}$ specific to given shear connection and specific situation $k_{flex,d} = \frac{P_{av,d}}{P_{1,d}}$
6	Determine effective shear resistance $P_{R,eff}$ $P_{R,eff} = k_{flex} P_1$ where P_1 is taken from Step 3	Determine effective design shear resistance $P_{Rd,eff}$ $P_{Rd,eff} = k_{flex,d} P_{1,d}$ where $P_{1,d}$ is taken from Step 3
7	Value $P_{Rd,eff}$ can replace value P_{Rd} of Eurocode 4, EN 1994-1-1 (CEN, 2004) for evaluation of compression force in concrete slab	

As given in the general algorithm, the effective shear resistance $P_{R,\mathit{eff}}$ is defined and determined by introducing the parameter k_{flex} considering the flexibility of shear connections

$$P_{R,\mathit{eff}} = k_{\mathit{flex}} P_1 \tag{2.1}$$

where P_1 is the shear force of the connector located at the end of the beam depending on the limiting slip value of s_1; and the parameter k_{flex} is calculated from the following equations

$$P_{av} = \frac{1}{n}\sum_{i=1}^{n} P_i \qquad k_{\mathit{flex}} = \frac{P_{av}}{P_1} \tag{2.2}$$

where the shear force P_{av} is the average from shear forces of connectors; and the factor k_{flex} depends on the following:

(i) the distribution and the number of shear connector rows within the shear span of the beam,
(ii) the assumed slip distribution function of shear connectors along beam length,
(iii) the assumed end slip value s_1 (for determination of P_1),
(iv) the load vs. slip relationship of shear connectors (for determination of shear forces of each connector P_i).

When the effective shear resistance $P_{R,\mathit{eff}}$ is determined, the compression force in the concrete slab of the composite beam can be then expressed for calculation of the plastic moment resistance. The necessary assumptions for the simplified algorithm are summarised in Section 2.2.

2.2. Simplified algorithm: assumptions

2.2.1. Simplified assumptions for the end slip value and slip distribution function

For simplification, the end slip value is assumed to be 6 mm, which is the same value required for the characteristic slip capacity of ductile connectors specified in Clause 6.6.1.1(5) of EN 1994-1-1 (CEN, 2004).

The slips between the concrete slab and steel beam in the composite beam originates from the strain difference at the interface of the slab and beam. For a simply supported composite beam in an elastic state, using shear connectors which have a linear load vs. slip relationship, the slip distribution along beam length is usually assumed to follow the shape of the integral of the moment diagram (Leskelä, 2017). Hanswille and Schäfer (2007) and Lawson *et al.* (2017) assumed a cosine shaped slip distribution as a simplification, which corresponded to a sinusoidal moment diagram. For a uniformly loaded beam, it is a reasonable approximation that has a second order moment diagram. Beyond the elastic state, plastic strains start to develop at the mid-span where the maximum bending moment locates. Outside the plastic zone, the rest remians in the elastic state. The slip which occurred from plastic deformation is constant in the elastic part of the beam. And the total slip can be simply determined as the sum of the slips from elastic and plastic deformations. The determination of slips due to plastic deformations remains a complex task and is hardly obtainable without the use of an advanced finite element modelling method.

Kozma (2020) conducted bending tests on composite beams with demountable shear connectors and measured the slips at each connector at different load levels, e.g. 50 kN, 100 kN, 200 kN and 500 kN, respectively. The results illustrated in Fig. 4 show that the slip distribution along beam length can be approximated with a cosine function, similarly to the elastic assumptions

$$s(x) = s_1 \cos\frac{\pi x}{L} \tag{2.3}$$

where s_1 is the end slip, x is the distance from the support, and L is the beam span.

