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Use of component method in the analysis of timber-steel connections

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Subject review

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Use of component method in the analysis of timber-steel connections

The use of component method for determining the moment resistance of an innovative beam-to-beam timber-steel connection is presented in the paper. The calculation of resistance of steel components is conducted based on EN 1993-1-8. The resistance of timber components is determined according to EN 1995-1-1, and based on the full-scale laboratory experiments and the finite element modelling results. The developed moment resistance calculation model, based on the component method, is well in line with the full-scale experimental and finite element modelling results.

Key words:

timber-steel connection, moment resistance of connection, component method

Pregledni rad

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Primjena metode komponentata u proračunu drveno-čeličnog priključka

U radu je predstavljena metoda komponentata za određivanje otpornosti na savijanje u inovativnom drveno-čeličnom priključku greda-greda. Proračun otpornosti čeličnih elemenata priključka proveden je u skladu s normama EN 1993-1-8. Otpornosti pojedinih drvenih elemenata određene su prema normi EN 1995-1-1, a temelje se na laboratorijskim ispitivanjima uzoraka stvarne veličine i rezultatima modeliranja konačnim elementima. Razvijeni model proračuna otpornosti na savijanje, prema metodi komponentata, dobro se podudara s rezultatima ispitivanja uzoraka stvarne veličine i modeliranja konačnim elementima.

Ključne riječi:

priključak drvo-čelik, otpornost na savijanje priključka, metoda komponentata

Übersichtsarbeit

Alfonsas Daniūnas, Tomas Gečys

Anwendung der Komponentenmethode bei der Analyse von Holz-Stahl-Verbindungen

In dieser Arbeit wird die Anwendung der Komponentenmethode zur Ermittlung des Biege widerstandes bei innovativen Holz-Stahl-Verbindungen zwischen Balkenträgern vorgestellt. Der Widerstand von Stahlelementen wird gemäß Normen EN 1993-1-8 berechnet. Für einzelne Holzelemente wird der Widerstand auf Laborprüfungen von Proben in Originalgröße und den Resultaten von Finite-Elemente-Modellen beruhend nach Norm 1995-1-1 ermittelt. Das entwickelte Model zur Berechnung des Biege widerstandes, das auf der Komponentenmethode basiert, stimmt gut mit den Resultaten der Untersuchungen an Proben in Originalgröße und an Finite-Elemente-Modellen überein.

Schlüsselwörter:

Holz-Stahl-Verbindungen, Biege widerstand von Verbindungen, Komponentenmethode

1. Introduction

Considerable economic benefits can be gained by accurate design of joints as cross-section dimensions of the entire element are mostly determined by the structure of the joint. The joint moment resistance can be determined using various methods such as experimental investigations and finite element modelling, or using mechanical methods, such as the component method. The moment resistance is investigated widely, for example, based on full-scale experiments for large-screw bolts [1, 2], glued-in rods [3, 4], and dowel-type fasteners [5, 6]. The finite element modelling is implemented to define moment resistance of the timber-steel joint with glued-in rods [4, 7], and also for the moment resistance of the joint presented in this paper [8]. These methods can be used to derive equations for some engineering calculation methods, such as the mechanical component method. The component method ranks among the methods that are most commonly used for determining the moment resistance and rotational stiffness of joints. This method is implemented in the European steel design code [9], which is widely used for the steel beam-to-beam or beam-to-column joints [10, 11]. No methods are currently provided in European timber structure design codes that can explain how to apply the component method for determining the moment resistance of combined timber - steel joints.

The implementation of the component method for the timber-steel joint under study is shown in this paper. The moment resistance calculation model presented for the timber-steel joint is an extended form of joint calculations for steel structures. The developed moment resistance calculation model is well in line with full-scale experimental investigations, as shown in previous publications presented by the authors [12-14].

2. Description of timber-steel joint

The component method is implemented for the beam-to-beam timber-steel joint, as shown in Figure 1. A detailed description of the presented timber-steel joint is given in the previous publication [12].

