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Experimental Study of Novel Demountable Shear Connectors for Steel-concrete Composite Buildings

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Abstract

Sustainable composite structures in building construction are assembled using demountable structural elements that can be reused in 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 and frame system for buildings. The key component of this construction is the demountable shear connector. In the current research, novel bolted shear connectors with embedded bolts and threaded rods are developed and studied that can fit the applied technology of the industrial partner. One of the leading aspects of this connection is the consideration of bolt hole clearance, since it occurs initial slip and stiffness reduction of the composite beam. In the first phase of the research program, demountable and economical structural details were developed, which can reduce the stiffness reduction with the proper resistance and ductility features. To study the behavior of these shear connections, a push-out experimental program was designed and completed in March and April 2023. It is observed that novel shear connectors have a proper behavior with sufficient resistance and ductility, which is applicable according to the Eurocode 4 standard and fits the objectives of the research and development project. In the paper, the developed structural details and the push-out experimental program are presented with general results and statements besides a detailed evaluation of a specified specimen type.

Keywords

sustainable structure, demountable composite structure, shear connector, push-out test

1 Introduction

Sustainability plays a huge role in the construction industry due to CO_2 emissions, building materials, and energy consumption. The aspiration is to leave the linear economic model and achieve the circular economy by recycling building materials and, more importantly, reusing structural elements mostly in their original form. In the ideal far future, there will be fully reusable – demountable – structures that serve as material banks [1].

The demountable structures are favorable for the reason of low energy and work investment during deconstruction because the structural elements are reused in the original form with minor changes and repairs only. The "design for deconstruction" is a new demand that must be considered during the design process in the BIM (Building Information Modeling) environment. Additional parameters such as preservation, storage, economy, etc. have emerged, and new key members are taking roles in order to coordinate, which is a new challenge for the engineering society [2].

Demountable structures could be temporary structures or buildings with standardized geometry. An insightful and simple example is the demountable parking house [2] which has standardized dimensions due to vehicles and lanes, has a temporary need due to some event or demand that can be easily demounted in order to build a new place where it is going to serve the new needs. In addition to this, any kind of structure can be dismantled with proper design, for example, the Stadium 974 in Qatar [3].

The current Research & Development & Innovation program is being completed in cooperation of Budapest University of Technology and Economics and KÉSZ Group, bim.GROUP Ltd., Hungary with the purpose of

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creating a new sustainable and demountable steel-concrete composite structural frame system for buildings. This new design follows international trends and adapts to Hungarian conditions based on the experience of the industrial partner. The main goal is to investigate the structural behavior of the new structure based on numerical and experimental analyzes in order to develop a Eurocode-based design method. On the basis of a state-of-the-art study, new design concepts and structural solutions have been developed focusing on novel demountable shear connections, which are the key elements of demountable construction.

To study the structural behavior of the shear connector, an experimental push-out program is completed. In addition to the push-out test, advanced numerical model development and validation is in progress. Based on the results and conclusions, a full-scale composite beam test will be designed and executed in the next phase of the project, continuing with the development of a design method.

This paper presents the first steps of the research program with the developed structural solutions and the push-out experimental program, highlighting the results and conclusions of the observed behavior.

2 Demountable shear connections – literature overview

The generally used welded headed studs in steel-concrete composite structures cause difficulties in the dismantling and reusing process; apart from this, the procedure requires huge work and energy investment. To achieve economic and effective demountability, a proper design of the demountable shear connection is needed, for which several solutions have been found in the literature.

The basic demountable shear connection is a structural bolt embedded in the reinforced concrete slab with a nut below the steel flange that allows the connection to be fixed and dismantled. There should be a second nut inside the panel that provides the right position of the connector. An example of an embedded structural bolt can be seen in Fig. 1.

According to several published research results, the embedded bolted shear connection behaves similarly to the welded headed stud. Experimental push-out and beam tests show that this type of demountable shear connection is applicable in practice because it meets the necessary load bearing capacity and ductility requirements [4, 5].

