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624(082)(0.034.2)
69(082)(0.034.2)

DRUŠTVO građevinskih konstruktera Srbije. Simpozijum 2020 (2021 ; Aranđelovac)
ASES International Symposium Proceedings [Elektronski izvor] / Association of Structural Engineers of Serbia, Symposium 2020, 13-15. maj 2021, Arandjelovac ; [urednici Zlatko Marković, Ivan Ignjatović, Boško Stevanović]. - Beograd : Univerzitet, Građevinski fakultet : Društvo građevinskih konstruktera Srbije, 2021 (Aranđelovac : Grafopak). - 1 USB fleš memorija ; 5 x 2 x 1 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. - Radovi na srp. i engl. jeziku. - Tiraž 200. - Bibliografija uz svaki rad. - Rezimei.

ISBN 978-86-7518-212-2 (GF)

а) Грађевинарство -- Зборници
COBISS.SR-ID 37698825

Izdavač: **Univerzitet u Beogradu Građevinski fakultet**
Beograd, Bulevar kralja Aleksandra 73/I
Suizdvač: **Društvo građevinskih konstruktera Srbije**
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Štampa: Grafopak, Aranđelovac

Tiraž: 200 primeraka

Beograd, maj 2021.

ДГКС
Друштво грађевинских
конструктера Србије

ASES
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Simpozijum 2020
Symposium 2020

Isidora Jakovljević[1], Milan Spremić[2], Zlatko Marković[3]

NUMERIČKA ANALIZA PONAŠANJA SMIČUĆEG SPOJA OSTVARENOG SA ZAVRTNJEVIMA I MOŽDANICIMA S GLAVOM

Rezime:

Prethodnih decenija intenzivno su ispitivana nova rešenja spojnih sredstava u smičućim spojevima spregnutih greda od čelika i betona. U ovom radu analiziran je montažno-demontažni podužni smičući spoj konstrukcionog čelika i pune armiranobetonske ploče, ostvaren pomoću zavrtnjeva i elastičnih moždanika s glavom. Ovakav spoj odlikuje se indirektnim prenosom sile smicanja kroz dodatni element, čelični lim, između betonske ploče i gornje nožice grede. Formiran je numerički model testa smicanja prema dostupnim prethodnim eksperimentalnim ispitivanjima. Model je iskorišćen za detaljnu analizu ponašanja podužnog smičućeg spoja, kao i za parametarsku analizu. Ispitivan je uticaj prečnika zavrtnja i prečnika rupe na ponašanje spoja pri smičućem opterećenju.

Ključne reči: spregnute grede od čelika i betona, demontažna veza, moždanici s glavom, zavrtnjevi, test smicanja

NUMERICAL STUDY ON THE COMPOSITE SHEAR CONNECTION WITH BOLTS AND WELDED HEADED STUDS

Summary:

In the past decades, many novel shear connectors for implementation in steel-concrete composite beams have been investigated. In this paper, a demountable shear connection between a structural steel beam and a solid concrete deck, consisting of bolts and welded headed studs, is analysed. This system features the indirect shear force transfer through the additional element, a steel plate that is placed between a concrete deck and a top flange. Following the experimental results of previously conducted push-out tests, a numerical model has been developed. The model is used for a detailed analysis of the system behaviour as well as for the parametric study. Influence of a bolt diameter and a bolt hole diameter on shear behaviour of the connection has been discussed.

Key words: steel-concrete composite beams, demountable connection, welded headed studs, bolts, push-out test

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1. INTRODUCTION

Steel-concrete composite floor framing systems are commonly used in construction nowadays, as they enable the most efficient use of two materials. A concrete slab is implemented in one of two ways: as a solid slab or as a composite slab cast in profiled steel sheeting. For joining a steel beam and a concrete slab, to prevent vertical separation and enable shear force transfer, shear connectors should be used. In the past decades, besides the most often applied welded headed studs, many novel shear connectors have been investigated. Some of the suggested solutions are perfobond rib connectors, channel shear connectors, various connectors with pins, etc. Contrary to all the mentioned connectors that are non-demountable, many attention has been paid to the development of various shear connectors that enable structure demountability.

