Christoph Odenbreit, Jie Yang, Alfredo Romero, András Kozma

ARTICLE

A Lego-like steel-framed system for standardization and serial production

A Lego-like steel-framed structural system has been developed within the frame of an RFCS project, REDUCE, to facilitate 1) deconstruction of composite structures, 2) circularity at structure and element levels, and 3) serial production in construction by promoting a greater standardization of structural elements. The system utilizes innovative demountable shear connections for composite flooring solutions with precast concrete elements, and adjustable steel connections for use in both beam-to-beam and beam-to-column connections. The first use case of the structural system has been realized in the Petite Maison project which is a demonstration project for circularity and contributes to the event ESCH2022. Each construction element is linked to a digital database and remains available for future reuse, as a result of the plug-and-play, demountable and robust features of the developed system. This paper presents the proposed demountable system, the results from experiments and finite element analyses on the behaviour of shear connections, composite beams, and steel connections, and indicates the analysing methods for structural engineers to open a pathway for full implementation of the structures built into digital tools, fabrication, and construction.

1 Introduction

The European Commission sets out the European Green Deal [1] for the EU in response to the climate change and challenges with the aim to reach net zero emissions by 2050. It provides the Circular Economy Action Plan [2] which promotes a greater circularity and prioritises reducing and reusing of materials before recycling them. The building and construction sector accounts for approximately 39 % of global emissions [3], and the associated Construction and Demolition Waste is the largest waste stream in the EU at over 800 million tonnes per year [4] which is 1.8 tonnes CDW in average per year per EU citizen. As a result, there are urgent needs in making this sector sustainable in order to align with the EU GD and CEAP.

With respect to reduction of embodied carbon emissions, reuse of materials has attractive advantages. For instance,

reusable steel elements recovered from existing steel structures have only a Global Warming Potential of 47 kg CO_2-e/tonne [5], compared to ca. 850 kg CO_2-e/tonne and 550 kg CO_2-e/tonne in new structural steels made from blast furnace and electric arc furnace production, respectively, concerning the product stage of Modules A1 to A3 defined in the Environmental Product Declarations guide of EN 15804:2012+A2:2019 [6]. With appropriate assessment of material characteristics and tolerances [7, 8], recovered steel sections may be CE marked in accordance with EN 1090 [9, 10] and be part of the continuous chain of construction products ecosystem.

The concepts of Design for Deconstruction (or Disassembly) [11] and Building as Material Banks [12] have to be widely adopted to maximize the impact of reuse, for carbon neutrality and resource efficiency. With the features of demountable and reusable, structures may be easily retrofitted, repurposed, or relocated in its entity, and the building components may be reused repeatedly. There are technical challenges to implement deconstruction and reuse for composite structures which are widely applied in multi-storey buildings due to structural and material efficiency. The connection between floor slabs and steel beams in composite flooring solutions is permanent and is provided by headed shear studs which are embedded in concrete floor slabs and also are welded to steel beams. Disassembling such structures is technically difficult and time- and labour consuming, and it results in building demolition at the end of service life in which the steel parts are sent to recycling, and concrete for down-cycling, or landfill.

Among others, the EU RFCS project REDUCE [13] explored the strategy of DfD and reuse for steel-framed composite structures and proposed a series of demountable shear connections solutions for in-situ [14] or prefabricated concrete slabs [15] and innovative steel connections for a greater standardization in the connecting elements and beam lengths. The proposed steel connections are suitable for use in both beam-to-beam and beam-to-column connections with large tolerances to facilitate standardization regarding beam lengths and the various column profiles. The shear connection solutions tested at the University of Luxembourg are found to have comparable loading capacity with the welded shear studs and can provide full demountability and easy disassembly for composite beams. With prefabrication of concrete slabs and a standardized, grid-oriented geometry, the structural elements are fully suitable for serial production, fast on-

site for (dis)assembly, implementation of digital tools and future reuse. The viability of the developed solutions has been proven by laboratory tests, numerical simulations, and the demonstration project Petite Maison [16].

This paper presents the proposed system which comprises demountable beams, columns, prefabricated floor slabs and adjustable steel connections tested at the University of Luxembourg. The key results and highlights from experimental, numerical, and analytical studies performed are summarized. The findings open a pathway for fully implementation of the structures built into digital tools, fabrication, and construction.

2 The Lego-like, demountable, and reusable steel-framed system

The developed Lego-like demountable and reusable steel-framed structural system comprises two innovations: (1) demountable shear connections suitable for use with pre-fabricated flat concrete floor slabs or profiled composite slabs, Fig. 1a, on down-stand steel beams, (2) adjustable steel connections provided by two L-elements, Fig. 1b, suitable for all the connecting members in open sections and are later extendable to use with tubular profiles. The L-element is welded from an end plate with fit bolt holes and a fin plate with elongated bolt holes which allows the plate to bridge a wide range of column profiles and beams in various length.