The structural bolts as the presented demountable shear connectors require oversized holes in the connecting elements because of different tolerances, which could be geometric, construction and erecting tolerances. Due to this bolt hole clearance, an initial slip occurs before the composite action – the bolts move in the holes without significant resistance, which causes a reduction in stiffness of the composite beam. This is an unfavorable but important phenomenon of the demountable shear connection that needs to be minimized and considered during the design process. According to Lam et al. [6, 7], if the bolt hole is at most 1 mm larger than the diameter of the bolt, this effect can be neglected. As a result of numerous studies and experimental programs, a Eurocode-based design guide was developed for this structural system [8]. There are other technologies to prevent initial slip and stiffness reduction, for example, injection of bolt holes, as proposed by Sarri [9], using mortar fills on site around bolts, or applying on site hole drilling. Erdélyi and Dunai [10] analyzed a light gauge floor system that is built with thin-walled C-sections with trapezoidal decking connected by a self-drilling screw as a shear connection. With this solution, the hole gap is eliminated, but this connection cannot be demounted. The friction grip bolt can also be a suitable solution for shear connection that provides sufficient ductility, as shown by Kozma et al. [11].

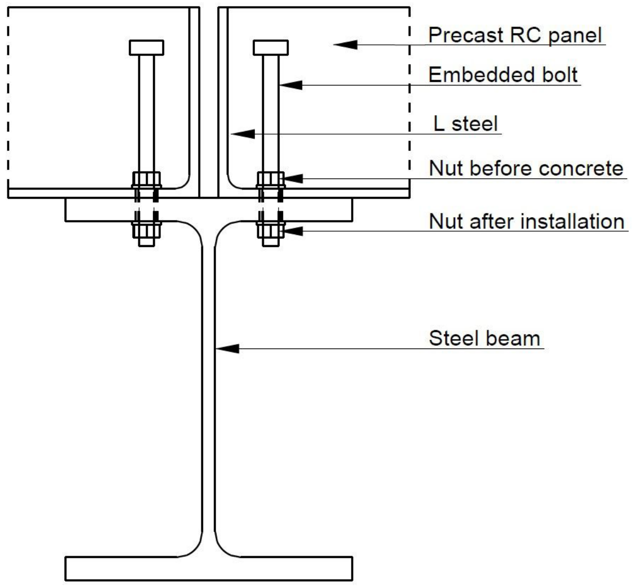

Fig. 1 Example of an embedded bolt as a shear connector

3 The proposed structural solution

The state-of-the-art study of international trends is considered in accordance with Hungarian design and technology conditions.

The proposed structural system is a hierarchical structure with hot rolled steel beams and fully precast reinforced concrete panels with embedded steel assemblies at the edges connected by demountable shear connectors – embedded structural bolts, or threaded rods (Fig. 1).

The novel features of these connectors are the following:

1. fully precast elements without on-site concreting,
2. embedded steel assemblies,
3. mortar filling around the connectors, and
4. connection plate between the precast slab elements.

The application of embedded steel L- or C-profiles in the panels provides a partial formwork for the perimeter that helps the pouring process and improves the fabrication and erecting tolerances, but more importantly, it provides the locations for the shear connectors. These steel assemblies have predrilled oversized bolt holes for the shear connectors at the bottom of the panels to prevent direct bolt-to-hole (steel-to-steel) contact and provide ductile behavior. The C-profiles have normal holes at the top, which improve the positioning tolerance of the bolts. These elements allow the precast panel to be fabricated with steel tolerances with approximately 4 mm hole clearance. Another option is to install the connectors on the construction site and use mortar filling around them to provide smaller and more favorable tolerances (2 mm). For this procedure, ribbed tubes are needed to be assembled in the concrete panel; then, during the erection, these tubes need to be filled with mortar – this technology is simple and widespread for precast concrete beam-to-column connections. A connection plate from the top of the panels provides greater stiffness for the connectors and mainly enhances the global stiffness and diaphragm effect of the entire slab.

Construction starts by erecting the steel beams followed by placing the precast reinforced concrete panels with the embedded connectors. For the detail of the mortar filling, the bolts must be positioned on site and filled the hole with mortar. The final step is to tighten the connectors with the lower nuts. The demounting process begins with loosening the bolts below the slab and then erecting and moving the panels in their original form without cutting any elements.

With this solution, it is easy to dismantle, does not use expensive and complex technologies such as friction grip bolts or resin injection into holes, and it minimizes on-site work. That also means reduced construction time and costs, which are important aspects on the industrial partner side.

4 The experimental study

4.1 Overview of the test program

The proposed composite structure and the demountable shear connection have a unique behavior. In the first phase, the bolted shear connection is studied as a key component. The developed structural details and technology, the different embedded bolts and threaded rods as shear connectors, on-site hole filling with mortar, connection plates as stiffener elements, and embedded steel assemblies, are investigated by a push-out test program in order to determine the characteristics of the behavior (initial stiffness, resistance, and ductility). In the next phase of the research, full-scale beam tests are carried out to investigate the global effects, mainly the initial slip with stiffness reduction and the continuity of the slab in addition to the demounting and reassembling process. These experiments are supplemented and extended by advanced numerical studies.