Demountability is the important advantage of steel structures, that is also desired in the case when composite steel-concrete systems are used. Following the world trend towards sustainable development, recycling and reuse of building materials, the interest towards developing the most efficient demountable shear connector could be understood. The environmental benefits of deconstructable steel-concrete floor systems during their production, serviceability life and reconstruction have been proven [1].

Different solutions regarding demountable connectors have been proposed by now. Commonly investigated are friction-grip bolted shear connectors [2–5], which transfer shear force through friction on the contact between a steel flange and a concrete slab. The main shortcoming of this connectors is attributed to the sudden slip which happens after friction force is overcome, leading to the additional deflections of the composite beam. By threading the body of a headed stud, a demountable connector similar to bolts could be produced [6]. However, this connector features difficulty in mounting before concrete casting and lower initial stiffness comparing to welded headed studs. The application of bolts with embedded nuts in a concrete slab, makes the process of bolt placing easier and partly increases the initial stiffness of connection. But, it still leads to the additional slip in the initial stage influenced by bolt-to-hole gaps, necessary from the point of execution [7]. To enable relatively easy replacement of bolts, some authors suggested the use of a bolted coupler system [5], which behaves similarly to bolts with embedded nuts. To prevent the initial slip of bolts, which induces additional deflections and stresses in a steel beam, it was suggested to inject epoxy resin in bolt holes, though it increases the time of the execution process. Two types of blind bolts were investigated in the purpose of making the process of bolt mounting easier and faster, as they enable installation from one side a workpiece [8]. The innovative design of demountable connectors was suggested including preloaded bolts and clamps [9], but further modifications are required to accomplish the proper strength and ductility of the system.

A possible connection layout that almost has not been investigated until today is a demountable shear connection consisting of both welded headed studs and bolts. Going through the wide literature research of demountable solutions, the authors of this paper came to the only one report dealing with this system [10]. The experimental study was conducted over 15 years ago, through the project “Composite bridge design for small and medium spans”, founded by the European Commission. Several solutions for prefabricated steel-concrete composite bridges were analysed, including high-strength bolts with embedded nuts, partially and fully prefabricated slabs with welded headed studs and combination of bolts and welded studs. Push-out tests were conducted under static and fatigue loads and results were compared to some analytical expressions, partly explaining the behaviour of the system. A limited number of tests was not sufficient for developing detailed design rules.

To get a deeper understanding of this shear connection, consisting of both welded headed studs and bolts, a numerical analysis based on the mentioned experimental results [10] is conducted in this study. After model verification, the system shear response is investigated through numerically obtained data, followed by further parametric analyses. Conclusions and comments on possible connection modifications are given in the end.

2. EXPERIMENTAL RESEARCH

The shear connection layout is presented in Figure 1.a. A solid concrete slab is prefabricated and a steel plate is embedded in concrete. Headed studs are welded to the steel plate, while bolts are mounted in holes predrilled in the plate. In that way, both headed studs and bolt heads are embedded in concrete. On the construction site, the prefabricated slab should be connected to the top flange of a steel girder via bolts. In the case of deconstruction, bolts could be easily unfastened and the concrete slab would be separated from the girder.

In this connection, the longitudinal shear force between a concrete slab and a steel girder is indirectly transferred, through the additional steel plate. There are two active shear planes: the surface between the slab and the plate and the surface between the steel plate and the beam flange.