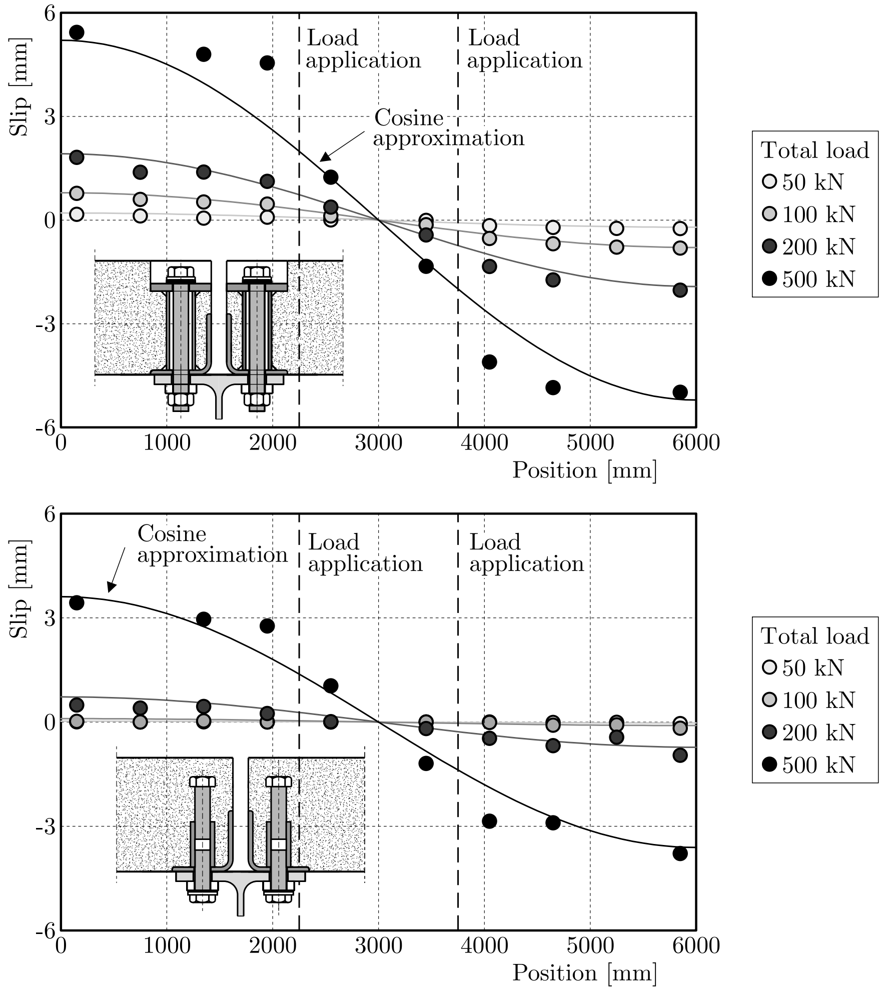


Fig. 4. Slip distribution measured from beam tests (6 m span beam)

2.2.2. Evaluation of k_{flex} and $P_{R,eff}$

Assuming that (i) end slip is 6 mm, meaning that the slip capacity beyond 6 mm is neglected, which is a conservative assumption, (ii) the slip distribution follows the cosine function, and (iii) for the uniformly distributed shear connector, the parameter k_{flex} depends then on the following two parameters: (iv) the number of shear connector rows n within shear span of the beam, and (v) the type of shear connections used.

The value of k_{flex} was calculated using Eq. (2.2) for different demountable shear connectors (e.g. Type P3.3 and Type P15.1) with multilinear behaviour tested by Kozma *et al.* (2019) and Kozma (2020). In Fig. 5, the results of shear connection systems P3.3 and P15.1 are illustrated. It is shown that as the number of shear connector rows n increases, the reduction factor k_{flex} decreases. However, as k_{flex} is determined from the average shear connector force, its value is not very sensitive to a change in n. Between 4 rows and 30 rows of shear connectors, k_{flex} varies between 0.71 and 0.79 for the analysed shear connection systems. For simplification, it is proposed to use $n = 6$ rows of shear connectors ($k_{flex} \approx 0.76$ for the investigated shear connection systems), which means that the average shear force of connectors P_{av} is determined from 6 values (6 reference points) instead of calculating it exactly from the actual number of n. This will cause a small error ($< 1\%$) when calculating the plastic moment resistance $M_{pl,\eta}$. This proposal has a considerable advantange that the parameter k_{flex} becomes then a specfic value which corresponds to the type of shear connection (shear resistance and load vs. slip relationships). Using Eq. (2.1), the effective shear resistance $P_{R,eff}$ is simply calculated by multiplying the parameter k_{flex} with the resistance P_1 at a slip value of 6 mm. The design value of the effective shear resistance $P_{Rd,eff}$ may be calculated from characteristic values considering a partial factor of 1.25

$$P_{Rd,eff} = k_{flex,d}P_{1,d} \tag{2.4}$$

The advantage of this procedure is that it is sufficient to calculate the effective shear resistance only once for a certain type of shear connection. Once the shear connector resistance is known, the calculation procedure of Eurocode 4 (CEN, 2004) is applicable. The design value $P_{Rd,eff}$ can be used to proceed with Eurocode 4 (CEN, 2004) for the moment resistance $M_{pl,Rd}$ of composite beams with nonlinear shear connectors.