The design moment resistance $M_{j,Rd}$ of the presented beam-to-beam joint depends on bearing capacities of several components. The bearing capacity of the weakest component provided in Figure 2 determines the moment resistance of the joint. While making a mechanical model of the joint, bearing capacities of the joint steel part components are determined according to the equations presented in the European steel design code [9]. Some equations, presented in the above mentioned code [9], have been improved to describe interaction between the timber and steel parts of the joint. Timber part bearing capacities are determined according to the Eurocode 5 [15]. Active components of the joint determine the moment resistance of the joint shown in Figure 2:

- End-plate bending in tension zone (*epb*) of the joint;
- Bolt tension (*bt*);
- Tension of longitudinal steel plate in the tension zone of the joint (*spt*);

- Bending of the tension back T-shaped anchoring steel plate (*ept*);
- Tension of timber in the tension zone of the joint (*tt*);
- Timber shear in the tension zone of the joint (*ts*);
- Compression of longitudinal steel plate in the compressive zone of the joint (*spc*);
- Bending of compression back T-shaped anchoring steel plate (*epc*).

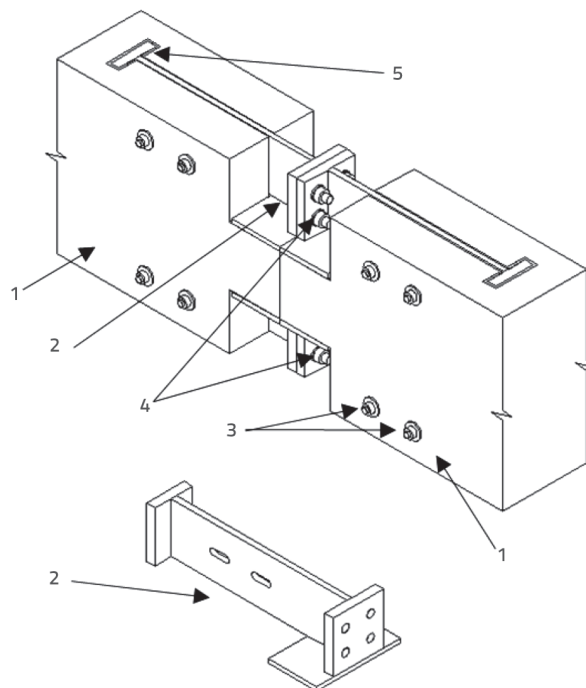


Figure 1. Detailing of timber beam-to-beam joint: 1-glued laminated timber element; 2-steel part of joint; 3-blots for timber clamping in tension zone of the joint; 4-steel bolts; 5-filler between timber and steel

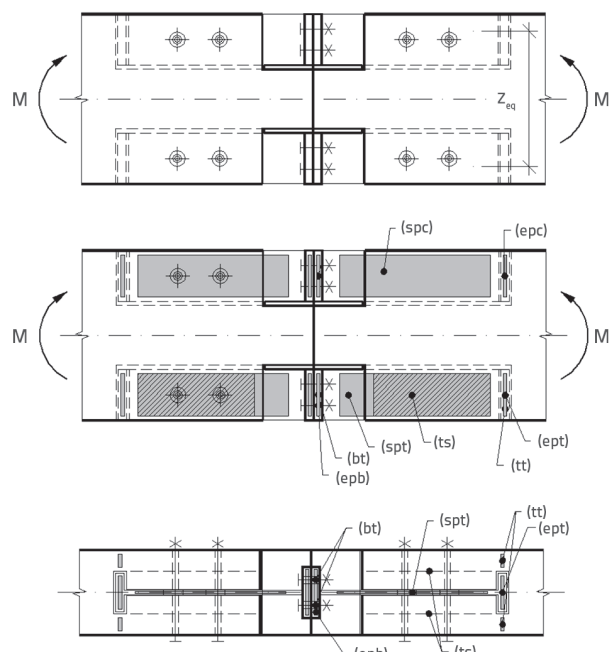


Figure 2. Active components of the joint

3. Moment resistance of joint defined according to component method

As mentioned in the previous section, the moment resistance consists of active timber and steel components, which are listed in the previous section. The bearing capacity of the weakest component determines the moment resistance of the joint. The design moment resistance of the beam-to-beam joint is determined by a well-known classical equation taken from joint mechanics:

$$M_{j,Rd} = \sum_{r=1}^n h_r F_{tr,Rd} \quad (1)$$

In Equation 1: $F_{tr,Rd}$ - effective design tension resistance of bolt-row r ; h_r - distance from the bolt row r to the centre of compression; r - bolt row number; n - total number of tension bolt rows. The distance h_r is assumed to be the distance between the tension bolt row r and the centre of the compressive part of the joint. The distribution of compressive normal stresses in the compressive part of the joint, shown in Figure 3, is assumed to be triangular. The depicted assumption is in good harmony with the finite element modelling results of the joint.