4.2 Push-out specimens

After the conceptual design, the push-out experimental program is developed for six different structural details, each of them with three pieces, a total of eighteen test specimens. The tests were completed in the beginning of 2023 in the Structural Laboratory of the Budapest University of Technology and Economics. The test program and the specimens are designed based on the Eurocode 4 standardized push-out arrangement [12] and improved by two research programs – Sarri [9] and Pavlović et al. [13]. The specimen details are the following and can be seen in Fig. 2:

- A) Embedded bolt (reference)
- B) Embedded bolt, mortal filling
- C) Through bolt
- D) Through bolt, connection plate
- E) Through bolt, mortal filling
- F) Through bolt, connection plate, mortal filling.

A test specimen was built with a HEB260 S235 steel column with four independent precast reinforced concrete panels of grade C50/60. In each case, two M16 8.8 thread up to head embedded bolts or through bolts (threaded rods) are designed for one panel, a total of eight shear connectors per test specimen. Specimen A) is similar to the design of the researchers referred [9, 13], which serves as an initial type and provides a comparison with the literature. Types A) and B) have L-shaped steel assemblies, and for the rest of the elements, a C-shaped steel assembly is designed. Three of the samples have mortar filling – B), E), and F) types. The mortar has a compressive strength of 62 MPa with a modulus of elasticity of 26 GPa, provided by the fabricator. For D) and F), a connection plate aims to provide stiffer support for the threaded rods.

The C-profiles in the panels and the connection plates are novel solutions. In these cases, the threaded rods do not have an embedded nut inside the concrete panel.

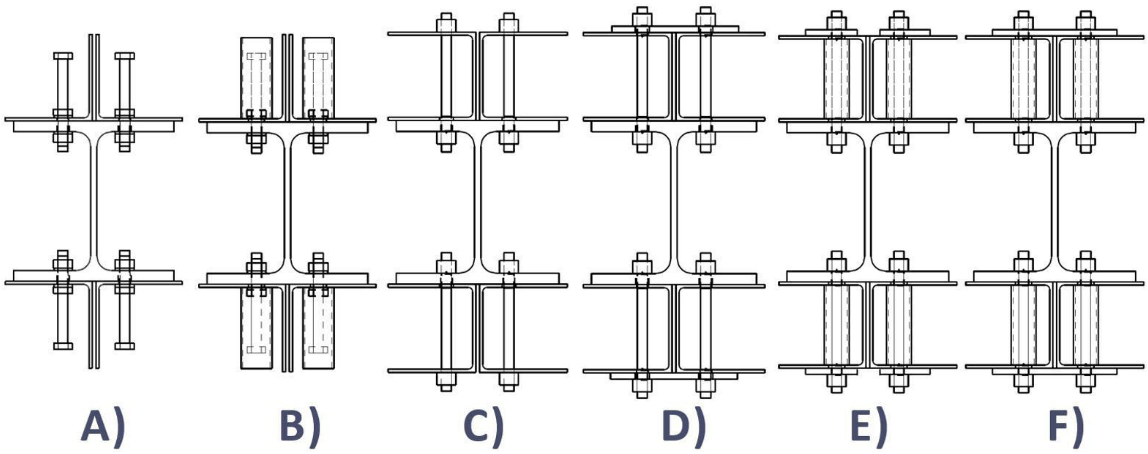

Fig. 2 The six specimen types designed for the push-out tests: A) Embedded bolt (reference), B) Embedded bolt, mortal filling, C) Through bolt, D) Through bolt, connection plate, E) Through bolt, mortal filling, F) Through bolt, connection plate, mortal filling

To fix through bolts, the washers and nuts are applied from the top of the panel and from the bottom of the steel flange, resulting in a new structural behavior for the connector. At both ends of the threaded rods, theoretically, two springs of different stiffness are supported by the shear connector – steel flange at the bottom and C profile with connection plate at the top – which provides slightly stiffer behavior than the original headed studs and the referred embedded bolts.

In order to provide ductile behavior, there is no direct contact between the bolt and the hole in the C-profile, allowing the deformation of the shear connector and the cracking of the concrete or mortar. For the actual push-out specimens, instead of oversized holes, rectangular openings were applied. The details of the new structural arrangement and the assumptions of the theoretical behavior can be seen in Fig. 3.

