Analysis and design of demountable steel-concrete composite structures

Summary of the PhD Dissertation

Krisztián Király

Budapest University of Technology and Economics

Supervisor:

László Dunai, DSc

Professor

Professional expert:

András Balázs Kocsis

European Engineer

Advisor:

Luis Calado, DSc

Professor

Budapest

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1 Introduction

Transitioning the construction sector towards a circular economy requires structural systems that reduce environmental impacts and embodied carbon, and, where feasible, enable the direct reuse of components. Design for deconstruction supports this ambition by treating buildings as recoverable material stocks and by prioritising solutions that preserve component value beyond a single service life [1]. Steel-concrete composite construction is well-suited to circular design, provided that steel and concrete can be separated without unacceptable damage; this has led to demountable composite systems in which demountable shear connectors, as key elements, provide composite action in service while enabling disassembly and reuse. Structural steel is readily recyclable, yet recent studies show that direct reuse can deliver markedly greater embodied carbon savings than recycling [2,3]. Prefabricated concrete can improve quality control and reduce on-site labour time and waste. Still, its carbon benefit over cast-in-situ solutions is project-dependent, which can be strengthened through low-carbon binders, recycled aggregates and structural optimisation for reuse [4,5]. Case studies confirm that demountable construction is feasible in practice, particularly for temporary or adaptable facilities –such as event venues [6], parking facilities [7], and offices [8] – where standardised prefabrication and dry connections enable rapid, low-waste reconfiguration.

Practical assembly tolerances typically require bolt-hole clearance, which causes initial slip and reduces the initial stiffness of demountable composite beams [9,10]. Accordingly, connector detailing and installation must balance constructability with stiffness, resistance, ductility, and reliable disassembly. Several studies have analysed and enhanced demountable shear connectors, for example, by using high-strength friction-grip bolts [11] and by injecting resin into oversized bolt holes to modify the initial slip response [12].

Recent research has proposed demountable connector concepts for both monolithic and precast slabs, and large-scale beam tests have shown that demountable composite beams can achieve adequate global behaviour comparable to welded-stud systems while remaining dismantlable for reuse [13,14]. Advanced finite element modelling has further clarified local interaction mechanisms and reproduced observed test responses [15]; however, many models remain specific to particular connector details, limiting their direct use for general beam design.

Design-oriented rules for demountable composite beams remain limited, since Eurocode 4 [16] provisions primarily address conventional (non-demountable) shear connections. To bridge this gap, Kozma [17] proposed a Eurocode-compatible characterisation method that converts the measured multi-linear load-slip response of demountable (primarily non-ductile) shear connectors into an effective shear resistance for composite beam design, using an assumed longitudinal slip distribution. Recently published guidance on demountable composite construction [18] provides practical recommendations for design; however, it is often connector-specific or overly general, making it less useful for proper design decisions. More accurate design guidance is therefore required to consider demountable shear connector detailing, particularly where bolt-hole clearance and construction tolerances significantly influence the structural response.

This research, conducted in cooperation with the Budapest University of Technology and Economics and the industrial partner KÉSZ Group, bim.GROUP Ltd., Hungary, aims to develop a reusable, demountable steel-concrete composite beam system that combines precast elements with practical detailing, improving fabrication tolerances, reducing on-site labour, and enabling rapid assembly and dismantling through straightforward, cost-effective construction methods. This research aims to establish a scientific foundation for the proposed system by evaluating its unique physical and mechanical responses through laboratory experiments and numerical simulations, and to develop a dedicated, Eurocode-consistent calculation procedure for the proposed system, including effective connector resistance, elastic and plastic moment resistance, and relevant serviceability limit states, including deflection and end slip, with explicit consideration of dismantling and reuse.

2 Proposed demountable steel-concrete composite system

The proposed structural system comprises hot-rolled steel beams and precast reinforced concrete panels. Composite action is provided by threaded rods embedded in the panels, which function as demountable shear connectors. Key innovations aimed at enhancing the bolt-hole clearance, fabrication and construction feasibility, along with structural performance (initial stiffness, resistance, and ductility) of the shear connectors are presented in *Figure 1* and include:

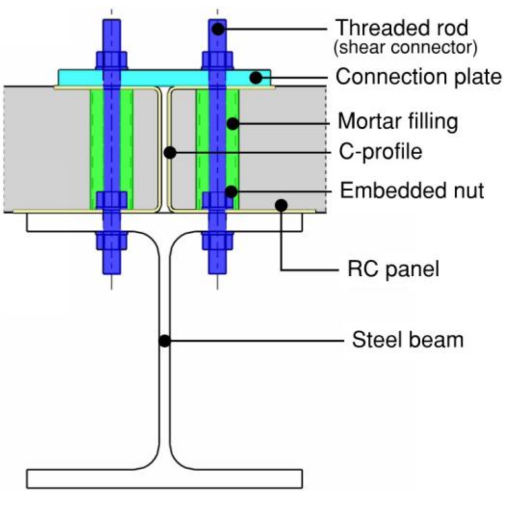

Figure 1. The proposed structural system

- completely precast reinforced concrete slab elements without on-site concreting,
- embedded steel C-profiles to improve panel alignment and bolt positioning,
- mortar filling (grouting) around the connectors to achieve tighter tolerances,
- embedded nuts within the mortar to enhance construction efficiency and stiffness, and
- connection plate between precast slabs to provide global structural stiffening.

Predrilled holes in the embedded C-profiles accommodate demountable shear connectors with a 2 mm clearance in the steel flange. The rods are tightened from the flange side, and the ribbed tubes in the precast slabs are then grouted, so the flange holes remain unfilled, and the connectors stay removable. A connection plate is added above the slab to enhance global stiffness and in-plane behaviour. As a simplified alternative, the connectors may be cast in without grouting; however, this requires a larger bolt-hole clearance of 4 mm to accommodate fabrication tolerances. In both cases, demounting is achieved by loosening the nuts, allowing separation without cutting while maintaining reliable composite action. A damaged connector can be removed by drilling and then replaced with a new connector, followed by refilling with mortar or concrete of comparable quality to preserve structural performance.

The proposed demountable system aligns with sustainability aspirations by enabling prefabrication, rapid assembly, disassembly, and element reuse, thereby preserving embodied carbon, minimising waste, and reducing life-cycle emissions relative to conventional composite floors with welded headed studs. A simplified embodied carbon analysis highlights the system's reuse potential by comparing a conventional composite floor to different reuse scenarios. With only recycling in Sc. 1, the embodied carbon of the developed system is 1.25 times that of the reference due to proposed detailing. In a low-reuse case of the elements in Sc. 2, assuming 80% reuse with all connector replacement, yields 83% of the reference, and in a high-reuse case Sc. 3, considering 95% element and 80% connector reuse, achieves 68%, demonstrating that even modest reuse offsets upfront carbon and confirms the system's viability for circular design. The comparison of the embodied carbon for 1 m long composite beam is provided in *Figure 2*.