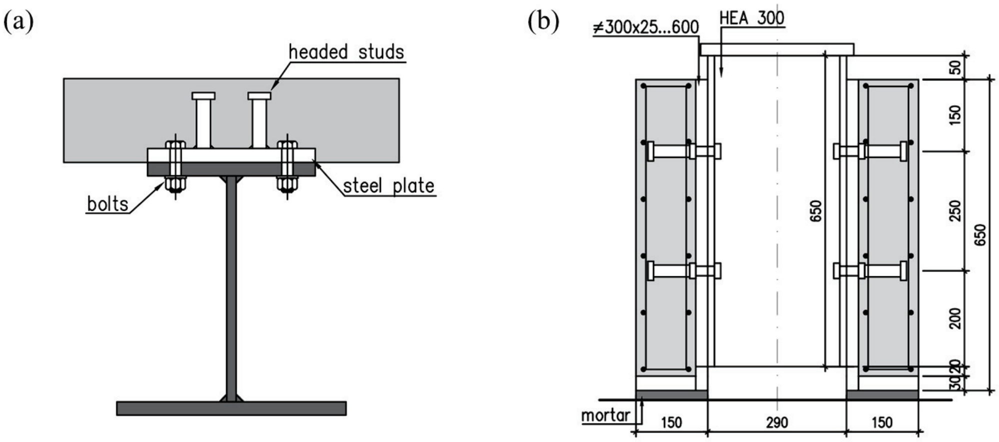

Figure 1 – (a) Connection layout, (b) Push-out test set-up [10]

Push-out tests were conducted at the University of Wuppertal, Germany, including two static and one fatigue test of the connection with welded headed studs and bolts, all according to the set-up presented in Figure 1.b [10]. Applied high-strength bolts were M20 of the grade 10.9, while headed studs were of the diameter Ø25 mm, with yielding strength of 420 MPa and tensile strength of 465 MPa. The steel plate was 25 mm thick, while the concrete slab depth was 150 mm. The load was applied on the steel profile HEA 300.

In both static push-out tests, the observed failure mode was labelled as a shear failure of bolts in the interface between the steel section and the additional steel plate. The visual assessment showed a distribution of cracks in the concrete slab. The recorded ultimate loads and corresponding displacements were:

- $P_u = 1740$ kN, $\delta_u = 1.81$ mm;
- $P_u = 1810$ kN, $\delta_u = 2.70$ mm.

3. NUMERICAL MODELLING

The numerical model of the push-out test was developed in the finite-element software package Abaqus [11]. The quasi-static analysis was performed through the solver Abaqus Explicit, including both geometrical and material nonlinearities.

The geometry of all elements was applied according to the experimental set-up. Due to double symmetry of the tested specimens, one-quarter of the specimen was modelled and appropriate symmetric boundary conditions were applied. The developed model is shown in Figure 2.

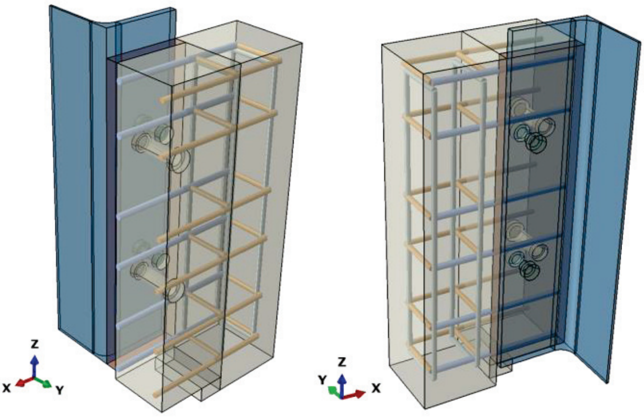

Figure 2 – Finite-element model

Between elements, interaction and constrain conditions were assigned. Welded studs were tied to the steel plate. On the contact surfaces between steel elements, the friction coefficient of 0.2 was adopted, while on the contact between steel and concrete parts, it was set to 0.3. To the reinforcement bars, which were modelled as truss parts, the embedded constraint was applied. Boundary conditions were defined on the bottom of the concrete deck, constraining all displacements at the reference point and connecting all nodes of the bottom surface to that point by a coupling constraint. Similarly, on the top of the steel profile, a vertical displacement is applied.