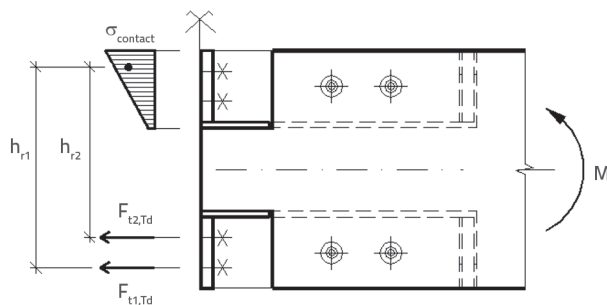


Figure 3. Distance from the tension bolt row r to the centre of compression

The effective design bolt-row r resistance $F_{tr,Rd}$ which determines the moment resistance of the joint, must be taken as the minimum component tension resistance value from the following active components:

- design resistance of the longitudinal steel plate compression in compressive zone of the joint ($F_{spc,Rd}$);
- design compression resistance of a T-shaped back plate, including the timber embedding compression in compression zone of the joint ($F_{epc,Rd}$);
- design resistance of a bending T-stub flange in tension zone of the joint ($F_{epb,Rd}$);
- design resistance of the tension steel plate in tension zone of the joint ($F_{spt,Rd}$);
- design shear resistance of a timber element in tension zone of the joint ($F_{ts,Rd}$);
- design compression resistance of a T-shaped back plate including timber embedding compression in tension zone of the joint ($F_{ept,Rd}$);
- design tension resistance at the remaining cross-section of the timber element ($F_{tt,Rd}$).

- The design tension resistance of the joint when one tension bolt row is determined:

$$F_{t,Rd} = \min\{F_{epc,Rd}; F_{spc,Rd}; F_{epb,Rd}; F_{spt,Rd}; F_{ept,Rd}; F_{ts,Rd}; F_{tt,Rd}\} \quad (2)$$

When there is more than one tension bolt row in tension zone of the joint, the effective design resistance $F_{tr,Rd}$ for each bolt-row should be determined in sequence, starting from the bolt row 1 (the bolt-row farthest from the centre of compression), then progressing to the bolt row 2 [9], as shown in Figure 4. When determining the value of $F_{tr,Rd}$ for the bolt row r the effective design tension resistance of all other bolt rows closer to the centre of compression should be ignored [10]. The following indices are used in Figure 4:

- (a) - design tension resistance of the 1st bolt row, farthest from the centre of compression, analysed as a separate bolt row;
- (b) - design tension resistance of the 2nd bolt-row analysed as a separate bolt-row;
- (a+b) - design tension resistance of the 1st and 2nd bolt rows, where these bolt-rows are analysed as a part of the bolt group.

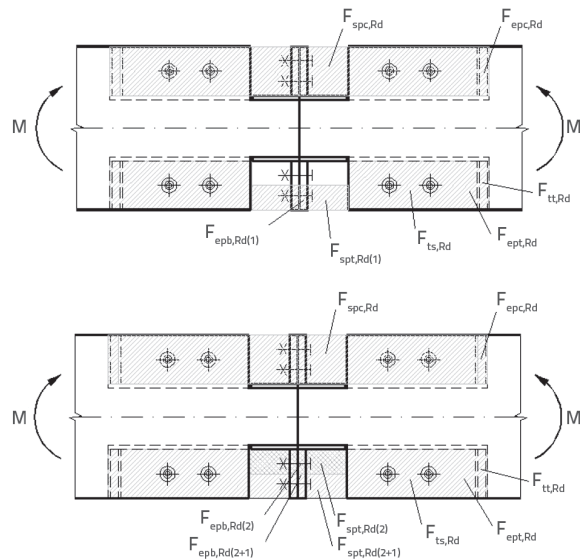


Figure 4. Moment resistance determination scheme: tension resistance of the 1st bolt row (above) and tension resistance of 2nd bolt row as a separate row, and as part of a bolt row group (below)