The main purpose of the push-out program is to analyze through bolts as a new shear connection with the effects of oversized holes and furthermore to study the new behavior and failure modes of the novel details by through bolts, on-site mortar filling, steel assemblies, and connection plates. The load-transferring effects of the connectors on the four panels are also an important aspect of the experimental study.

4.3 Loading and measurement details

The push-out test setup and loading plan are designed according to Eurocode 4 [12], and the estimated failure load is determined, which is approximately. 600 kN. In the tests, 25 preloading cycles are executed at lower load levels – from nearly 60 kN to 280 kN – then every sensor resets to zero and starts loading so that the failure does not occur in less than 15 minutes. The purpose of

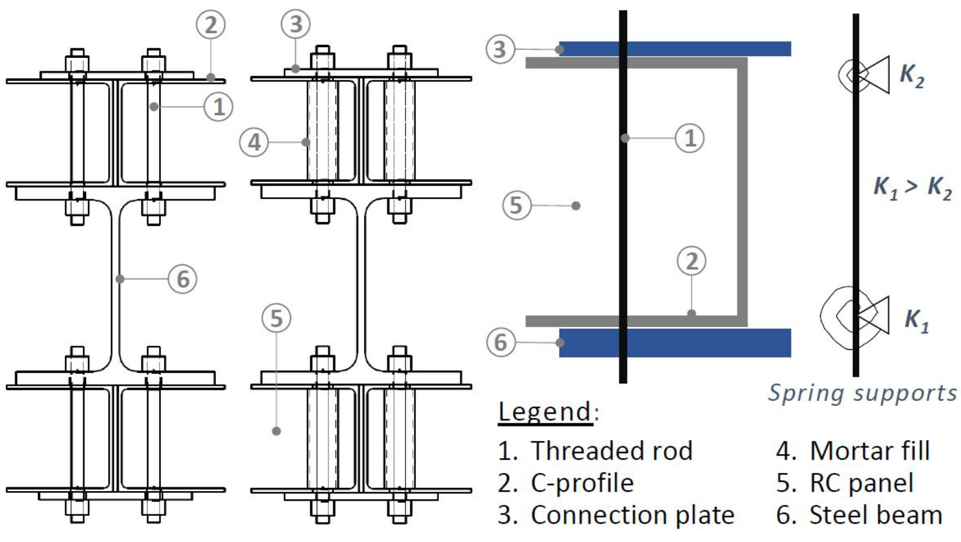

Fig. 3 Details of the novel structural arrangement and the theoretical behavior model

the cycles is to eliminate friction and to move the bolts to the load bearing position to eliminate the initial slip. Note that this phenomenon will be analyzed in detail during the beam tests. The interface of the panel and the beam is greased to minimize friction.

The loading is applied by the WPM 6000 kN capacity hydraulic testing machine. During the tests, global vertical displacement (GV 1-2) is measured between the steel web at both sides and the supporting table, which allows one to show the total displacement and the rotation of the specimen, too. Relative vertical displacements (J1/2-V and B1/2-V) are also recorded between each panel and the steel column. Horizontal displacements (J1/2-H and B1/2-H) are measured between the panels and the flange of the HEB260 column – detachment of each panel – and between the neighboring panels (J/B-HPA). All displacements are measured by LVDTs.

Above every bolt hole in the steel flange – in the direction of the load introduction – the strain gages measured the stresses which show the stress distribution of the bolts in order to analyze the effect of the force transfer between the connectors (J1/2-SA/F and B1/2-SA/F). The setup of the sensors can be seen in Fig. 4. A prepared test specimen is shown in Fig. 5.

After the push-out experiments, material tests are performed in order to determine the real material properties of the shear connection, the concrete, and the mortar filling.