Material properties were assigned to the model according to the measured data given in the report of the experimental research [10]. For the steel profile, steel plate, reinforcement bars and headed studs, simplified linear models were defined. Considering that damage of bolts was recorder during the experiment, nonlinear stress-strain plastic curve and ductile damage evolution were added to the material model. Concrete tensile and compressive behaviour was defined all according to the model given by Pavlović et al. [7], setting the modulus of elasticity to 34.52 GPa and concrete cylinder strength to 49.1 MPa, as it had been experimentally determined.

To get the appropriate model response simulating a quasi-static experiment, a target time increment for appropriate mass scaling was obtained through the result convergence study. Similarly, the optimized mesh was set according to the mesh convergence study. For solid parts, the applied finite elements were tetrahedral C3D10M and hexagonal elements with reduced integration C3D8R. Size of elements was varied trough the model, with the smallest size of 5 mm applied on headed studs and bolted connectors and the steel and concrete parts in their surroundings. The biggest elements of the size 15 mm and 20 mm were set to the perimeter areas where plastic deformations and failure are not expected.

The numerical model was verified through comparison with experimental results. Experimentally and numerically obtained load-slip curves are given in Figure 3. As it could be observed, a very good agreement is accomplished between the numerical model response and one recorded experimental curve. Unfortunately, possible reasons for a divergence in the response of two tested specimens were not mentioned in the report [10].

The developed model was used for the study of the connection behaviour, including parametric analysis, all described in further.

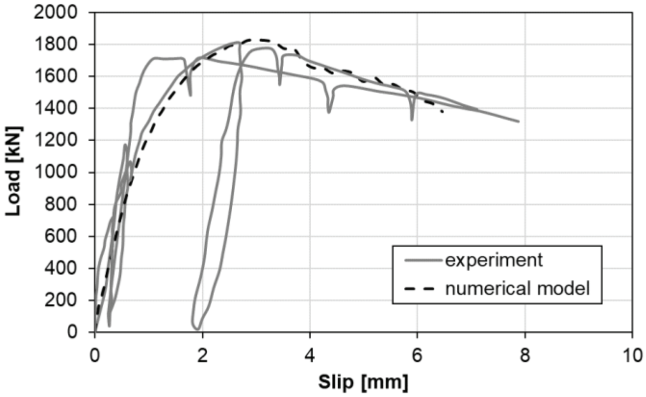

Figure 3 – Load-slip curves

4. RESULTS AND DISCUSSION

According to the numerical model, the ultimate load of P_u = 1828 kN happens at the slip of 3.00 mm. The slip capacity corresponding to $0.9P_u$ in the post-ultimate region is 4.30 mm, implying that according to Eurocode 4 [12], this connection cannot be classified as ductile. The connection ductility is directly affected by the occurred failure mode due to exceeding of the bolt shear resistance.

Taking into account that the analysed connection features two shear planes, a comparison of a slip between the profile flange and the steel plate and a slip between the steel plate and the concrete deck is made. A vertical displacement of the steel profile, marked as a total slip, is plotted in Figure 4, as well as a vertical displacement of the steel plate, marked as a plate slip. It could be observed how two slip values change during loading time. At the point when the ultimate load is reached, the slip between the flange and the plate is almost doubled compared to the slip between the plate and the deck. In further, this difference is increasing simultaneously with bolt failure and large deformations. At the same time, the slip between the concrete deck and the plate remains almost constant.