The design tension resistance of the first bolt row (farthest from the centre of compression) is determined according to the following equation:

$$F_{t1,Rd} = \min\{F_{epc,Rd}; F_{spc,Rd}; F_{epb,Rd(1)}; F_{spt,Rd(1)}; F_{ept,Rd}; F_{ts,Rd}; F_{tt,Rd}\} \quad (3)$$

The design tension resistance of the second bolt row analysed as a separate bolt-row and as a part of bolt-row group with the first bolt-row, is determined according to the equation below:

$$F_{t2,Rd} = \min\left\{ \begin{array}{l} F_{epc,Rd} - F_{t1,Rd}; F_{spc,Rd} - F_{t1,Rd}; F_{epb,Rd(2)}; F_{epb,Rd(2+1)} - F_{t1,Rd}; \\ F_{spt,Rd} - F_{t1,Rd}; F_{ept,Rd} - F_{t1,Rd}; F_{ts,Rd} - F_{t1,Rd}; F_{tt,Rd} - F_{t1,Rd} \end{array} \right\} \quad (4)$$

If joints are analysed with more than two bolt rows in tension zone of the joint, the design tension resistance of the i bolt-row is determined as a minimum value from equations:

$$F_{ti,Rd} = \min \left\{ \begin{matrix} F_{epc,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd}; F_{spc,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd}; F_{spt,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd}; \\ F_{ept,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd}; F_{ts,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd}; F_{tt,Rd} - \sum_{j=1}^{i-1} F_{ij,Rd} \end{matrix} \right\} \quad (5)$$

$$F_{ti,Rd} = \min \left\{ F_{epb,Rd(i)}; F_{epb,Rd(i+(i-1))} - F_{t(i-1),Rd}; \dots; F_{epb,Rd(i+(i-1)+\dots+1)} - \sum_{j=1}^{i-1} F_{ij,Rd} \right\} \quad (6)$$

$$F_{ti,Rd} = \min \left\{ F_{spt,Rd(i)}; F_{spt,Rd(i+(i-1))} - F_{t(i-1),Rd}; \dots; F_{spt,Rd(i+(i-1)+\dots+1)} - \sum_{j=1}^{i-1} F_{ij,Rd} \right\} \quad (7)$$

The design resistance equations of the above mentioned components will be discussed below.

The design compressive resistance of the longitudinal steel plate $F_{spc,Rd}$ shown in Figure 1 (position 2) in compressive zone of the joint, is calculated as a minimum value determined from the compressed plate and column web in transverse compression, according to [9], Equation 6.9.

The design resistance of a bending T-stub flange in tension zone of the joint $F_{epb,Rd}$ is determined according to [9], Table 6.2. There are 3 different failure modes of a T-stub flange: complete yield of the flange, bolt failure with yield of the flange, and bolt failure. The minimum bearing capacity of these modes should be taken. The design tension resistance of the longitudinal plate of the steel detail $F_{spt,Rd}$ provided in Figure 1, position 2, is determined as the minimum value of the column web in tension according to [9], 6.2.6.3. The tension design resistance is obtained for individual bolt rows, and for a bolt-row group. The effective width $b_{eff,t,wb}$ of the tension steel plate is taken to be equal to the equivalent T-stub representing the end-plate in bending.

The design compression resistance of a T-stub plate, including the timber embedding compression in compression zone of the joint $F_{epc,Rd}$ is determined by transforming the equation 6.4 [9] into a form suitable for timber material:

$$F_{epc,Rd} = f_{c,0,d} b_{eff} l_{eff} \quad (8)$$

In equation (8): $f_{c,0,d}$ is the design compressive strength of timber material; b_{eff} and l_{eff} are the effective width and length of the T-stub flange, as determined according to Figure 5. The additional bearing width c is determined according to Equation 6.5 [9] by replacing the design bearing strength of the joint f_{jd} with the design compressive timber strength $f_{c,0,d}$.

