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# BEHAVIOUR AND DESIGN OF BOLTED CONNECTORS WITH MECHANICAL COUPLER: AN OVERVIEW

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## ABSTRACT

The construction industry is one of the most important parts of economic development of society but it also has a very negative impact on the environment. Using the three concepts of circular economy: reuse, reduce and recycle, it is possible to decrease its negative impact. The steel-concrete composite structures and prefabricated structures enable, environmentally beneficial, circular life-cycle of buildings. For structural performance during the lifecycle, it is very important to have an adequate connection between the steel and reinforced concrete members.

Different types of connectors have been widely used in composite structures. Demountable ones are advantageous in terms of reuse. In the last few years, the innovative demountable steel-concrete bolted connector with mechanical coupler has been proposed. There are two types of these bolted connectors depending on the type anchorage i.e., with the rebar anchor or with the second bolt.

This paper gives an overview of previous research of bolted connectors with mechanical coupler capacity under static load. Influence of key parameters on the shear behaviour of the connector was observed: concrete compressive strength, connector dimensions and concrete edge distance. The shear and tension resistances of individual parts of the commercially available connectors were determined using recommendations of design codes and technical documentation. In case of the connector loaded in tension, it was concluded that the resistance is governed by the resistance of the rebar anchor. In case of the connector loaded in shear, design recommendations were also compared with the previous experimental tests. It was concluded that the shear resistance highly depends on the connection layout and concrete strength.

**Keywords:** Circular economy, Steel-concrete connections, Demountable connections, Mechanical coupler

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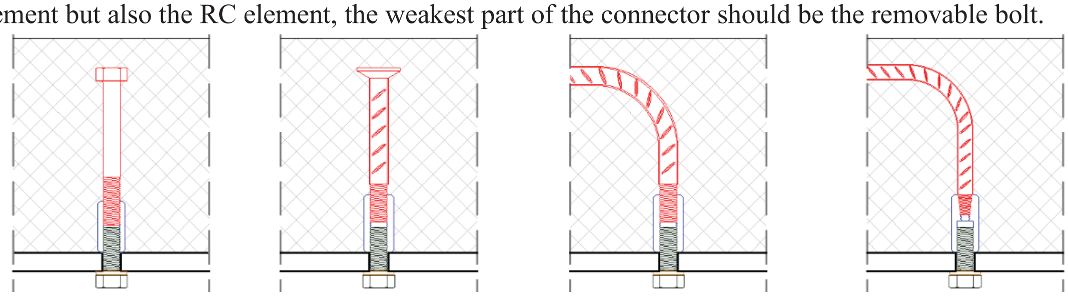
## 1. INTRODUCTION

The construction industry is known as one of the most harmful for the environment, it is responsible for the consumption of large amounts of natural resources, emission of polluting gases and production of waste. The negative impact on environment occurs during the entire lifecycle of buildings, especially during the construction and demolition [1]. Concrete is the most used construction material, but concrete plants consume 1000 million of tones of water, 1500 million of tons of cement and 10.000 million of tones of aggregates every year [2]. All raw materials used for concrete production remains trapped until the end of building use, and after that they become an unused construction and demolition waste [1].

In the light of sustainable development, it is necessary to reduce negative impact of construction to the environment. The circular economy (CE) is an essential part of sustainable development and it is based on the three terms: reduce, reuse and recycle [3]. In the construction industry CE refers to move from linear models (buildings are manufactured from raw materials, used and then discarded) to circular models (parts of building or whole buildings are reused, recycled or remanufactured) [3]. It is important to create a structural solution that can increase the circularity of buildings. Utilization of steel-concrete composite structures improves structural efficiency: the use of concrete in areas that are dominantly exposed to compression forces and the steel in areas exposed to tension. Structural steel as a material can be recycled an infinite number of times and it is highly compatible with the concept of CE [3]. The negative impact of concrete can be reduced by using supplementary cementing materials instead of cement and by using the demolished concrete as an alternative to natural aggregate [4]. The usage of prefabricated concrete elements enables improvement of sustainability attributes: encompassing carbon emissions, construction wastage, human resources, accidents, project cost and construction period [5].

It is very important to have an adequate connection between the steel and reinforced concrete members in steel-concrete composite and mixed structures. The connection should provide the adequate performance of structure during lifecycle and possibility for repeated use of steel and concrete components as well as the connection itself [3]. Conventionally and widely used welded stud shear connectors are disadvantaged in this regard because of lack of reuse (demountable) possibilities. New generation of bolted connectors with mechanical coupler could be easily dismantled, which could improve the sustainability of steel-concrete composite structures [6]. At the same time, mechanical couplers provide a flat surface for the reinforced concrete (RC) element at the place of the connector, making disassembly easier compared to other demountable connector solutions [7]. This type of shear connector consists of a steel coupler embedded in a RC element, anchored by an embedded bolt or a reinforcement as it is showed in Fig. 1. The steel element is connected to the RC element by installing the second bolt into the coupler [8], [9]. In order to ensure the possibility of reusing not only the steel element but also the RC element, the weakest part of the connector should be the removable bolt.

