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DEMOUNTABLE CONNECTIONS WITH MECHANICAL COUPLERS LOADED IN SHEAR AND TENSION

Summary: This paper presents the main aspects of a comprehensive study of demountable steel-precast concrete connections consisting of a demountable bolt and embedded mechanical coupler with a rebar anchor. The study included experimental and numerical analysis of the connection under pure tension, pure shear, and combined shear and tension loading. The research was conducted at the University of Belgrade, Faculty of Civil Engineering and published in the PhD thesis "Demountable connections between steel and reinforced concrete elements with mechanical couplers under combined shear and tension loads". The distance between the connector and the concrete edge, connector diameter, and concrete strength were examined as the main parameters affecting the failure modes, load-displacement behaviour and corresponding resistance of the connection. The results presented in this paper should contribute to the better understanding of the connection behaviour and design implications.

Keywords: demountable connections, couplers, rebar anchors, combined shear and tension

DEMONTAŽNI SPOJEVI SA MEHANIČKIM SPOJNICAMA OPTEREĆENI NA SMICANJE I ZATEZANJE

Rezime: U ovom radu prikazani su najznačajni apsekti opsežnog istraživanja demontažnih spojeva čeličnih i prefabrikovanih betonskih elemenata koji su ostvareni pomoću demontažnog zavrtnja i ubetonirane mehaničke spojnice sa armaturnim ankerom. Istraživanje je obuhvatilo eksperimentalnu i numeričku analizu razmatranog spoja pri dejstvu sile zatezanja, pri dejstvu sile smicanja, kao i pri kombinovanom dejstvu sila smicanja i zatezanja. Istraživanje je sprovedeno na Građevinskom fakultetu Univerziteta u Beogradu i objavljeno je u doktorskoj disertaciji „Demontažni spojevi čeličnih i armiranobetonskih elemenata sa mehaničkim spojnicama pri interakciji smicanja i zatezanja". Kao glavni parametri koji utiču na vid loma, ponašanje i odgovarajuću nosivost spoja analizirani su rastojanje konektora od ivice betona, prečnik konektora i čvrstoća betona. Prikazani rezultati treba da doprinosu boljem razumevanju ponašanja ovakvih spojeva i najvažnijih aspekata njihovog proračuna.

Ključne reči: demontažni spojevi, mehanička spojnica, armaturni anker, interakcija smicanja i zatezanja

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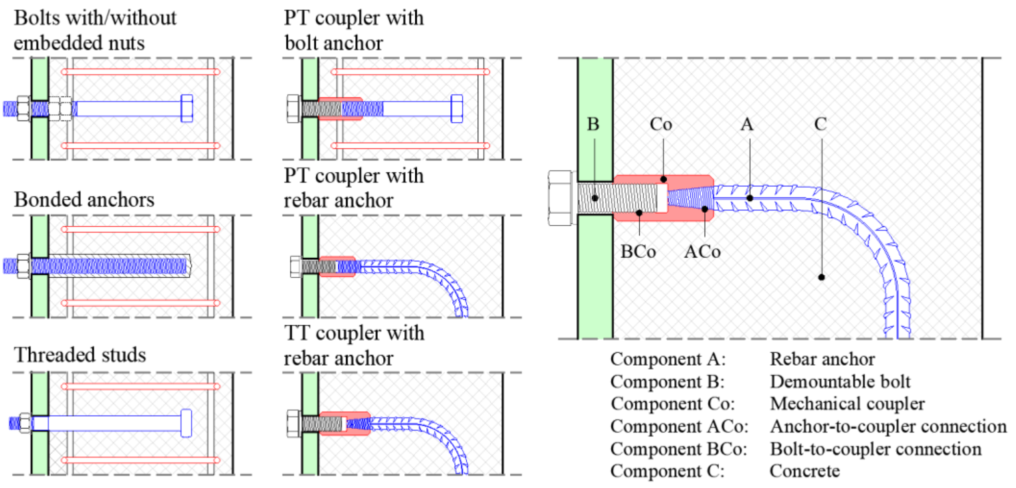
1. INTRODUCTION

Composite and mixed steel–concrete structures have become widely used in modern construction practice due to efficient use of steel and concrete, as well as the reduced construction time and costs of office buildings, parking garages, bridges, etc. In recent years, the construction industry has been focused on sustainable design and the circular economy. Structural steel is fully recyclable, while prefabricated reinforced concrete (RC) elements contribute to lower carbon emissions, reduced construction waste, shorter construction periods, and improved overall sustainability [1], [2]. To further enhance the reuse potential of these structures at the end of their service life, the Design for Disassembly (DfD) has become an important design consideration [3].

