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Experimental and Numerical Studies of Novel Demountable Shear Connections

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ABSTRACT

Sustainable composite structures for building construction are assembled using demountable structural elements and shear connectors that can be reused and fit into the circular economy. The current research and development project, in cooperation with Budapest University of Technology and Economics and KÉSZ Group, bim.GROUP Ltd, Hungary, aims to design a novel demountable steel-concrete composite slab system for buildings. Based on the international trends and the practice of the company, new structural details were developed using precast reinforced concrete panels, embedded bolts, and through bolts – as the demountable shear connectors – with steel assemblies and mortar filling to provide better tolerances. Enhancing the tolerances means decreasing the initial slip and the stiffness reduction of the composite beam, which is the critical phenomenon of demountable composite structures. A push-out experimental program was designed and completed to study the behaviour of the developed shear connections. During the push-out tests, it was observed that the novel shear connections have proper behaviour with sufficient stiffness, resistance, and ductility. In parallel with the tests, a numerical model is developed in the ATENA program to extend the experimental study, which is the basis of the further development of the connectors. The paper presents the developed structural details and the conclusions of the push-out experimental program, with the first results of the numerical analyses.

Keywords: sustainable structure, demountable composite slab, shear connector, push-out test, numerical analysis

1 INTRODUCTION

The sustainable construction sector plays a significant role and holds the potential to contribute to a circular economy through the recycling of construction materials and the reuse of structural components. Demountable steel-concrete composite structures prove to be highly efficient in fulfilling sustainable goals due to their minimal energy and labour requirements during the deconstruction process. To disassemble composite structures, it is necessary to use a demountable shear connector, which could be a structural bolt instead of a welded headed stud. This solution is applicable in practice because it meets the necessary resistance and ductility requirements.
Considering tolerances is essential because the reusing process requires oversized bolt holes in the structural elements. This results in an initial slip before the activation of composite action, leading to a reduction in the stiffness of the composite beam. It is important to apply proper design and technology to mitigate this unfavourable phenomenon. In recent research, several solutions are proposed to prevent the initial slip. A more comprehensive review and summary were published previously by the authors (1).

The ongoing research and development program is currently in progress through the cooperation of the Budapest University of Technology and Economics and the KÉSZ Group, bim.GROUP Ltd, Hungary, to develop a novel demountable steel-concrete composite structural frame system for buildings. The proposed structural system fulfils the sustainable requirements by following international trends and adapting to conditions based on the experience and practice of the industrial partner. This research focuses on the investigation of the structural behaviour of the new structure and the development of a Eurocode-based design method.

The demountable shear connection, the key element of the proposed structural system, is a bolted shear connection with novel features that determine the characteristics of the structural behaviour (initial stiffness, resistance, and ductility). This connection undergoes examination through push-out tests and numerical analyses. In the subsequent phase of the research, full-scale beam tests will be conducted to study the behaviour of a composite beam, with a specific focus on the initial slip, stiffness reduction, and continuity of the slab during the demounting and reassembling process.

This paper presents the proposed structural solution, the summarised results and evaluation of the push-out experimental program, and the numerical model.

2 THE PROPOSED SHEAR CONNECTOR

The proposed structural system is constructed with hot-rolled steel beams and precast reinforced concrete panels connected by embedded threaded rods, which are the demountable shear connectors. The innovative components of the developed connectors can be seen in *Fig. 1 a)* and detailed as follows:

1. precast elements without on-site concreting for improved construction accessibility,
2. embedded steel C-profiles to enhance panel tolerances and bolt positioning,
3. mortar filling around the connectors to reach better tolerances, and
4. connection plate between the precast slab elements to provide global stiffening.

This structural approach facilitates a straightforward assembly and disassembly process using uncomplicated technologies, thereby decreasing construction time and costs. Additional technical details of the proposed configuration can be found in (1).

