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An innovative reversible shear connection for efficient steel-timber composite floor beams

Summary: The challenges the construction industry is facing to reduce its environmental impact and to efficiently used the available resources lead to an extensive search for sustainable construction alternatives. In the last decades, competitive Engineered Wood Products (EWPs) appeared in the market. The synergy between EWPs and steel, in the so-called steel-timber composite (STC) form, can be an efficient and sustainable solution for the execution of building floors and decks. Various shear connections for STC have been developed. However, the majority relies in the dowel-type connectors, with limited mechanical performance strongly affected by the flexibility of the EWPs. Furthermore, the non-linear and permanent deformations often developing in a low range of loading, may hinder reuse of the materials and strongly limit the non-destructive disassembly at end of life. Thus, this paper presents the development of a new reversible shear connector for efficient steel-timber composite floor beams meeting the needs of an optimize use of construction materials through reuse. First, a brief overview of existing shear connections for STC is given, identifying their potential and limitations. Then, the concept of the new proposed connection is exposed. Finally, a preliminary assessment through analytical calculations and numerical simulations is done, demonstrating the efficiency of the proposed shear connection towards a designed for disassembly (DfD) STC composite beam.

Keywords Steel-timber composite; Reversible shear connection; Component method; FEM simulation; Design for Disassembly

1   Introduction

The construction industry is responsible for the consumption of approximately 40% of global materials, the production of large waste streams (35% of the total solid waste generated in Europe) and 36% of carbon emissions [1]. At the same time, it is expected that approximately 70% of the world population will live in cities by 2050 [2], increasing the pressure on the urban built environment. In order to answer the demand, the need for new constructions will keep growing in parallel to the need for extending the life of the built heritage is necessary (e.g. through renovation, rehabilitation and re-adaptation). As the demand for construction materials will continue to grow, the industry is under pressure to implement a paradigm shift to sustainable use of

available resources, increasing efficiency, reducing waste and carbon emissions. The transition towards a circular construction presents an opportunity to accomplish the required change. The relevance of developing circular structural solutions is fundamental to achieve sustainable end-of-life scenarios: i) deconstruction rather than demolition; ii) extension of the life of structural materials; iii) adaptation of structure through life (or between life-cycles) according to the needs. The synergy between Engineered Wood Products (EWPs) and steel in the composite form, especially through the development of circular structural solutions, offers a promising solution for the construction industry to significantly diminish its environmental footprint. There is therefore a growing interest in steel-to-timber composite (STC) structures which is reflected in scientific literature [2], international working groups to develop design standards (e.g. ECCS-TC11-WG6) and already in some practical realisations [4].

In composite members, namely beams and floors, structural efficiency and feasibility are strongly dependent of the shear connection between the materials, where both mechanical performance and ease of execution must be combined. Moreover, circular construction principles require that construction solutions are thought for an extended end-of-life of members and/or materials. Accordingly, the concept of Design for Disassembly (DfD) and for reusability has been established and is nowadays a design concept under implementation in various fields of the construction sector. Thus, the key role of the shear connection is further stressed. In particular, the research on steel structural members combined with timber has been intensively increased in the last decade [5]. Currently, most of the solutions consider the use of a bolt (or screw) as shear connectors transferring the shear forces through bearing. Though these solutions are attractive for their easy implementation, the mechanical efficiency and the disassembly, after end-of-life, may still limit the overall potential of STC solutions.

Hence, there is still the need to further develop shear connectors between steel and timber which may improve the composite action efficiency while meeting the needs of DfD towards a circular use of members and/or materials. In order to contribute to this gap, the present paper presents an innovative reversible shear connection for STC floor beams. First, a brief overview on the various solutions already available in the literature is given. Then, the conception of the proposed shear connector is exposed. Finally, preliminary numerical and analytical models are described, and discussed to demonstrate the potential of the developed solution through a comparison with more common ones.

2   Overview of existing shear connectors for steel-timber composite floors

2.1   Collection of solutions

The various type of solutions that can be found for shear connections in STC developed in the past decade are summarized in Table 1. The latter includes the reference, the type of connection and load transfer mechanism from steel to timber (often most critical in STC). The analysis of the collected solutions on their structural efficiency to meet the demands for easy disassembly while maximising the reuse of the construction elements is provided in the next section. Note that the given list does not provide an extensive review on STC shear connections but rather an overview on the various types of connections found in the literature. More detailed review maybe found in [5].