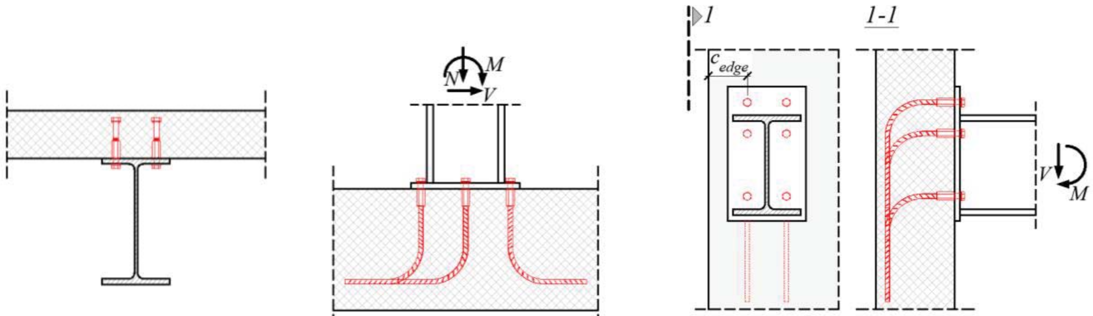


**(a)** bolt anchor (parralel threaded coupler) **(b)** headed rebar anchor (par. threaded coupler) **(c)** bent/straight rebar anchor (par. threaded coupler) **(d)** bent/straight rebar anchor (taper threaded coupler)

**Fig. 1.** Bolted connectors with mechanical coupler – different anchor types

In general, the connectors in steel-concrete connections are exposed to the shear force, tension force, combination of shear and tension forces and, rarely, to the bending moment. The composite steel-concrete connections are commonly loaded by longitudinal shear force while connections in mixed structures by combination of shear and tension forces. Common failure modes of shear connectors are: steel (bolt) shear failure, pullout failure, pryout failure and concrete edge failure [9]. For bolted connectors with the mechanical coupler and rebar anchor there are two potential failure modes: steel (bolt) shear failure and/or concrete edge failure. For connectors with rebar anchoring pryout and pullout failures cannot be expected due to sufficient length of rebar anchor and adequate anchorage of the connector [9]. On the other hand, headed connectors are more appropriate in case of thin RC members.

The tension behaviour of those connectors is a more complex, because the fact that these connectors are made from three different elements and three different materials. The behaviour under tension load, or combined load, depends on the behaviour of the weakest part of connection [7]. In this regard, anchoring the connector with rebar anchor is also more effective compared to headed anchors since concrete cone failure or blow-out failure could not be expected nor supplementary reinforcement is needed.




**(a)** composite beam **(b)** steel column-RC foundation **(c)** steel beam-RC wall/column

**Fig. 2.** Typical connections in steel-concrete composite and mixed structures

Bolted connectors with mechanical couplers have been used in structural design practice for more than 15 years. Main aim of this connection is to provide connection between steel column and RC foundation or steel beam and RC wall/column, as shown in Fig. 2. Since there were no specific guidelines and code recommendations for their design, the structural designers had to use engineering judgement for design and detailing of connections with this type of connector. In this regard, the analogy with shear studs and anchor bolts with constant diameter of the length of the connector was employed, which were covered by several design codes. In September 2015, European Organization for Technical Approval (EOTA) has published European Assessment Document – EAD 330012-00-0601: Cast-in anchor with internal threaded socket [10]. Apart from connectors with different anchoring system presented in Fig. 1, this document covers connectors with mechanical coupler (threaded socket) anchored with a steel rod or by a deformed socket itself.

This paper gives an overview of previous research results and available recommendations for design of this type of connections. The comparison between shear resistance obtained from experimental tests and code recommendations was done. Also, the comparative analysis of shear and tension resistances of commercially available connectors with mechanical couplers was performed and discussed.

## 2. PREVIOUS RESEARCHES

In the past few years, few research groups have experimentally tested shear behaviour of steel-concrete connections with mechanical couplers and gave the recommendations for design process. The layout and procedure of the experimental testing was pretty similar in all cases, which were in accordance to recommendations of standard push-out test given in EN 1994-1-1. Two concrete prismatic RC elements with embedded mechanical coupler and rebar/bolt for anchoring were made. Steel element were put between two RC elements and connected with each one with bolts. The static load (force) was applied to the steel element and the shear force parallel to the concrete edge were transferred to the bolts. The ultimate force that connection can bear and the slip between concrete and steel element were measured.

The testing carried out by Milosavljević et al. [9] was done with a layout that reflected connections illustrated in Figs. 2(b) and 2(c). The other testing was representing the connections shown on Fig. 2(a). Table 1 shows summarized results of previous testing provided by four different research groups. The main characteristics of test specimens were given: bolt diameter $d_b$, coupler diameter $d_{co,out}$ and length $l_{co}$, diameter $d_a$ of second bolt or rebar, ultimate stress for all steel elements, mean concrete cylinder strength $f_{cm}$ and concrete edge distance $c_{edge}$. Except the tests provided by Milosavljević et al. [9] that had the rebar anchors, the others had the second bolt for anchoring. The steel grade of rebar anchor was

B500B and for bolt anchorage 8.8 for all series, except two series named B5 and B6 which had 10.9 steel grade. Series P15.1 uses pre-tensioned bolts and P15.2 uses epoxy resin injected bolts. The series R and SR also used epoxy resin and steel-resin injected bolts while specimens in series N had oversized holes without resin. Test results are expressed in terms of ultimate force of the connection $V_{Rm,b}$ and concrete edge failure load $V_{Rm,c}$. Milosavljević et al. [9] have shown that edge distance have significant effect on the behaviour and shear capacity and failure mode of the connection. As it is presented in Table 1, concrete edge failure occurred for series A and B, while all other series had steel (bolt) failure. It should be noted that the concrete edge failure did not represent the ultimate failure of the connectors but did affect the overall behaviour of the connection.