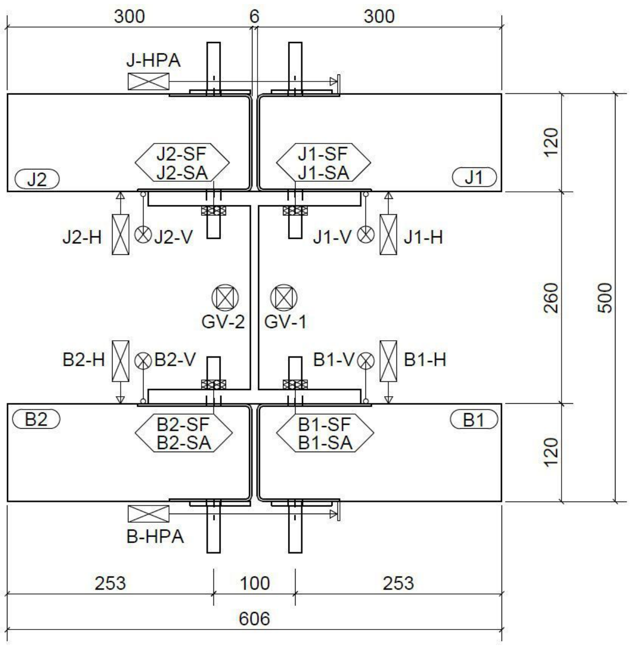

Fig. 4 Sensor setup for the push-out tests

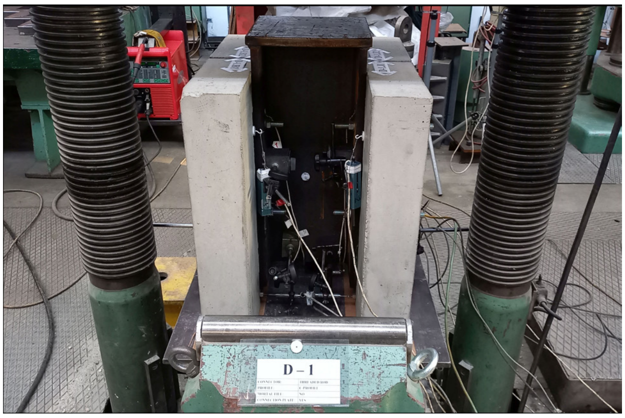

Fig. 5 The prepared push-out test specimen

5 Experimental results

5.1 Initial data and force-displacement diagrams

In this paper, the general statements and preliminary conclusions of the push-out tests are presented with a more detailed evaluation of a specified specimen, type C), which is the basis of the proposed structural details.

According to Eurocode 4 [12], the estimated design resistance of one specimen is 480 kN – with a shear resistance of 60 kN of one bolt, which is the dominant failure in addition to the crushing of the concrete (81 kN). The characteristic resistance is 600 kN (75 kN for each bolt) which is the estimated failure of the specimen. The main outcome of the push-out tests is the force-relative displacement diagram, which shows the characteristics of the global behavior (initial stiffness, resistance, and ductility). These diagrams can be seen in Fig. 6 without the preloading cycles, which contain the results for all specimen types. Fig. 6 shows the average displacement values of the four vertical LVDTs for each type.

5.2 Ultimate behavior

According to the presented force-displacement results, ductile behavior is observed with relative displacements of 6–8 mm at load levels of 500–570 kN, below the estimated resistance. Type A) (A-1) is an exception because rigid behavior was detected with brittle shear failure of the bolts which is caused by the extra stiffness of the embedded nut and performed with poor ductility. At this construction – against suggestions from the literature, but considering the needs of the fabricator partner – the bolt hole clearance is greater, 4 mm instead of 1 mm. The embedded nut provides higher stiffness but prevents ductile bolt deformation and concrete cracking. The brittle and ductile failure of the bolts can be seen in Fig. 7. Concrete cracking and mortar cracking with the bolt deformation are shown in Fig. 8.