Table 1 Collection of various type of shear connections for STC floor beams available in the literature

Authors	Type of connection	Load-transfer mechanism to timber
C. Loss et al. (2016) [6]	Type A: Dowel Type, screws, including inclined screws, steel rings	Type A: dowel action (bearing/embedment strength) or withdrawal capacity (inclined screws)
	Type B: Glued type, bonded-in dowel or bonded-in perforated steel plate	Type B: chemical adhesion
	Type C: Combined, steel ring/connector and bonded-in dowel	Type C: combination of previous
A. Hassanieh et al. (2016) [7]	Type A: Dowel type, coach screws	Type A and B: dowel action (bearing/embedment strength)
	Type B: Dowel type, highs strength bolts	
A.A. Chiniforush et al. (2019) [9]	Type A: Dowel type, coach and dog screws	Type A: dowel type
	Type B:Dowel type, post-tensioned bolts	Type B: slip resistant follow by dowel action (bearing/embedment strength)
	Type C: Contact type, Post-tensioned bolts in grout pockets	Type C: mechanical interlock
A. Romero and C. Odenbreit (2024) [9]	Dowel-type, steel tube with preload bolts	Slip resistant follow by dowel action (bearing/embedment strength).

2.2   Limitations of the existing solutions

Table 1, the most frequently used connector is the dowel-type due to the simplicity of execution and the variety of fasteners (including dimensions) available in the market. However, dowel-type solutions, for which the mechanical response is mainly governed by the embedment strength between fastener and EWP (including bending deformation of the fastener), exhibit a much more flexible behaviour (lower initial stiffness) when compared to equivalent shear connection systems in steel-concrete composite structures (e.g. welded headed studs), and thus, inducing a decrease of the composite action within STC beams and consequently, of the efficiency of the solution. In particular, the connection slip, already significant in the elastic range, cannot

be neglected. Moreover, due to the lower flexibility of EWP, plastic hinges in the fastener, combined with timber local crushing (embedment action), easily develop, so limiting the load capacity and thus, resulting in permanent deformations. However, the presence of permanent deformations in the connection from an early stage can hinder the reuse of the structural components or even, in the case of ultimate limit state scenario, require the use of destructive methods for disassembly. The literature shows that these limitations can be overcome with the use of adhesive or grout pockets; however, execution and disassembly limitation make this solution not attractive for circularity. Slip-resistant connection type combined with dowels possess a high initial stiffness, delaying the dowel action. If this solution has high potential from a mechanical point of view, its execution is more complex, e.g. relies on preloading to be controlled on site during application and mastered all along the structure life, in particular when accounting for time-dependent effects, which can impact the friction slip stage e.g. due to the creep effects on the EWP. For these reasons, the development of a shear connections for STC which can overcome the flexible response of the EWP while incorporating easy assembly-disassembly, with non-destructive methods, and thus extending the life of the materials, is still required and the solution proposed in this paper aims to meet this need.

3 Conception of an innovative reversible shear connector for STC beams

The developed connection consists of two connections in series, namely, between EWP and connector, and between steel beam and connector. In order to realize these connections, a steel block with prismatic shape (hereon denominated as steel connector), self-drilling screws and structural bolts (partially or fully threaded) are used, as illustrated in Fig. 1. To mobilize a mechanical interlock between timber and steel, a steel connector is integrated in a groove realized in the timber panel, using a Computer Numerical Controlled (CNC) machine (Fig. 1-a). The steel connector is fixed to the timber by means of screws; therefore, the connector is fabricated with holes to install the screws. A conical shape hole (countersunk) allows the interlock between the screw head and the steel connector (Fig. 1-b), providing the necessary resistance to a pull-through load. On the point side of the screw, the mechanical interlock between screw threads and wood will guaranty the resistance to pull-out. The so-described system allows to: i) the pre-installation of the connector in the EWP during manufacturing in the factory (installation on site is still possible but more challenging); iii) the transfer of shear forces through contacts between the steel connector and the boundary of the groove and iii) the resistance of the steel connector