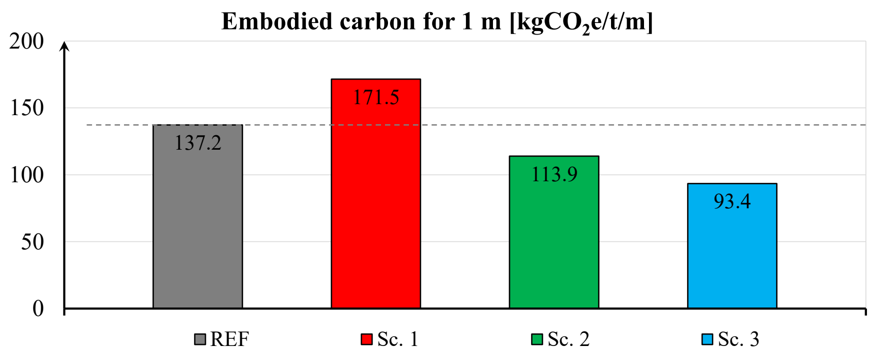

Figure 2. Embodied carbon comparison for 1 m in each scenario

3 Analysis and behaviour of the shear connectors

A push-out test programme was carried out to assess the proposed demountable shear connector in six configurations, each tested on three nominally identical specimens, focusing on the effects of oversized bolt holes, embedded C-profiles, threaded rods, mortar filling and connection plates. Each specimen comprised an HEB260 S235 steel member connected to four precast C50/60 panels, with two M16 8.8 connectors per panel (eight connectors per specimen). Configurations A-B served as reference details using L-profiles with embedded bolts and cast-in nuts, whereas configurations C-F employed embedded C-profiles with threaded-rod connectors and nuts with washers only at the slab top and below the steel flange. All connectors were installed to a snug-tight condition to represent practical site assembly. Specimens B, E and F used on-site mortar filling around the threaded rods, placed after the concrete had gained sufficient strength and the rods had been positioned in ribbed steel tubes preinstalled in the panels. The mortar had a characteristic compressive strength of 62 MPa and a characteristic elastic modulus of 26 GPa. In addition, specimens D and F included a connection plate on top of the panels to increase the stiffness of the shear connector. The configuration of the specimens is illustrated in *Figure 3*, and a prepared specimen is shown in *Figure 4*.

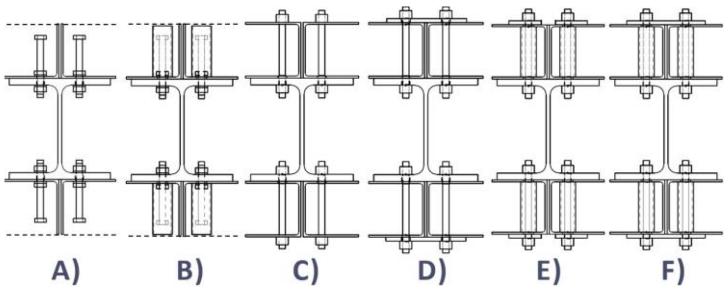

Figure 3. The push-out specimen types

Figure 4. The prepared push-out test specimen

The push-out tests followed the Eurocode 4 loading history, comprising 25 preloading cycles followed by monotonic loading in a 6000 kN-capacity testing machine, with LVDTs to monitor global and relative displacements, and strain gauges installed on the steel flange to measure stress distribution. Material tests indicated a concrete strength of 70.7 MPa, mortar strength of 59.4 MPa and a bolt tensile strength of 944.6 MPa.

Preloading cycles were used to remove installation uncertainties by mobilising bolt adjustment and panel movements, so that the measured residual slip (about 1.5-3.4 mm) could be treated as initial slip and the subsequent transformed force-displacement curves would characterise connector stiffness, resistance, and ductility more consistently across configurations. Both the directly recorded and the transformed force-relative displacement curves were evaluated and presented for each connector configuration in *Figure 5*. All variants exhibited similar behavioural characteristics with a consistent three-stage load-slip response – (i) elastic, (ii) plastic transition and (iii) plastic deformation – while detailing improvements altered the behaviour. The ultimate resistances fell within a relatively narrow range, characterised by ductile failure, governed by shear-bending of the bolts, accompanied by local concrete or mortar cracking and spalling around the connectors, as shown in *Figure 6*.

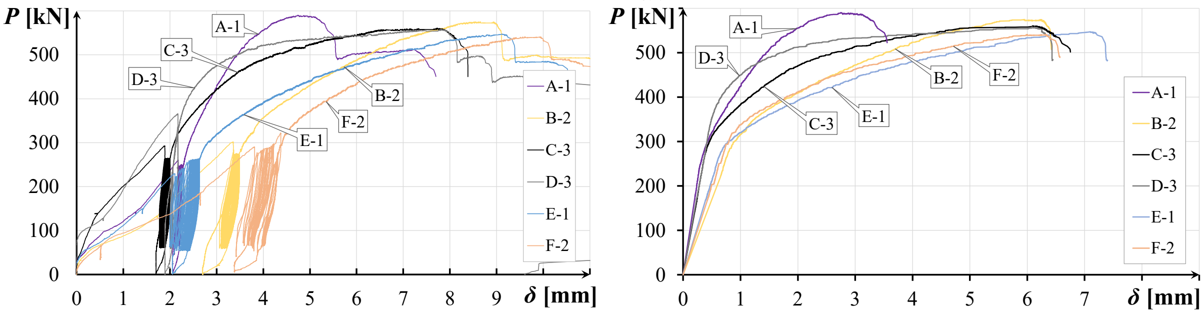

Figure 5. Force-relative displacement diagrams for each specimen with (left) and without initial stage (right)

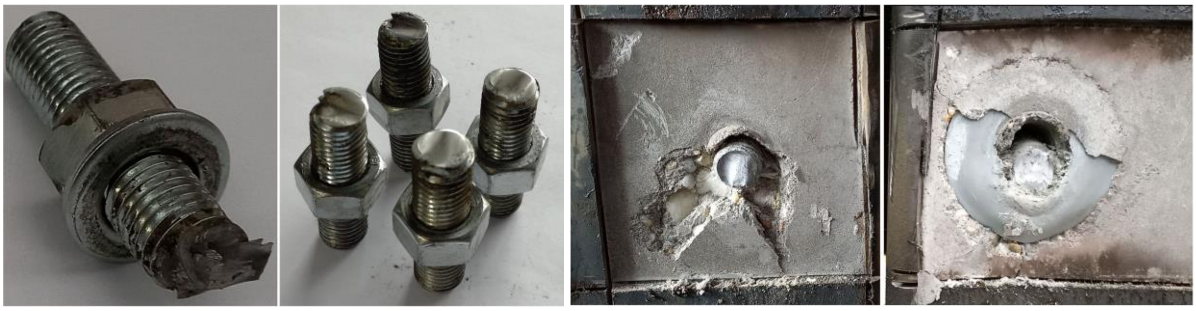

Figure 6. Failure of the bolts (left), concrete cracking and mortar filling with bolt deformation (right)

Mortar filling enhances slip capacity and bolt force redistribution, without a significant reduction in shear resistance, while it does reduce the initial stiffness of the connection. Embedded nuts increase connector stiffness, and combining them with mortar filling resulted in a more pronounced hardening branch with only slightly increased slip compared to other configurations, making it the most effective solution. The local region of concrete or mortar surrounding the connector, with controlled bolt-hole clearances, is a key driver of structural behaviour, while the connection plate does not influence connector performance.

Numerical models developed in ATENA [19] reproduced stiffness, resistance, and failure modes accurately, as indicated in the force-deflection diagrams in *Figure 7 (left)* and in the failure mode in *Figure 7 (right)*. Based on the validated models, a parametric study was conducted, demonstrating that bolt position and bolt grade predominantly govern the stiffness and resistance of the demountable shear connection, while concrete grade and thickness mainly influence cracking and durability and do not alter the fundamental response of the connectors.