The disassembly and reuse of structural components can be enabled with the use of demountable connectors, which provide an alternative to conventional welded headed studs that cannot be dismantled. In this regard, the main challenge is to develop demountable connections that maintain adequate structural performance while allowing the repeated reuse of steel and concrete components as well as the connection itself [4]. Figure 1(a) presents some of the most widely investigated types of traditional demountable connectors, such as bolts with or without embedded nuts, post-installed bonded anchors, and threaded studs. Although the application of aforementioned connectors can enable disassembly and reuse of steel elements, the possibility of reuse or replacement of other components of the connection is limited. The limitations occur due to the fact that traditional connectors cannot be replaced and a risk of physical damage of the exterior part of connector during the assembly, building service life and disassembly of structural elements.

New generation of bolted connectors with mechanical coupler are shown in Figure 1(b). This type of connector consists of a mechanical coupler embedded in a RC element, anchored by an embedded bolt anchor or rebar anchor. Mechanical couplers can have either parallel threads (PT) or taper threads (TT) used for connection with the anchor. The steel element is connected to the RC element by screwing the demountable bolt into the embedded coupler.



(a) Traditional demountable connectors

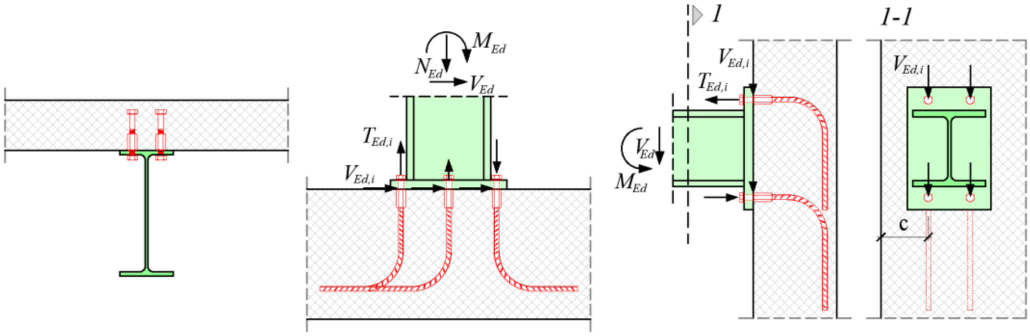
(b) Demountable connectors with mechanical coupler

(c) Connection components for bolted connector with mechanical coupler and rebar anchor

Figure 1: Demountable connectors for steel-concrete connections

These connectors can be easily disassembled, which could improve the sustainability of steel-concrete structures. In addition, mechanical couplers provide a flat surface of the RC element at the location of the connection, making assembly and disassembly easier compared to the traditional solutions for demountable connections. Finally, the possibility of reuse of all connection components can be assured if the "weakest" component of the connector is the demountable bolt [5].

Over the past few decades, the connectors with mechanical couplers have been primarily used in construction practice for connections in steel-concrete composite and mixed structures, as shown in Figure 2. In composite beams, with relatively small depth of concrete slab, the connectors with embedded anchor bolts are most commonly used (see Figure 2(a)). In this type of connections, the connectors are mainly loaded in longitudinal shear. In contrast, for the steel column-to-foundation joints, or steel beam-to-RC wall/column joints, the connectors with rebar anchors are the typical choice of structural engineers, as shown in Figures 2(b)-2(c). Depending on the layout of the joint, the connectors are loaded in combined tension and shear loads, with various combination of these loads. The latest research is also focused on the demountable precast frame structures, in which bolted connectors with mechanical coupler and rebar anchor are used in beam-to-column joints and column-to-foundation joints [6]. However, since the connections are usually highly overdesigned, no detailed consideration was paid to the actual behaviour of the connectors under arbitrary loads. Furthermore, the current European standard EN 1992-4:2018 [7] does not define the rules nor recommendations for the design of this type of connections.



(a) Steel-concrete composite beam

(b) Steel column-to-RC foundation joint

(c) Steel beam-to-RC wall (or RC column) joints

Figure 2: The application of demountable connectors with mechanical couplers in steel-concrete composite and mixed structures

Over the last 15 years, the research conducted by several research groups was focused on the behaviour of single connectors with different configurations, under pure shear load or pure tension load. Yang et al. [8] have investigated shear behaviour of bolted connectors with PT mechanical coupler and bolt anchor in push-out tests (see Figure 1(b)). All specimens failed due to shear failure of demountable bolt. After testing of one specimen series, authors reused RC elements to assemble additional specimen which practically had the same shear resistance as original specimens. Kozma et al. [4] have investigated the behaviour of the same connector type for composite beams with injected oversized bolt holes in steel element and prefabricated concrete decks, in order to improve the execution efficiency. All specimens failed due to shear failure of demountable bolt.

Milosavljević et al. [9] and Milićević et al. [10] have investigated the shear behaviour of a bolted demountable connector with a TT mechanical coupler and rebar anchor (see Figure 1(b)), through experimental and numerical push-out tests. The study was focused on connectors positioned near the concrete edge and loaded parallel to the concrete edge, representing typical steel beam-to-RC column/wall connections (see Figure 2(c)). The effects of concrete edge distance *c*, concrete strength, and connector diameter were evaluated. Concrete edge failure was observed for connectors placed close to the edge in low-strength and normal-strength concrete, whereas bolt shear failure governed when the edge distance was sufficient. Based on the results, prediction equations for concrete edge failure resistance were proposed.