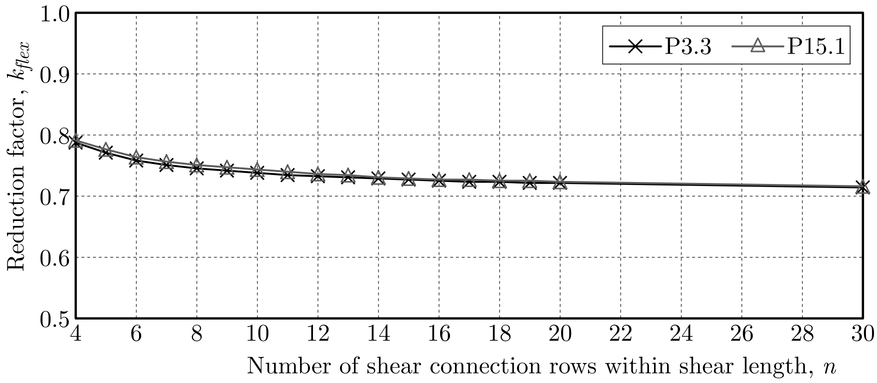


Fig. 5. The relationship of the reduction factor k_{flex} and the number of shear connector rows n

2.3. Scope and limitations

The presented algorithm is limited by the following conditions and assumptions:

i. the composite beam is a typical downstand beam with a concrete deck placed on the top of the steel beam,
ii. the beam is simply supported and is subjected to a positive bending moment (by e.g. uniformly distributed loading),
iii. the curvature of the beam is sufficient for the development of plastic stress distribution in the beam section,
iv. the beam section is symmetric to its vertical axis,
v. the steel profile is in Class 1 or Class 2 specified in EN 1993-1-1 (CEN, 2005),
vi. the distribution of the shear connection along beam length is either equidistant or according to the shear force in the beam,
vii. the load vs. slip relationship of the shear connection can be represented by a monotonic increasing curve.

3. Evaluation of the simplified analytical algorithm against Finite Element Model results

To evaluate reliability of the developed algorithms, finite element analyses were performed by using the commercial software Abaqus® (Simulia, 2017). A total of 78 numerical simulations were performed considering various parameters such as beam length (6 m, 8.1 m, 16.2 m), steel profiles (IPE 270, IPE 360, IPE 450, IPE 600), concrete grade (C20/25, C45/55), shear connector spacing (300 mm; 600 mm) and type of shear connection. Table 2 summarises the range of the investigated parameters.

Table 2. Parameters considered in FEA

Parameter	Investigated range
Loading	uniformly distributed load (UDL)
Beam length	6 m; 8.1 m; 16.2 m
Steel profiles	IPE 270; IPE 360; IPE 450; IPE 600
Steel grade	S355
Concrete grade	C20/25; C45/55
Material properties	measured values; design values
Spacing of shear connectors	300 mm; 600 mm
Type of shear connection	welded stud (P0) friction bolt in a cast-in steel cylinder (P3.3); two bolts coupled with a mechanical coupler device (P15.1)

3.1. Validation of finite element models and a proof of the assumed slip distribution function

First, full scale beam bending tests with the test setup illustrated in Fig. 6a were reproduced to validate finite element models. The developed models used shell elements and considered material nonlinearities as well as nonlinear load-slip behaviour of shear connections. Validation of the models was performed by comparing numerical results against experimental results from the beam tests. The comparisons of load vs. end slips and slip distribution along beam length of one composite beam (using P15.1 demountable shear connections) are given in Figs. 6b and 6c, respectively. It is found that the numerical results can represent the results from beam tests with a sufficient accuracy. More details on the beam tests and finite element analyses can be found in the doctoral thesis of Kozma (2020).

Figures 7a and 7b provide the numerical results of slip distributions from beams of 6 m and 16.2 m spans in comparison with a cosine function, respectively. With the varied parameters given in Table 2, it can be concluded that the assumed cosine slip function in the simplified algorithm remains a reasonable approximation in the plastic state.

3.2. Comparisons and statistical evaluation of the simplified algorithm for plastic moment resistance

By applying the algorithm presented in Section 2 and assumptions for the simplified algorithm, the results of plastic moment resistance of the analysed 78 composite beams were obtained. Analytically ($M_{pl,\eta}$) and numerically ($M_{u,FEM}$) obtained resistance data for all the considered beam configurations are summarized in Fig. 8. The resistance model uncertainty parameters were also determined for each case

$$\theta_i = \frac{M_{u,FEM,i}}{M_{pl,\eta,i}} \tag{3.1}$$

The mean value of model uncertainties μ_θ, the standard deviation σ_θ and the coefficient of variation V_θ were determined as 1.049, 0.061 and 0.058, respectively. The corresponding coefficient of variation is relatively low (< 6%). These indicate that the developed simplified algorithm is in good agreement with the numerical simulations.