The following aspects have been considered for the steel-framed system to facilitate standardization and serial production.

Floor grids: the most typical planning grid for the Continent is 1.35 m, which leads to typical column spacings of, e.g., 5.4 m, 8.1 m, or 10.8 m. The geometry of floor slabs and beam lengths may be standardized based on these values.

Standard nominal beam length in which the beam length may be standardized as, e.g., (column spacing – 2×200 mm), with 200 mm between the centerline of the column and the adjacent beam end. The beam lengths are therefore 5 m, 7.7 m, and 10.4 m for column spacings of 5.4 m, 8.1 m, and 10.8 m, respectively. With this proposal, the beams may not be restrained by the original column design and be re-used elsewhere in a same planning grid but connected to a wide range of column profiles with depth of column section not exceeding 400 mm.

Standard adjustable steel connections in which the proposed adjustable steel connection, as shown in Fig. 2, may be used for all the connections within the same frame structure. This applies to beam-to-beam, and beam-to-column connections, as illustrated in Fig. 1b. With the slotted holes in the L-elements, Fig. 2b, the connections can provide large tolerances for connecting beams to their supporting members in various profiles (the tolerances or the limit of bridging distance depend on the length of the slotted holes in the L-element).
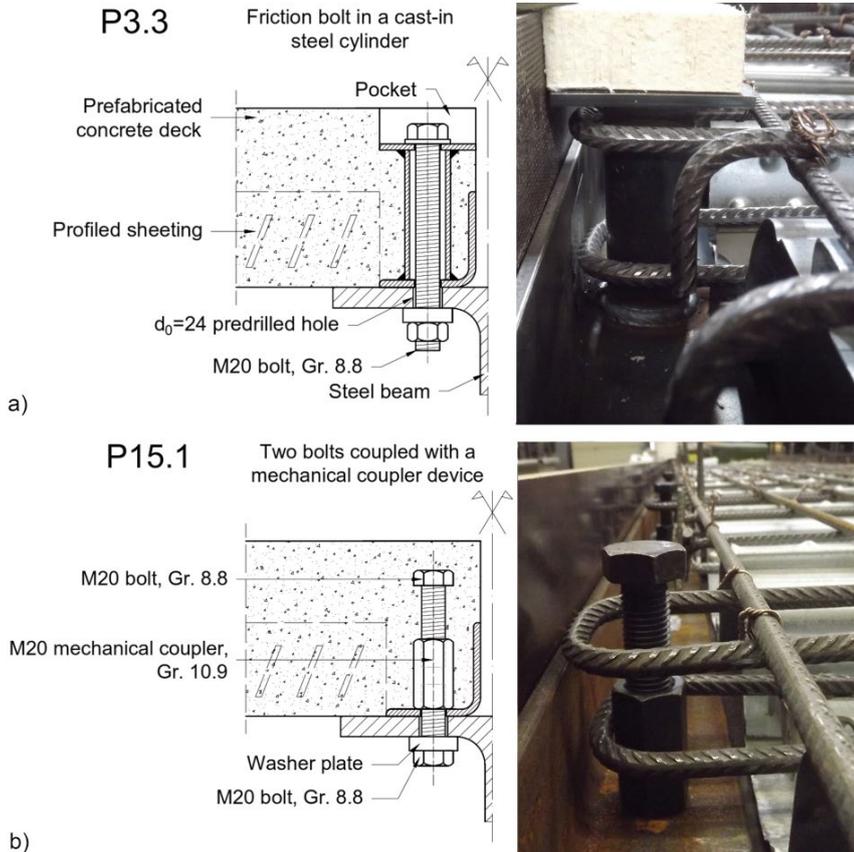
Demountable shear connections: bolted connections, Fig. 3a,b, between the concrete slab and steel beams, for use with prefabricated flat concrete slabs or profiled composite slabs which may be designed with standardized geometry and configurations.
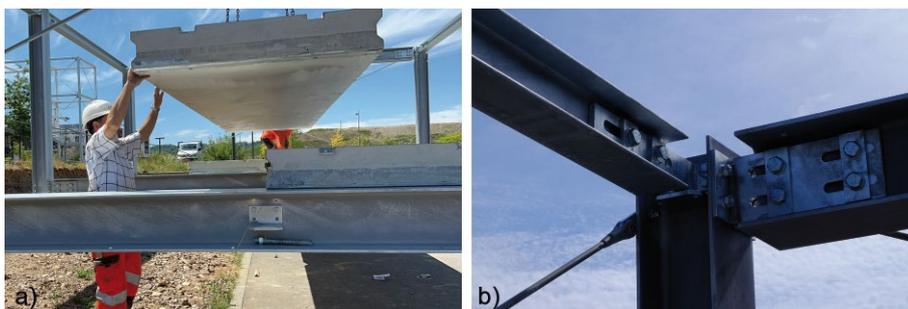
Fig. 1 Demountable and reusable steel-framed structural system: a) prefabricated modular slab elements lifted to be assembled to their supporting beams with bolts, photo from the Petite Maison project, b) adjustable and standardized steel connections connecting beams to a corner column in both its major and minor axes, from the Petite Maison project, providing large tolerances in beam length and various of column profiles within a standardized grid
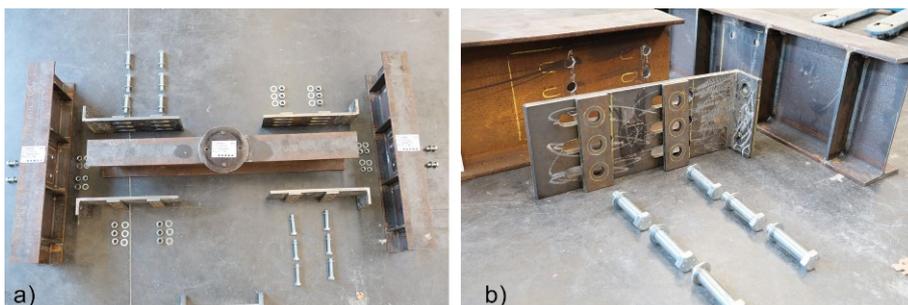
Fig. 2 Adjustable steel connection designed for use in both beam-beam and beam-column connections: a) steel connection kit demonstrated as beam-to-beam connection, b) connecting elements