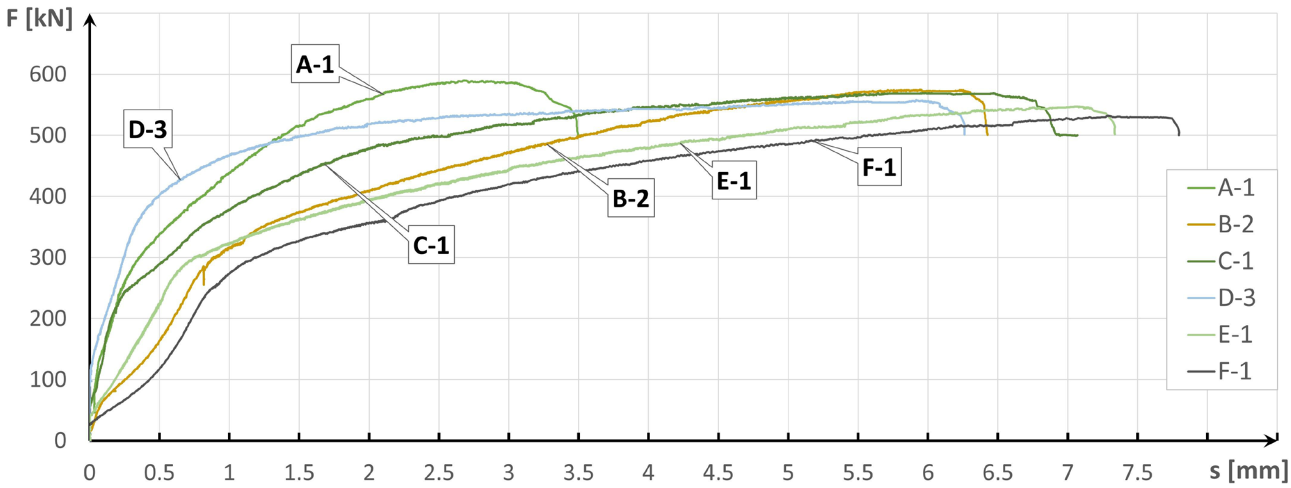

Fig. 6 Force-relative displacement diagram for each specimen type

(a) (b)

Fig. 7 (a) Brittle shear failure and (b) combined ductile shear and bending failure of the bolt

(a) (b)

Fig. 8 (a) Failure of the concrete and (b) the mortar fill with the deformation of the bolt

Based on the observed failure modes and the force-relative displacement curves, each connection type has slightly different initial stiffness and ductility; the characteristic of each type is similar, but every detail (mortar filling, connection plate, etc.) modifies the behavior in an altered way.

Test specimens without mortar fill (A-1, C-1, D-3) show larger initial stiffness than the others (B-1, E-1, F-1) but larger ultimate slip values occur, – relative displacements – which means more favorable ductility. The relevant curves of these specimens are smoother than those of the others. At lower load levels, the mortar fill allows greater deformation of the bolts and provides a more favorable force distribution, while the concrete is more rigid and cracks only at higher load levels.

Type D) (D-3) is the stiffest specimen with connection plates without mortar fill and has the lowest amount of ultimate relative displacement of 6 mm. In this case, the plateau of the curve is almost horizontal.

Every specimen – except A-1 – has nearly the same ultimate load level (500–570 kN). The significant difference is the characteristic of the force-relative displacement curves and the magnitude of the ductility. According to Eurocode, sufficient ductility is required to allow designers to use the plastic method for composite structures for building construction.

On the basis of the recorded stresses and the observed behavior, this structural system does not allow for full load distribution at lower load levels. The reason for this is mainly the oversized holes in the beam flange and the exact positions of the bolts in the holes. To reach a uniform force distribution, bolt deformation and local damage of the concrete and mortar are required, which can occur only at higher load levels. The mortar fill provides a better force distribution at lower load levels, since its elastic modulus is less than the concrete (E_{mortar} = 26 GPa < E_{concrete} = 37 GPa).

Based on the results and observations, the uniform force distribution is based on the real positions of the bolts in the holes, the ductility of the bolts and the local damage of the concrete and mortar.

5.3 Ultimate forces and displacements

The ultimate forces and displacements are determined for each specimen as follows. The ultimate force is the largest force value measured during the tests (P_{ult}). The relative displacement recorded corresponding to the ultimate force is defined as the ultimate displacement (δ_{ult}). These push-out test values are evaluated for each type of connector by the average values (AV) and the coefficient of variation (CV), as can be seen in Table 1.

The ultimate forces and displacements are close to each other – except for type A) as previously explained. The comparison of the evaluated P_{ult} and δ_{ult} – related to type C) connector – is presented in Table 2.

6 Evaluation of behavior – specimen type C)

6.1 Preloading cycles

The main objective of the preloading cycle for the actual push-out tests is to eliminate the initial slip by positioning the bolts. The surfaces of the beam and panel were greased, and any remaining friction was removed by cycles. The cyclic force-relative displacement diagram (average of four sensors) of C2 test specimen is shown in Fig. 9.