4. Conclusions and outlook

The investigated bolted shear connections have lower stiffness and nonlinear load-slip behaviour when compared to those of typical welded shear studs. The bolted connections have a slip ca-

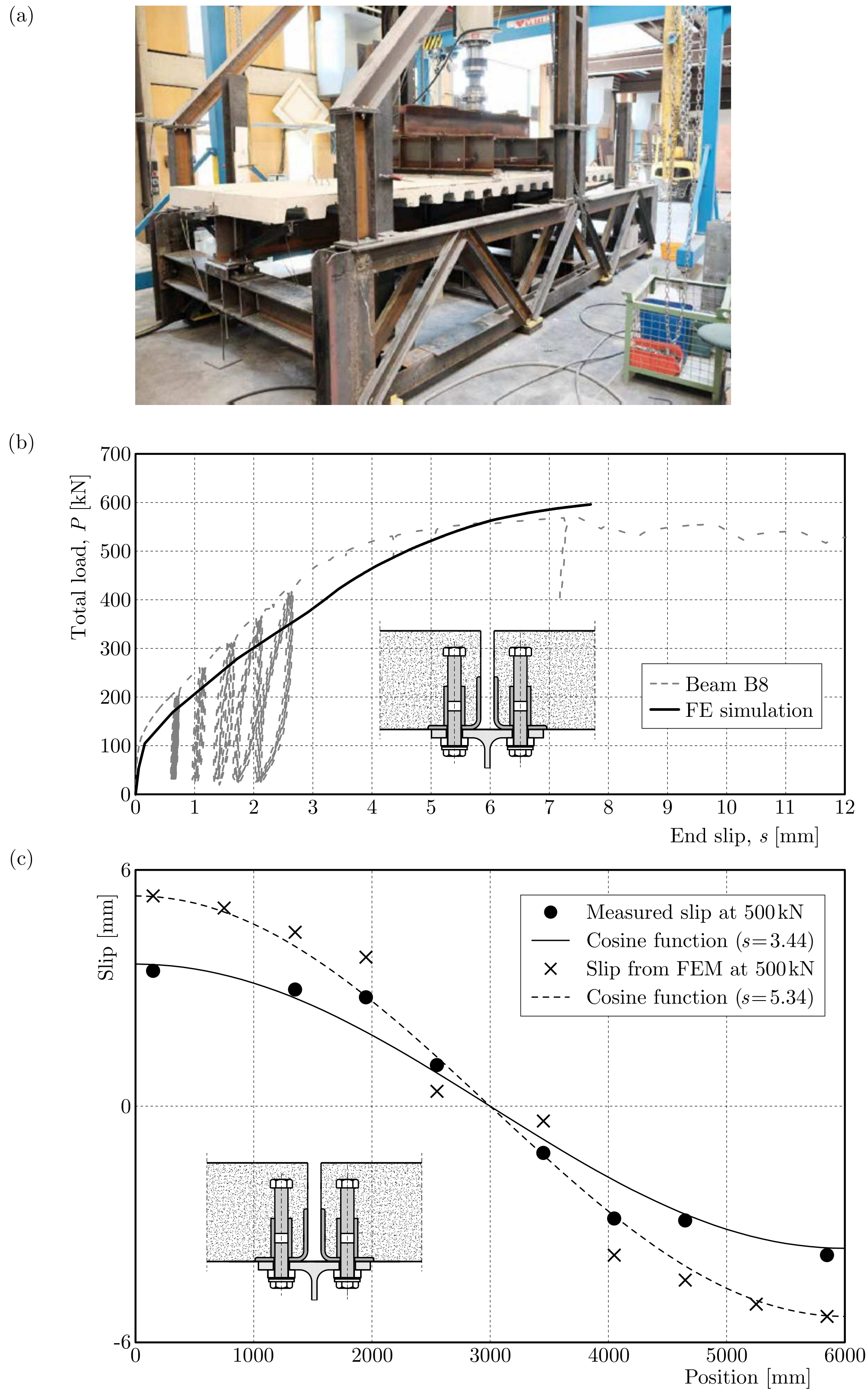


Fig. 6. Beam test (a) test setup and comparisons of experimentally and numerically obtained (b) load-slips and (c) slip distribution along beam length at a 500 kN jack load