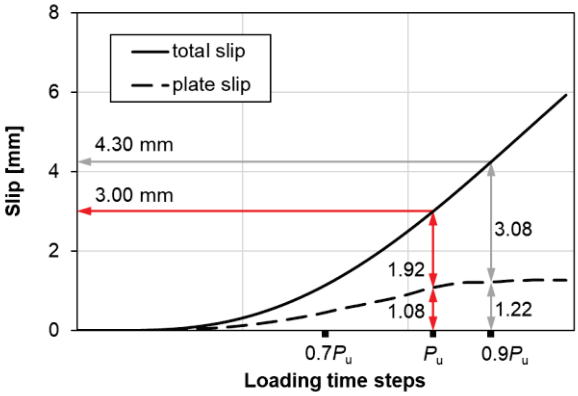

Figure 4 – Comparison of profile (total) and plate vertical displacement

Deformed shapes of shear connectors at the point of ultimate load are shown in Figure 5.a. The bolt deformation due to shear is noticeable, in the opposite to the headed stud deformation which is rather insignificant. According to design rules given in Eurocode 3 [13] and Eurocode 4 [12], accounting the connection geometry and material properties, the resistance of headed studs in composite shear-concrete connection and the resistance of bolts in steel shear connection are similar. At first glance, it seems that design predictions are in disagreement with experimental and numerical results. However, there is a parameter that has not been taken into account in the calculation, as explained in the following.

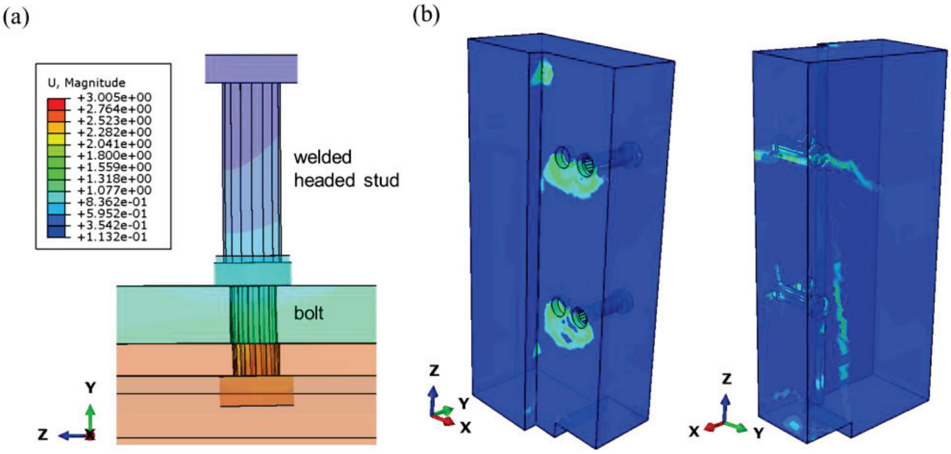

Figure 5 – (a) Deformed shapes of connectors, (b) Concrete cracks

Concrete cracks due to exceeding of the concrete compressive and tensile strength, at the point of reaching P_u, are given in Figure 5.b. Significant crack distribution is observed nearby both welded headed stud and embedded bolt head, implying that the head has a certain bearing contribution in the composite connection. According to the numerical model, the shear force that is transferred by a head is approximately 20% of the force in a headed stud.

Two additional models were developed to compare the connection response with the equivalent connection where shear force is only transferred on the surface between the concrete slab and the plate, i.e. the plate and the profile flange. To accomplish this, artificial constraints were added to the model without making any other modifications. The comparison of models' behaviour at serviceability loads is given in Figure 6. The stiffness of each model is calculated as the ratio between $0.7P_u$ load and corresponding slip. As could be observed from the absolute and relative results given in Table 1, the stiffness varies for three cases. When shear force is only transferred on the surface between the steel plate and the profile flange, the increase of stiffness is almost 50% compared to the analysed demountable connection. When slip only happens in the plane between the concrete slab and the steel plate, the stiffness is nearly doubled than in the original connection. It could be concluded that by the development of a demountable connection with indirect shear force transfer and two active shear planes, the initial stiffness is smaller comparing to the equivalent non-demountable connection with welded headed studs.