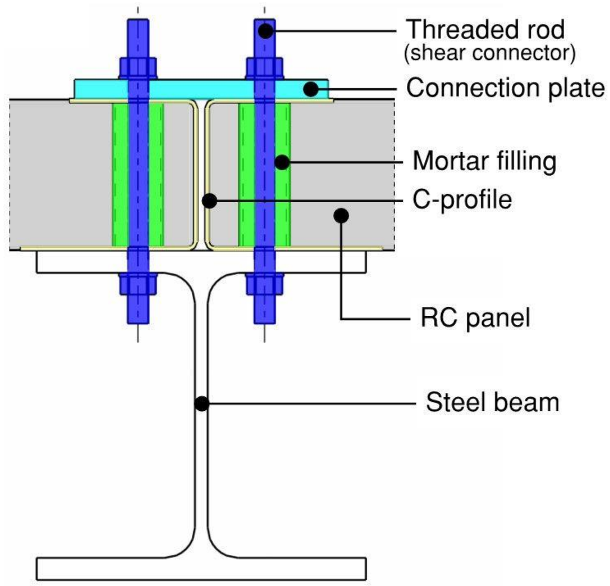
3 THE PUSH-OUT EXPERIMENTAL PROGRAM

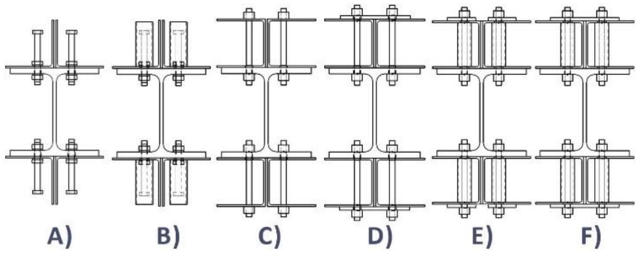
3.1 The push-out specimens and measurement details

To investigate the behaviour of the proposed shear connector along with structural details such as oversized holes, C-profiles, through bolts, mortar filling, and connection plates, a push-out experimental program was designed and executed. This program involved six distinct structural arrangements, each comprising three specimens, resulting in a total of eighteen specimens. The tests were completed in the Structural Laboratory of the Budapest University of Technology and Economics. The specimen details can be seen in *Fig. 1 b)*.

A push-out test specimen comprises an HEB260 S235 steel column connected to four independent precast reinforced concrete panels of C50/60 grade. The connection is established using two M16 8.8 threaded bolts or through bolts (threaded rods) for one panel, resulting in a total of eight shear connectors per test specimen.

Specimens A) and B) are designed with L-steel and embedded structural bolts with embedded nuts, representing an initial concept. A C-profile is used in the panel for the remaining specimens, featuring larger oversized holes on the steel flange side. This design prevents direct contact between the shear connector and the bolt hole of the assembly. The connectors for these types consist of embedded threaded rods without embedded nuts inside the concrete. Nuts and washers are positioned at the top of the panels and the bottom of the steel flanges. Specimens B), E), and F) were constructed by on-site mortar filling near the connectors, which has 62 MPa compressive strength with 26 GPa modulus of elasticity. Specimens D) and F) are equipped with a connection plate designed to enhance the stiffness of the shear connector.



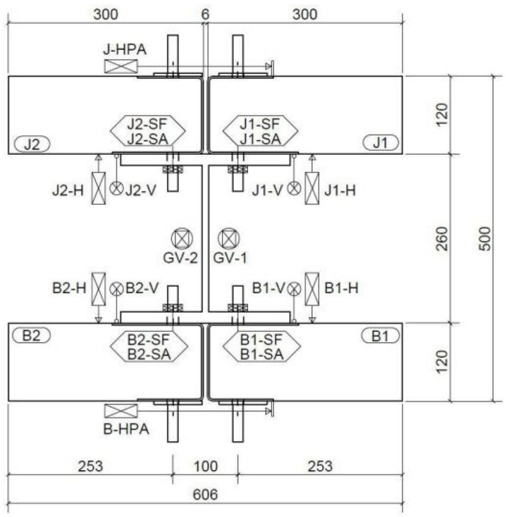


A) Embedded bolt
B) Embedded bolt, mortar filling
C) Through bolt
D) Through bolt, connection plate
E) Through bolt, mortar filling
F) Through bolt, connection plate, mortar filling

a) b)

