

Review

Advancements in Timber–Steel Hybridisation: A Review on Techniques, Applications, and Structural Performances

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Abstract

Timber–steel hybridisation offers a balanced approach by capitalising on the high strength-to-weight ratio and sustainability of the timber while also benefiting from the high stiffness and ductility of the steel, contributing to the improved performance of hybrid structural elements. This paper reviews key aspects of timber–steel hybridisation, with a particular emphasis on the connection methods between timber and steel, including adhesive bonding and mechanical fastening, as well as the different types of reinforcement configurations. In particular, this review covers two main types of adhesives used in timber–steel hybrid systems, namely, epoxy and polyurethane, and two primary types of mechanical fasteners, namely, bolts and screws. The mechanical performances of all hybridisation methods are reviewed. The importance of surface treatments, such as shot blasting for steel and mechanical abrasion for timber, is also discussed as a key factor in optimising adhesive bonds. Furthermore, various reinforcement configurations, including top, bottom, side, and embedded arrangements, are evaluated for their impact on the structural efficiency and fire performance. To support this evaluation, calculations have been carried out to illustrate how different reinforcement configurations influence the stress distribution in timber–steel hybrid beams. By providing detailed insights into these critical aspects, this paper serves as a valuable decision-making tool, offering guidance for researchers and industry professionals for selecting the appropriate bonding techniques and configurations to meet specific structural objectives and advance sustainable construction practices.

Keywords: timber–steel hybridisation; hybrid configuration; hybrid bonding; adhesives; mechanical fasteners



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1. Introduction

Timber–steel hybridisation has gained recognition in structural engineering as an innovative approach, combining the distinct strengths of both materials. Timber, a renewable resource, is valued for its high strength-to-weight ratio, aesthetic appeal, and exceptional thermal insulation, while it also contributes to environmental sustainability through carbon storage [1–3]. Steel provides superior stiffness, ductility, and load-bearing capacity, effectively addressing some limitations of timber, such as its lower stiffness and brittle behaviour in tension and bending [4–7]. The integration of timber and steel in

hybrid systems therefore not only aims to optimise the structural performance but also promotes more sustainable construction practices through efficient material uses and reduced environmental impact.

The hybridisation of timber and steel spans various applications, ranging from individual structural elements like beams and columns [8,9] to entire building frameworks [10–12], and it extends to timber connections where steel is used for its strength and ductility [13–17]. With a focus on hybrid beams, a critical component of this hybridisation is the bonding between the timber and steel, which enables effective composite action for seamless load transfer, thereby enhancing both strength and stiffness [5]. Studies have investigated various bonding methods, with some focusing on adhesives [18,19], while others have explored mechanical fasteners [5,6]. Additionally, the existing studies have examined the combined use of adhesives and mechanical fasteners to achieve optimal bonding [20,21].

To optimise adhesive bonding, treatments are commonly applied to both steel and timber surfaces prior to bonding [22]. Steel surfaces may undergo treatments like etching, brushing, or shot blasting to eliminate contaminants and create rougher surfaces, thereby promoting stronger adhesion with adhesives [18,23,24]. Similarly, timber surfaces can be prepared through sanding or other mechanical methods to eliminate surface imperfections and enhance bonding [25,26].

Another key facet of timber–steel hybridisation lies in the strategic arrangement of the two materials. With respect to reinforcement configurations, steel can be positioned in the tension zone (referred to as the “bottom” arrangement throughout this paper, as is typically the case in beams) [4,27,28] and in the compression zone (referred to as the “top” arrangement, also as is typically the case in beams) [5,29,30] to improve the overall strength and stiffness. Research has also explored embedding steel within the timber [8,31,32] or placing it on the sides [33,34] to enhance lateral stability, amongst others. Beyond the structural performance, the placement of the steel relative to the timber is also important for fire resistance, taking advantage of timber’s natural thermal insulation properties, due to its cellular structure, and thereby plays a crucial role in mitigating heat transfer [35–39].