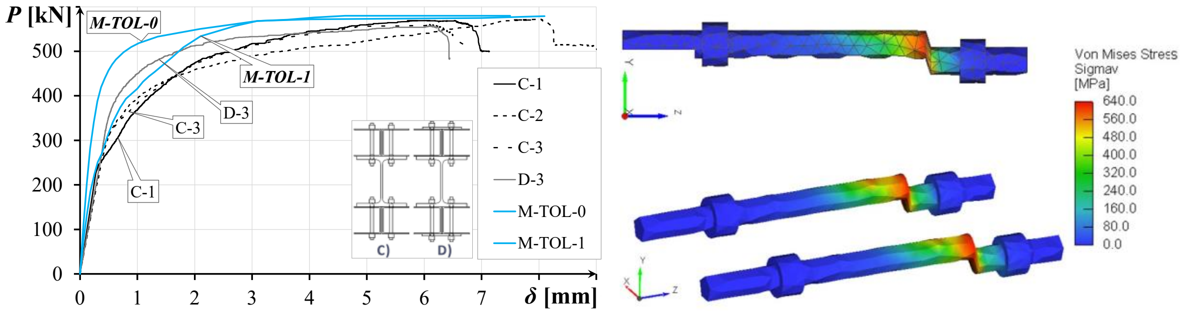

Figure 7. Force-relative displacement diagrams of type C-D (left) and plastic failure of the bolts (right)

The proposed demountable connector configurations provide adequate stiffness, resistance, and ductility for practical applications in demountable composite beams.

4 Experimental analysis and behaviour of the composite beams

A full-scale beam test programme was carried out to analyse the global response of the proposed demountable steel-concrete composite beams. Four specimens with a 5.8 m span were tested in four-point bending, with loads applied 1.45 m from the beam ends, to compare the performance of the proposed shear-connector configurations. Each specimen comprised an IPE360 S355 steel beam and two 120 mm thick precast C50/60 concrete slabs within a single cross-section, cast in S235 steel C-profile frames. Specimens DC1-C, DC2-E and DC3-F used two longitudinally continuous concrete panels, whereas DC4-G comprised a separated 5-5 panel arrangement. DC1-C used directly embedded connectors; the remaining specimens employed mortar filling with embedded nuts. The shear connectors were installed at 290 mm longitudinal spacing, symmetrically located 50 mm from the centreline, and tightened to 40 Nm. Connection plates were provided on the panels in DC3-F and DC4-G. The general details of the composite beam and the shear connection are presented in *Figures 8* and *9*. *Figure 10* shows the prepared DC2-E and DC4-G specimens, highlighting the assembled precast panels and connection arrangement.

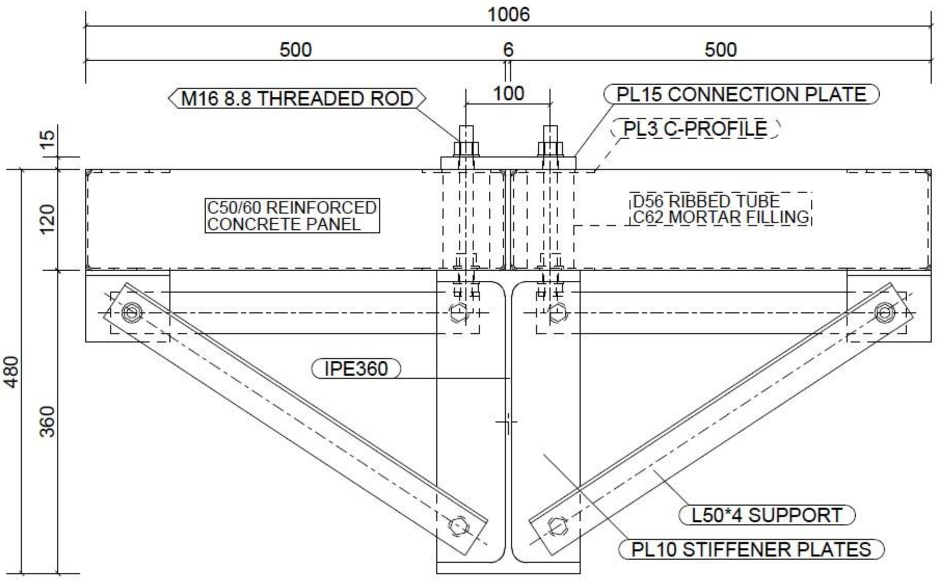

Figure 8. General details of the composite beam

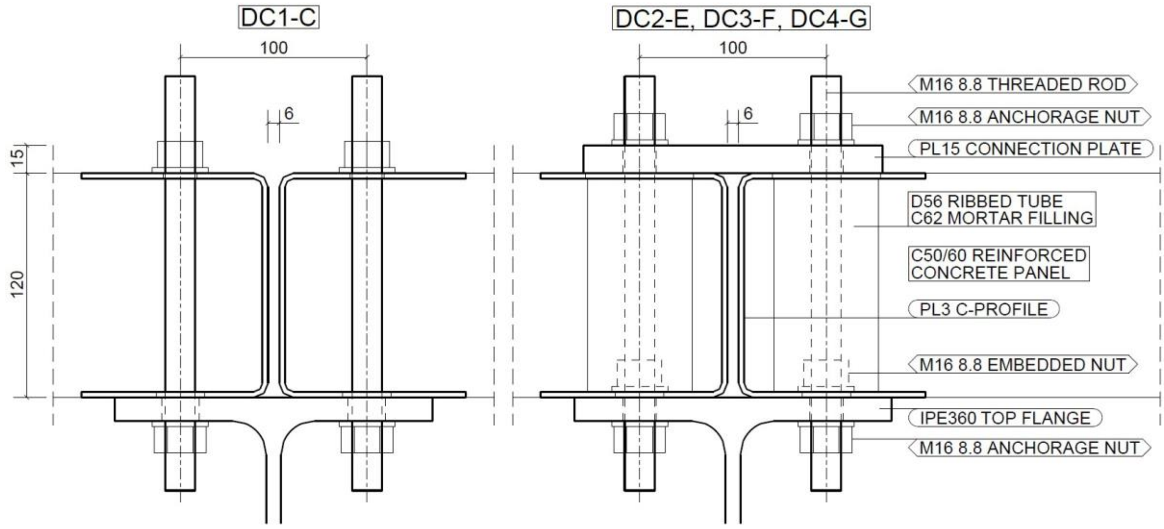

Figure 9. Details of the demountable shear connections

Figure 10. Prepared test specimens

During four-point bending, the mid-span deflection was measured, while end slip and internal slip were recorded using LVDTs. Strain gauges on the steel sections and concrete slabs were used to monitor stress development. Material testing indicated compressive strengths of 76.2 MPa for the concrete and 70.6 MPa for the mortar filling, and ultimate tensile strengths of 941.8 MPa for the connectors, 544.6 MPa for the IPE360 section, and 508.0 MPa for the C-profiles. A prepared test specimen is shown in *Figure 11*.

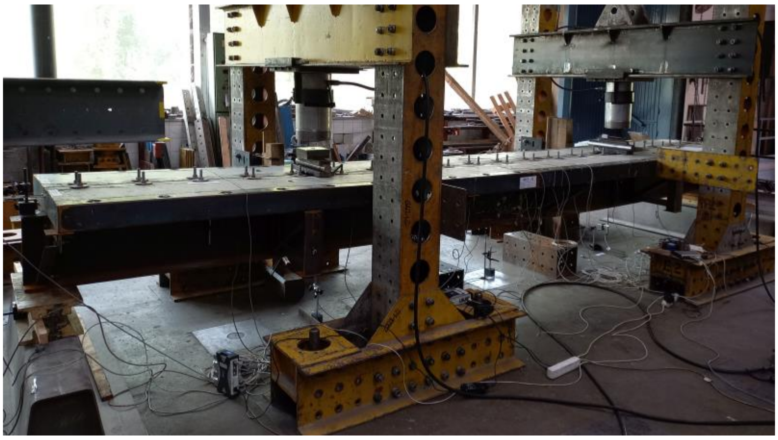

Figure 11. Test setup with specimen DC4-G – loading frames and measurement equipment

All specimens showed ductile global behaviour, with failure governed by combined plastic shear and bending of the bolts at the beam ends, consistent with the push-out response, and accompanied by increasing beam deflection and panel end slip. The force-deflection curves are provided in *Figure 12 (left)* for every specimen, which remained linear up to the yielding of the steel beam's lower flange, followed by a plastic phase to peak load and a moderately ductile post-peak response. The concrete panels remained predominantly elastic, with only minor cracking near the tension plane at ultimate load. The large plastic deformation is presented in *Figures 12 (right).*