Fig. 1 a) The proposed structural solution and b) the specimen types of the push-out experimental program

According to guidance for demountable composite structures (2), the estimated resistance of one shear connector is 75,4 kN, and the specimen is 602,9 kN, using characteristic material properties. The test setup and loading system are designed in accordance with Eurocode 4 (3). The process begins with 25 preloading cycles aimed at eliminating friction between the steel flanges and the panels, and the initial slip of the connectors could occur. The loading is applied using the WPM 6000 kN capacity testing machine. Throughout the tests, both global and relative vertical displacements were measured by LVDTs. Strain gauges, positioned above each shear connector in the loading direction, monitored the stresses in the flanges of the steel section, providing insight into the stress distribution of the bolts. A prepared push-out specimen and the sensor setup are shown in *Fig. 2*.



a) b)

Fig. 2 a) The prepared push-out test specimen and b) the setup of the sensors

According to the material tests, the concrete has an average compressive strength of 70,7 MPa, and the mortar fill has an average flexural and compressive strength of 7,5 MPa and 59,4 MPa, respectively. Additionally, the threaded rod exhibits an average tensile strength of 944,6 MPa.

3.2 The evaluation of the test results

3.2.1 General behaviour

After the preloading cycles, the measured force-relative displacement diagrams are transformed to the origin on the basis of the initial stiffnesses of each curve. The transformed graphs of the average displacement values of the four vertical LVDTs for every type of specimen are shown in *Fig. 3 a).* The ultimate force (P_e) is defined as the maximum load level reached during testing, along with the corresponding ultimate relative displacement (δ_e). Additionally, the 90% of ultimate force (P_{Rk}) is calculated, including the associated slip, before reaching ultimate resistance (δ_{Rk}). The characteristic relative displacement (δ_u) is determined following Eurocode 4 (3), requiring a minimum value exceeding 6 mm to meet ductile criteria and enable the plastic design method. The overview of the defined parameters based on the force-relative displacement diagrams can be seen in *Fig. 3 b).*

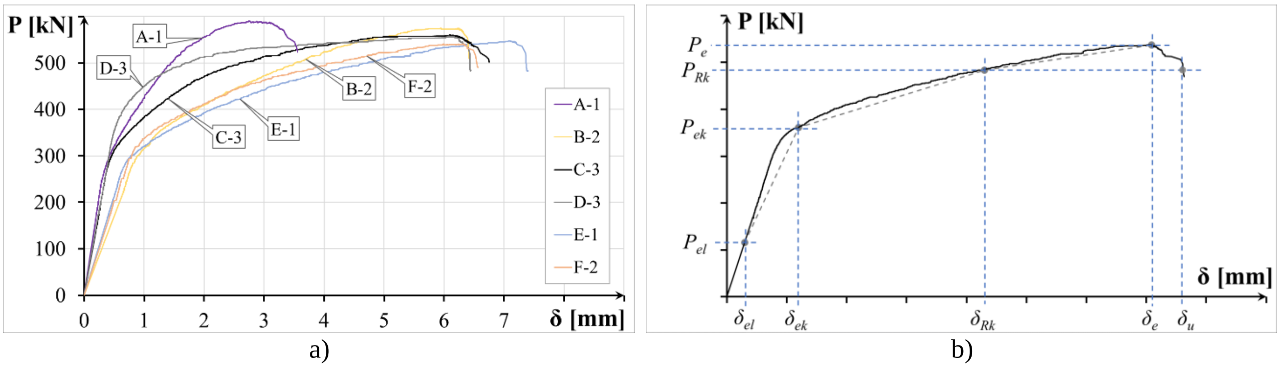


Fig. 3 a) Force-relative displacement diagram for each specimen type and b) the definition of the studied parameters