Although previous studies have established the shear behaviour of this type of the connector, its behaviour under combined shear and tension loads remains insufficiently understood. In this regard, understanding the behaviour of the connection under pure tension load is crucial. Owing to its three-component configuration (bolt, mechanical coupler, and rebar anchor), the connector exhibits more complex tensile behaviour than conventional connectors, which was examined in the preliminary tension tests on in-air specimens by Milićević et al. [11]. The "component method", which is commonly used for the analysis of joints and connections, can be extended to the local analysis of the connector under arbitrary loads, as defined in Figure 1(c). Therefore, the "weakest" component mainly governs the overall behaviour of the connection. Finally, if the rebar anchor is adequately designed, all concrete failure modes under tension load can be reduced to a minor concrete damage or even be excluded, without the need of supplementary reinforcement.

Comprehensive experimental and numerical study of the behaviour of single bolted connectors with TT mechanical coupler and rebar anchor under pure tension load, pure shear load as well as combined shear and tension loads is presented in doctoral thesis [12]. In this paper, the short overview is given and discussed, with the most important design considerations.

2. EXPERIMENTAL STUDY

Experimental study of demountable connections realised via bolted connectors with TT mechanical coupler and rebar anchor was separated divided in five phases:

- Testing of material properties of connection components;
- Testing of in-air specimens of bare connector under tension load;
- Testing of the connection under tension load in pull-out tests;
- Testing of the connection under shear load in push-out tests;
- Testing of the connection under shear and tension loads in modified push-out tests.

All experimental tests were conducted at the Faculty of Civil Engineering, University of Belgrade. Testing of in-air specimens was conducted in order to gain insight into the local behaviour of the connector under tension load, which was used as the basis for the analysis of connection behaviour examined in pull-out tests. Push-out tests were conducted with aim to expand the current database of shear resistance and overall behaviour of the connection [9], [10]. Finally, the resistance and behaviour of the connection under combined shear and tension loads was obtained from modified push-out tests, with different ratios of tension-to-shear load.

The general overview of all specimens used for the testing of the connection behaviour, as well as the specimens tested in the previous research [9], is presented in Table 1. Regarding the geometrical and material characteristics of the connection components, it can be noticed that the experimental programme included two different diameters of the connector (M20 and M16 bolts, with corresponding diameters of coupler and rebar anchor), two different concrete classes (C20/25 and C30/37), as well as two different concrete edge distances (c = 75 mm and c = 150 mm). Specimen groups A, B, C were tested in order to examine the behaviour of the connection with the influence of concrete edge distance and corresponding concrete edge failure, while specimen group D was tested in order to examine the behaviour of the connection without an effect of concrete edge. In total, 31 specimens were tested in this experimental study, with 9 specimens used from the previous study [9]. In addition, 6 in-air specimens of the bare connectors were tested, with M20 and M16 bolt diameters (3 specimens in each series).

For demountable bolts, taper-threaded mechanical couplers and rebar anchors, steel grades 8.8, C45+C and B500B were used, respectively. Built-up steel elements with steel grade S355 were used in pull-out tests, push-out tests and modified push-out tests. For push-out tests conducted by Milosavljević et al. [9], steel section HEB 260 with steel grade S235. Details regarding testing results of material properties of connection components are given in [5], [9].

Table 1: The overview of programme for connection experimental testing

Specimen group	Tension load level	Shear load level	Bolt	Coupler	Rebar anchor	Concrete class	Concrete edge distance	Number of specimens
	T/T_u [-]	V/V_u [-]	Diameter [mm]	Diameter [mm]	Diameter [mm]		c [mm]	
A	1.00	-	M20	27	16	C20/25	75	3
	-	1.00						4
	0.25	V_1/V_u						3
	0.50	V_2/V_u						3
	0.75	V_3/V_u						3
B	1.00	-	M20	27	16	C30/37	75	2
	-	1.00						3
	0.75	V_3/V_u						1
C	1.00	-	M16	22	12	C20/25	75	3
	-	1.00						6[a)]
	0.70	V_3/V_u						3
D	-	1.0	M20	27	16	C30/37	150	1 + 3[a)]
	0.75	V_3/V_u						2

a) Test results obtained by Milosavljević et al. [9]

2.1. THE BEHAVIOUR OF DEMOUNTABLE CONNECTORS AND CONNECTION UNDER PURE TENSION LOADS

As stated before, experimental testing under tension loads was conducted in two phases. Firstly, the behaviour of bare connectors was conducted in order to obtain detail insight into the behaviour of each component of the connector, as well as the behaviour and tension resistance of the connector as a whole. The testing was conducted by using tensile testing machine, as presented in Figure 3.