**Table 1.** Results of previous experimental testing

| Authors | Test series | Bolt | | | Coupler | | | Anchor | | | Concrete elements | | | Test results | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $d_b$ | Steel grade | $f_{u,b}$ | $d_{co,out}$ | $l_{,co}$ | $f_{u,co}$ | Type | $d_a$ | Steel grade | $f_{cm}$ | $c_{edge}$ | Edge reinf. near the connector | $V_{Rm,b}$ 1) | $V_{Rm,c}$ 2) |
| | | mm | | MPa | mm | mm | MPa | | mm | | MPa | mm | connector | kN | kN |
| Milosavljević et al. [9] | A | M16 | 8.8 | 837.7 | 22 | 59 | 790.0 | Rebar | 12 | B500B | 26.6 | 75 | 2xØ8/135 | 86.0 | 65.8 |
| | B | | | | | | | | | | 26.9 | 75 | 2xØ10/55 | 90.5 | 65.7 |
| | C | | | | | | | | | | 37.7 | 100 | 2xØ8/135 | 95.8 | - |
| | D | M16 | 8.8 | 907.0 | 22 | 79 | 808.0 | | 12 | B500B | 32.6 | 150 | 2xØ8/70 | 89.9 | - |
| | E | M20 | 8.8 | 948.0 | 27 | 93 | 803.0 | | 16 | B500B | 39.4 | 150 | 2xØ8/70 | 138.9 | - |
| Kozma [3] | P15.1 | M20 | 8.8 | 948.7 | 30 | 60 | 1000* | Bolt | M20 | 8.8 | 35.4 | 47 | 2xØ8/75 + L-profile | 142.3 | - |
| | P15.2 | | | | | | | | | | | | | 131.1 | - |
| Nijgh et al. [8] | R | M20 | 8.8 | 879.0 | 30 | 60 | 1000* | Bolt | M20 | 8.8 | 38.6 | 47 | Ø8 loop + L-profile | 115.6 | - |
| | SR | | | | | | | | | | | | | 118.2 | - |
| | N | | | | | | | | | | | | | 122.4 | - |
| Yang et al. [6] | B-1,2 | M18 | 8.8 | 1029.7 | 27 | 54 | 1029.7 | Bolt | M18 | 8.8 | >40.8 | 150 | - | 170.1 | - |
| | B-3,4,9 | M22 | 8.8 | 985.6 | 32 | 66 | 985.6 | | M22 | 8.8 | | | - | 229.8 | - |
| | B-5,6 | M22 | 10.9 | 1212.6 | 32 | 66 | 1212.6 | | M22 | 10.9 | | | - | 297.7 | - |
| | B-7,8 | M27 | 8.8 | 825.1 | 41 | 81 | 825.1 | | M27 | 8.8 | | | - | 346.4 | - |

*Nominal values; 1) Bolt shear failure load; 2) Concrete edge failure load

Milićević et al. [11] gave the recommendation for concrete edge failure load as expressed in Eq. (1).

$$V_{u,c} = 47 \cdot \sqrt{f_{cm}} \cdot c_{edge}^{2/3} \cdot d_{co,out} \cdot \left(\frac{l_{f,eq}}{12 d_{co}}\right)^{0.3}, l_{f,eq} = l_{co} + \frac{30 d_a^{1.5}}{f_{cm}^{0.38} d_{co,out}} \leq 12 d_{co,out} \quad (1)$$

## 3. EUROPEAN TECHNICAL DOCUMENTATION

EAD 330012-00-0601 [10] gives the recommendations for calculating characteristic ultimate loads for single connectors loaded in tension and shear. Most of those recommendations were related to the Technical Specification CEN/TS EN 1992-4: 2009 and ETAG 001, Annex C. In 2018, the European standard EN 1992-4 [12] has been published. It has replaced the earlier guidelines for design of anchors for use in concrete. In the following sections, design resistances from EAD 330012-00-0601 [10] and EN 1992-4 [12] for connectors loaded in pure tension and pure shear are given and discussed.