Table 1 Ultimate loads and displacements for each type of connector

Spec. type	Ultimate force			Ultimate displacement		
	P_{ult} [kN]	P_{AV} [kN]	P_{CV} [%]	δ_{ult} [mm]	δ_{AV} [mm]	δ_{CV} [%]
A-1	590.1			2.68		
A-2	584.3	589.7	0.9	3.26	2.77	16.5
A-3	594.7			2.36		
B-1	551.3			7.21		
B-2	575.0	572.3	3.4	5.95	6.49	10.0
B-3	590.5			6.30		
C-1	568.8			5.97		
C-2	572.1	567.1	1.1	8.30	6.76	19.6
C-3	560.5			6.02		
D-1	533.5			10.35*		
D-2	520.9	537.5	3.5	8.95	7.43	28.9
D-3	558.2			5.92		
E-1	547.0			7.07		
E-2	560.6	546.4	2.7	6.97	6.86	4.0
E-3	531.5			6.56		
F-1	531.9			7.29		
F-2	540.8	537.8	1.0	6.22	6.58	9.4
F-3	540.8			6.22		

* Bolt pulled out – different behavior – excluded from AV and CV

Table 2 Comparison of the ultimate forces and displacements

	P_{ult}	δ_{ult}
A/C	1.04	0.41
B/C	1.01	0.96
C/C	1.00	1.00
D/C	0.95	1.10
E/C	0.96	1.01
F/C	0.95	0.97

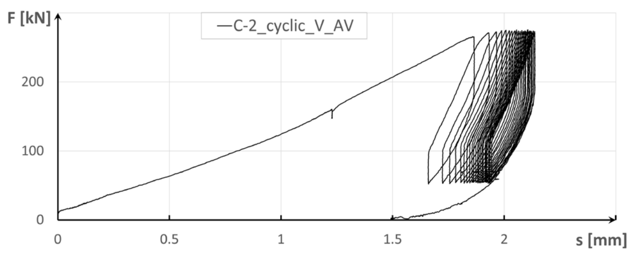

Fig. 9 Cyclic force-relative displacement diagram of specimen C2

In the first cycle, the slope of the curve – the initial stiffness – is linear. In every cycle, the displacement increases slightly with small increments. At the end of the cycles, 1.5 mm of remaining relative displacement is recorded. This value includes the positioning of the bolts in the holes (with 4 mm clearance) and the panels, which can move independently and cause global rotation of the specimen. The same results are observed in the force-stress diagrams. These remaining values are reset to zero before the final load cycle begins. The characteristic of the cyclic curves is the same for every specimen with 1.5–3 mm remaining slip, which is equal to the initial slip of the shear connection. The global effect of the initial slip will be analyzed in the next phase of the research by beam tests. The shear resistance and ductility of the connectors are independent of the initial slip and the initial stiffness.

6.2 Force-relative displacement diagram – stiffness

The force-relative displacement diagram of specimen C3 can be seen in Fig. 10 with the displacement of every panel and the average of them. The panel positioning mentioned above is also observed during the final load cycle – one panel moves less at the same load level than the others.

The force-relative displacement diagram of every specimen type C) with the average of them is shown in Fig. 11.

The initial slip is excluded by the preloading cycles, as mentioned before. The characteristic and the slopes of the curves are very similar. At 300 kN load level, the slope is changing, the stiffness is reduced to one third of the initial

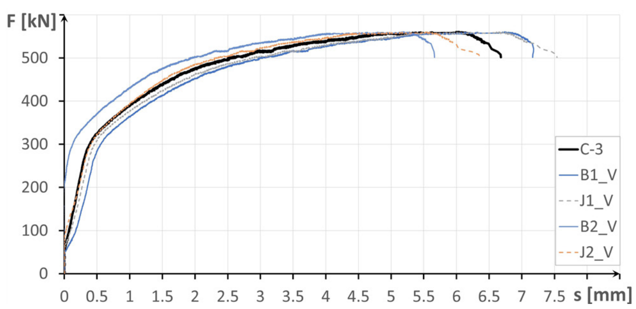

Fig. 10 Force-relative displacement diagram of specimen C3

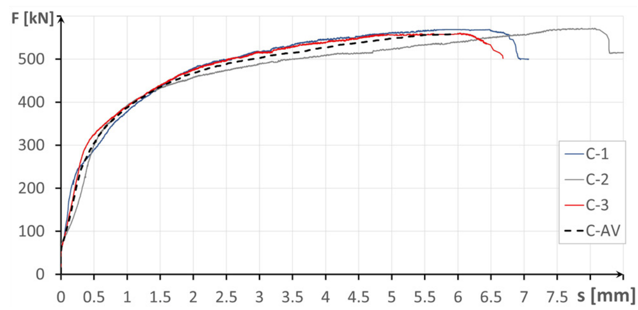

Fig. 11 Force-relative displacement diagram of every C) type specimen

stiffness, then to a nearly horizontal – ca. 10% of the initial stiffness – branch is observed. The failure occurs at nearly 570 kN for every specimen with a slip of 6.5–8.5 mm.