Fig. 3 Developed demountable shear connections: a) cylinder system, P3.3, b) coupler system, P15.1

The developed system and standardization solutions have been realized in the Petite Maison project which contributes to the event ESCH22. The Petite Maison building is open to public tours from 15 July 2022 until early 2023 and is planned to be deconstructed after that. The elements of the building will be linked to virtual databases to facilitate reuse in future projects.
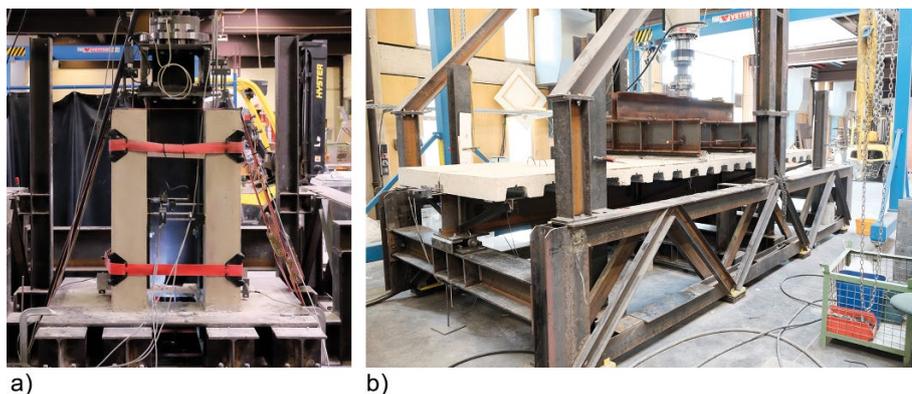
3 Demountable shear connections

3.1 General

Shear connections with certain shear resistance and deformation capacity can ensure steel beams act compositely with their supported floor slabs for increased stiffness and load resistance. Fig. 3 illustrates two types of demountable shear connection designed for prefabricated slabs and for (dis)assembly and reuse of composite beams. Such designs have the following advantages: (1) the floor slabs can be (de-)attached from their supporting steel beams and both the slabs and the beams are potentially reusable, (2) the bolts are replaceable in case of any damage during (dis)assembly and future reuse of structures or slab elements, in addition, the shear connection type P3.3 allows installation access from the top of the composite slab, (3) the shear connection is robust and has comparable shear resistance to headed shear studs, (4) the designs allow prefabrication of concrete slabs or composite slabs with profiled decking, (5) pre-tensioning of bolts may be applied to control initial slips.

Noted that (i) steel angles are used in Fig. 4 configurations to reinforce the concrete edge of the slab at the vi-

Fig. 4 Experimental test campaign: a) push test on shear connections, b) bending test of composite beam

cinity of the bolted connection, (ii) there is always a solid strip regardless of slab types, solid or profiled, to ensure the amount of concrete around the demountable shear connector for shear resistance, (iii) the cast-in cylinders (used in connection type P3.3) are welded to the steel angles, and special care is required during the welding process to avoid any excessive deformation. The performance of the proposed shear connections has been tested in the form of push tests [17] and composite beam tests [18], as shown in Fig. 4, in accordance with EN 1994-1-1 [19] and validated by using finite element simulations.