The design compression resistance of a T-stub, including the embedding compression in tension zone of the joint $F_{ept,Rd}$ has an analogous determination as for $F_{epc,Rd}$ subtracting the thickness of the longitudinal groove t_{gl} from the effective width b_{eff} . Shear stresses in the timber element distribute unevenly along the height of the anchoring steel detail, as shown in Figure 6. The design shear resistance of the timber element is determined from the following equation:

$$F_{ts,Rd} = 2h_v L_v f_{v,d,mean} \quad (9)$$

In equation (9) the mean design timber shear strength value is determined as follows:

$$f_{v,d,mean} = \frac{f_{v,d}(h-h_v)}{h} \quad (10)$$

According to hacked joint methods given in [16], the timber shear strength f_d value may be used in calculations when the condition $200 \text{ mm} < L_v \leq 8b_c$ is satisfied. The value b_c is the width of the timber compression part as shown in Figure 6. When the shear plane length is more than $L_v > 8b_c$, the uneven distribution of shear stresses along the length should be evaluated.

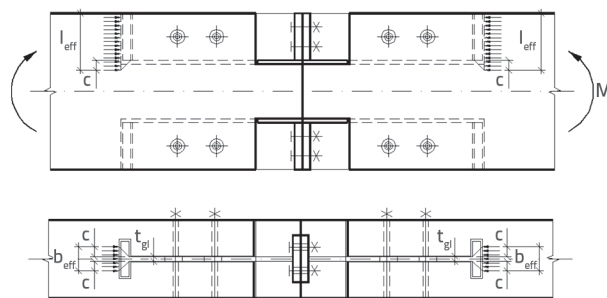


Figure 5. The effective width and length of the T-stub flange: side view of the joint (above); view from above (below)

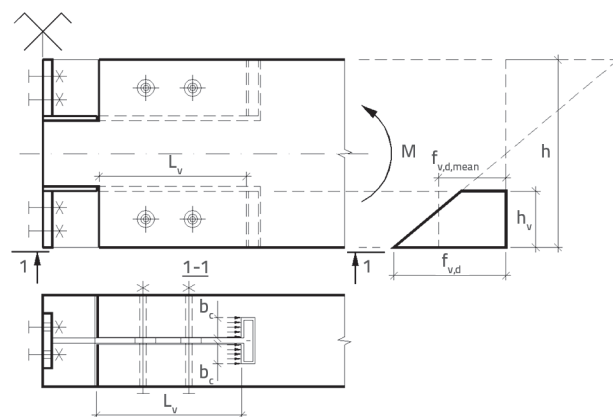


Figure 6. Uneven shear stress distribution in timber shear area

4. Numerical example of moment resistance calculation as per component method

Moment resistance calculations, based on the above described component method, are presented. As mentioned in the section 3, there are 7 different timber and steel components that determine the moment resistance of the entire joint. Calculations are conducted using actual timber and steel strength values as determined during the experimental investigation [12-14]. The timber and steel properties are summarized in Table 1. Physical and mechanical properties of timber are determined according to EN408:2010. These

values are mean experimental values based on the total of 15 specimens that were used for the determination of material properties after the main experiment presented in the previous paper [12].

Table 1. Timber and steel properties

Timber	Steel
$E_L = 11586 \text{ [N/mm}^2\text{]}$	$E = 210000 \text{ [N/mm}^2\text{]}$
$f_{c,0} (f_{t,0}) = 44.2 \text{ [N/mm}^2\text{]}$	$f_y = 275 \text{ [N/mm}^2\text{]}$
$f_v = 3.49 \text{ [N/mm}^2\text{]}$	-

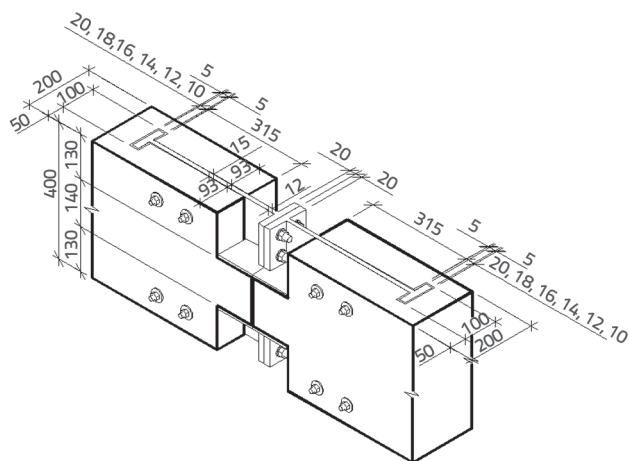


Figure 7. Dimensions of analysed timber-steel joint

Table 2. Moment resistances of joint

Determination method	Moment resistance [kNm]
$M_{j,Rd}$	54.50
$M_{j,FEM}$	55.75
$M_{j,exp}$	57.23

Three joints with the same geometrical parameters, as shown in Figure 7, were experimentally tested according to the previous publication [12]: J-1-CEM, J-2-CEM and J-3-CEM. The failure mode of all experimentally tested joints was timber shear, while the full shear block was split off in tension zone of the joint [12]. The analysed joint was also investigated using the finite element modelling methods. The finite element modelling results of the analysed joint shown in Figure 7 are presented in previous papers [8].