This review paper expands on the key facets of timber–steel hybridisation highlighted above, including the use of adhesives for bonding the timber and steel, mechanical fasteners for connections, and various reinforcement configurations, focusing on how each contributes to enhancing the structural performance. The flowchart in Figure 1 outlines the structure of this paper, which covers the key adhesive types, focussing on epoxy and polyurethane (PUR), alongside the role of bolt and screw mechanical fasteners. Various reinforcement strategies, including top, bottom, side, and embedded configurations, are evaluated for their impact on structural efficiency and fire resistance. By synthesising and quantifying these findings, this paper aims to serve as a valuable decision-making tool, offering guidance to researchers and industry professionals for selecting the appropriate bonding techniques and configurations to meet specific structural objectives and advance sustainable construction practices.

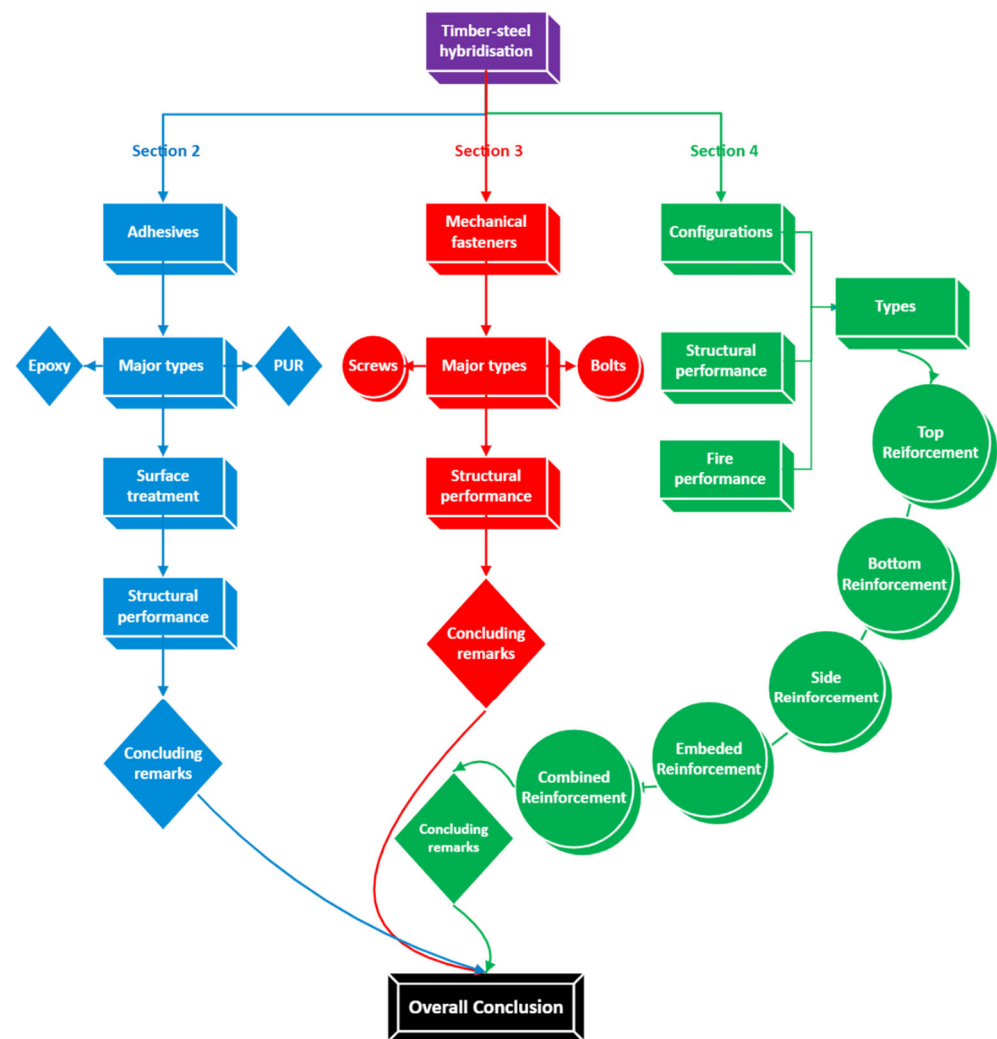


Figure 1. Review flowchart.