to a pull-out load (and consequently, to separation forces when integrated in the composite solution) through the screw. To fix the steel connector to the steel beam, threaded holes are made in the connector allowing to bolt together both parts (Fig. 1-c). To accomplish the bolted connection between the steel beam and the connector (and thus the EWP), predrilled holes are made in the steel beam (Fig. 1-d). The transfer of the shear forces from the steel connector to the beam flange is ensure through bolt bearing. The implementation of the shear connector in a STC beam is illustrated in Fig. 2.
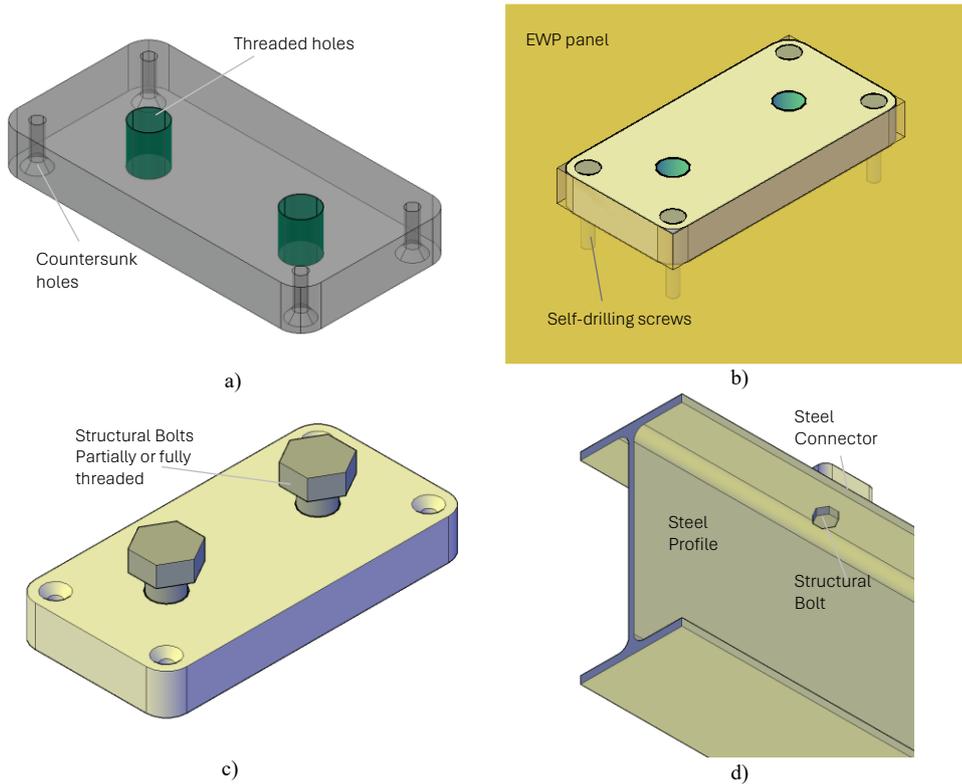

a)

b)

c)

d)

Fig. 1 a) Steel connector; b) Connection between steel connector and EWP panel; c) Detail of bolt-connector connection; d) Connection between steel connector and steel profile (*Patent application pending*)
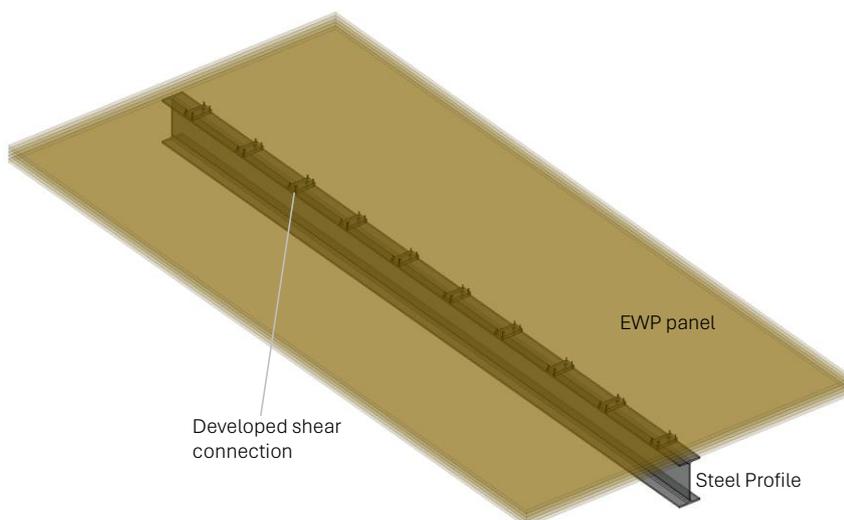