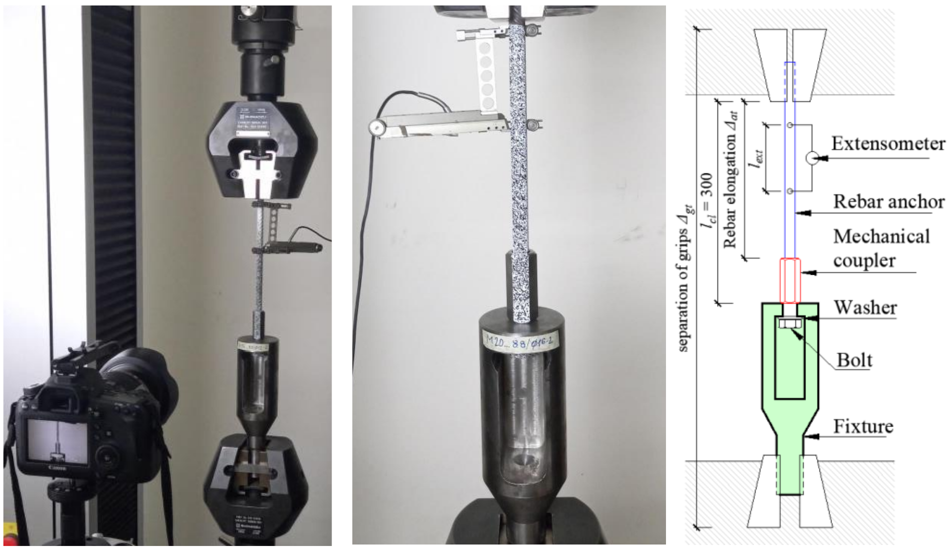
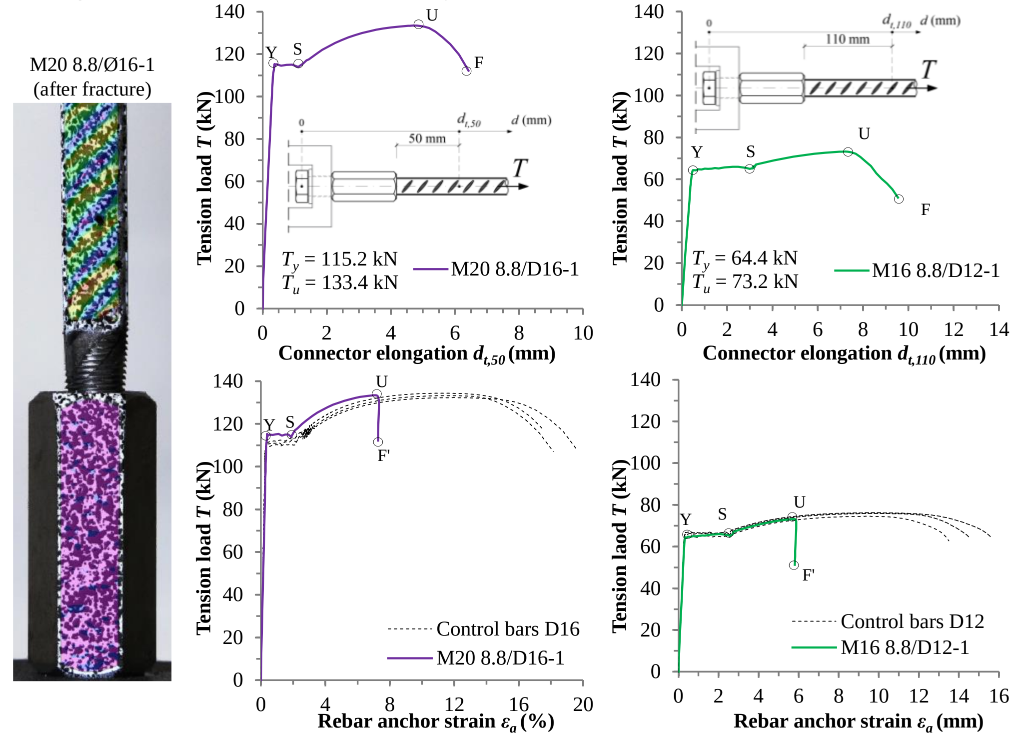


Figure 3: The layout of in-air specimens used for testing bare connectors under tension load

Testing machine provided the measurement of tension force T and separation of grips Δ_{gt}, while the elongation of the rebar anchor and corresponding strains ε_a were measured by an extensometer with a gauge length l_{ext} = 100 mm. The local deformations, strain localization and fracture of connector parts at the axis of the connector were measured using Digital Image Correlation (DIC) method. All details regarding preparation of specimens, testing and measurement procedures, can be found in [5], [11].