2. Adhesive Technologies

2.1. General

Structural adhesives are substances that structurally bond materials together [40]. The use of adhesives in timber applications has a long history, as highlighted by Vallee et al. [41]. This is seen in early practices like papyrus laminating [42], wood veneering [43], and furniture manufacturing across civilisations [44]. Initially, natural adhesives were common but sensitive to environmental degradation [45]. The Industrial Revolution introduced protein-based adhesives, which have improved the bond strength and durability for applications like laminated wooden aeroplane structures and Glued Laminated Timber (GLT) beams [46,47]. Citing the Rockefeller Foundation’s 1953 annual report [48], Vallee et al. [41] noted that after World War I, the emergence of “modern synthetic” adhesives, such as phenol–formaldehyde (PF) and urea–formaldehyde (UF), represented a major turning point, leading to the widespread use of various formaldehyde-based adhesives. In the wood industry, highly reactive isocyanates are now frequently used, including polymeric diphenylmethane diisocyanate (pMDI), emulsion polymer isocyanates (EPis), and polyurethane (PUR) adhesives. Additionally, polyvinyl acetate (PVAc) and poly(ethylene-vinyl) acetate (EVA) dispersions are commonly employed in furniture production. Epoxy (EP) adhesives, although effective, are less commonly used in the industry due to their relatively high cost [49].

In the manufacture of modern Engineered Wood Products (EWPs), such as laminated veneer lumber (LVL) and Cross-Laminated Timber (CLT), various adhesives are employed to create robust bonds between the timber elements; i.e., bonds that are stronger than the timber itself and that lead to failure within the timber itself rather than at the bonded surface [50,51]. Common adhesives used include PF, widely used in plywood and LVL [52,53], and resorcinol–formaldehyde (RF) and PUR, typically used in GLT and CLT [54,55].

2.2. Major Types of Adhesives Used in Timber–Steel Hybridisation

In timber–steel hybrid structures, epoxy and PUR are the most commonly used adhesives [18,56] found in the literature, and this review paper therefore focusses on these two products, acknowledging that other adhesives may also be used but require further research. For instance, the use of PF adhesive has also been highlighted [57]. Epoxy and PUR were found to create strong bonds between timber and steel components, improving the composite action and enhancing the load-carrying capacity of the structural members [18,58]. Gaining insight into the performances of all these adhesives can aid in selecting the most suitable type and formulation for optimal performance. It is worth noting that bonding steel to timber with adhesive provides design flexibility, especially in joints [59], allowing architects to explore innovative and aesthetically pleasing construction possibilities.

2.2.1. Epoxy Resin

Epoxy, a versatile and widely used resin, stands out as an important adhesive in timber–steel hybridisation due to its high bonding strength and versatility [18,51,57]. Two common types of epoxies have been identified for use in the hybridisation of timber and steel: conventional epoxy and toughened epoxy adhesives [18,60]. Vallee et al. [41] confirmed its strong adhesion to most materials, which makes it suitable for structural reinforcement.

Conventional epoxy is a two-component (2C) adhesive that combines resin and hardener before application, enabling bonding at both low and high temperatures. While capable of withstanding significant static loads, its susceptibility to brittle fracture limits its resistance to dynamic forces, such as impact and cyclic loads [61,62].

Toughened epoxy is created by incorporating special additives to enhance resilience. The key to toughened epoxy adhesive is the introduction of a second, more flexible and dispersed phase into the stiff epoxy matrix [61]. Toughened epoxy adhesives are designed to achieve lower stiffness than conventional epoxy, improving toughness with a flexible microstructure through void growth, shear banding, and rubber bridging [61,63,64].