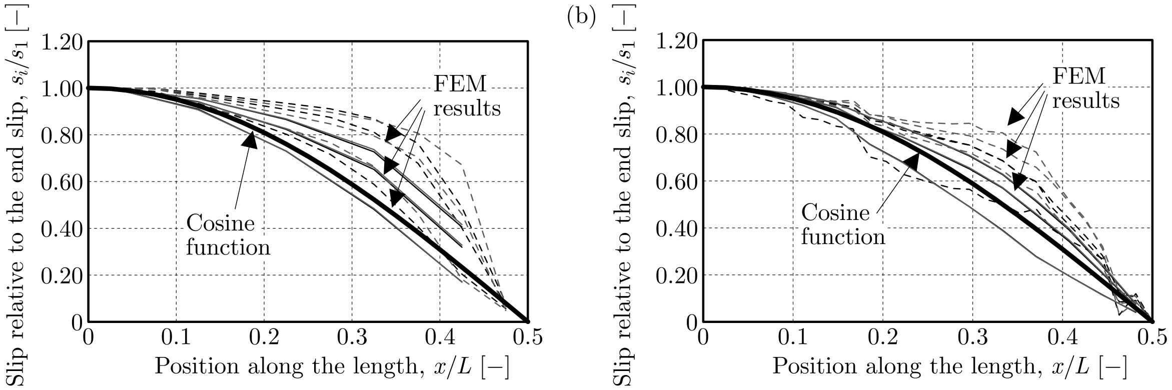


Fig. 7. Relative slip distributions in comparison with a cosine function: (a) results of 6 m demountable composite beams, (b) results of 16.2 m demountable composite beams

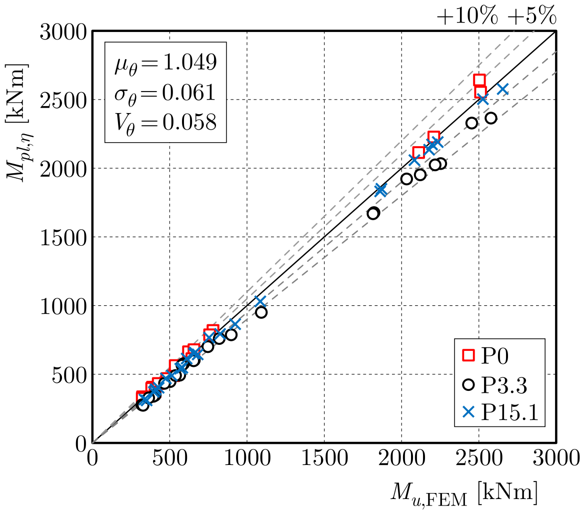


Fig. 8. Comparison of the moment resistance obtained from the FEA and simplified algorithm

pacity which is greater than 6 mm, but the bolts failure by shear fracture which is a non-ductile failure mode. However, experiments showed that beam specimens using such shear connections exhibited plastic behaviour and high ductility despite the non-ductile failure of the applied connections. To avoid the uneconomic elastic design, analytical algorithms were proposed for composite beams using nonlinear shear connections for determination of the plastic moment resistance. Plastic moment resistance data analysed from the proposed simplified algorithom were compared against virtual experimental data produced by validated finite element models. The considerd parameters in finite element analyses were beam length (6 m, 8.1 m, 16.2 m), steel profiles (IPE 270, IPE 360, IPE 450, IPE 600), concrete grade (C20/25, C45/55), shear connector spacing (300 mm; 600 mm), and shear connections using friction bolts in cast-in cylinders, coupled bolts with a mechanical coupler device, and welded stud as a benchmark.

It was found that the plastic moment resistance $M_{pl,\eta}$ of composite beams with nonlinear shear connection can be determined with a high accuracy using the proposed simplified algorithm and respective assumptions. Basic assumptions used in the development of the simplified algorithm include: a cosine slip distribution function, an end slip of 6 mm, and an effective shear resistance of the shear connectors $P_{R,eff}$ defined by a newly introduced reduction factor k_{flex}. As the considered range of parameters is limited, further research is forseen on the following aspects:

(i) The slip distribution function for composite beams under different loading patterns and when the bending moment diagram differs from a parabolic shape. A cosine function was assumed for use in simply supported beams under a uniformly distributed loading.
(ii) The minimum degree of shear connection required for beams and the minimum slip capacity required for shear connections.
(iii) The applicability of the safety concept of EN1994-1-1, Annex B, for presented calculation methods.
(iv) The aforementioned points (i)-(iii) concern, however, only boundary conditions, which do not affect validity of the proposed algorithms.

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