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# Behaviour of hybrid timber beam-to-tubular steel column moment connections

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ABSTRACT

This paper presents an experimental and numerical study into the response of bolted connections between Glulam timber beams and tubular steel columns. Six specimens involving two different connection types subjected to monotonically increasing bending action are examined. The first connection type incorporates top and seat angles blind-bolted to the column and jointed to the beam through long bolts. The second connection type is formed by a steel T-stub slotted into the timber beam and connected to it by means of transverse bolts. In addition, two reinforcing techniques aimed at enhancing the response of the slotted-in T-stub configuration are investigated. These include the provision of a bottom wedge angle between the beam and the column as well as the use of perpendicular-to-grain screws to delay wood splitting. The experimental set-up, connection configurations and material properties are introduced followed by a detailed account of the test results and observations. The main behavioural patterns are identified from the experiments and key response characteristics such as stiffness, capacity and failure mechanism are discussed. This paper shows that the use of bottom wedge angles leads to significant enhancement in the flexural yield strength of the T-stub connections, accompanied by a relatively small change in the location of the bolt-group point of rotation (monitored herein by means of Digital Image Correlation techniques). Besides, the use of reinforcing screws is shown to be an effective detail for substantially increasing the rotational ductility of the connections. Finite element simulations of the tests are also presented, together with a detailed description of the modelling approaches employed, in order to gain further insight into the behaviour of the connections. Finally, the applicability of simplified component-based expressions, which are suitable for practical design assessment procedures, for the estimation of the stiffness and capacity of the proposed hybrid glulam-to-tubular column connections are presented and discussed.

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## 1. Introduction

Hybrid structural systems that combine materials of complementary properties have the potential to achieve significant levels of efficiency. In this context, the behaviour of hybrid reinforced concrete beams-to- steel column connections has been the subject of a number of studies e.g. [1,2]. In contrast, despite their merits, research on the response of timber-steel hybrid systems is less common. Available investigations include the study of Dickof et al. [3] which proposed to combine the lightness, economy and sustainable characteristics of laminated timber panels with the ductility of steel beam-column elements to create a multi-storey timber-steel framed structure of high lateral stiffness. Likewise, the use of hybrid timber-steel flooring systems formed of Cross-Laminated Timber (CLT) and steel beams has been studied by Okutu et al. [4]. It was shown that the use of timber flooring systems results in a significantly lighter structure leading to reduced column sizes and more economical foundations. Other examples of the implementation of timber-steel hybrid systems include the Earth Science Building of the University of British Columbia in Canada [5] and the Banyan Wharf building in the UK [6] that employ moment resisting and shear wall configurations, respectively.

Structural timber clearly offers a number of advantages, especially in terms of carbon storage potential, construction economy and lightness. In this context, the architectural versatility of framed construction, relative to solid wall systems, can be further enhanced by the aesthetic and structural efficiency of tubular columns. Such configuration has the advantage of requiring smaller column sections (in comparison with a whole timber moment resisting frame solution) and a relatively less constrained connec-