3.2 Behaviour from push tests and finite element modelling

Standard push tests can determine the most important characteristics of shear connectors in terms of their shear resistance, slip capacity, stiffness, and modes of failure. Fig. 5a presents representative load versus slip relationships obtained from push tests for the shear connection type P3.3. A set of three specimens was tested in three loading regimes: 1) monotonic increasing load, 2) with 25 cycles of load between 5 % and 40 % of failure load measured from 1), 3) with 25 cycles of load from 2) with additional unloading and reloading cycles after every 0.5 mm to 1 mm increments in the relative slip. A reuse test was also performed, denoted by P3.3-3R, by using new bolts after a first test to represent a second life of the composite structure.

The tested shear connections are found to be robust, with high shear resistance, and a slip capacity exceeding 6mm, which is a slip value defined for headed weld studs for

them to be classified as ductile connectors [19]. The load versus slip behaviour can be divided into: (i) friction phase, due to pre-tensioning, the initial stiffness is high, 250 to 500 kN/mm, (ii) reduced stiffness with large slip due to bolt hole tolerances, (iii) bearing and shear phrase with a stiffness of 15 kN/mm to 20 kN/mm. These stiffness values are relatively low compared to headed welded studs with stiffness of 40 to 60 kN/mm when applied with profiled decking [20]. Noted that the term "initial stiffness" is used for the description of the stiffness in the (i) stage and determined as the secant stiffness, S_{ini}, by using Eq. (1):

$$S_{ini} = \frac{F_s}{s_{Fs}} \tag{1}$$

where F_s is the measured friction resistance and s_{Fs} is the corresponding value of the slip.

The specimen P3.3-3R with reused steel beam and composite slabs and with new bolted shear connectors has comparable performance compared to the first-use specimens, and therefore demonstrates the reusability of the composite structure. However, the friction coefficient of the galvanized specimens was reduced to from 0.48 to 0.23 after first use. This affects only the (i) friction phase, not the ultimate failure loads.

Fifteen push tests have been performed. Among all cases, shear fracture of the bolts occurred, as shown in Fig. 6a, while only thread penetration was observed in the beam flange, Fig. 6b. The obtained failure loads from the push tests ranged from 130.2 kN to 172.3 kN per bolt. Considering Eq. (2) for estimating shear resistances of bolted
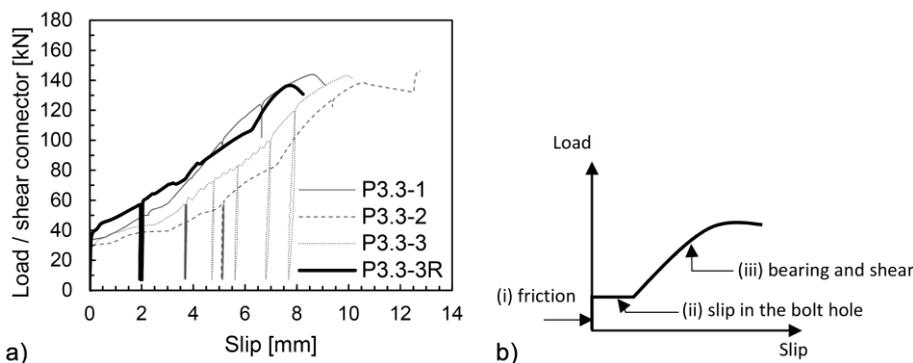

Fig. 5 Typical load vs. slip relationships: a) results from shear connection type P3.3 including reuse test denoted by P3.3-3R, b) simplified curves
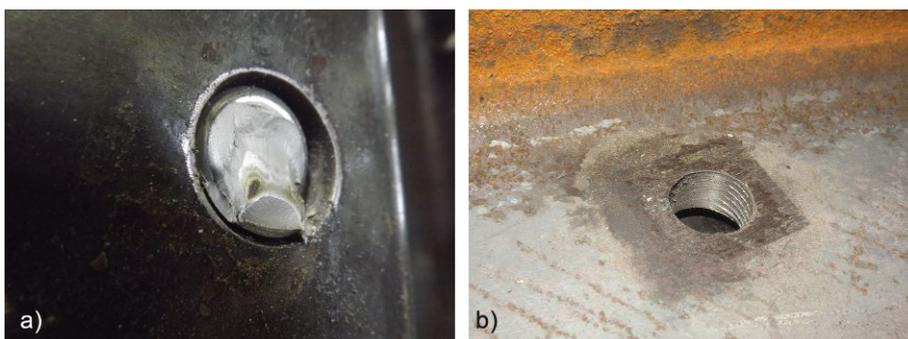