Fig. 2 Steel-timber composite floor beam implementing the developed shear connection (*Patent application pending*)

4   Preliminary assessment of the connection

4.1   Analytical modelling

The mechanical behaviour of the developed connection can be assessed applying the component method philosophy [10]. Accordingly, the activated connection components must be identified, as given in Fig. 3 and Table 2. A spring mechanical model is idealized based on the load transfer mechanism. Next, to determine the connection mechanical properties, namely, strength and stiffness, each connection component must be mechanically characterized. At this stage, the latter is accomplished applying the design prescriptions given in the Structural Eurocodes. Table 2 summarizes the relevant code and clause for each component. It must be noted that the component method is prescribed by the FprEN 1993-1-8 [10] but not explicitly by FprEN 1995-1-1 [11]; therefore, the components involving the EWP need yet further validation. Finally, the connection stiffness (k_{con}) and strength (F_{con}) are obtained as given in (Eq. 1) and (Eq. 2).

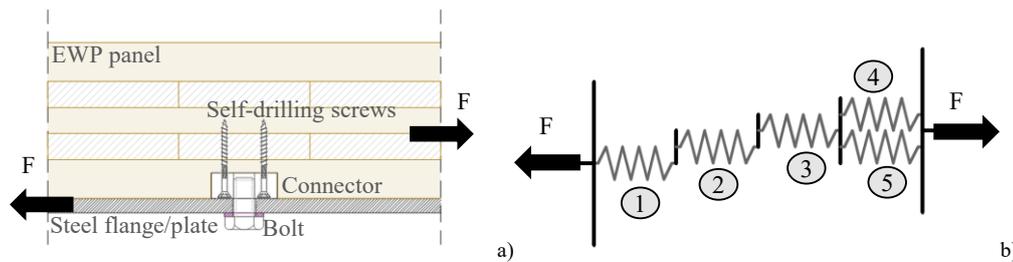a)   b)

Fig. 3 a) Shear connection b) Spring component based mechanical model (*Patent application pending*)

Table 2 Identification of activated connection components and reference to determine key mechanical properties

Component	Stiffness (coefficient)	Strength
1 - Bolt-flange/plate in bearing	FprEN 1993-1-8:2023 [10], Annex A – A.15, $k_1 = k_b$*	FprEN 1993-1-8:2023 [10], Clause 5.9, $F_1 = F_{b,Rd}$
2 – Bolt in shear	FprEN 1993-1-8:2023 [10], Annex A – A.14, $k_2 = k_v$*	FprEN 1993-1-8:2023 [10], Clause 5.9, $F_2 = F_{v,Rd}$
3 – Bolt-connector in bearing	FprEN 1993-1-8:2023 [10], Annex A – A.15, $k_3 = k_b$*	FprEN 1993-1-8:2023 [10], Clause 5.9, $F_3 = F_{b,Rd}$
4 – CLT in compression	Not given, assumed $K_4 = E_0 (A_{ef}+A_c)/2h_{ef}$	FprEN 1995-1-1:2025 [11], Clause 8.1.5, $F_4 = f_{c,0} A_{ef}$,
5 – Dowel (screw) connector-EWP connection	FprEN 1995-1-1:2025 [11], Clause 11.3.8, $k5 = K_{sls,v}$**	FprEN 1995-1-1:2025 [11], Clause 11.2.3, $F_5 = F_{v,D}$

*The code gives stiffness coefficient, ** The code identifies the stiffness as slip modulus where the value for ULS loading should be equal to $k_{SLS,V}$ divided by 1.5.