When compared to PUR (see the discussion in Section 2.2.2), epoxy is often considered a more versatile adhesive type due to its moderate pressure requirements and tolerance to variations in glue line thickness, despite its brittleness and higher stiffness, which allow less load redistribution than PUR. Epoxy can also withstand higher levels of stresses [41].

2.2.2. Polyurethane (PUR)

PUR adhesives, like epoxy, are versatile bonding agents categorised as one-component (1C) and 2C systems [65]. In the 1C category, these adhesives come pre-formulated and do not require mixing before application. In the 2C category, the mixing of separate components—polyol and isocyanate—is needed [65]. The fine-tuning capability of 2C PUR, similar to toughened epoxy's additive inclusion, allows for tailored formulations suitable for specific applications. PUR structural adhesives are fully joined via urethane bonds, where a polyol resin component is cured with an isocyanate hardener component [65].

In more details, 2C PUR adhesives are employed as structural adhesives capable of resisting creep [65]. They maintain their durability at the required working temperatures but must be in a liquid state during application to ensure proper surface wetting, which is essential for effective adhesion [65,66]. One-component PUR adhesives play a predominant

role in elastic bonding and sealant applications [65]. However, reports have also suggested that 1C PUR adhesives can be used as structural adhesives for bonding wood to other materials, such as fibre-reinforced plastic (FRP), enabling hybridisation [54]. This is attributed to their dual-phase morphology and, consequently, their lower level of cross-linking per unit volume, making them more ductile than other forms of adhesives [54,67].

2.3. Surface Treatment for Optimal Adhesion

2.3.1. Steel Surface Treatment

The treatment of the steel surface is a critical aspect of promoting the improved adhesion of the steel material to its substrate. Prior to bonding, it is important to ensure that the steel surface is free from contaminants such as dirt and grease, which could impair the bonding process [17,18,68]. Additionally, the surface should be made rough through mechanical treatments to enhance the bonding strength [69]. However, it was advised by Kawecki [56] that investigations should be conducted to understand the influence of different surface treatments before bonding specific elements with a given adhesive. Some of these treatments include the following:

- Etching is a common method of treating steel surfaces and involves removing material from the surface using chemicals or electric currents [70]. This process serves to create a controlled roughened surface that promotes adhesion between the steel and bonding agents [18,23].
- Mechanical abrasion through brushing is another effective method for roughening the surface of steel prior to bonding [70,71]. This process entails, for instance, using carbide steel brushes attached to power machines to mechanically abrade the steel surface, enhancing its roughness and facilitating better adhesion [18].
- Shot blasting, or grit blasting, represents a more aggressive approach to surface treatment, involving the propulsion of small abrasive particles at high velocity onto the steel surface [4]. This method effectively removes rust and contaminants, leaving behind a highly roughened texture conducive to improve adhesion. Shot blasting is particularly advantageous for steel surfaces that require thorough cleaning and preparation prior to bonding. Fernando [72], citing sources [73,74], has highlighted the superiority of shot blasting among other mechanical abrasion methods.

Additionally, Burnett et al. [24] examined the efficacy of different surface treatment measures on the shear strength of aluminium bonded to wood using PUR and a water-based PVAc. The results demonstrated how pretreatment enhances the strength of hybrid wood–metal composites. In the experiments, the aluminium underwent the following surface treatments: (i) cleaning with isopropanol (reference pretreatment), (ii) plasma treatment, resulting in a 400% increase in the lap shear strength compared to isopropanol cleaning alone, (iii) laser treatment, resulting in a 484% increase in the lap shear strength, and (iv) a combination of laser and plasma treatment, resulting in a 488% increase.

2.3.2. Timber Surface Treatment

In addition to steel, timber surfaces also benefit from treatments to enhance adhesion. Timber inherently possesses properties that facilitate bonding, such as its porous structure. However, certain treatments can further optimise its bonding capabilities. For instance, surface roughening through mechanical abrasion or sanding enhances the mechanical interlocking between timber and bonding agents, thereby improving the adhesion strength [18,75,76].