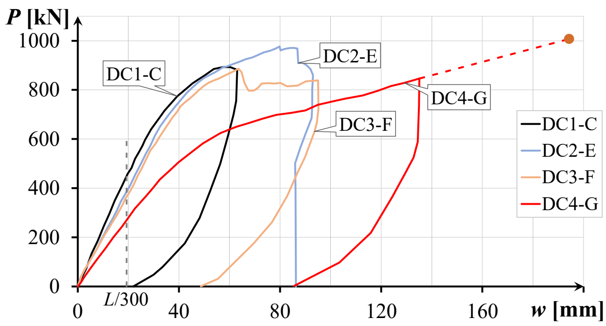

Figure 12. Force-deflection diagrams comparison (left) and plastic deformation of specimen DC4-G (right)

The two-panel beams (DC1-C, DC2-E, DC3-F) exhibited similar stiffness and resistance with moderate ductility. DC1-C was the stiffest, attributed to its higher concrete strength and the directly embedded connector detail, whereas the mortar filling solutions in DC2-E and DC3-F produced a softer response and improved connector force sharing without an apparent increase in resistance. For DC3-F, the connection plates did not improve ultimate performance; the response was governed by non-uniform slip and limited load redistribution. DC4-G with a multi-panel arrangement was the most deformable and ductile, and achieved the highest resistance, consistent with improved redistribution through relative panel movement and more effective connector force distribution. In this configuration, connection plates are essential for transferring longitudinal forces between panels.

Force-end slip curves revealed the shear connector and panel movement characteristics, showing symmetric, minimal end slip. DC2-E and DC3-F showed slight asymmetry in slip development. DC4-G exhibited distributed slip and multiple nonlinear transitions, due to individual panel activation, enabling a more even stress distribution among connectors. *Figure 13* represents the force-end slip diagrams for DC1-C and an end slip comparison.

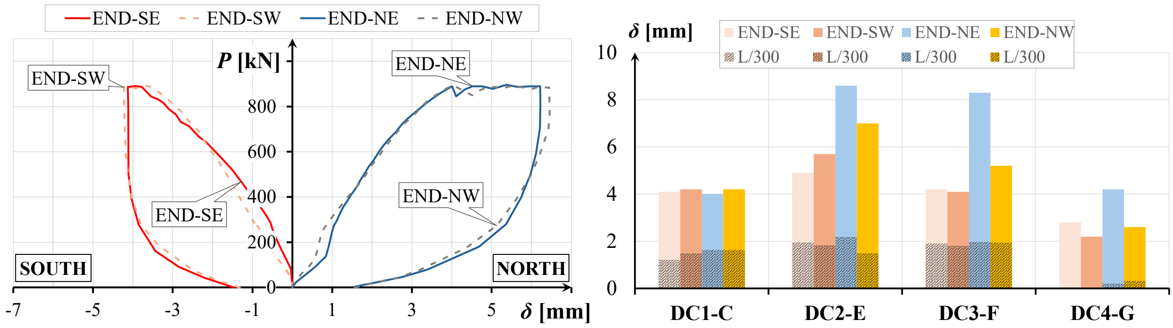

Figure 13. Force-end slip diagrams of specimen DC1-C (left) and end slip comparison (right)

Strain measurements indicated yielding in the lower steel flange, followed by plasticity extending into the web at higher load, while the concrete remained linear to ultimate behaviour. The neutral axis shifted during loading, indicating redistribution under partial shear connection. The force-strain diagram and the strain distribution of DC1-C are shown in *Figure 14*.

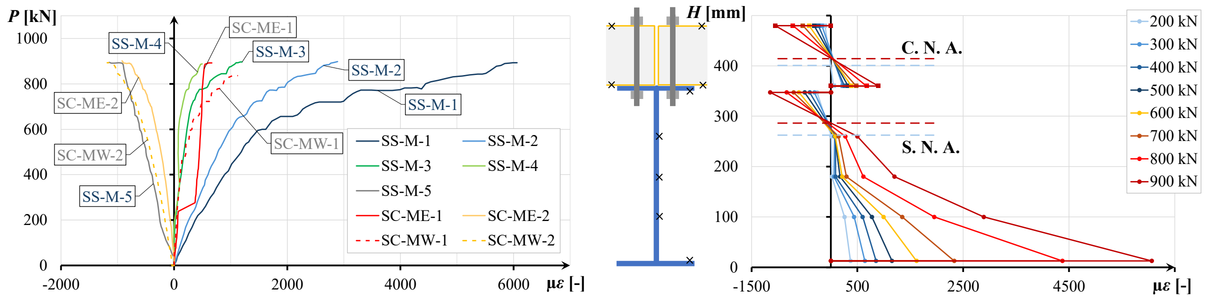

Figure 14. Force-strain diagrams (left) and strain distribution diagrams of specimen DC1-C (right)

At the serviceability deflection limit ($L/300 = 19.3$ mm), the response remained elastic, with no evidence of plastic deformation. The maximum measured end slip was 2.2 mm, without cracking, indicating compatibility with dismantling, although reassembly was not tested.

In conclusion, embedded nuts in mortar filling, combined with enhanced bolt-hole clearance, lead to reduced initial stiffness but improved ductility and a more favourable shear force distribution among connectors. This highlights that construction tolerances and accurate bolt positioning are governing parameters for the effectiveness of the shear connection and for the composite beam stiffness and ultimate response. For multi-panel arrangements, connection plates are required to transfer longitudinal forces between adjacent panels and to maintain structural integrity. The experimental programme verified that the proposed system achieves adequate structural performance while enabling practical assembly and disassembly.

5 Numerical analysis and behaviour of the composite beams

To extend the study of the composite beam and to develop a mechanical model and support a Eurocode-consistent design approach, a finite element model was developed in ANSYS [20] and applied to the tested specimens with continuous panels: DC1-C and DC2-E/DC3-F. Specimen DC4-G, with a longitudinally separated panel arrangement, due to its complexity, is out of the scope of this research. The global model represents only half the beam length, with a symmetry boundary condition at midspan. The IPE360 steel beam was modelled using shell elements, whereas the concrete panels and C-profiles were modelled using solid elements. The shear connection was idealised using nonlinear spring elements between the steel flange and the panels. Frictionless contact definitions were assigned between the relevant interfaces to transfer only vertical forces, consistent with the experimental intent. Steel material behaviour was defined by multi-linear stress-strain diagrams based on measured properties, while concrete was modelled as linear elastic, as no plastic behaviour was observed during the tests. The analysis was run under incremental displacement control with a maximum increment of 0.2 mm, a maximum element size of 25 mm, and mesh convergence was checked. The general details of the numerical model are shown in *Figure 15*. Connector spring curves were calibrated from the push-out results using two bounding definitions: SUP (supremum) and INF (infimum). The SUP representation neglects preloading and corresponds to favourable bolt positioning with higher initial stiffness, whereas the INF includes preloading and captures unfavourable positioning with reduced initial stiffness due to initial slip but increased ductility. The applied spring characteristics for both connector types are provided in *Figure 16*.