Where: E_0 is the Young modulus of the EWP in grain direction; A_{ef} is the effective stressed area assuming a stress propagation within the EWP element as prescribed in the FprEN 1995-1-1 [11]; A_c is the actual mechanical interlock contact area; h_{ef} is the stress distribution depth within the EWP as prescribed in the FprEN 1995-1-1 [11]; $f_{c,0}$ is the EWP compressive strength in the

grain direction.

$$\frac{1}{k_{con}} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_4 + k_5}$$ (Eq. 1)

$$F_{con} = \min(F_1; F_2; F_3; F_4 + F_5)$$ (Eq. 2)

4.2   Numerical modelling

A finite element method (FEM) model is developed in the general purposes' software Abaqus [12], to further complement the preliminary assessment of the shear connection response. All parts of the connection are simulated using reduced integration 3D volume finite elements (C3D8R). The materials behaviour is reproduced through the following constitutive models available in the software "library": i) Steel, elasto-plastic with isotropic and kinematic hardening; ii) Wood, orthotropic elasticity (*Engineering Constraints*) with anisotropic yield criterion (Hill's criterion). The latter has a limited applicability to simulate wood post-elastic behaviour, in particular for problems governed by brittle failure modes. However, at this stage, given that the main load transfer mechanism between connector and wood consist of local contact (compression), the use of this model is acceptable in the framework of a preliminary analysis. Next, the mechanical contact between parts is modelled through "hard" contact model, in the normal direction (no penetration allowed), and through an isotropic Coulomb friction model (μ=0.25 for wood-steel and $\mu = 0.4$ for steel-steel), in the tangential direction. To validate the implemented modelling techniques, a "classical" dowel-type shear connection from the available literature [12] has been previously simulated. The developed models, for respectively, dowel-type and new developed shear connection, are illustrated in Fig. 4 a) and b). In Fig. 5 the force-deformation curve reproducing the dowel-type shear connection, comparing test and simulation, is given. The chart shows a general good agreement between both. Main deviations occur in the initial stage and in the post-yielding stage. The first may be attributed to the lack of calibration of the preloading used in the tests. The second due to wood material model used in the numerical simulation, assuming anisotropic yielding. At this stage, and for comparison purposes between the two connection solutions, these deviations are seen as acceptable. Next, Fig. 4 c) and d) show the deformed shape of the two connections. It is possible to observe, that though a different connection detailing, deformations in the wood are mainly concentrated in the limited depth of the EWP panel adjacent to the steel flange. Given the higher contact area of the new connector, its mechanical performance is expected to be superior.   The potential of the new developed

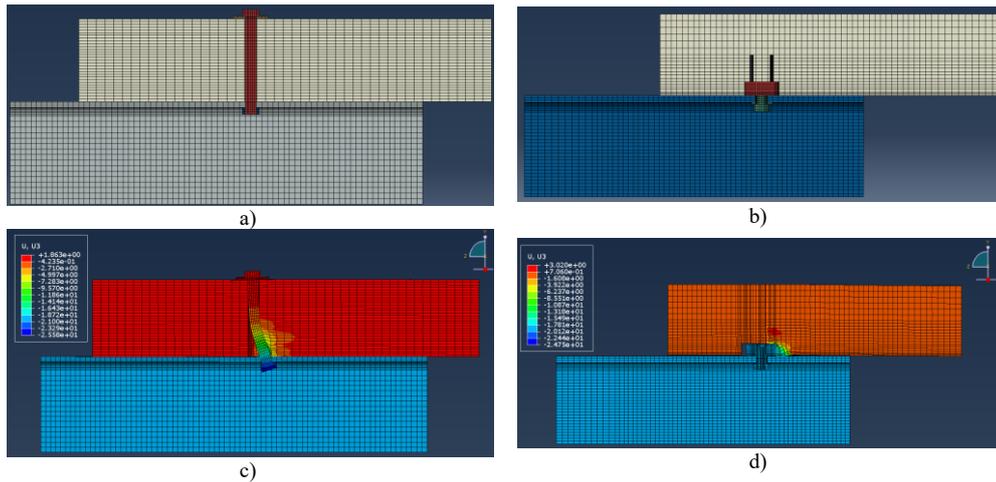connection is discussed in the next section.