Furthermore, chemical treatments such as priming or pretreatment with adhesion promoters can enhance the bonding performance of timber surfaces [77,78]. These treatments serve to modify the surface chemistry of the timber, creating more favourable conditions

for bonding with adhesives or coatings. However, such treatments represent an additional manufacturing step.

2.4. Structural Performance of Adhesive Bonds in Timber–Steel Hybrid Connections

To assess the performances of different adhesives and their formulations in bonding steel to timber, Kemmsies [18] conducted an investigation by manufacturing samples similar to the one depicted in Figure 2. The study evaluated how effectively various adhesives (epoxy, toughened epoxy, and PUR) bonded spruce timber to a 6 mm steel plate at room temperature. The influence of the glue line thicknesses (0.5 mm, 1 mm, and 2 mm) was examined, along with a comparison of timber-cutting methods (circular saw and moulder). The samples were tested in shear using a universal testing machine, which applied an axial load directly to the embedded steel plate. This force acted to pull the plate out of the timber slot, thereby generating shear stress along the adhesive interface. A small gap was maintained between the bottom of the steel plate and the base of the groove in the timber to avoid obstruction and ensure that load transfer occurred entirely through the glue line. The relative slip between the timber and steel was measured using displacement transducers mounted near the glue line, allowing for the evaluation of the adhesive performance under shear loading.

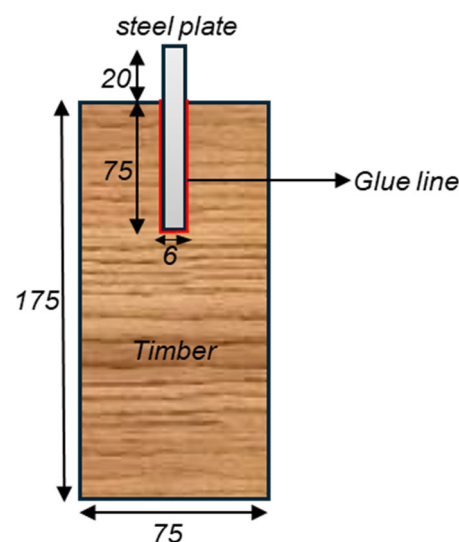


Figure 2. Timber–steel hybrid setup (adapted from Kemmsies [18]) (all units in mm).

Among the three adhesives tested, PUR emerged as the top performer, achieving a shear strength of 8.6 MPa at a 0.5 mm glue line thickness. This was 109% higher than the samples glued with toughened epoxy, which was the lowest performer. Furthermore, PUR demonstrated an approximately 43% better performance than conventional epoxy for the same glue line thickness. The same investigation also revealed that a 1 mm glue line thickness was optimal for both epoxy and toughened epoxy, with improvements of 27% and 24%, respectively, compared to the less favourable 2 mm glue line thickness. For PUR, however, a 0.5 mm glue line thickness outperformed both the 1 mm and 2 mm thicknesses by about 28%, with minimal difference encountered between the two thicker glue lines. Additionally, the investigation found no statistical difference between the two cutting methods, indicating that both methods were equally adequate.

Furthermore, the study by Kemmsies [18] highlighted that epoxy adhesives are more brittle, with failures occurring due to adhesion problems at the steel plate–glue interface. In Kemmsies' study [18], failure in the samples manufactured with PUR adhesives developed at the wood–glue interface due to CO₂ bubble entrapment [18]. While Kemmsies [18] and

Feligioni et al. [79] have suggested that glue line thickness is a crucial parameter affecting shear performance, another study indicates that it has no significant impact [80].