### 3.1. Failure modes and resistance of the connector loaded in tension

According to EAD 330012-00-0601 [10], tension resistance of the connector depends on the type of anchoring to concrete. For connector with mechanical coupler with rebar anchor with sufficient anchorage length shown in Fig. 1(b)-(d), characteristic tension resistance depends on the "weakest link" of the connector which is determined according to Eq. (2).

$$N_{Rk} = \min \begin{cases} N_{Rk,b} = A_{s,b} \cdot f_{uk,b} & \text{, for bolt failure} \\ N_{Rk,co} = A_{s,co} \cdot f_{uk,co} & \text{, for mechanical coupler failure} \\ N_{Rk,a} = A_{s,a} \cdot f_{yk,a} & \text{, for rebar anchor failure} \\ N_{Rk,aco} & \text{, for failure of the rebar-coupler connection} \end{cases} \quad (2)$$

In the previous equation, $A_{s,b}$ and $f_{uk,b}$ are net section area and characteristic ultimate tensile strength of the bolt, $A_{s,co}$ and $f_{uk,co}$ are net section area and characteristic ultimate tensile strength of mechanical coupler while $A_{s,a}$ and $f_{yk,a}$ are section area and characteristic yield strength of rebar anchor. Net section area of the coupler $A_{s,co}$ is based on the area of the hollow hexagonal (or circular) section. The resistance $N_{Rk,aco}$ of the connection between reinforcement bar and mechanical coupler depends on the type of the connection and it is established by the manufacturer via experimental tests.

For connector with rebar anchor (see Fig. 1(c) and 1(d)), the adequate anchorage length should be provided in order to avoid pull-out failure. Anchorage length can be determined according to EN 1992-1-1. Similarly, for headed connectors presented in Fig. 1(a) and 1(b) the adequate embedment depth located should be provided in order to avoid concrete cone failure. In case of connectors located near concrete edge and loaded in tension there is a possibility of various concrete failure modes i.e., concrete cone failure, concrete blow-out failure and concrete splitting failure. These failure modes can be successfully mitigated with adequate detailing of rebar anchor via bends or hooks (Fig. 1(c) and 1(d)).

Since EAD 330012-00-0601 [10] gives only characteristic resistances for evaluation of test results, it does not give recommendations for partial safety factors. According to EN 1992-4 [12], partial safety factors for connectors loaded in tension depends on the type of failure mode. For permanent and transient design situations, partial safety factors are defined as follows:

$$\begin{aligned} &\gamma_{M,s} = 1.2 \cdot f_{uk}/f_{yk} \geq 1.4 && \text{, for connector failure} \\ &\gamma_{M,c} = 1.5 && \text{, for concrete failure} \\ &\gamma_{M,re} = 1.15 && \text{, for reinforcement failure} \end{aligned} \quad (3)$$

### 3.2. Failure modes and resistance of the connector loaded in shear

As in case of connectors loaded in tension, failure modes of the connector loaded in shear can be distinguished by the way the connector is anchored and the proximity of concrete edge. In connections between steel beam and RC column/shear wall, as shown in Fig. 2(c), shear force acts on the connector parallel to the concrete edge.

When then connectors are located far away from concrete edge, two failure modes can occur: (1) steel failure and (2) concrete pry-out failure. Latter failure mode occurs only when short connectors are used, usually for connectors with layout shown in Fig. 1(a) and 1(b). According to EAD 330012-00-0601 [10], characteristic shear resistance for steel failure mode $V_{Rk,s}$ is determined as:

$$V_{Rk,s} = \min \begin{cases} V_{Rk,b} = \alpha_b \cdot A_{s,b} \cdot f_{u,b} & \text{, for bolt failure} \\ V_{Rk,co} = \alpha_{co} \cdot A_{s,co} \cdot f_{u,co} & \text{, for mechanical coupler failure} \end{cases} \quad (4)$$

In the previous equation, $\alpha_b$ and $\alpha_{co}$ are shear reduction factors for bolt and mechanical coupler respectively. EAD 330012-00-0601 [10] recommends the value $\alpha_{co} = 0.5$ for coupler while EN 1992-4 [12] recommends $\alpha_b = 0.5$ for bolts with $f_{uk,b}$ =500-1000 MPa.

For connectors located near concrete edge, concrete edge failure can govern the resistance of the connector. According to EN 1992-4 [12], concrete edge failure load for shear acting parallel to the concrete edge is based on failure load for shear force acting perpendicular to the concrete edge. For single anchors embedded in uncracked concrete members with sufficient thickness, characteristic concrete edge resistance is determined according to Eq. (5).

$$V_{Rk,c} = V^0_{Rk,c} \cdot \psi_{\alpha,V} \quad (5)$$

The initial value of the characteristic resistance of a connector loaded perpendicular to the edge is calculated as:

$$V^0_{Rk,c} = 2.4 \cdot d^{\alpha}_{nom} \cdot l^{\beta}_{f} \cdot \sqrt{f_{ck}} \cdot c^{1.5}_{edge} \quad \text{, with } \alpha = 0.1 \left(\frac{l_f}{c_{edge}}\right)^{0.5}, \beta = 0.1 \left(\frac{d_{nom}}{c_{edge}}\right)^{0.2} \quad (6)$$

Distance $c_{edge}$ represents the distance between the connector and the concrete edge. The effective length of connector under shear loading $l_f$ and outside diameter $d_{nom}$ depend on the layout of the connector. For bolts or studs with uniform cross-section over their length diameter $d_{nom}$ is equal to the diameter of the anchor $d_b$ while the value of $h_{ef}$ has to be used as effective anchorage depth $l_f$ with the following limitations: $l_f \leq 12d_{nom}$ for $d_{nom} \leq 24$ mm and $l_f \leq 8d_{nom}$, for $d_{nom} > 24$ mm.