The test results for characteristic specimens of connectors with bolt diameters M20 and M16 are presented in Figure 4. All specimens failed due to stripping of taper threads at the end of rebar anchor, with relatively small strains in mechanical coupler and demountable bolt, as shown in Figure 4(a). The overall behaviour of the connector was governed by the behaviour of rebar anchor up to the ultimate load, as shown in Figures 4(b) and 4(c). The presented results indicate that yield load T_y (point “Y”) and ultimate load T_u (point “U”) are similar to the corresponding resistances of controlled bars. After the attainment of ultimate load, the overall elongation of the connector increased (part U-F), while the strains in rebar anchors did not increase (part U-F’). This effect was attributed to the slip between rebar anchor and mechanical coupler, due to stripping of taper threads. Bolts were easily removed from couplers.



(a) Failure mode (b) Connector with M20 bolt (c) Connector with M16 bolt

Figure 4: Experimental testing results for in-air specimens

In the second phase, the testing of the connection with the connectors embedded in precast RC elements was conducted. The schematical layout of tested specimens is presented in Figure 5. Test specimens were assembled from one built-up steel element connected to precast RC element, by connecting demountable bolt to the embedded mechanical coupler and rebar anchor. The dimensions of RC elements and reinforcement detailing were similar to the specimen layout used for push-out tests by Milosavljević et al. [9]. Although two connectors were placed in one RC element, the pull-out testing was done on only one connector at the time. It is important to note that the shape and dimensions of rebar anchors are determined based on the required anchorage length and mandrel diameter according to EN 1992-1-1:2004 [13].

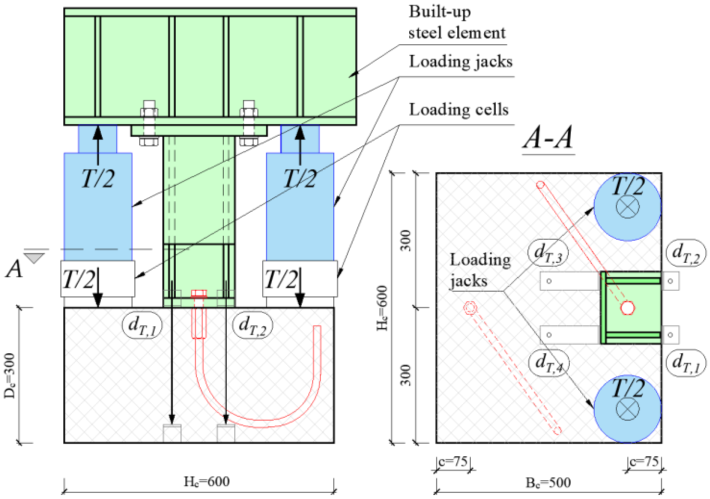
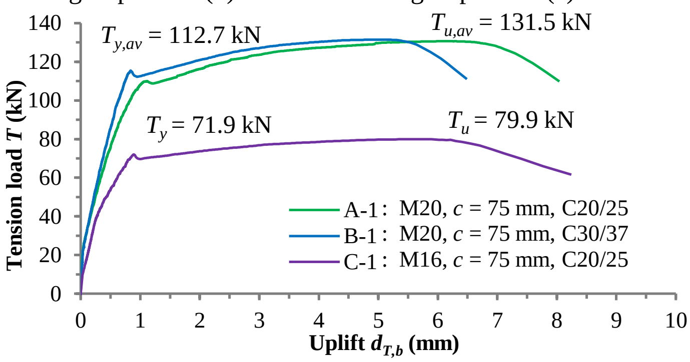


Figure 5: The layout of pull-out specimens used for testing the connection under tension load

After the specimens were assembled, two loading jacks were placed between steel element and RC element, as shown in Figure 5. Loading Two loading cells were placed at the bottom of loading jacks in order to continually measure the applied tension load. During the testing of all specimens, measuring of displacements was done with four LVDTs (linear variable differential transducers). The uplift of steel element from RC element was measured, resulting in values $d_{T,1}$-$d_{T,4}$. Based on the measured values and the location of LVTDs in plan (section A-A in Figure 5), the uplift at the location of the bolt $d_{T,b}$ was obtained. Test results for characteristic specimens are presented in Figure 6.