Exploring alternatives to mechanical fasteners, Nabati et al. [58] investigated the impact of epoxy resin on enhancing the flexural response of sandwich beams with a steel core, utilising various combinations and configurations of timber, steel plates, and CFRP. The study revealed the exceptional performance of the epoxy resin, which maintained strong adhesion without any observed slippage between the layers, with the failure modes described as the “longitudinal destruction” of the timber. Complementing this, Kawecki [56] studied the structural performances of adhesives in timber–steel hybridisation by comparing traditional bolted connections to those enhanced with adhesives (1C PUR or PVAc) by applying a tightening torque of 4 Nm to the bolts as the clamping pressure. The use of adhesives resulted in a 2.365% (24-fold) increase in the stiffness and 14.4% and 27.1% increases in the connection capacities for the PUR and PVAc, respectively, under tensile loading. These findings collectively highlight the significant benefits of incorporating adhesives in timber–steel hybrid connections, demonstrating moderate improvements in the load-carrying capacity but significant improvement in the stiffness.

Recently, Haase et al. [51] compared different techniques for bonding timber and steel, aimed at identifying the most efficient ones. The study primarily examined the efficacy of adhesive bonds (epoxy and PUR), dowel-type fasteners, and punched metal plate fasteners (PMPFs) using small-scale specimens, as depicted in Figure 3. The results mirrored those of Kawecki [56], as discussed in the previous paragraph, showing that the adhesive-bonded specimens exhibited high stiffness but brittle behaviour, with the adhesive enabling shear failure to occur in the timber itself rather than at the glue line. Haase et al. [51] found that adhesive bonds were 93 times stiffer than dowel-type fasteners and 5.5 times stiffer than PMPFs. Additionally, the load-carrying capacity of the adhesive bonds increased by approximately 80% compared to that of dowel fasteners and by 30% compared to that of PMPFs, confirming their superior short-term mechanical performance in timber–steel hybrid sections. Haase et al. [51] concluded that combining adhesive bonding and PMPFs, due to their high load capacity and joint stiffness, offers a promising solution for use in composite beams.

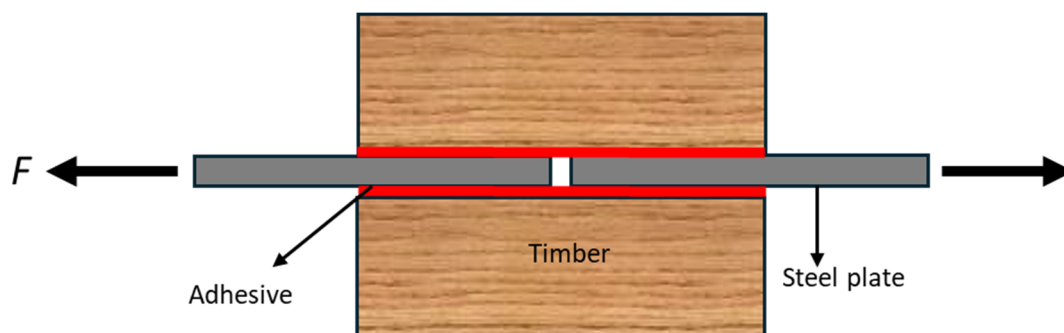


Figure 3. Timber–steel bonding test setup (adapted from Haase et al. [51]).

Using a similar approach to that of the two studies [51,56] described above, which investigated different manufacturing solutions for bonding steel and timber elements, Gilbert et al. [81] experimentally tested various timber–steel hybrid assembly solutions and analytically compared the resulting composite actions on a simply supported hybrid beam. Different connection types, as shown in Figure 4, were proposed and tested in shear, using LVL and 5 mm thick steel plates: embedding a steel plate within the timber with PUR adhesive (Type 1) or heavy-duty screws (Type 2), and connecting the steel to the surface of the timber with PUR adhesive and self-tapping screws (Type 3) or screws

alone (Type 4). The results demonstrated that connections using the PUR adhesive enabled near-to-full composite action, with failure occurring in the timber, similar to the findings of Kawecki [56]. In contrast, connections relying solely on screws did not achieve full composite action, demonstrating a significantly lower shear capacity and less effective bending stiffness. The manufacturing of an unrealistically high number of screws was found to be needed to obtain steel–timber hybrid beams with near-to-full composite action.