6.3 Bolt-force distribution

The purpose of the stress record is to analyze the load distribution between the bolts. As mentioned above, the actual position of the bolts in the holes determines the load transfer effect of the bolts. The stresses are measured in the steel flange and not in the bolts, which means that the magnitude of the stresses is not informative but shows the distribution. The applied force-stress diagram of the C-3 specimen can be seen in Fig. 12. In the diagram, the continuous line shows the upper bolts, and the dashed line represents the lower bolts.

The first observation is that every bolt has a different stress value for the same load level. Up to 350 kN, the force-stress curves for each bolt are nearly parallel to each other, except in the early stage where the bolts are mobilizing. According to the force-slip curves, for C-3 at 280 kN and 400 kN, stress redistribution is observed. After the first or first two bolt failures at once, the stress redistribution occurred again, but the specimen cannot take greater load increments. In addition to this, smaller stresses are observed at the lower bolts – the upper bolts were closer to the perimeter of the holes, which need to deform to mobilize the lower bolts. In this case, during the fabrication

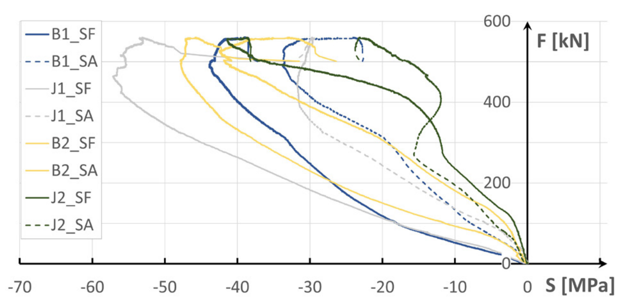

Fig. 12 Force-stress diagram of specimens C3

process, the bolts were placed in the same position, since the same formworks were used. This effect comes from the geometry – bolt position, tolerances – and could happen for any bolt position scenario. The effects and behavior presented are valid for the rest of the specimens.

6.4 Failure mode and resistance

The failure occurs on average at 570 kN, which is about 10% less than the estimated resistance (630 kN). All specimens failed due to failure of the shear and shear-bending interaction of the bolt at the steel-concrete interface plane. In all cases, progressive failure occurred: at maximum load level, the first or the first two bolts failed at once; after the force drop, the remaining bolts mobilized then failed the next or the next two connectors. According to the stress distribution, all the bolts worked, but there are some that have larger loads that caused the first connector to fail.

The bending and plastic deformation of the shear connector is detected in addition to the detachment from the concrete. Local cracking and spalling of the concrete are observed in the near region of the bolts. The failed bolt of specimen C-2 with local cracking and spalling of the concrete can be seen in Fig. 13.

7 Conclusions

The primary objective of the presented research program is to design and develop a new demountable and sustainable structural system that considers international trends but also adapts to the conditions of the industrial partner, and finally develop a Eurocode-based design guide. After conceptual design – cooperating with the university and industrial partner – novel structural details are developed by precast reinforced concrete panels with embedded threaded rods and C-profiles with connection plates as a demountable shear connector. To study the novel behavior, a research program is planned that includes push-out tests, full-scale beam tests, and numerical analysis as well. The paper presents the first phase of the program, details and first results of the completed push-out tests with six different types of specimens. In the following, the general observations of the test results are concluded, focusing on the behavior of specimen type C).

Fig. 13 Bolt and concrete failure of C2

All specimens, except type A) – show similar behavior characteristics. The modifications of the details (e.g. mortar fill, connection plate, etc.) show a clear effect on the behavior. In general, the measured failure loads are in a narrow range for each specimen (500–570 kN) with a maximum slip of 6–8.5 mm. The ultimate forces and displacements are defined, evaluated, and compared for each type of shear connector.

It is observed that the mortar fill provides less initial stiffness, but a better force distribution between the bolts and higher ductility. This finding gives potential for further development of connections with mortar fill.

On the basis of the stress distributions, an oversized hole in the flange prevents equal force distribution for shear connectors at lower load levels. After deformation/cracking of the bolt and concrete/mortar at higher load levels, the force distribution is more uniform.

Shear connectors have ductile failure, which is a combined mode of shear and bending with local concrete cracking and spalling.

The bolts failed progressively; at the maximum load level, the first or the first two bolts failed at once, then a load redistribution is observed. This effect depends on the ductility of the shear connection and the real position of the bolt in the hole.

Based on the above experimental observations, mortar fill type shear connections (types B, E, and F) will be studied and developed further before their application in beam tests.

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