Fig. 4 Developed FEM models to simulate push-out tests, a) Dowel-type (bolt) connection, undeformed; b) New developed connection, undeformed; c) Dowel-type connection deformed; d) New developed connection, deformed.
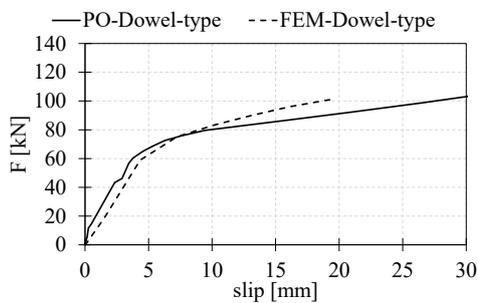

Fig. 5 Comparison between push-out tests (PO) [12] and finite element numerical simulation (FEM) of classical dowel connection
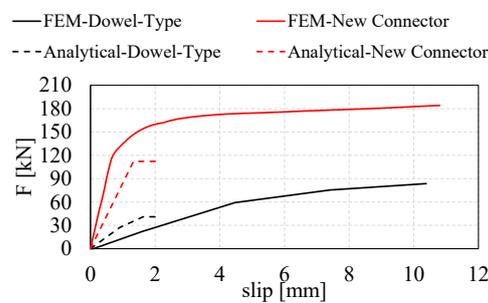
Fig. 6 Force-slip curves comparing dowel-type and new connector

4.3   Comparison with other traditional solutions

To assess the potential of the developed shear connector, both numerical simulations and analytical calculations are used. The numerical models for both solutions have been described in the previous section. The analytical model for the new developed connection has been exposed in Section 4.1. For the traditional dowel-type shear connection between CLT and steel profile (plate), strength and stiffness are computed as prescribed in the prEN1995-1-1:2025[11]. All materials properties (mechanical and geometrical) considered were the same, namely steel profile, CLT and bolts. **Erreur ! Source du renvoi introuvable.** compares the force-slip curves between connection type and approach. Both analytical approaches deviate from the numerical results for which the lack of accuracy may be attributed to the following: i) adaptation of model to evaluate the local mechanical interlock in the CLT which is not explicitly covered in the code (**new connector**); ii) overestimation of connection stiffness (**dowel type**), often reported in the literature. This constitutes a perspective of further development. The results demonstrate, inde-

pendently of the approach, that the new developed connection depicts a stronger and stiffer behaviour within the elastic regime, thus, reducing the slip between materials. Consequently, improved composite action is expected. Moreover, from the numerical simulation performed on the traditional solution, it is observed that plastic deformation develops in the connection, at the level of the bolt, at low level of load. Such plastic deformation may hinder easy disassembly (e.g. requiring destructive methods) and reusability of the materials (namely EWP panel).

5   Conclusions

A new reversible shear connection for performant steel-timber composite floor beams, meeting the demands of the circular economy, has been presented in this paper. The preliminary calculations using numerical and analytical approaches confirm the efficiency of the developed shear connection: a stiffer behaviour (more efficient composite action), and higher resistance in elastic domain. Such a behaviour prevents the development of permanent damage under service loading and consequently, allow disassembly towards a circular use of the structural components.

The proposed concept is now requiring an experimental validation. Accordingly, a research project is currently ongoing at Construction Engineering Research Group (CERG) of Hasselt University (Belgium) in consortium with WoodLab of Gent University (Belgium). Within this project, significant experimental data will be produced to further assess and validate the mechanical performance of the proposed shear connector under short-term and long-term loading including the impact of moisture variations in EWPs. Moreover, at Hasselt University and at University of Liege, PhD theses are ongoing on the above-mentioned thematics.

Finally, the potential range of application of the present connector goes beyond the STC floor beams. This connector has the potential to be implemented in other structural (and non-structural) applications, between different types of materials and EWPs e.g. EWP shear-walls to steel frame, RC concrete layer to EWP panels, etc.

Conflict of Interest

A patent application (EP25180501 on 03/06/2025) has been filed, covering the design and application of the described connector.

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