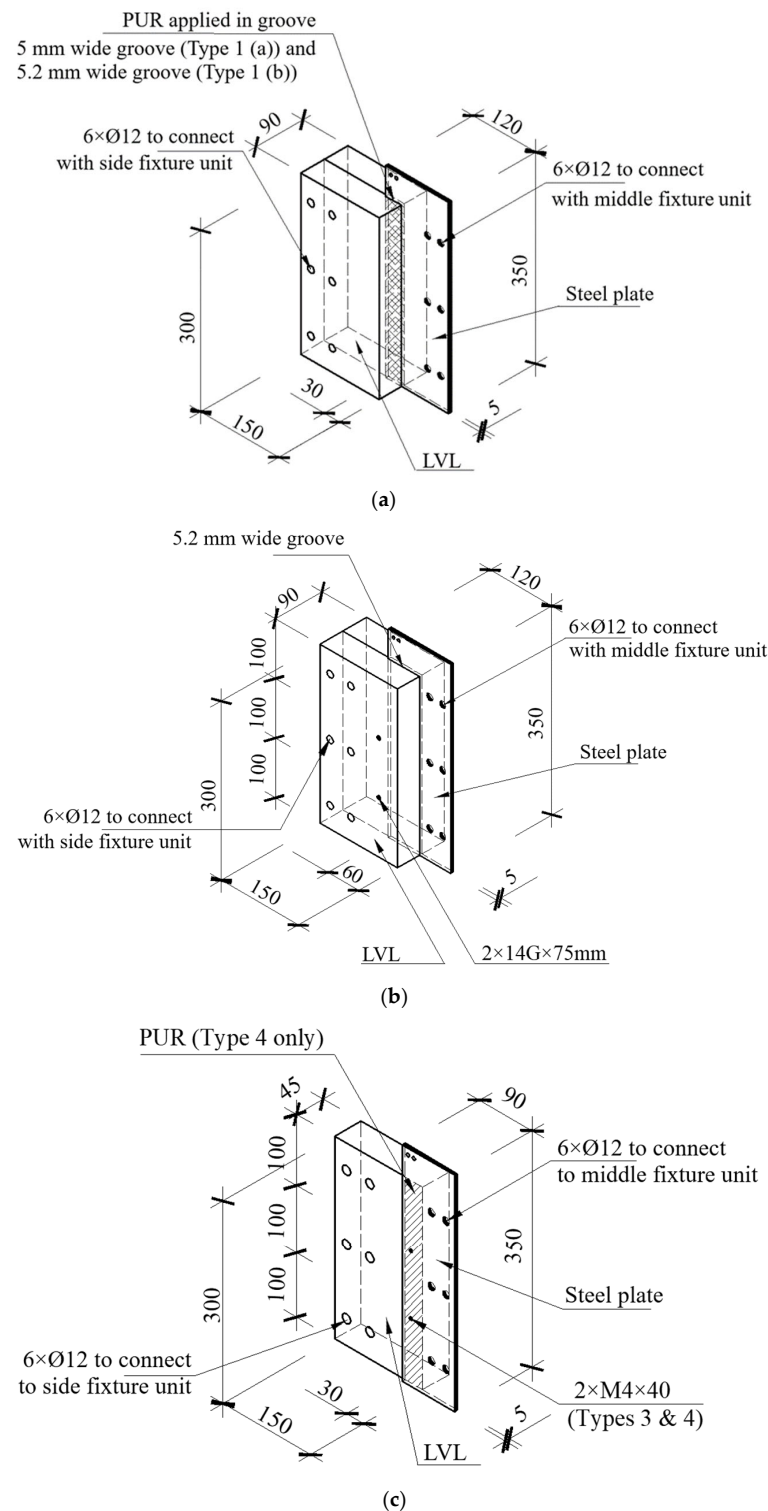


Figure 4. Timber–steel hybrid connections: (a) Type 1; (b) Type 2; (c) Types 3 and 4 (from Gilbert et al. [81]) (all units in mm).