(a) Failure mode – group A (b) Failure mode – group B (c) Failure mode – group C



(d) Load-uplift curves

Figure 6: Experimental testing results for pull-out specimens

From the presented results, it can be noticed that the failure mode of the connection examined in pull-out tests is the same as obtained from in-air tests, i.e., the failure occurs due to stripping failure of rebar-to-coupler connection realised by taper threading. As a result, the mechanical couplers were pulled out of the RC element (see Figures 6(a)-6(c)). Bolts were easily demounted. In case of specimens in group A, the concrete damage occurred to the largest level and extent. Single crack located at the axis of the connector occurred in all cases, after yielding of the rebar anchor. At the front (top) side of RC elements, the breakout of small concrete cone occurred, due to loss of bond between the connector and surrounding concrete. In case of group B (with higher concrete strength) and group C (with smaller connector diameter), concrete cracks did not appear on the tested specimens. Yield and tension loads obtained from pull-out tests were very similar to the yield and tension loads of corresponding in-air specimens, with differences up to 4%. In respect to the tension resistance, it can be seen that there are no significant differences between groups A and B, with the same connector diameter and different concrete strength. The reason lies in the fact that, in both cases, rebar anchors were dimensioned and shaped in a manner that prevents concrete failure modes. Therefore, under this assumption, the "weakest" component of the connection is rebar anchor, i.e., the anchor-to-coupler connection. Furthermore, it was demonstrated that the use of yield resistance of rebar $T_{y,a}$ in the design of the connections with bolted connectors with TT coupler and rebar anchor under tension load is reasonable approach. Finally, Milićević et al. [5] demonstrated that the use of lower bolt grade will lead to bolt failure.

2.2. THE BEHAVIOUR OF DEMOUNTABLE CONNECTION UNDER PURE SHEAR LOADS AND COMBINED SHEAR AND TENSION LOADS

The behaviour of the connection under pure shear load as well as combined shear and tension loads was examined through the push-out tests and modified push-out tests, respectively. In this regard, the same layout of test specimens was used, as shown in Figure 7. The specimens consisted of two precast RC elements connected by two built-up steel elements with U-shaped cross section with stiffeners. Each precast RC element had two connectors, i.e., embedded mechanical couplers with rebar anchors. In total, each specimen contained four connectors. Similar layout and reinforcement were used by Milosavljević et al. [9]. The connection was realised by inserting demountable bolts into embedded mechanical coupler. In push-out tests, the vertical load on specimens was applied through vertical jack, and thick steel plate used for equal distribution of the load to the built-up steel elements. In modified push-out tests, a set of two horizontal jacks was placed between built-up steel elements, used for the application of tension load on the connectors.

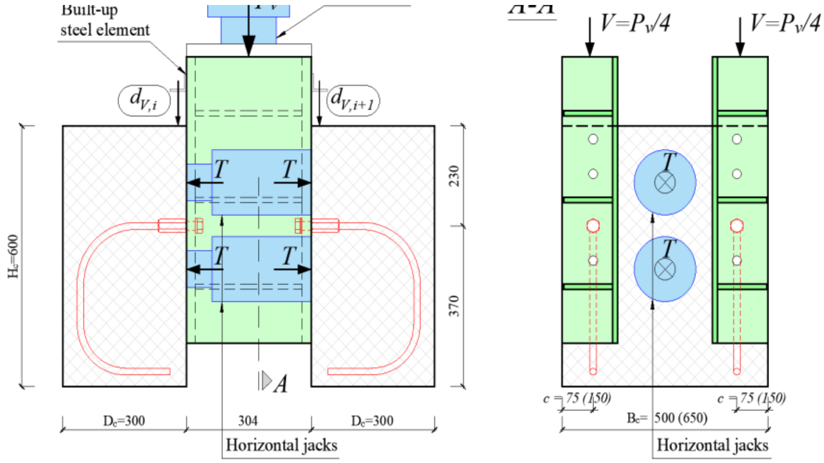
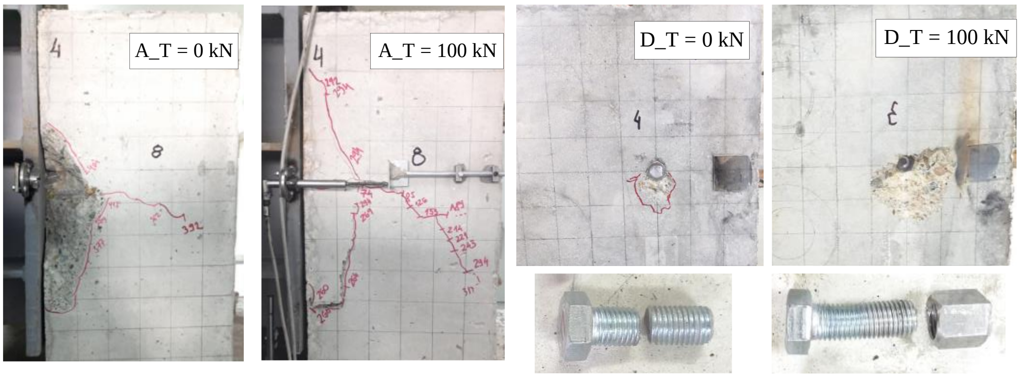