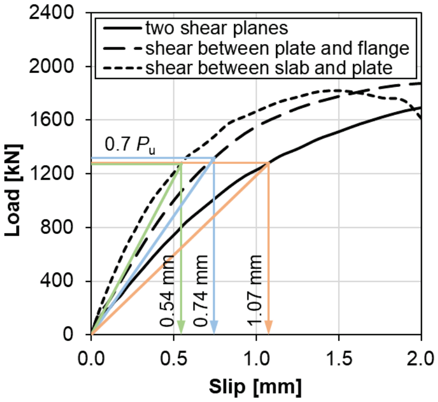

Figure 6 – Load-slip curves

Table 1 – Stiffness at serviceability loads

	Stiffness, k_{SLS} [kN/mm]	k_{SLS} / $k_{SLS,\text{dem.}}$ [-]
demountable connect. with two shear planes	1191	1.00
shear between plate and flange	1773	1.49
shear between slab and plate	2336	1.96

In further, it was analysed how the increase of the bolt diameter influences the load-slip response. The obtained force-slip curves for models with bolts of the diameter 18, 20, 22 and 24 mm are presented in Figure 7, while properties of each connection are summarized in Table 2. Shapes of load-slip curves for models with bolts M18 and M20 correspond to each other: the stiffness is almost the same in serviceability domain, the ultimate load levels are proportional to bolt cross-sectional area and ductility is increasing with bolt diameter. In both cases, the failure due to bolt shear happened. However, for larger bolts, this trend is not present. The difference in the ultimate load for specimens with bolts M22 and M24 is not significant, because of the concrete failure that is characteristic for both models. The increase in stiffness at serviceability loads of 6% and 15% is present for models with bolts M22 and M24, comparing to the original connection with bolts M20. The slip at $0.9P_u$ in the post-ultimate region decreases with the bolt diameter increase. Slip capacity of the connection with bolts M24 is nearly 40% lower than for the original connection with M20.

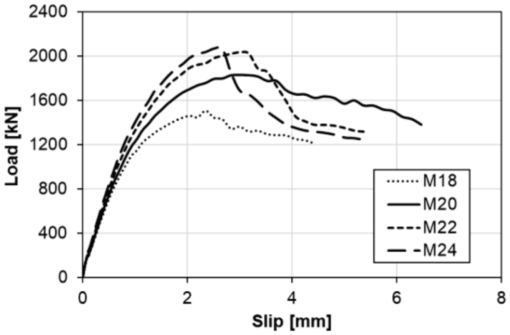

Figure 7 – Load-slip curves for varied bolt diameter

Table 2 – Stiffness at serviceability loads, ultimate load and slip capacity for varied bolt diameter

Bolt	Stiffness, k_{SLS} [N/mm]	Ultimate load, P_u [kN]	Slip, $\delta_{0.9Pu}$ [mm]
M18	1208	1508	3.03
M20	1191	1828	4.30
M22	1265	2036	3.56
M24	1373	2067	2.72

In the developed model calibrated to the experimental results, bolts M20 were placed in the holes so that bolt to hole clearance was voided before loading in the push-out test. However, in real structures, the additional slip of the connection induced by the existence of bolt to hole gaps is present and it should be considered during composite beam design. This initial slip affects the structural response of the connection and might induce additional deflections of the steel beam.

In Figure 8, there are presented load-slip curves when holes of the diameter 20 mm, 21 mm and 22 mm were cut through the flange and the plate and when bolts were placed centrally inside the holes. Two cases are analysed: preloaded and non-preloaded bolts. Due to the same bolt diameter and material strength, all presented solutions show the same ultimate load level. However, shapes of curves are different implying that bolt-hole clearance influences the stiffness and slip capacity of the connection. A solution with preloaded bolts leads to the sudden slip after friction forces are overcome when a gap between a bolt and a flange hole is annulled. In the case of bolts without the applied pretension force, a bolt-hole gap is voided it the initial stage of loading for low load levels.