For connectors with mechanical coupler, EAD 330012-00-0601 recommends using the outside diameter of the coupler (socket) $d_{co,out}$, which is the diameter of the inscribed circle of hollow hexagonal section or the outside diameter of the hollow circular section. The length of the coupler $l_{co}$ should be used for the effective length of the connector $l_f$. Diameter $d_{co,out}$ and length $l_{co}$ are limited to the values of $d_{co,out} \leq$ 25 mm and $l_f \leq$ 200 mm ($l_f \leq 8d_{co,out}$).

Factor $\psi_{\alpha,V}$ in Eq. (6) takes into account shear load direction and it is equal to $\psi_{\alpha,V} = 2.0$ in case of shear load acting parallel to the concrete edge.

According to EN 1992-4, partial safety factors for connectors loaded in shear depends on the type of failure mode. For permanent and transient design situations, partial safety factors are defined as follows:

$$\begin{aligned} &\gamma_{M,s} = 1.0 \cdot f_{uk}/f_{yk} \geq 1.25 \text{ for } f_{uk} \leq 800 \text{ MPa and } f_{yk}/f_{uk} \leq 0.8 && \text{, for connector failure} \\ &\gamma_{M,s} = 1.5 \text{ for } f_{uk} > 800 \text{ MPa or } f_{yk}/f_{uk} > 0.8 && \text{, for connector failure} \\ &\gamma_{M,c} = 1.5 && \text{, for concrete failure} \end{aligned} \tag{7}$$

## 4. COMPARATIVE ANALYSIS

In this section, two types of comparative analysis were conducted. Firstly, a comparison between code recommendations for shear resistance of the connector and experimental resistances presented in Section 2 was conducted. In this regard, mean prediction equations were used instead of characteristic equations given in Section 3. Afterwards, an overview of several types of commercially available bolted connectors with mechanical coupler and rebar anchor was given. For each type of the connector, design tension and shear resistances were determined and results were compared and discussed.

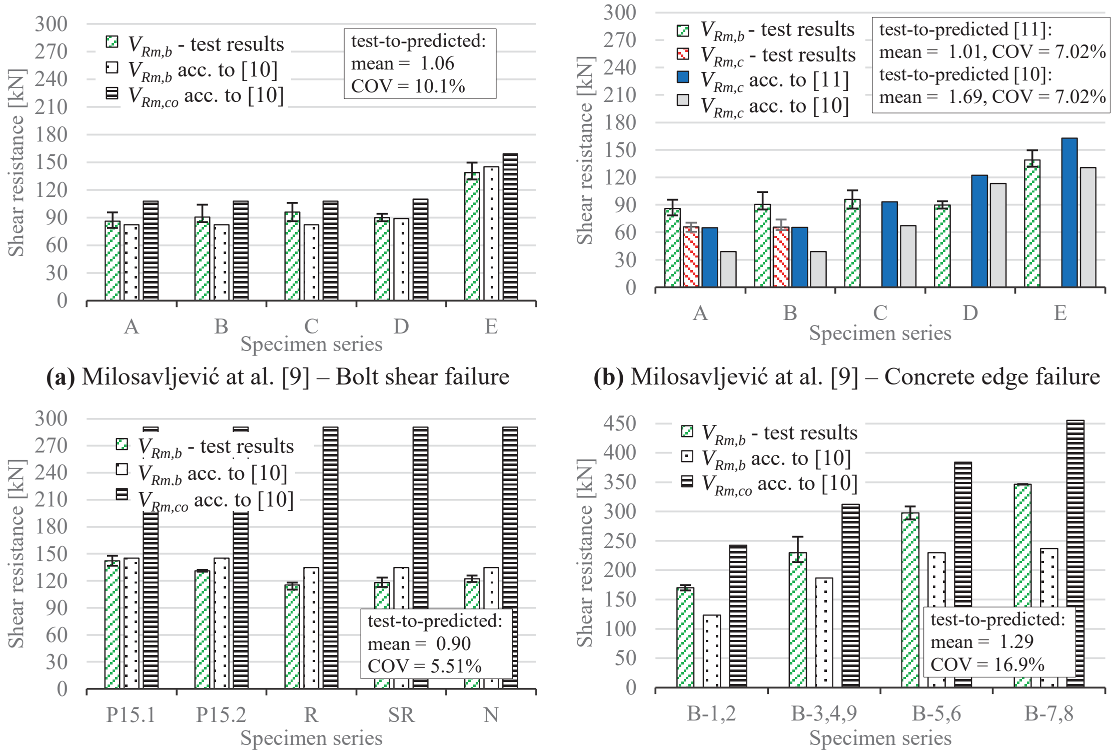
### 4.1. Code recommendations vs. experiments

Shear behaviour of bolted connectors with mechanical coupler were investigated only by few research groups, with different configuration of the connection and the connector itself. The connection layouts and experimental test results are presented in Table 1. For comparison purposes, shear resistance is calculated according to design recommendations given in Section 3. For steel failure load, shear resistance is calculated according to Eq. (4), using mean values of measured steel strength of bolts $f_{u,b}$ and couplers $f_{u,co}$ from Table 1. Furthermore, shear resistance of the connector was multiplied by a factor 1.25 in order to take into account the difference between characteristic resistance $V_{Rk,s}$ and mean resistance $V_{Rm,s}$, according to Grosser [13].