Fig. 6 Typical mode of failures: a) bolt after fracture, no bearing deformation in the angle plate, b) thread penetration in the beam flange
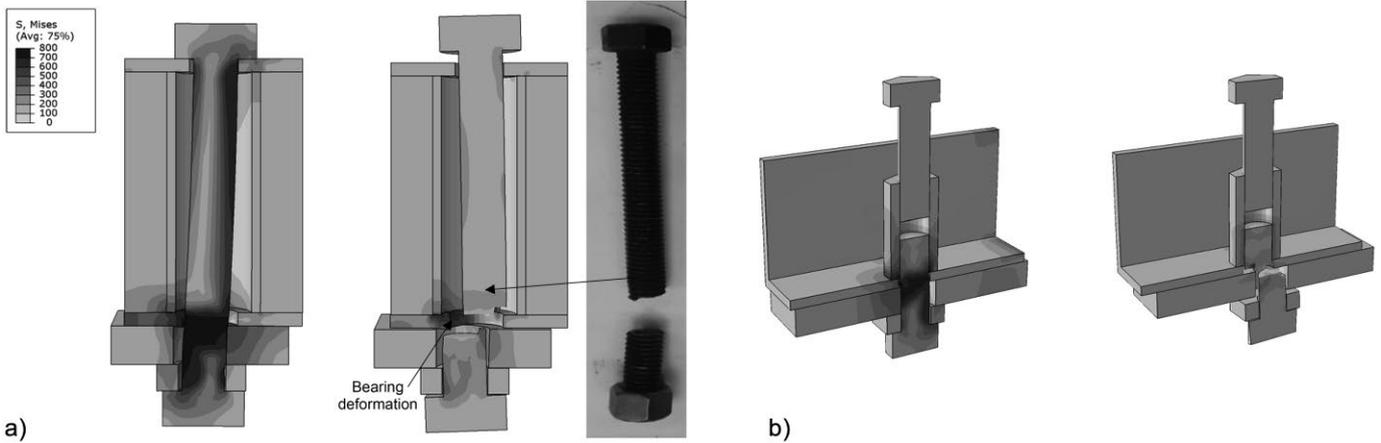
Fig. 7 Stress contour and mode of failures from numerical model of shear connections: a) type P3.3, b) type P15.1

connections, the coefficient for shear resistance from 0.58 to 0.67 based on the failure loads from push tests. This indicates that the shear resistance of the tested demountable shear connections may be determined according to Eq. (2) with a coefficient of 0.58 as a lower boundary.

$$F_v = \alpha_v \cdot f_{u,b} \cdot A_s \qquad (2)$$

where $f_{u,b}$ is the tensile strength and A_s is shear area.

To better understand the behaviour of the shear connections, finite element models have been developed by using ABAQUS [21]. Only the vicinity of the shear connections is modelled for simplification. Fig. 7 illustrates the stress contour obtained from FE modelling for the tested shear connections, which shows the high stress areas and predicted mode of failures. The obtained FE results are found comparable to the push test results with sufficient accuracy. It was found that material strength, pre-tensioning load, the friction coefficient and the bolt hole clearance are the most important parameters for the load-slip behaviour of the demountable shear connections, based on virtual experiments performed by using the developed FE models. Modelling techniques can be found in [15].

Considering user comfort and functions of structures, Serviceability Limit States (SLS) have to be fulfilled. For calculations of deflections of a composite beam, the equation of Lawson et. al. [22] for the determination of the effective second moment of area $I_{y.eff}$ of a composite section can be applied for demountable shear connections. Among other parameters, this equation uses the stiffness of shear connection, k_{sc}. Based on analysing results, the secant stiffness at a load level of 70% of the obtained characteristic shear resistance P_{Rk} is a good approximation for serviceability calculations of deflections, end slip and stresses, as shown in Eq. (3).

$$k_{sc} = 0.7P_{Rk} / s \qquad (3)$$

where s = value of the slip at 0.7 P_{Rk}.