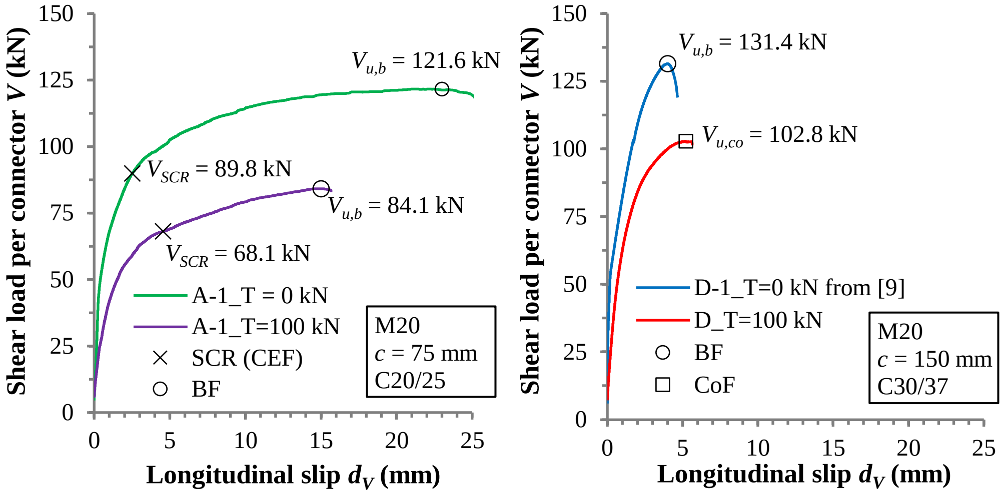
Figure 7: The layout of modified push-out specimens used for testing the connection under pure shear load and combined shear and tension loads

For investigation of shear behaviour, the vertical load in push-out tests was applied in two phases: (1) cyclic loading up to 40% of ultimate load, and (2) monotonic loading up to failure, in accordance with EN 1994-1: 2004 [14]. For investigation of the behaviour under combined loads, after application of cyclic vertical load, tension load was applied to the predetermined value in the second phase. In the third phase, tension load was kept constant, while the vertical load was applied until failure of the connection. At the location of the connectors, four LVDTs were placed in order to monitor longitudinal slip between steel and RC elements, resulting in values $d_{V,1}$-$d_{V,4}$. In addition, uplift between steel and RC elements, as well as separation of RC elements were monitored during testing (not shown in Figure 7 for simplicity reasons). In addition, concrete cracking at the sides of RC elements was monitored during testing. As presented in Figure 7, the concrete edge distance was varied by changing the total width B_c of precast RC elements, in order to achieve the concrete edge distance c = 75 mm (groups A, B and C) and c = 150 mm (group D).

The results of push-out tests and modified push-out tests, for characteristic specimens from group A and group D are presented in Figure 8. For modified push-out tests, the applied tension load was T = 100 kN ($T/T_u \approx 0.75$), which was less than yield load of the connection under pure tension load (see Figure 6). The shear load per connector was calculated as one fourth of the total vertical force, while longitudinal slip per connector was calculated as the average value of slips $d_{V,1}$-$d_{V,4}$.



(a) Failure modes – group A (b) Failure modes – group D



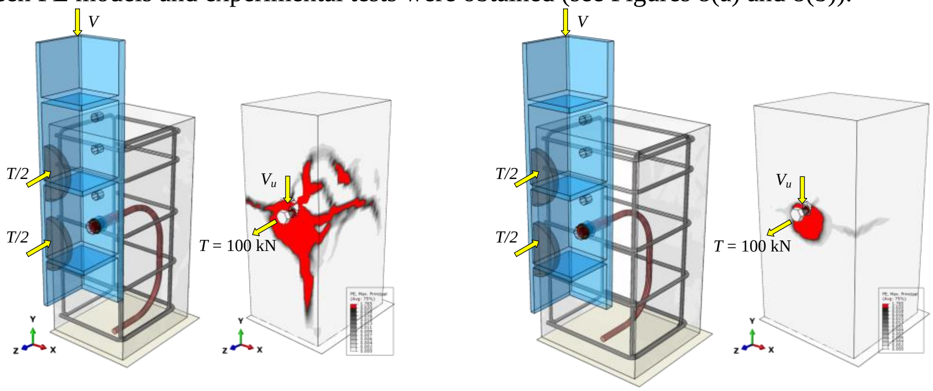
(c) Load-uplift curves – group A (d) Load-uplift curves – group D

Figure 8: Experimental testing results for push-out specimens and modified push-out specimens

The results have shown significant difference in the failure modes of the connection depending primarily on the concrete edge distance. In case of group A, the extensive concrete damage and cracking occurred, characteristic to concrete edge failure (CEF), both under pure shear load and under combined loads, as presented in Figure 8(a). Shear load V_{SCR} corresponds to the appearance of the first inclined crack at the sides of RC elements. The concrete breakout body was limited to the concrete cover depth. However, due to adequate anchorage of the connector, the connection was able to sustain further increase of shear load up to shear load $V_{u,b}$, which corresponded to the failure of demountable bolt (Figure 8(c)). Similar behaviour was observed by Milosavljević et al. [9]. The application of tension load resulted in the reduction of shear resistance, stiffness and longitudinal slip capacity. In case of group D, shear resistance and stiffness were significantly higher, with the much smaller longitudinal slip at failure (Figure 8(d)). In case of pure shear load, the failure of the connection occurred due to shear failure of the bolt, while coupler failure occurred under combined shear and tension loads, due to higher degree of concrete damage below the connector, as shown in Figure 8(b). The observed failure modes required in-depth analysis of the results in regard to the corresponding shear resistances of the connection, particularly in case of concrete failure mode and coupler failure mode.