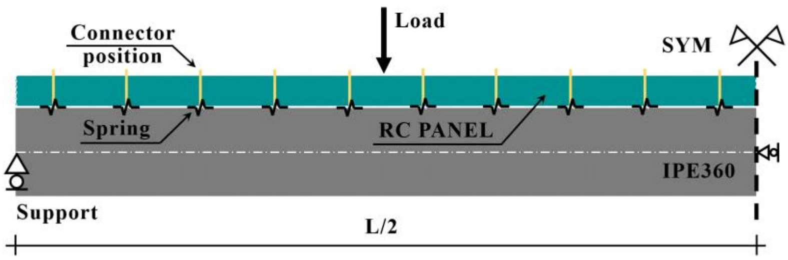

Figure 15. General details of the numerical model

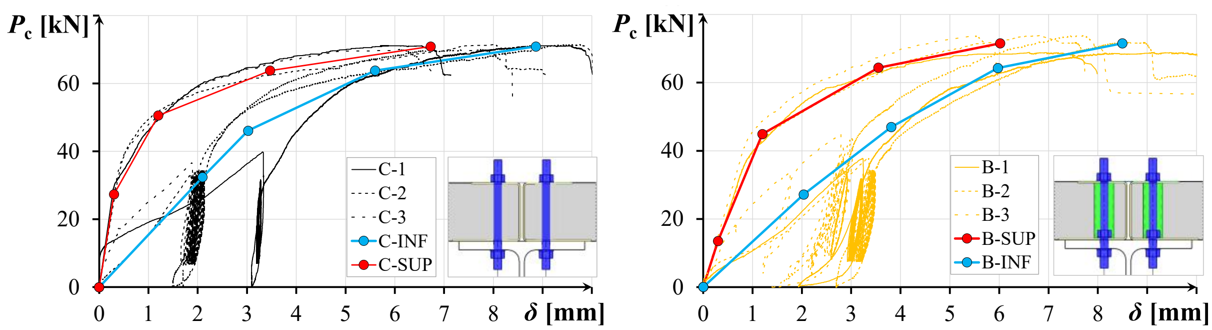

Figure 16. Spring characteristics for DC1-C (left) and DC2-E/DC3-F (right)

The numerical analyses captured the observed response and failure mode, namely, an initial linear range followed by yielding of the steel member and the development of large plastic deformations. The deflected shapes with Huber-Mises-Hencky (HMH) equivalent stress distributions at failure for the SUP models of DC1-C and DC2-E/DC3-F are shown in *Figure 17*. *Figure 18* compares the numerical SUP and INF bounds with the measured force-deflection curves for the analysed specimens, showing that the tests fall between the two envelopes, consistent with variability in bolt positioning within the tested beams. At ultimate load, the INF representation provides higher deformation capacity and may mobilise higher resistance through improved redistribution and connector utilisation (as reflected by DC2-E). In contrast, the SUP model better represents specimens with a stiffer initial response and provides closer estimates of deflection and resistance (as for DC1-C and DC3-F), confirming that bolt position is a governing parameter for ultimate behaviour.

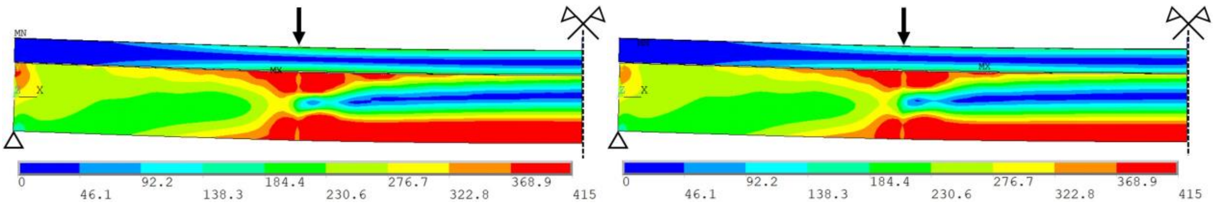

Figure 17. Numerical result – HMH stress at failure load of DC1-C (left) and DC2-E/DC3-F (right) in MPa

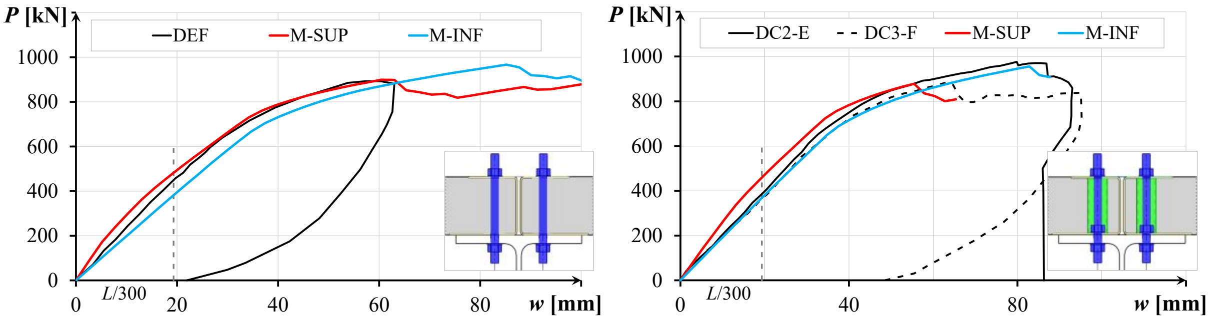

Figure 18. Numerical results – force-deflection diagrams for DC1-C (left) and DC2-E/DC3-F (right)

The simulations reproduced the experimental trends in stiffness, resistance, and ultimate deflection and a large-scale parametric study was conducted to investigate variations in steel grade, section geometry, degree of shear connection, and span, confirming the system's suitability for typical building applications. The results show that steel grade, steel-section geometry and degree of shear connection are the dominant drivers of stiffness and resistance. In contrast, concrete grade and panel thickness have only secondary effects. The C-profile in the panel, with a minor confining effect, is able to enhance both local and global structural performance, in addition to its constructional benefits, and should be considered in the design. *Figure 19* represents the effect of the steel grade and the steel section for specimen DC1-C, and it can be concluded that the higher-strength steel enhances the performance of the beams, whereas maintaining the same deflection, while increasing the cross-section greatly improves both the initial stiffness and the ultimate resistance, but reduces the corresponding deflections at failure, indicating lower ductility. The results indicate stable, predictable performance within a practical design range, forming the basis of the proposed calculation method.

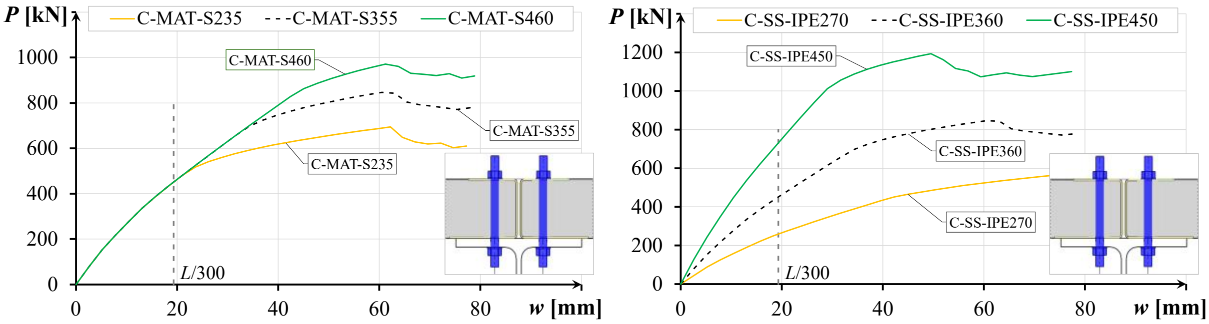

Figure 19. The effect of the steel grade (left) and steel section(right) for specimen DC1-C

Slip distributions govern the global response of the composite beams and were evaluated against the numerical predictions at 200 kN, 600 kN and 900 kN (ultimate). *Figure 20* illustrates the results for DC1-C and DC2-E/DC3-F. The measured distributions were asymmetric between the two sides, and with increasing load, the slip magnitude increased, and the curve shape evolved, consistent with the measured force-end slip response. The models captured these trends and the overall distribution pattern, although they generally overestimated slip amplitudes along the span. The experimental distribution is closely approximated by a cosine function, in line with previous research on composite beams. An apparent change in the slip profile occurred at the load introduction points, beyond which slip decreased markedly. After yielding of the steel flange, no pronounced plastic slip redistribution was observed, unlike the behaviour reported for composite beams with more ductile headed studs. Nevertheless, the nonlinear response indicates continued contribution of the connectors within the constant moment region, with reduced effectiveness towards mid-span.