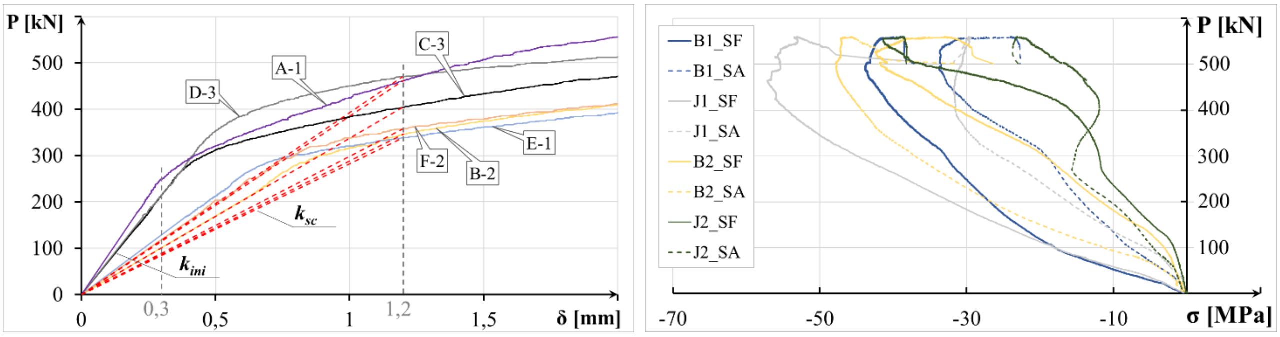
On the basis of the test results, three main stages of the behaviour are observed, the (i) elastic, (ii) plastic transition, and (iii) plastic deformation stages. After reaching the linear elastic part (P_{el}), non-linear partial plasticity development and gradual stiffness reduction occur in the plastic transition stage due to the connectors' deformation and concrete/mortar local cracking. In the final stage, following a 1,2 mm relative displacement, the shear connectors display substantial plastic deformation with major relative displacements and minor hardening branches until reaching the ultimate resistance (P_e), characterising the ductility of the shear connector.

3.2.2 Initial stiffness

For each test specimen, two stiffness values are defined. The initial stiffness (k_{ini}) is determined as the slope of the first segment of the transformed force-relative displacement diagram, calculated as the ratio of the 0,3 mm relative displacement (δ_{el}) to the corresponding force (P_{el}). Additionally, the secant stiffness (k_{sc}) is calculated as the ratio of the 1,2 mm relative displacement (δ_{ek}) to the corresponding force (P_{ek}). The definition of the initial stiffnesses is presented in *Fig. 4 a).*

3.2.3 Bolt force distribution

The analysis of the force-stress diagram revealed that non-uniform bolt force distribution, although minor stress redistribution is observed at higher load levels, but complete plastic redistribution does not occur, leading to a progressive failure mode of the shear connectors. Specimens containing mortar demonstrate a more favourable distribution of loads attributed to their increased deformation capacity. The load-transferring effect and force distribution among shear connectors depend on various factors, including the proposed shear connection, applied bolt hole clearance, actual bolt positions, shear connection ductility with bolt deformation, and local damages to concrete and mortar filling. To illustrate the effect, the force-stress diagram of test specimen C-3 can be seen in *Fig. 4 b)*, where the continuous lines show the upper and the dashed lines the lower bolts.



a) b)

Fig. 4 a) The definition of the initial and secant stiffness and b) force-stress diagram for specimen C-3

3.2.4 Failure mode of the shear connectors

The failure of the specimens occurred due to the plastic shear-bending interaction of the bolts within the plane of the steel-concrete interface, as shown in *Fig. 5 a)*. Plastic deformation and bending of the shear connectors, coupled with detachment from the concrete or mortar, are identified with local concrete cracking and spalling (*Fig. 5 b) left*). Larger bolt deformations and detachments are observed for connectors with mortar fillings (*Fig. 5 b) right*).

a) b)

Fig. 5 a) Ductile failure of the bolts and b) failure of the concrete (left) and the mortar filling (right) with the bolt deformation

3.2.5 Evaluation of the test results

The push-out experimental program results are evaluated on the basis of the previously defined aspects, including force-relative displacement diagram, initial stiffness, bolt force distribution and ultimate behaviour. The average (AV) of the evaluated *k*, *P* and *δ* values are compared and presented for each type of shear connector in *Table 1*.