3. NUMERICAL ANALYSIS

Extensive nonlinear finite element (FE) analysis was conducted in order to develop and calibrate FE models of push-out and modified push-out specimens based on the results of experimental study. The FE analysis was conducted using Abaqus/Explicit software [15]. Double vertical symmetry boundary conditions were applied for all specimens, as shown in Figure 9. All components of the connection were included, with corresponding material properties and boundary conditions. Detailed description of FE analysis is presented in doctoral thesis [12]. The calibration of FE models was conducted primarily based on the global failure mode (concrete edge failure or connector failure) and corresponding shar resistance, as well as shear stiffness and longitudinal slip. Overall, the difference of FE analysis results and experimental test results were up to 12% for bolt shear failure load $V_{u,b}$ and concrete edge failure load $V_{u,SCR}$. The maximum principal plastic strain distribution in concrete (PE, Max. Principal), representing concrete crack distribution, is also presented in Figure 9. In this regard, it can be concluded that good match between FE models and experimental tests were obtained (see Figures 8(a) and 8(b)).



(a) FEM_A_T=100 kN (b) FEM_D_T=100 kN

Figure 9: FE analysis of modified push-out tests – model layout and crack distribution

The FE models were used for detailed analysis of the stresses, strains and section forces in the connector components, i.e., demountable bolt, mechanical coupler and rebar anchor. The plastic strain distribution in the connector components before the failure of the connection is presented in Figure 10. In case of FEM_A_T=100 kN, it can be seen that demountable bolt and rebar anchor exhibited high strains caused by bending with axial force, with high rotation of the connector, due concrete edge failure and large longitudinal slip. In contrast, demountable bolt and mechanical coupler exhibited large strains in case of FEM_D_T=100 kN. Due to large crushing of concrete beneath the coupler, the coupler behaved similarly to cantilever.

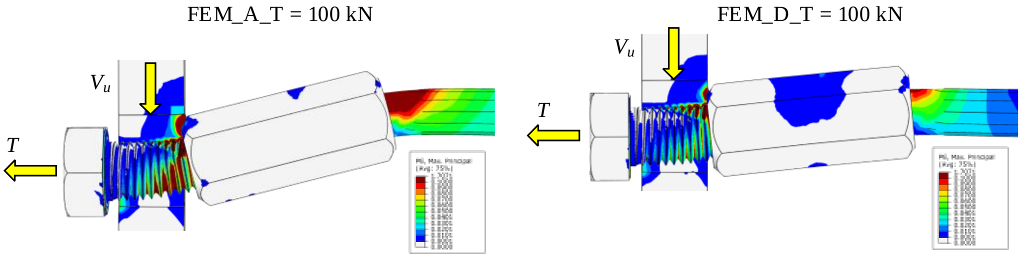


Figure 10: Plastic strain distribution in connector components

The obtained FE models were used for comprehensive numerical parametric analysis, which included the main parameters that affect the behaviour and resistance of the connection, i.e., concrete edge distance, concrete strength, the level of the applied tension load. The results of the numerical parametric study and experimental tests were used to derive new prediction models for the resistance of the connection based on the “component method” given in [12], with the aim of supplementing the existing calculation models for connection resistance in the European design standard [7].

4. CONCLUSIONS

This paper presents the overview of the comprehensive experimental and numerical study of demountable steel-concrete connections realised by demountable bolt, taper threaded mechanical coupler and rebar anchor under pure shear and pure tension loads, as well as combined shear and tension loads. The following conclusions were drawn from this investigation:

- The behaviour of bare connector under tension load strongly depends on its “weakest” component. For the analysed connector, the “weakest” component was rebar anchor, i.e., the rebar-to-coupler connection with resistance similar to the corresponding control rebar.
- By adequate dimensioning of rebar anchor, in terms of anchorage length and mandrel diameter, all concrete failure modes of the connection subjected to tension load can be prevented, which would lead to the same failure mode as bare connectors.
- The failure modes, resistance and behaviour of the connection under pure shear load strongly depends on the concrete edge distance. By increasing concrete edge distance, the failure mode shifts from concrete edge failure to bolt failure.
- Under combined shear and tension loads, the specimens with small concrete edge distance exhibited the concrete edge failure mode with the reduction of shear resistance. Specimens with large concrete edge distance exhibited coupler failure.
- The “component method” can be used for the design of the demountable connections realised by bolted connector with mechanical coupler and rebar anchor under pure tension loads, pure shear loads, and combined shear and tension loads.

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