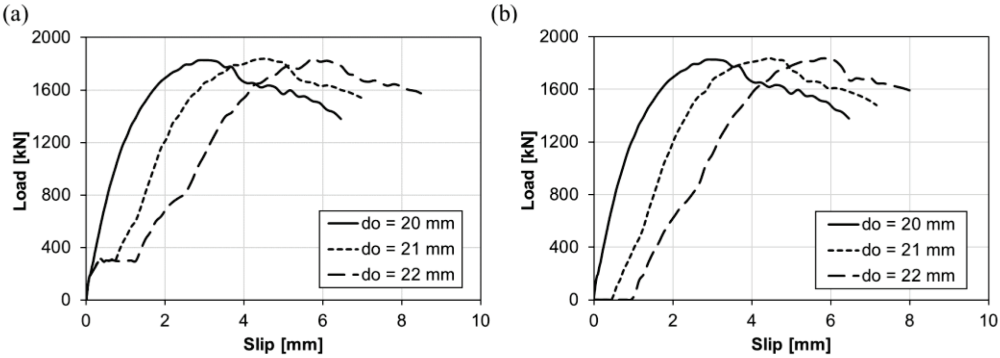

Figure 8 – Load-slip curves for varied hole diameter for:
(a) preloaded bolts, (b) non-preloaded bolts

However, in both mentioned cases it is important to underline that this slip is smaller than the slip of composite shear connections achieved only with bolted connectors, e.g. friction-grip bolts [2] or bolts with embedded nuts [14]. Smaller bolt-hole gaps in a connection with welded headed studs and bolts are influenced by smaller execution tolerances when connecting two steel elements, than when connecting a concrete and a steel part. During the production of prefabricated concrete decks with embedded bolted connectors, a precision of bolt placing is questionable. On the other hand, in the connection analysed in this paper, the application of the additional steel plate simplifies the execution, as before concrete casting bolts are easily set in the right position defined by holes, predrilled in the steel plate.

5. CONCLUSIONS

At the time when significant efforts are put into the research of demountable composite steel-concrete connections, especially applicable in floor design, a certain contribution is given through this paper. The connection with welded headed studs and bolts, as a solution that has been mostly neglected by researchers, is analysed. Shear force transfer is accomplished through the additional steel plate on the contact between a concrete deck and a steel beam. As nowadays numerical analysis is a powerful tool that helps in phenomena and process understanding, it is applied in this study of the shear connection. After the numerical model verification against the experimental data of push-out tests [10], it is used for deeper study of the connection and further parametric analyses.

Considering all the results presented in the paper regarding the connection response to shear, some conclusions could be drawn. Bearing elements against shear are bolts on the plate-flange surface and welded headed studs and bolt haeds on the plate-deck surface. The presence of two shear planes, which enables deconstruction of the system, leads to the smaller initial stiffness of the connection comparing to the equivalent non-demountable connection with welded headed studs.

In the analysed connection, the observed failure mode is bolt shear. Increasing the bolt size, this failure could be avoided and critical points could be transferred to headed studs and adjacent concrete. In this way, load-slip response closer to the behaviour of non-demountable connections with welded headed studs could be achieved.

For the adopted bolt size, the appropriate hole diameter should be selected considering standard fabrication tolerances in steel manufacturing. The influence of the initial slip due to bolt movement should be considered in a beam design, whether bolts are preloaded or not.

Even though this connection has been initially developed for application in composite bridge design, it may be also considered for application in floor systems, including some geometry modifications and further studies to choose the optimal connection layout. The influence of a steel plate thickness could be discussed and application of a much thinner element than 25 mm may be considered. In order to investigate the possible application of this connection in building design, further simulations of connection shear response should be conducted including headed studs of a diameter Ø16mm, Ø19mm and Ø20mm, commonly present in composite floor structures. Additionally, the analogous system where the solid concrete slab is replaced by the composite slab with profiled steel sheeting could be developed and investigated.

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