For concrete edge failure, shear resistance $V_{Rm,c}$ was calculated according to Eq. (1) proposed by Milićević et al. [11] and by design recommendations according to Eqs. (5) and (6). The latter was calculated using mean concrete strength $f_{cm}$ instead of characteristic concrete strength $f_{ck}$. The resistances obtained by using Eqs. (5) and (6) were multiplied by 1.33 in order to take into account the difference between characteristic resistance $V_{Rk,c}$ and mean resistance $V_{Rm,c}$, according to Grosser [13]. The comparative analysis results are presented in Fig. 3.

According to EN 1992-4 [12] and EAD 330012-00-0601 [10], ultimate shear resistance of the connector is governed by bolt shear failure in all cases. This conclusion is confirmed by experimental test results. The best average test-to-predicted ratio was obtained for test results from Milosavljević et al. [9], as shown in Fig. 3(a). Nijgh [8] have concluded that the average shear reduction factor for bolts is $\alpha_b$ = 0.547 while Yang et al. [6] obtained significantly higher value $\alpha_b$ = 0.824, due to high friction between concrete and steel profile which was not greased. As stated earlier, coupler shear resistance was higher than bolt shear resistance in all cases. However, it should be noticed that for similar bolt diameter mechanical couplers used by Kozma [3], Nijgh [8] and Yang et al. [6] have significantly higher shear resistance than coupler used by Milosavljević et al [9]. The main reason for this conclusion is larger diameter of corresponding mechanical coupler $d_{co,out}$ and somewhat higher steel ultimate strength $f_{u,co}$.

Comparison the concrete edge resistances is shown in Fig. 3(b). It can be concluded that prediction equation provided by Milićević et al. [11] gives significantly better test-to-predicted ratio than design recommendations from EN 1992-4 [12] and EAD 330012-00-0601 [10]. Furthermore, it can be noticed that according to EAD 330012-00-0601 specimens from series C and E should have exhibited concrete edge failure before bolt failure which did not occur in experimental tests [9].




**(a)** Milosavljević at al. [9] – Bolt shear failure

**(b)** Milosavljević at al. [9] – Concrete edge failure

**(c)** Kozma [3], Nijgh [8] – Bolt shear failure

**(d)** Yang et al. [6] – Bolt shear failure

**Fig. 3.** Comparison of mean shear resistances according to design code and experimental tests

## 4.2. Design resistances of bolted connector with mechanical coupler and rebar anchor

An overview of several types of bolted connectors with mechanical coupler and rebar anchor used in the construction industry as a commercially available product is presented in Table 2.

**Table 2.** Geometrical and mechanical characteristics of connector parts

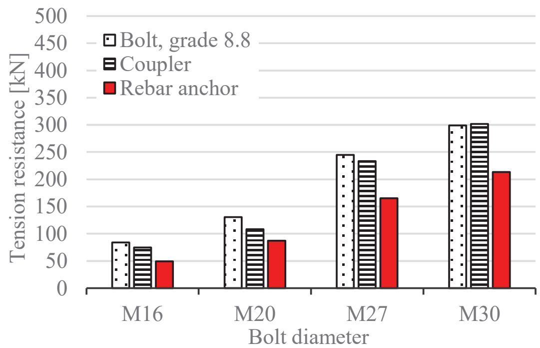
| Manufacturer (Connector type) | Bolt | | | Mechanical coupler | | | | Rebar anchor | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $d_b$ | Steel grade | $f_{uk,b}$ | $d_{co,out}$ | $l_{co}$ | Steel grade | $f_{uk,co}$ | coupler-rebar conn. type | $d_a$ | Steel grade | $f_{yk,a}$ |
| | mm | | MPa | mm | mm | | MPa | | mm | | MPa |
| Erico Lenton (S13N) [14] | M16 | 8.8[a)] | 800.0 | 22 | 58 | C45+C, 1.4462 | 650.0[c)] | taper thread | 12 | B500B | 500.0 |
| | M20 | | | 27 | 68 | | | | 16 | | |
| | M27 | | | 40[b)] | 104 | | | | 22 | | |
| | M30 | | | 45[b)] | 110 | | | | 25 | | |
| Peikko (Copra H) [15] | M16 | 8.8[a)] | 800.0 | 25 | 48 | S355J2 | 470.0[c)] | parallel thread | 16 | B500B | 500.0 |
| | M20 | | | 30 | 60 | | | | 20 | | |
| | M30 | | | 50 | 90 | | | | 32 | | |
| Halfen (HSC-B) [16] | M16 | 8.8[a)] | 800.0 | 24 | 48 | 1.0715, 1.4571, 1.4404 | 500.0[c)] | taper thread | 16 | B500B | 500.0 |
| | M20 | | | 30 | 60 | | | | 20 | | |
| | M27 | | | 41 | 75 | | | | 25 | | |
| DIN 6334 [17] | M16 | 8.8[a)] | 800.0 | 24 | 48 | 8.8[a)] | 800.0 | parallel thread | 16 | B500B | 500.0 |
| | M20 | | | 30 | 60 | | | | 20 | | |
| | M27 | | | 41 | 81 | | | | 28 | | |
| | M30 | | | 46 | 90 | | | | 32 | | |