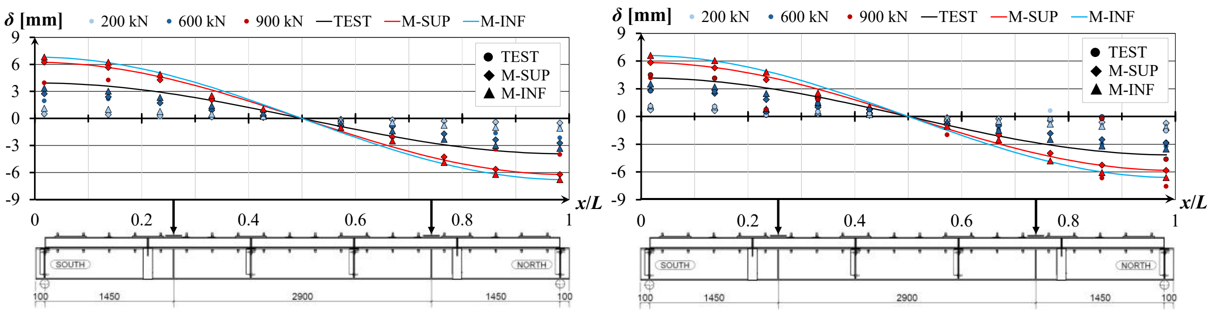

Figure 20. The slip distribution of test specimen DC1-C (left) and DC2-E/DC3-F (right)

Slip and longitudinal shear force distributions were evaluated for different degrees of shear connection during the numerical simulation, as key parameters for the global behaviour, and are presented in *Figure 21* for DC1-C for half the span, assuming symmetric behaviour.

The slip distributions retain a similar shape for different degrees of shear connection, and are well approximated by a cosine function, with a distinct break at the points of load introduction, as observed previously. The shear force distributions show a comparable, monotonically decreasing pattern, indicating that end connectors remain most highly engaged and that force remains nearly constant up to the loading points, supporting the common assumption that beam-end connectors govern shear transfer efficiency. Increasing the degree of shear connection reduces slip and shear force along the span – especially between the loading points and mid-span – while mobilising more end connectors and increasing global resistance.

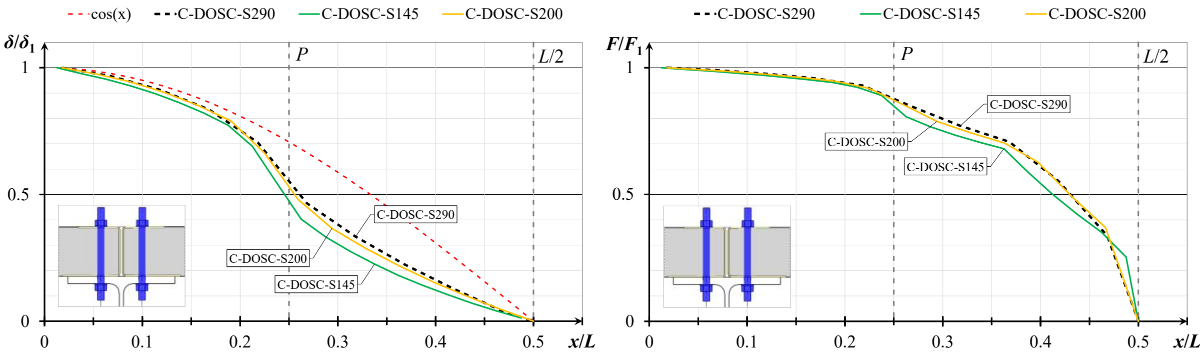

Figure 21. The effect of different degrees of shear connection on slip distribution (left) and bolt force distribution (right) for specimen DC1-C

Loading introduction conditions on the composite beam modify the bending moment and vertical shear force diagrams and, therefore, change the longitudinal slip and shear force. In the proposed system, the demountable shear connection exhibits elastic-plastic behaviour. Consequently, the slip profile and longitudinal load transfer are governed by the current connector resistance and directly control the beam's load-bearing capacity. These effects were analysed and found to be a key parameter influencing the ultimate behaviour.

Accordingly, the proposed system provides plastic redistribution capacity – consistent with its measured deformation capability of the connectors – although less efficiently than headed studs. The Eurocode 4 plastic design concept may therefore be adopted to estimate plastic bending resistance, with modification provided that the calculation procedure is adapted to reflect the specific slip development and connector characteristics of the proposed system.

6 Design method development

The proposed Eurocode-consistent algorithm evaluates composite beam bending resistance at ULS using both elastic and plastic approaches and includes SLS checks for deflection and end slip. It adopts a cosine-based slip distribution and explicitly implements the connector-specific multi-linear load-slip response, accounting for bolt-hole tolerances and reduced initial stiffness. The method is formulated for simply supported, symmetric composite beams in sagging bending, comprising a Class 1 or 2 steel I or H section with steel grades S235-S460, connected to a longitudinally continuous C50/60 concrete panel by uniformly spaced demountable shear connectors with a degree of shear connection higher than 45%. It targets building applications at ambient temperature under vertical loading, with spans of 5-8 m and span-to-depth ratios of 13-22, and is defined for connector models with a maximum bolt-hole clearance of 4 mm. In accordance with Eurocode 4 Annex B, the characteristic connector resistance from push-out testing is taken as 0.9 times the lowest measured failure load. In the proposed procedure, the measured connector load-slip curves are therefore converted into characteristic multi-linear models by applying a downward shift while preserving the original shape. The resulting SUP and INF characteristic mechanical models for both connector types are given in *Figure 22*.

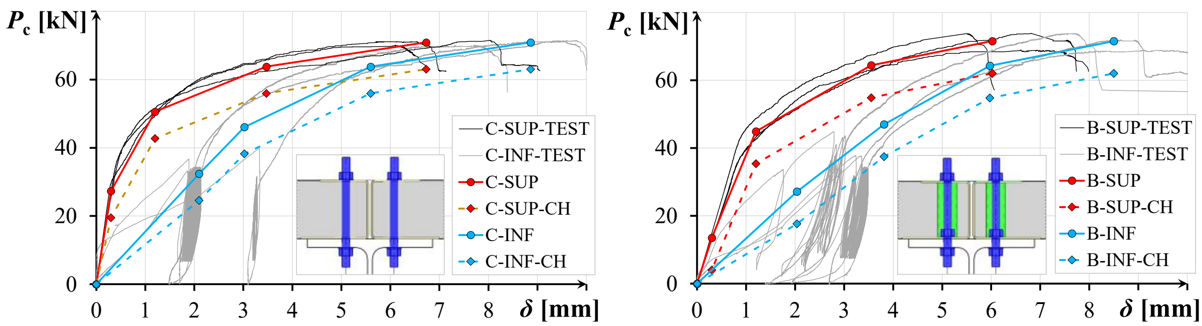

Figure 22. The characteristic mechanical models for DC1-C, connector type C (left) and DC2-E/DC3-F, connector type B (right)

In the ultimate limit state, the method allows plasticity in the steel beam and shear connectors, together with limited cracking of the concrete panel, until the first connector fails. The plastic moment resistance is obtained by determining an effective connector resistance from a cosine slip distribution with a limiting end slip of $s_1 = 4.0$ mm, evaluating with the conservative SUP connector model, and refining with a novel cosine-based weighting function corresponding to the slip distribution and to account for the varying effectiveness of individual connectors along the span. The calculation procedure steps are as follows:

1. Assume a cosine-based slip distribution $s(x)$ along the beam length, with the end slip $s_1 = 4.0$ mm, and compute slip values, s_i, for each connector position according to Eq. (1), where x is the position of the connector, and L is the beam span.

$$s_i = s(x_i) = s_1 \cos\left(\frac{\pi x_i}{L}\right) \tag{1}$$

2. Determine the resistance of each connector, P_i, from its slip, s_i, and the corresponding SUP mechanical model (according to *Figure 22*).
3. Apply the cosine-based weighting function, $w(x)$, and calculate the weights, w_i, for each connector according to Eq. (2).

$$w_i = w(x_i) = \cos\left(\frac{\pi x_i}{L}\right) \quad (2)$$

4. Normalise the weights to obtain $w_{i,norm}$ using Eq. (3).

$$w_{i,norm} = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (3)$$

5. Compute the weighted shear force of each connector, $P_{i,w}$, in accordance with Eq. (4).

$$P_{i,w} = P_i \cdot w_{i,norm} \quad (4)$$

6. Sum the weighted shear forces of all connectors to obtain the characteristic effective shear resistance, $P_{Rk,eff}$, according to Eq. (5).

$$P_{Rk,eff} = \sum_{i=1}^{n} P_{i,w} \cdot w_{i,norm} \quad (5)$$

7. Determine the design effective shear resistance, $P_{Rd,eff}$, by applying the partial factor $\gamma_v = 1.25$ according to Eurocode 4.
8. Proceed to calculate the plastic bending resistance of the composite beam using the Eurocode 4 plastic design method.

An elastic design approach may alternatively be used, allowing only limited plasticity in the shear connectors while keeping stresses in steel and concrete within the prescribed limits. The elastic bending resistance is obtained from the composite second moment of area, $I_{y,comp}$, evaluated from the steel section and panel geometry together with the connector stiffness, $k_{sc,d}$, and the equivalent connector spacing, $s_{sc,eq}$, with the resulting resistance governed by the stress limits as defined in [18]. The connector stiffness, $k_{sc,d}$, is taken from the INF mechanical model, which conservatively represents the initial elastic response, including the effect of initial slip. It is defined as the initial slope of the load-slip curve, giving 11.7 kN/mm and 8.7 kN/mm for connector types C and B, respectively.

At the serviceability limit state, the composite beam is verified for in-service performance by checking stress limits, deflection and end slip, with end slip controlled, in particular to preserve reusability. Under characteristic service combinations, the steel section, concrete panel and shear connectors are required to remain in the elastic range. The checks are performed using the composite elastic second moment of area, $I_{y,comp}$, together with the same elastic connector stiffness, $k_{sc,d}$, adopted for the elastic analysis. Based on the experimental and numerical evidence for this system, an end slip limit of 3.0 mm is adopted as a conservative criterion, accounting for bolt-hole clearance and elastic bolt deformation under service loading.

Figure 23 compares the experimental and numerical moment-deflection response of specimen DC1-C and DC2-E/DC3-F with the calculated elastic and plastic bending resistances, using the measured specimen properties and the adopted connector models for consistency. The comparison indicates that the plastic resistance derived with SUP bound reproduces the ultimate response, whereas the elastic resistance and the serviceability deflection criterion (*L*/300) are consistent with INF bound. The procedure provides an accurate and conservative design envelope in which SUP governs ULS resistance, and INF governs SLS stiffness.

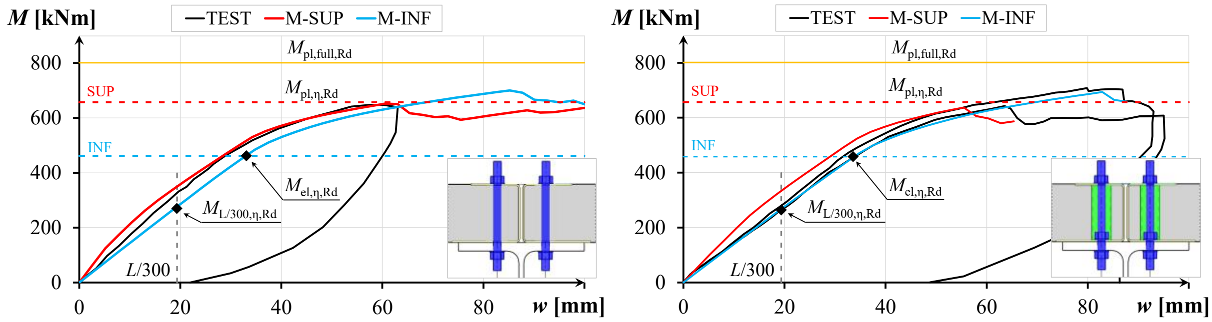

Figure 23. Validation of the proposed calculation procedure for specimen DC1-C (left) and DC2-E/DC3-F (right) – comparison of moment-deflection responses

The proposed calculation method was validated against both experimental and numerical results and applied to multiple cases in the parametric study, consistently demonstrating good accuracy and enabling engineers to design the proposed demountable composite beams with reliability while accommodating reusability, thereby contributing to more sustainable construction practices.

7 Conclusions of the dissertation

7.1 New scientific results

Thesis 1

I have developed a novel demountable shear connection for a steel-concrete composite floor system, which supports sustainability-driven design by adapting the detailing of the industrial partner and enabling straightforward fabrication, erection, and deconstruction procedures. The characteristic response of this connection has not been reported in the literature to date. I have analysed and evaluated its structural behaviour through a push-out test programme and numerical simulations.

T1a) I have proposed a fully prefabricated, reusable demountable composite floor system comprising a hot-rolled steel beam, precast reinforced-concrete panels with embedded steel profiles, connection plates, and mortar filling, connected by demountable shear connectors formed by threaded rods and embedded nuts. Within this system, I have analysed six different shear-connection configurations through push-out tests, from which I finally proposed two optimised connector solutions.

T1b) I have characterised the structural behaviour of the proposed demountable shear connectors based on the push-out tests, demonstrating a consistent three-stage load-slip response with adequate stiffness, resistance and ductility, and identified the governing failure modes. From both experimental and numerical investigations, I have quantified the influence of connector detailing and key parameters on connector performance.

Publications corresponding to the thesis: [KK1] – [KK10]

Thesis 2

I have designed and conducted a full-scale beam test programme, involving four different structural arrangements on 5.8 m span specimens, to analyse and evaluate the global behaviour of the proposed composite beam, whose system configuration has not been previously reported in the literature.

T2a) I have confirmed that the proposed demountable composite beam provides adequate stiffness, resistance, and a ductile global failure mechanism, exhibiting elastic behaviour at serviceability load levels and demonstrating practical potential for dismantling and reuse. I have evaluated the effects of different configurations, structural arrangements and shear connector details.

T2b) I have demonstrated that a multi-panel slab arrangement provides significantly greater ductility, with extensive plastic deformation, pronounced panel movements, and improved redistribution of forces among the connectors. Compared with the continuous two-slab arrangements, the multi-panel configuration exhibited a 10-13% increase in ultimate resistance, while achieving 2.4-3.6 times greater ultimate mid-span deflection and 30-40% lower global stiffness. I have shown that connection plates are essential in multi-panel configurations to ensure longitudinal force transfer between adjacent panels and to maintain overall system integrity.

Publications corresponding to the thesis: [KK11], [KK12]

Thesis 3

I have developed and validated numerical models for the two-slab arrangement of the proposed demountable steel-concrete composite beam system to extend the experimental investigation of its global behaviour. I have conducted a large-scale parametric study confirming the system's suitability for typical building applications.