4 Behaviour of composite beams

4.1 Behaviour of composite beams from bending tests

Two composite beam tests have been performed with one for each of the shear connection type P3.3 and P15.1. Each specimen comprised of a 6.3 m long IPE 360 steel beam in grade S355 and two prefabricated composite slab elements in 150 mm depth and 790 mm width using ComFlor 80 decking. Solid strips are considered near the shear connections which provide comparable shear resistance compared to solid slabs. The beams have a clear span of 6 m with a uniform shear connection spacing of 600mm based on the slab profile and a nominal degree of shear connection of 37% which is slightly lower than the specified value for welded headed studs in EN 1994-1-1. The steel beam is supported along its length during the installation, which corresponds to a propped construction technique. During the tests, the composite beams are simply supported and are subjected to two-point loading. A benchmark test 2-10 in the DISCCO project [23] using headed welded studs is selected for comparison. Fig. 8 illustrates the comparisons of experimental results of load versus mid-span deflections and load versus end slips. The results show that: (i) within the serviceability limit states of $L/300$ deflection limit, the composite beam remains in the elastic range, (ii) the composite beam can support about a load exceeding a deflection of $L/50$, (iii) the composite beam has a slip capacity of about 9.5 mm, (iv) the comparisons against the benchmark test indicate that the composite beam with demountable shear connections generally has lower stiffness and higher load resistance, which should be noted in calculations of Serviceability Limit State and Ultimate Limit State.

Concrete crushing occurred at the final stage of the experimental test at the peak loads and after the deflection limit of $L/50$ and followed by shear fracture of bolts which were also observed from push tests, as shown in Fig. 9. Regarding demountability, the beam specimens can be dismantled easily after the tests by using hand tools.
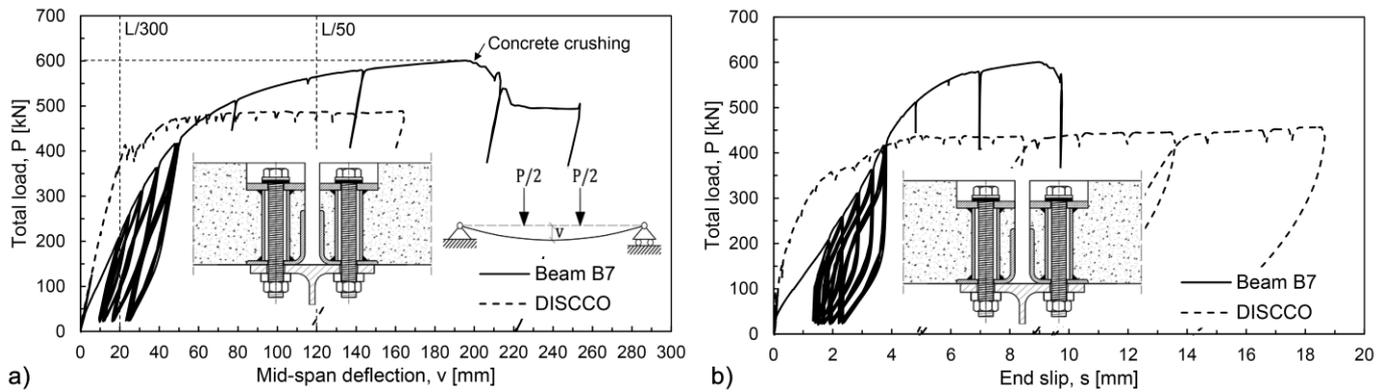
Fig. 8 Comparisons aginst a benchmark test 2-10 in DISCCO project [23]: a) load vs. mid-span deflections, b) load vs. end slips
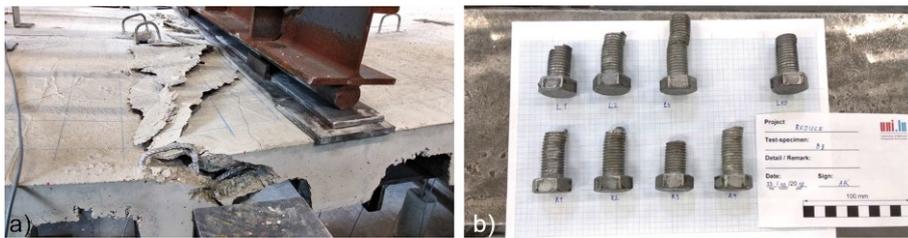

Fig. 9 Failures observed from beam tests: a) concrete failure, b) bolt failure

4.2 Simplified algorithm for plastic moment resistance

In contrary to headed welded studs with ultimate loads reaching after only 1 to 2 mm of relative slip, the demountable shear connections have monotonic increasing load versus slip behaviour. The plastic design method specified in EN 1994-1-1 may not be applied. For the calculation of plastic moment resistance of composite beams with demountable shear connectors, it is proposed to use an effective shear connector resistance, $P_{\text{Rd.eff}}$, given in Eq. (4):

$$P_{\text{Rd,eff}} = k_{\text{flex}} \cdot P_{\text{Rd}} \tag{4}$$

where k_{flex} is a specific parameter for shear connection and depends on (i) the load-slip behaviour, (ii) the slip distribution, (iii) the loading situation, (iv) the number of shear connectors, and (v) the distribution of the shear connectors along the beam length, etc. It is generally in the range of 0.80 to 0.90 based on experimental and numerical analyses. For equidistantly placed shear connectors, 0.85 is generally a good approximation.