Table 1. The average of the stiffnesses, ultimate forces, and relative displacements

Type	P_{el} [kN]	k_{ini} [kN/mm]	P_{ek} [kN]	k_{sc} [kN/mm]	P_{Rk} [kN]	δ_{Rk} [mm]	P_e [kN]	δ_e [mm]	δ_u [mm]
A	254,3	847,7	453,3	377,8	530,7	1,86	589,7	2,77	2,61
B	108,1	360,4	359,0	299,2	515,1	3,55	572,3	6,02	5,05
C	218,7	729,1	404,7	337,2	510,4	3,47	567,1	6,73	6,07
D	179,6	718,3	398,0	392,5	502,4	1,80	558,2	6,10	5,79
E	123,1	410,3	357,7	298,1	491,7	3,96	546,4	6,79	6,18
F	119,0	396,7	343,0	285,8	483,1	4,18	536,7	6,71	5,94

Specimens containing mortar fillings showed lower initial stiffness due to the lower elastic modulus of the mortar. It can be concluded that the characteristics of the mortar filling, particularly in the region near the bolts, significantly influence the initial and secant stiffnesses.
The presented ultimate forces are close to each other in a range of 520-570 kN with ~6-7 mm ultimate relative displacements, and significant differences are not observed.
Type A) stands out as an exception due to its rigid behaviour, attributed to the brittle shear failure of the bolts with small slip values. This behaviour is influenced by the extra stiffness of the embedded nut, resulting in poor ductility. The embedded nut provides higher stiffness and ultimate resistance but prevents ductile bolt deformation and concrete cracking.
Shear connectors of type B), featuring embedded bolts and nuts in mortar filling, demonstrate increased rigidity, resulting in higher ultimate resistance with significant hardening effect and prevention of larger plastic deformation.
The resistance decreasing and the slight hardening branch during the plastic deformation stage of mortar filling in types E) and F) are observed. Although the load distribution and plastic transition are more favourable due to the presence of mortar filling, achieving higher resistance is not possible.
Types C) and D) without mortar filling show slightly higher resistance with a minor plastic hardening effect in the final stage of behaviour because of the higher strength and modulus of elasticity of the concrete.
The characteristic slip for every specimen is nearly 6 mm, which is close to the ductility criteria of the Eurocode 4 standard (3), however no horizontal plateau observed.
On the basis of the behaviour, it can be concluded that specimen types with mortar fillings, particularly E) and F), are the most favourable shear connections. This is attributed to the material properties of the mortar near the connectors, which significantly influence the effectiveness of the bolts. Additionally, the smaller bolt hole clearance in these types proves to be a more beneficial solution.
A more detailed evaluation of the push-out experimental program is presented in (1) and (4).

4 NUMERICAL ANALYSIS OF THE SHEAR CONNECTOR

4.1 The details of the numerical models

To further analyse the behaviour of the proposed shear connectors, a numerical model is under development for the push-out specimens using ATENA finite element software. In this chapter the numerical model is presented for test specimen type C) with through bolts without embedded nuts or mortar filling as a reference of the novel solutions.
The numerical model for the full push-out specimen is constructed by 3D volume finite elements. As in the actual specimen, the HEB260 column and the C-profile are modelled as S235 steel using characteristic material properties. The M16 8.8 threaded rods and nuts, as the shear connectors, are modelled by volume elements with an effective diameter without the threads, applying the characteristic modulus of elasticity (210 GPa) and the characteristic yield strength (640 MPa). The

four C50/60 concrete panels are constructed by volume elements, using a characteristic value of the modulus of elasticity (37,3 GPa) and the measured strength (70,7 MPa).
Apart from these, two load-transferring elements are modelled at the top of the steel column and at the bottom supports of the concrete panels. The full 3D finite element model is presented in *Fig. 6 a)*. The material models for the steel column and C-profiles are linear elastic and perfectly plastic. The shear connectors also have the same model but with different yield stress (640 MPa). The Drucker-Prager failure model follows the concrete part. The characteristics of the applied material models with the model parts can be seen in *Fig. 6 b)*.