T3a) I have proposed combining mechanical models of the demountable shear connectors derived from push-out tests, in which a favourable (SUP) model represents a stiffer connector response with negligible initial slip, while an unfavourable (INF) model characterises a softer connector response with pronounced initial slip due to bolt-hole clearance, in order to obtain an enveloping and adequately safe representation of the structural response for implementation in global numerical models and for use in the proposed design method.

T3b) I have identified, through a parametric study, the key parameters governing global behaviour, in particular the steel grade, the geometric properties of the steel section, and the degree of shear connection, and I have verified the system's applicability in practice.

T3c) I have analysed the slip and bolt-force distributions and shown that, for four-point bending, the slip distribution can be tolerably well represented by a cosine-based function, providing a sufficiently accurate basis for estimating the beam's load-bearing capacity. From these distributions, I have concluded that the mid-span connectors participate efficiently in force transfer due to plastic slip redistribution at ultimate behaviour, and that both the degree of shear connection and the load introduction strongly influence the ultimate resistance by governing connector efficiency.

T3d) I have shown that, the plastic moment resistance can be determined using the Eurocode-based plastic design approach, with the modification that the effective shear connector resistance is obtained from the proposed connector mechanical models and a cosine-based slip distribution along the span, thereby reflecting the specific behaviour of demountable bolted connectors.

Publications corresponding to the thesis: [KK13], [KK14]

Thesis 4

I have developed a Eurocode-based design method for the proposed demountable composite system, extending and applying the existing Eurocode 4 procedure for composite beams to the specific behaviour of demountable shear connectors. The method enables the determination of composite beam moment resistance in the ultimate limit state using both plastic and elastic approaches and provides deflection and end-slip limits for the serviceability limit state within the investigated range, specifically span-to-depth ratios of 13-22, steel grades S235-S460, concrete grade C50/60, and a degree of shear connection higher than 45%.

T4a) I have formulated the effective shear connector resistance for plastic design using a cosine-based slip function with a limiting end slip of 4 mm, evaluated using the SUP connector model, and refined it using a novel cosine-based weighting function to account for the varying effectiveness of individual connectors along the span.

T4b) I have proposed the shear connector stiffness, $k_{sc,d}$, to be taken as the initial stiffness of the INF characteristic connector model for the elastic determination of moment resistance, deflection and end slip. I have recommended a 3.0 mm serviceability end slip limit under the characteristic load combination to reflect elastic connector deformation and bolt-hole clearance effects.

T4c) I have validated the proposed method against experimental and numerical results, and applied it to multiple cases from the numerical parametric study, consistently demonstrating good accuracy and providing a practical basis for a reliable design that accommodates dismantling and reuse.

Publications corresponding to the thesis: [KK15], [KK16], [KK17]

7.2 Publications on the subject of the theses

[KK1] K. Király and L. Dunai, "Experimental Study of Novel Demountable Shear Connectors for Steel-concrete Composite Buildings," *Period. Polytech. Civ. Eng.*, vol. 68, no. 2, pp. 647–656, 2024, doi: 10.3311/PPci.22732.

[KK2] K. Király, L. Dunai, L. Calado, and A. B. Kocsis, "Demountable shear connectors – constructional details and push-out tests," *CE/Papers*, vol. 6, no. 3–4, pp. 53–58, 2023, doi: 10.1002/cepa.2416.

[KK3] K. Király, L. Borsi, L. Dunai, and N. Kovács, "Development and evaluation of demountable shear connectors for steel–concrete composite structures," *Proc. Inst. Civ. Eng. – Struct. Build.*, 2025, doi: 10.1680/jstbu.24.00160.

[KK4] K. Király, L. Borsi, N. Kovács, L. Dunai, and A. B. Kocsis, "Experimental and Numerical Studies of Novel Demountable Shear Connections," in *Proc. 15th Nordic Steel Construction Conf. (Nordic Steel 2024)*, Luleå, Sweden, 2024.

[KK5] K. Király, L. Borsi, N. Kovács, and L. Dunai, "Investigation of the behaviour of demountable shear connectors embedded in concrete and mortar," in *Proc. 15th fib Int. PhD Symp. in Civil Engineering*, Budapest, Hungary, 2024, no. 66, pp. 317–324.

[KK6] K. Király, L. Borsi, N. Kovács, and L. Dunai, "Numerical studies on the local phenomena in the behaviour of demountable shear connections," in *Proc. 14th Central European Congress on Concrete Engineering (CCC 2024)*, R. Nenadlová and P. Vejda Johová, Eds., 2024, pp. 253–266, ISBN: 978-80-908943-1-0.

[KK7] K. Király, "Fenntartható öszvérszerkezetek; Doktoranduszi kutatás előkészítése [Sustainable composite structures: preparation for doctoral research]," *Acélszerkezetek (MAGÉSZ)*, vol. XIX, no. 1, pp. 38–43, 2022 (in Hungarian). [Online]. Available: https://www.magesz.hu/wp-content/acelszerkezetek/aszerk2201.pdf

[KK8] K. Király, "Beszámoló az Eurosteel 2023 konferenciáról. Középpontban a fenntartható építőipar [Report on the Eurosteel 2023 Conference: Focus on sustainable construction],” *Acélszerkezetek (MAGÉSZ)*, vol. XX, no. 4, pp. 10–12, 2023 (in Hungarian). [Online]. Available: https://www.magesz.hu/wp-content/acelszerkezetek/aszerk2304.pdf

[KK9] K. Király, “A fenntartható építőipar törekvései és a tartószerkezetek beépített karbonlábnyoma [Sustainable construction ambitions and the embodied carbon of structures],” *Mérnök Újság*, vol. XXXII, no. 7, pp. 42–45, 2024 (in Hungarian). [Online]. Available: https://mernokvagyok.hu/wp-content/uploads/2024/12/Mernok-Ujsag-2407.pdf

[KK10] K. Király, L. Dunai, L. Calado, and A. B. Kocsis, “Push-out tests of demountable shear connectors for sustainable composite structures,” *Steel Constr.*, vol. 17, no. 4, pp. 200–211, 2024, doi: 10.1002/stco.202300044.

[KK11] K. Király, L. Dunai, L. Calado, and A. B. Kocsis, “Experimental study on demountable steel-concrete composite beams,” *J. Constr. Steel Res.*, vol. 231, 2025, doi: 10.1016/j.jcsr.2025.109582.

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[KK15] K. Király, L. Dunai, L. Calado, and A. B. Kocsis, “Development and design of demountable composite beams,” *Structures*, submitted for publication, 2025.

[KK16] K. Király, L. Dunai, and A. B. Kocsis, “Szétszerelhető öszvérgerendák szerkezeti viselkedése és tervezése [Structural behaviour and design of demountable composite beams],” in *Proc. XXIX Nemzetközi Építéstudományi Konferencia*. 2025.

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7.3 Further research and development

Future work will focus on industry-led product development and pilot implementation with KÉSZ Group, bim.GROUP Ltd. prioritises optimising the precast, prefabricated reinforced concrete panel concept, including refining the panel geometry and reinforcement arrangement to support enhanced manufacturing, transportation, and construction requirements, as well as repeatable quality assurance, while considering long-term durability and sustainability. Building on the observed behaviour of multi-panel arrangements, the diaphragm action of the slab system under lateral loading represents a crucial research direction. The global in-plane stiffness and resistance, load-transfer mechanisms of panels, and the influence of joint detailing on diaphragm performance should be investigated. Besides, further studies should extend joint behaviour analysis to continuous beams and beam-to-column connections, assessing stiffness, resistance, damage localisation, and reusability across multiple life cycles. Further investigations should extend the scope of joint behaviour to include continuous and beam-to-column configurations, with an emphasis on disassembly and reuse, and on quantifying slab diaphragm action under lateral loading. Additional strands address fire behaviour, serviceability and dynamics, especially vibration performance, besides cyclic and seismic diaphragm response, including joint hysteresis and performance criteria linked to reusability.

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