[a)] Adopted steel grade, permissible bolt steel grades 5.6-12.9; [b)] Circular hollow section; [c)] Minimum values of tensile strength within specified range for corresponding steel grade

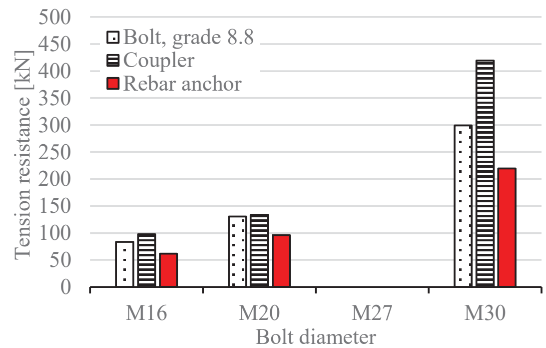
The main difference between those connectors is the type of the hexagonal mechanical coupler used for threaded splice connection between bolt and rebar anchor. For the same bolt diameter, they differ in dimensions and steel grade of the mechanical coupler, diameter of the connecting rebar anchor and the type of the connection between the coupler and rebar anchor, as shown in Table 2. In order to compare design resistances of various types of connectors with mechanical coupler loaded in tension and in shear, typical connection between steel beam and RC column shown in Fig. 2(c) is analysed. In all cases, concrete class C30/37 and concrete edge distance $c_{edge}$ = 200 mm were adopted. Geometrical and mechanical characteristics of connector parts are adopted according to Table 2. It was assumed that all connectors are anchored via rebar anchors with sufficient anchorage length and adequate bend radius to avoid blow-out failure under tension load.

**Design tension resistance**

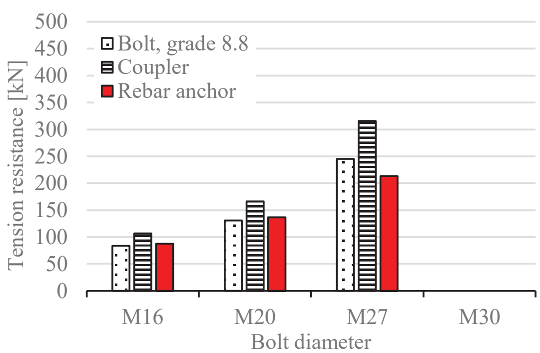
Design tension resistance of bolted connectors with mechanical coupler and rebar anchor was calculated using Eqs. (2) and (3). Tension resistance was determined by taking into account type of coupler-rebar connection i.e., taper threaded or parallel threaded connection. The first type ensures full capacity of the rebar anchor, as confirmed by Milićević et al [7]. In case of parallel threads, the threaded part of the rebar anchor has the same net section area as removable bolt which reduces the tension capacity of rebar anchor and the connector as a whole [6], [15]. The results of comparative study are presented in Fig. 4.



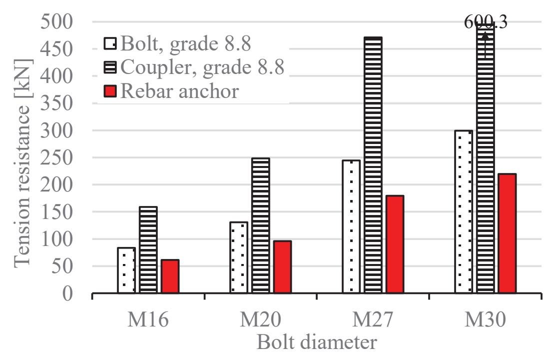

**(a)** Erico Lenton (S13N)




**(b)** Peikko (Copra H)




**(c)** Halfen (HSC-B)




**(d)** DIN 6334

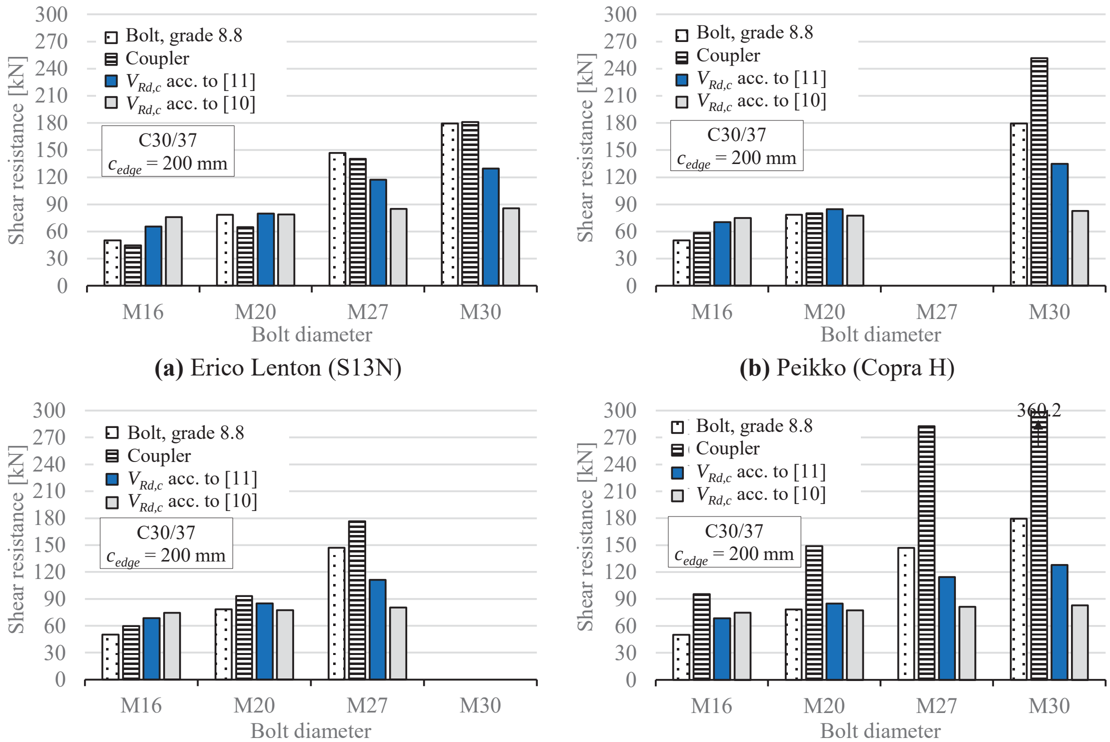
**Fig. 4.** Comparison of design tension resistances according to codes and design recommendations