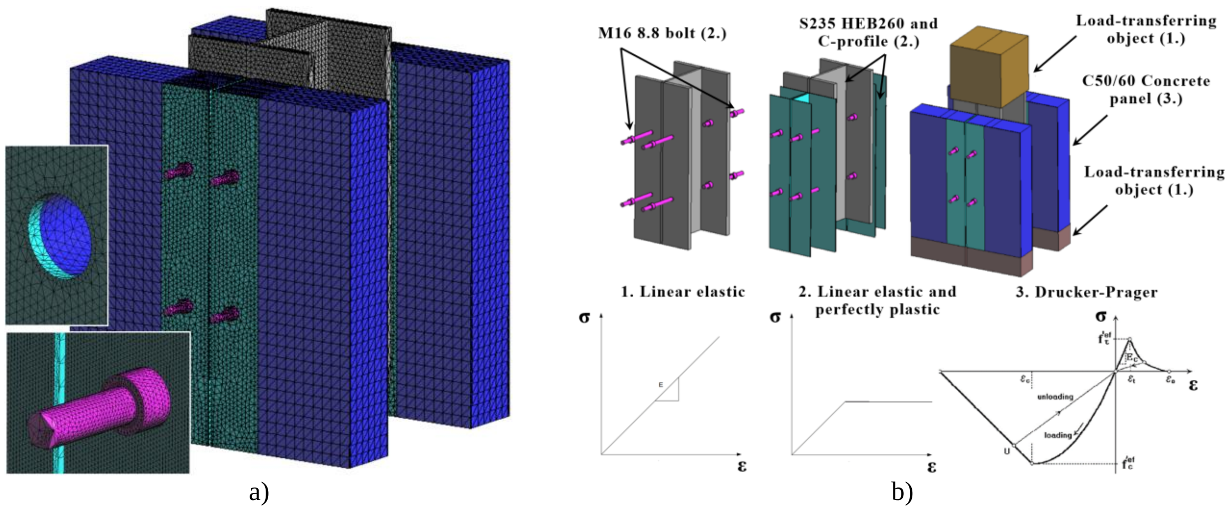
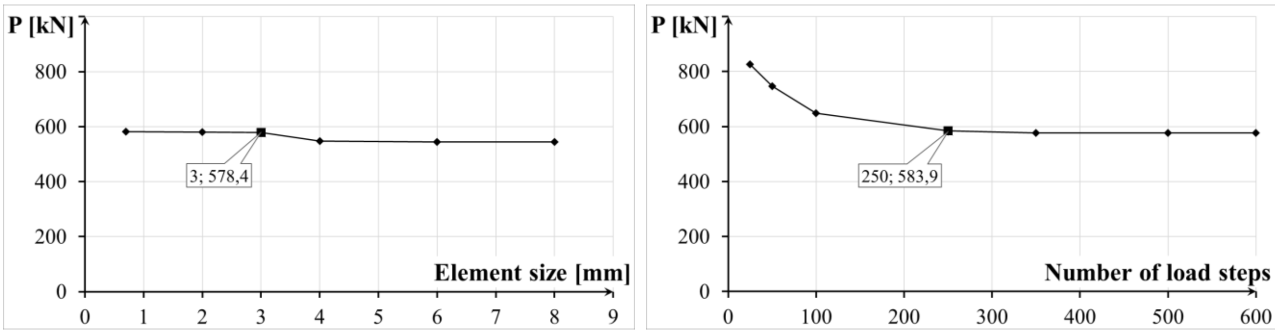


Fig. 6 a) The full 3D model and b) the applied material models

The elements of the embedded bolts and C-profiles are directly connected to the elements of the panels. An actual gap is modelled between each concrete panel. The interfaces between the steel column flange and the panels' C-profiles are modelled using master-slave contact elements with no friction, as these surfaces were greased during the experiments. Interfaces between the bolts and holes, in addition to the nuts and flanges in the column, are also modelled using master-slave contacts with a friction ratio of 0,2.
The bolt holes in the steel flange were 18 mm, with shear connectors placed uniformly in the middle for every bolt. Note that the actual model does not account for the effects of tolerances and the actual positions of the connectors in the holes.
The model verification is completed by sensitivity analysis involving varying mesh sizes and loading rates. A comparison of their effects on the ultimate resistance is illustrated in *Fig. 7 a)* and *b)*, respectively. On this basis, the finite element mesh of the model generally consists of 10 mm wide elements and 1-3 mm wide elements near the shear connectors, as illustrated in *Fig. 6 a)*. The applied finite elements are triangle-based tetrahedral shapes with ten nodes. The displacement-based load is applied to the upper load-transferring element at a rate of 0,04 mm/step, which means 10 mm over 250 steps, and the reaction force of the supporting elements is measured. Monitor points are set on the bolts to determine the vertical relative displacement.