With proper assumptions for the slip distribution and the end-slip, the developed compression force in the concrete can be estimated accurately by using $P_{\text{Rd.eff}}$, hence the EN 1994-1-1 method for the determination of the plastic moment resistance of composite beams with partial shear connection remain applicable for the developed shear connections. A simplified algorithm for the determination of plastic moment resistance of composite beams with (non-ductile) demountable shear connections has been proposed and is illustrated in Fig. 10.
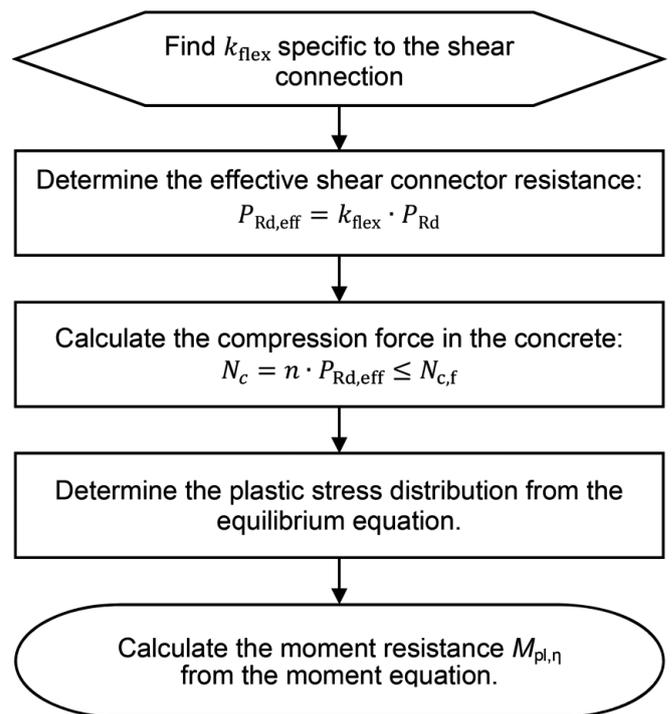

Fig. 10 Simplified algorithom for the determination of plastic moment resistance of composite beams with (non-ductile) demountable shear connections

5 Adjustable steel connection

5.1 General

The simplest and widely used connections are those with end plates and/or fin plates. These plates are usually welded to beam or column members with a small tolerance for erection and installation. To promote a "standardized nominal
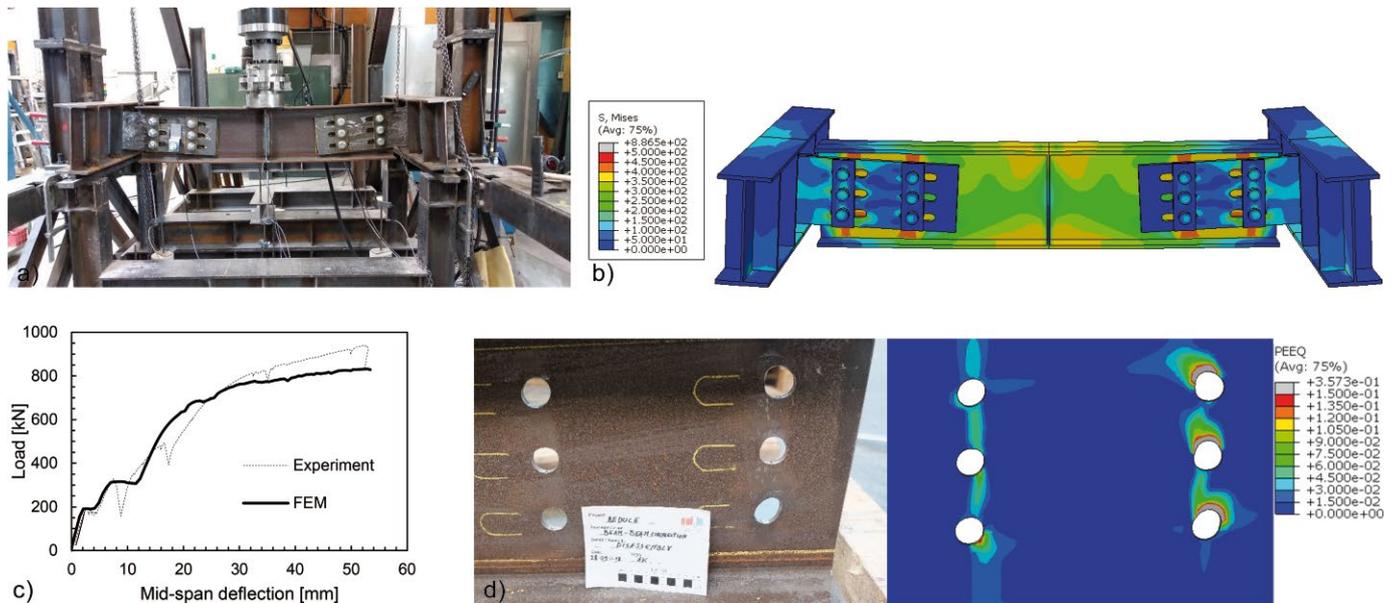
Fig. 11 Adjustable beam-to-beam connection: a) experimental test, b) stress contour from FE modelling, c) load vs. mid-span deflections, d) comparison of bearing in bolt holes between test and FE modelling