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**Nomenclature**

| | |
|---|---|
| $A_t$ | tensile stress area |
| $D$ | summation of all fasteners radii $r_i$ squared |
| d | fastener diameter |
| $d_{SB}$ | standard bolt diameter |
| $d_w$ | bearing capacity of the steel plate inserted into the glulam beam |
| $d_s$ | screw diameter |
| $E_{i,Emb}$ | embedment Young's modulus |
| $F_{t,Rd}$ | tension resistance of the bolts |
| $F_{ax.Rk}$ | characteristic withdrawal capacity of the bolt |
| $F_{v,Rk,conf1}$ | characteristic load-carrying capacity of a steel-to-timber connection |
| $F_{v,conf1}$ | effective design load-carrying capacity |
| $F_{shear}$ | shear capacity of Type 1 connection |
| $F_{T,Rd}$ | design resistance of the blind-bolted angle |
| $F_{m,d,\max}$ | force acting at Bolt-1 |
| $F_{m,d,\max,h}$ | horizontal component of the force acting on Bolt-1 |
| $F_{m,d,\max,h.k}$ | characteristic horizontal component of the force acting on Bolt-1 |
| $F_{d,H,row1}$ | total effective horizontal force acting on Bolt Row-1 |
| $F_{shear\_limit}$ | plug shear failure capacity |
| $F_{screwi}$ | screw force |
| $G$ | shear modulus |
| $h_{gl}$ | height of the glulam beam |
| $h_{ef}$ | effective height |
| $h_A$ | length of the vertical (column) leg of the angle |
| $K_{CF}$ | bearing stiffness of the column face |
| $K_{HB}$ | hollo-bolt axial stiffness |
| $K_t$ | tension stiffness of the angle's horizontal leg |
| $K_{ser}$ | slip modulus of each individual fastener |
| $l_{ef1}$ | connection effective length |
| $l_{ef}$ | connection effective depth |
| $M_{y.Rk}$ | characteristic yield moment of the bolt |
| $M_{y,angle}$ | yield moment capacity of Type 1 connection |
| $M_{shear}$ | moment capacity at ultimate associated with brittle shear failure |
| $M_d$ | applied moment |
| $M_{d,y}$ | moment capacity of Type 2 connection |
| $M_{d,PS}$ | moment capacity for plug shear failure |
| $M_{y,s}$ | yield moment of the screw |
| $M_T$ | total moment capacity |
| $M_{d,angle}$ | moment capacity associated with the wedge angle contribution in Type 2 connection |
| $n_{b,ef}$ | effective number of fasteners connecting the angle to the glulam beam in the direction parallel to the grain |
| $n_b$ | number of bolts in the direction parallel to the width of the beam |
| $n_{s,pl}$ | number of bolt-rows. |
| $n_{row1}$ | number of bolts in the direction parallel to the grain |
| $n_{row1,ef}$ | effective number of bolts in the direction parallel to the grain |
| $P$ | ratio between the radius of the foundation zone and the fastener diameter |
| $R_i$ | strength associated with screw failure |
| $r_{fill}$ | corner radius of the angle |
| $r_{\max}$ | position vector of Bolt-1 with respect to the point of rotation |
| $r_i$ | distance from fastener to the point of rotation for Type 2 connection |
| $S_{config1,init}$ | rotational stiffness of Type 1 connection |
| $S_{config2}$ | rotational stiffness of Type 2 connection |
| $t_f$ | angle thickness |
| $t_1$ | distance parallel to the width of the beam between the side of the beam and the inserted metal plate |
| $t_{Tstub}$ | thickness of the metallic plate |
| $w_f$ | width of the angle |
| $w_b$ | width of the glulam beam |
| $y_1$ | vertical distance between Bolt-1 and the centre of rotation |
| $y_A$ | distance between point of rotation and the bearing zone of the wedge angle |
| $\beta_1$, $\beta_2$, $\gamma_1$ and $\gamma_2$ | empirical parameters |
| $\gamma_M$ | material safety factor |
| $\sigma_{Emb}$ | embedment stress |
| $\sigma_{FZ}$ | stress of the foundation zone |
| $\sigma_{11,emb,k}$ | characteristic embedment strength parallel to the grain |
| $\sigma_{y,f}$ | yield stress of the angle |
| $\sigma_{ub}$ | tensile strength the appropriate bolt grade |
| $\sigma_{c,90}$ | compression strength of the beam perpendicular to the direction of the grain |
| $\sigma_{v,k}$ | characteristic shear strength of glulam |
| $\rho$ | wood density |

tion configuration due to the avoidance of the perpendicular-to-grain weaknesses of a wooden column. However, the lack of practical details for connecting tubular columns and timber beams may limit the application of this hybrid solution. In terms of timber connections, Bainbridge and Mettem [7] conducted a review on available connection configurations for whole timber moment-resistant frames and highlighted the benefits of using mechanical dowel type connections. Similarly, significant research has been recently conducted on practical semi-rigid connection alternatives in whole steel frames with tubular columns [8–11]. Nevertheless, details for semi-rigid connections joining timber beams and tubular columns have not been proposed.

This paper deals with the flexural response of a new type of hybrid bolted connections between Glulam timber beams and tubular steel columns by means of numerical and experimental studies. Issues related to the shear resistance and multiple load combinations are outside the scope of this paper. A total of six connection specimens are tested under monotonically increasing bending action. Two connection configuration alternatives are examined. The first connection type incorporates top and seat angles blind-bolted to the column and jointed to the beam via four vertical long bolts. The second joint configuration employs a steel T-stub pre-welded to the steel column, and slotted-in and bolted to the timber beam by means of twenty transverse bolts. In addition, two reinforcing techniques aimed at enhancing the response of the slotted-in T-stub configuration are investigated. The first reinforcing method involves the use of a bottom wedge angle that enforces a dependable bearing surface in the joint thus increasing its capacity. The second reinforcing technique examined herein employs steel screws inserted in the direction perpendicular-to-grain aimed at delaying or preventing splitting of the wood fibres. The test set-up, specimen details and material characterization are first introduced followed by a detailed account of the experimental findings. Continuous measurements, obtained by means of Digital Image Correlation (DIC) techniques, are presented and employed to obtain a full account of the migration of the point of rotation

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