a) b)

Fig. 7 a) Sensitivity of the mesh size near the shear connector and b) loading rate compared to the ultimate resistance

4.2 Validation of the numerical models

The force-relative displacement diagram obtained by the analysis is compared to the results of the push-out tests in *Fig. 8*. The numerical result shows high initial stiffness, a shorter range of plastic transition, and a horizontal plastic deformation stage. The ultimate resistance of the model is 583,9 kN, which is in good agreement with the average resistance of specimen type C), 567,1 kN, with a deviation of 3%. The initial stiffness of the model is 2094,1 kN/mm, which is nearly three times larger than the 729,1 kN/mm stiffness of the specimen.

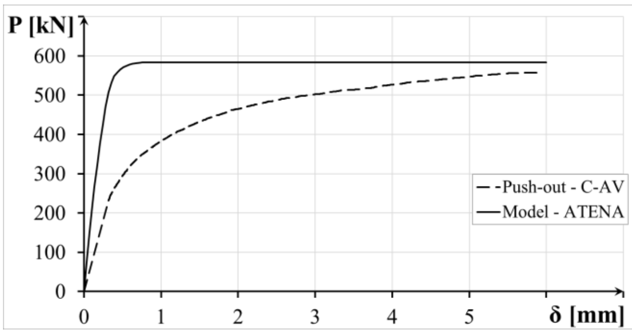


Fig. 8 Comparison of the numerical and experimental results

The primary cause of the discrepancy in the initial stages of the behaviour is attributed to the impact of tolerances and the positions of the bolts. In the model, the shear connectors are defined at the centre of the bolt hole, and due to symmetry, the rotation of the panels with the bolts cannot occur.
This implies that all the connectors work together with equal load distribution. However, the force distribution among the bolts is different during the experiments, as discussed previously, resulting in a softer connection. In the final plastic transition stage, after force redistribution, the bolts are close to equal distribution but cannot be reached completely. This explains the good prediction of the ultimate resistance and the significant differences in stiffness. The modelling of this effect is under investigation.
The yielding and plastic deformation of the bolts, along with local concrete cracking and bolt detachment, without significant cracking far from the connectors, are observed in the model as two important failure modes, consistent with observations during the push-out tests. These failures in the model can be seen in *Fig. 9,* which represents the real failure of the shear connector.

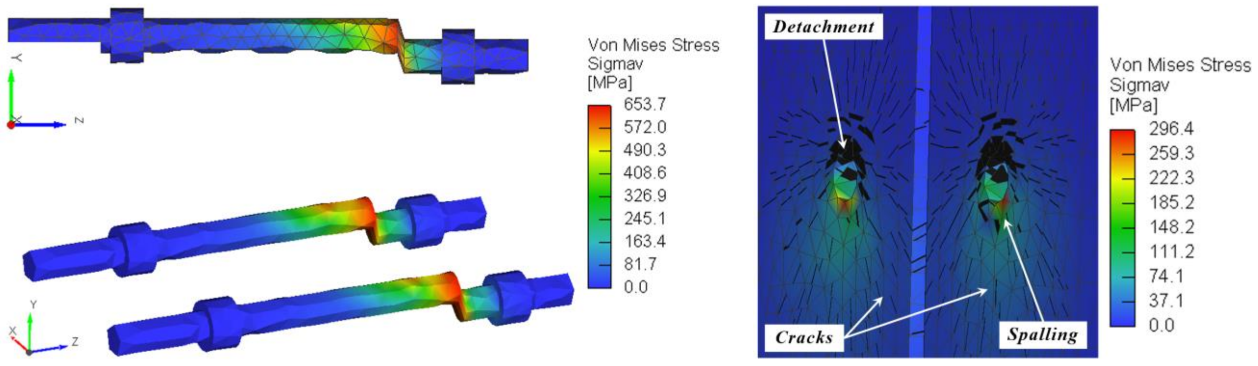


Fig. 9 a) Plastic failure of the bolts and b) the local damages of the concrete with cracking, spalling and detachment