beam length" and for serial production, an extendable steel connection has been developed, as shown in Fig. 2a, for large tolerances and for beams connecting to a wide range of column profiles (section depths). This connection comprises L-elements made from end plates and fin plates, as shown in Fig. 2b, which has slotted holes and makes the connection extendable. With the adjustment potentials, the beam with standardized length (shorter length) may be connected to column profiles of various sizes or to primary beam within the same planning grid, which facilitates the beam reuse. The same principle may be applied when the beam is connected to a reinforced concrete wall.

5.2 Behaviour of connections and analysing method

The steel connection developed was tested in the form of beam-to-beam connections, as shown in Fig. 11a. The primary beams were pin-supported, and the secondary beam was loaded at mid-span by using a 1000 kN capacity hydraulic jack. It is found from the test that (i) the ultimate load is twice as the calculated bearing resistance, (ii) bearing failure of the web of the secondary beam governs the failure, (iii) the connection is robust and can transfer the shear force without developing significant bending moments in the supporting members.

Finite element modelling was performed by using the nonlinear finite element software ABAQUS and dynamic explicit solver technique, to predict the behaviour of the connection. For simplicity, the radii of the sections and the threads of the bolts are neglected in the model. "Damage for ductile materials" was adopted in the model for steel elements with the material law calibrated against standard tensile specimens following similar approaches presented in Pavlovic [25]. "C3D8R" finite elements (eight-node linear brick, reduced integration) were used with "General Explicit Contact" for contacts with interaction defined as

"Hard Contact" in the normal direction and Coulomb friction with a friction coefficient of 0.2 in the tangential direction. The pre-tension force in the bolts was applied as a thermal contraction using a predefined field of an artificial temperature difference and an artificial thermal expansion coefficient. A constant velocity of 0.2 mm / second in the vertical direction was applied at the loading point of the secondary beam. The comparison of the results shows a good agreement between the numerical simulation and the experiment in terms of deformations and load-deflection response, as shown in Fig. 11b–d. Further parametric studies are planned to expand the reference data of the developed steel connection.

The joint is classified as a nominally pinned and may be designed based on EN 1993-1-8 [25] considering: (i) shear failure of the bolts, (ii) bearing failure of the beam web, and (iii) bearing failure of the plate with slotted holes.

6 Conclusions

This paper presents a Lego-like demountable and reusable steel-framed system suitable for geometrical standardization and serial production. This system promotes the use of: (i) planning grids of 1.35m, (ii) standardized nominal beam length as (column spacing $- 2 \times 200$ mm), (iii) prefabricated slab elements and standard slab geometry based on the (i) planning grid, (iv) demountable shear connections, and (v) adjustable and standardized steel connections suitable for use in every connection of the frame structure. Experimental tests, numerical simulations and analyses suggest that:

- the developed system is robust, demountable and has potential for reuse,
- using the proposed effective shear resistance, the composite beams with the developed demountable shear

connections may be designed in accordance with the rules for plastic design specified in EN 1994-1-1,

– the adjustable steel connection developed is within the scope of EN 1993-1-8 and is applicable and compatible with the current standard design rules.

Acknowledgements

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Authors

Professor Dr Christoph Odenbreit
christoph.odenbreit@uni.lu
ArcelorMittal Chair of Steel Construction
Université du Luxembourg
Campus Kirchberg, Université du Luxembourg
6, rue Richard Coudenhove-Kalergi
1359 Luxembourg, Luxembourg

Dr Jie Yang (corresponding author)
jie.yang@uni.lu
Université du Luxembourg
Campus Kirchberg, Université du Luxembourg
6, rue Richard Coudenhove-Kalergi
1359 Luxembourg, Luxembourg

Alfredo Romero MSc
alfredo.romero@uni.lu
Université du Luxembourg
Campus Kirchberg, Université du Luxembourg
6, rue Richard Coudenhove-Kalergi
1359 Luxembourg, Luxembourg

Dr András Kozma
a.kozma@desa.lu
DESA Ingénieurs-conseils s.à r.l.
1, Square Peter Dussmann
5324 Contern, Luxembourg