Component method theoretical, experimental and finite element modelling results, in terms of moment resistance, are summarised in Table 2. The mean value of the experimentally determined moment resistance $M_{j,exp}$, as presented in the previous publication [12], is given in Table 2. The component method calculation results are in good correspondence with the finite element modelling and experimental results. The differences between component method calculations and finite element modelling or experimental results are in the range of 5.1 %.

In Table 2, $M_{j,Rd}$ is the moment resistance determined using the theoretical component method, as provided for in section 3. $M_{j,FEM}$ is the moment resistance, determined using the finite element model [8]. $M_{j,exp}$ is the experimental moment resistance determined by the laboratory experiments, as presented in the previous publication [12].

The parametric study changing the end-plate thickness of the T-shaped back plate is presented further down in this section. The end-plate of the base model joint, shown in Figure 7, is 20 mm in thickness. The step of the end-plate thickness reduction is 2.0 mm, until the thickness is reduced to 10 mm. Then the theoretical and finite element modelling results will show that the moment resistance is caused by another failure mode rather than by timber shear. The theoretical calculation and finite element modelling results are summarized in Table 3. The summarized results show good correlation between the component method calculations and the finite element modelling results. Changing the T-shaped end-plate thickness, the failure mode of the joint changes from brittle, caused by timber shear ($F_{ts,Rd}$), to ductile, caused by yield of the steel detail

Table 3. Moment resistances for different T-shaped end-plate thicknesses

T-shaped end-plate thickness [mm]	$M_{j,Rd}$ [kNm]	Failure caused by component	$M_{j,FEM}$ [kNm]	Failure caused by component
20	54.50	$F_{ts,Rd}$	55.75	$F_{ts,Rd}$
18	54.50	$F_{ts,Rd}$	55.82	$F_{ts,Rd}$
16	54.50	$F_{ts,Rd}$	55.91	$F_{ts,Rd}$
14	54.50	$F_{ts,Rd}$	55.97	$F_{ts,Rd}$
12	48.62	$F_{ept,Rd}$	50.60	$F_{ept,Rd}$
10	38.88	$F_{ept,Rd}$	42.31	$F_{ept,Rd}$

$F_{ept,Rd}$ - the design resistance of a T-shaped back plate, including timber embedding compression in tension zone of the joint

$F_{ts,Rd}$ - the design shear resistance of a timber element in tension zone of the joint

($F_{ept,Rd}$). When the end-plate thickness is 12 mm and less, the moment resistance of the joint is determined by the steel detail yield ($F_{ept,Rd}$). In this case, the developed component method, validated with the finite element modelling results, shows the possibility for designing the joint, in such a way that the failure of the entire joint is controlled by steel yielding rather than by timber shear.

5. Conclusion

The component method is used for calculating bending resistance of the timber-steel beam-to-beam joints based on an extension to the component method provided for steel structures joints according to EN1993-1-8. The calculation model developed using the component method corresponds well with the experimental and finite element modelling results. Main conclusions are given below as follows:

- The component method was implemented for the first time for this type of timber-steel beam-to-beam joint moment

resistance calculations. The resistance of steel components was determined on the basis of equations provided in EN1993-1-8. The resistance of timber elements was determined according to EN1995-1-1.

- The component method calculations are in good agreement with the full-scale experimental and finite element modelling results.
- The presented component method resistance calculation model shows that the joint can be designed in such a way that the joint failure causes steel plate yielding because of bending, rather than due to timber shear in tension zone of the joint.
- The design compression resistance of a T-shaped back plate, including timber embedding compression in tension zone of the joint ($F_{ept,Rd}$), can be calculated as the design compression resistance of a T-stub flange ($F_{c,Rd}$), assuming that the design bearing strength of the joint is equal to the timber compressive strength (f_{cd}). This was proven by the finite element modelling results.

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