The results suggest that the failure of the rebar anchor prevails in almost all cases, regardless of the diameter of the connector. For the same bolt diameter, Halfen connectors have highest tension resistance because they use larger rebar anchors and taper threaded connection. Despite smaller anchor diameter, Erico Lenton taper threaded connectors have similar tension resistance as Peikko and DIN 6334 connectors. Similar design tension resistance of bolts and couplers can be noticed for Erico Lenton connectors and Peikko connectors with small diameters, as shown in Fig. 4(a) and Fig. 4(b). In some cases, tension resistance of couplers is even lower than the resistance of bolts. It should be noted that for bolt steel grade 5.6, the bolt tension failure would govern the resistance of the connector in all cases.

**Design shear resistance**

Design shear resistance of commercially available connectors was determined similarly to the experimentally tested connectors, as presented in Section 4.1. The characteristic shear resistance of the connector $V_{Rk,s}$ was calculated according to Eq. (4), while characteristic concrete edge resistance $V_{Rk,c}$

was calculated according to Eqs. (5) and (6). Characteristic concrete edge resistance $V_{Rk,c}$ was also calculated according to Milićević et al. [11], using characteristic concrete strength $f_{ck}$ in Eq. (1) instead of mean concrete strength $f_{cm}$. The obtained values were divided by 1.33 in order to take into account the difference between the characteristic resistance $V_{Rk,c}$ and mean resistance $V_{Rm,c}$ [13]. For calculating the design shear resistances, partial safety factors were used according to Eq. (7). The analysis results are presented in Fig. 5.




**(a)** Erico Lenton (S13N) **(b)** Peikko (Copra H)

**(c)** Halfen (HSC-B) **(d)** DIN 6334

**Fig. 5.** Comparison of design shear resistances according to codes and design recommendations

For shear failure of the connector (i.e., bolt and coupler resistances) similar conclusion can be drawn as for tension resistance, since the shear reduction factors for bolts $\alpha_b$ and couplers $\alpha_{co}$ are both equal to 0.5. In case of Erico Lenton connectors, shear resistance of mechanical couplers is somewhat lower than shear resistance of corresponding bolts and, therefore, mechanical coupler would be the weakest link. Peikko connectors with small diameters have similar shear resistance of bolts and corresponding couplers, while the weakest part of all other connectors is removable bolt. It should be noted, however, that the design steel resistance in shear (and tension) is practically based on the yield strength instead of ultimate strength (see Eqs. (3) and (7)) which severely penalises the resistances of both bolts and couplers.

For the adopted concrete strength and edge distance, the results indicate that shear failure would occur in case of the connectors with M16 and M20 bolts while concrete edge failure can be expected for larger connectors. It should be noticed that connector diameter has larger effect on the concrete resistance $V_{Rd,c}$ proposed by Milićević et al. [11] than proposed by EN 1992-4 [12] and EAD 330012-00-0601[10]. Similar conclusion can be drawn even if the EAD's limitation on the coupler diameter $d_{co,out} \leq 25$ mm was disregarded. Unlike, according to EN 1992-4, concrete edge distance $c_{edge}$ has larger effect on shear resistance with power law of 1.5 as opposed to 2/3 given in Milićević et al. [11]. The latter was found more appropriate for shear load acting parallel to concrete edge by Grosser [13].

## 5. CONCLUSIONS

This paper presents an overview of shear and tension resistances of demountable bolted connectors with mechanical couplers. Resistance was determined from previous experimental testing and current design code recommendations. It can be concluded that tension resistance mainly depends on the rebar anchor resistance as the weakest part of the connector. Unlike, the shear resistance depends on concrete class and concrete edge distance. When steel member is connected to RC member with limited dimensions i.e., to RC columns or end of RC shear wall, shear resistance of the connection can be governed by concrete edge failure with shear load acting parallel to the concrete edge. The recommendation for concrete edge failure load given by Milićević et al. [11] gives better test-to-predicted ratio than recommendations from EN 1992-4 [12] and EAD 330012-00-0601 [10].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