According to the results and observations of the numerical analyses, it can be concluded that the presented model is able to follow the behaviour of the proposed shear connectors. The resistance is adequate, and the dominant failure modes align with the push-out results, but further model improvement is required. Note that the threads of the bolts are not modelled, excluding their penetration into the steel flanges. While this might result in a minor discrepancy, it's important to highlight that this effect was not observed during the test.

4.3 Further development of the numerical model

The first results of the numerical model represent the behaviour of the developed shear connector, but further improvements are needed, particularly in the modelling of tolerances and bolt positions, along with the application of a more accurate material model for the shear connectors which can consider the plastic deformation and failure accurately.

The further goal by the improved model is to study the impact and sensitivity of material properties of the concrete, mortar filling, and shear connector, in addition to making minor geometric adjustments related to panel thickness and bolt diameter, considering different tolerances with bolt positions. This study will allow the improvement of the shear connector and provide a proper basis for the mechanical model for developing the design method.

5 CONCLUSIONS

As the primary objective of the presented research program, six types of novel demountable shear connections have been designed and analysed by push-out experiments and numerical models in ATENA finite element software. The proposed structural solution is constructed using a steel beam with precast reinforced concrete elements, demountable shear connectors (bolts and threaded rods), steel assemblies, mortar filling around the connectors, and connection plates.

Despite all types of specimens exhibiting similar behavioural characteristics, the detailing modifications, particularly those related to the through bolt and mortar filling, evidently impact the behaviour. The initial and secant stiffnesses with the ultimate forces and relative displacements are defined, evaluated, and compared for each type of shear connector. It is observed that the bolt hole clearance prevents equal force distribution for the shear connectors, even in the ultimate behaviour. The shear connectors have a ductile failure with major plastic deformations, which is a plastic shear-bending interaction failure with local concrete or mortar cracking and spalling. Based on the test results, three main stages of the behaviour are observed – the (i) elastic, (ii) plastic transition, and (iii) plastic deformation stages.

The material properties of the concrete or the mortar filling around the connector highly determine the behaviour – the stiffness, resistance, and ductility – of the shear connection. Specimens with mortar filling have smaller stiffness, but the resistance is not significantly decreased comparing to other types, allowing more beneficial bolt hole clearance with a more favourable force distribution.

The results of the numerical model and the experiments are compared, and the resistance and failure modes are observed to follow the real behaviour characteristics. Still, the initial stiffness and ductility results require further improvements, the model should consider the effects of the tolerances and the actual positions of the bolts. The model is under development, and the next step is a parametric study in order to develop the detailing of the shear connectors.

It can be stated that the proposed structural solutions are applicable based on the test results. The potential shear connection types with mortar filling (types B, E and F) will be further studied and developed in order to increase the ductility and reach more beneficial force distribution. Apart from this, full-scale beam tests are designed to study the element level behaviour.

ACKNOWLEDGMENT

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REFERENCES

1. **Király, K. and Dunai, L.** Experimental study of novel demountable shear connectors for steel-concrete composite buildings. *Periodica Polytechnica Civil Engineering.* 2024, 10.3311/PPci.22732.

2. **Coelho, A.M.G., Lawson, M., Lam, D., Yang, J.** Guidance on demountable composite construction systems for UK practice. *SCI P428.* 2020, ISBN 13: 978-1-85942-245-8.

3. EN 1994-1-1, Eurocode 4, Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings, CEN, Bruxelles, 2004.

4. **Király, K., Dunai, L., Calado, L., Kocsis, A.B.** Push-out tests of demountable shear connectors for sustainable composite structures. *Steel Construction.* 2024, under review.