The superiority of the glue in bonding timber and steel has also been highlighted by Hassanieh et al. [82], with glued connections exhibiting 50% higher strength and 75% greater stiffness compared to mechanical connectors. This was established through push-out tests, which revealed that while adhesive-based joints offer substantial performance benefits, the adhesive-bonded connections showed significantly less ductile behaviour than the connections using metal fasteners, such as screws or dowels. This may lead to catastrophic brittle failure and the reduced potential for load redistribution after the initial damage occurs.

In addition to these behavioural limitations, adhesive-bonded connections can also hinder disassembly and may pose challenges during on-site construction. Unlike mechanical fasteners, which can typically be removed and reinstalled, glued joints are not easily reversible. This limits the potential for deconstruction, reuse, or recycling at the end of a building's service life. These considerations are increasingly important for achieving sustainable and adaptable structural systems.

2.5. Concluding Remarks

Studies on the short-term structural performances of adhesives in timber–steel hybridisation have highlighted the high strength, with failure developing in the timber but not at the glue line, and high stiffness, allowing near-to-full composite action to develop. When selecting adhesives and designing hybrid structures, one should consider the following key points:

- **Adhesive selection:** Both epoxy and PUR adhesives show strong adhesion between steel and timber. PUR adhesives have been noted for their ductility and usually superior performance in overall strength when gluing timber to steel. However, due to its versatility, epoxy has some manufacturing advantages and still provides good bonds between the two materials. Notably, both adhesive bonds typically fail within the timber rather than at the glue line, showcasing their effectiveness at creating strong composite action between different materials.
- **Surface preparation:** The optimal surface treatment method depends on the material and application. Shot blasting has been shown to be particularly effective for steel, as it thoroughly cleans and roughens surfaces, significantly enhancing adhesion. While laser and plasma treatments also offer substantial improvements, shot blasting was found in the literature to be a more aggressive abrasion method with better results. For timber, mechanical abrasion with or without chemical treatments, such as priming, would enhance adhesion by improving the surface texture and chemistry. The choice of treatment should be tailored to the specific needs and bonding requirements of the materials involved.
- **Adhesive application:** For polyurethane (PUR), a thinner glue line of approximately 0.5 mm was found to be more effective, whereas for epoxy, a slightly thicker line of around 1 mm was reported to enhance performance.
- **Disassembly and end-of-life reuse:** While adhesive bonding offers several advantages, it can hinder disassembly during construction, maintenance, or future modifications, as bonded joints are much more difficult to separate than mechanical fasteners. This also presents challenges at the end-of-life stage of a building, where recycling or repurposing hybrid structural products bonded with adhesive may be limited compared to mechanically fastened components, which are generally easier to remove and reuse.

3. Mechanical Fasteners

3.1. General

Connecting timber elements through mechanical fasteners has been employed in carpentry for centuries, ensuring the effective transmission of forces between structural elements [51]. Unlike adhesives, which rely on chemical bonding, mechanical fasteners secure components through mechanical interlocking. This allows for immediate assembly and potential disassembly, such as with bolts that fit into pre-drilled, slightly oversized holes to enhance construction flexibility [83,84]. Other common fastener types include nails, screws, and dowels.

Bolt-type mechanical fasteners first appeared in the 15th century (although threaded fasteners came earlier in the form of wood screws) and became more commonplace during the Industrial Revolution [85]. While adhesives are primarily used in the manufacturing process to create EWP, fasteners play an important role in securing EWPs together during construction [86–89].

In modern applications, mechanical fasteners are also used to connect different structural materials, such as timber and concrete [90–92] or timber and steel [51,56,93], to form hybrid structural components.

3.2. Major Types of Mechanical Fasteners Used in Timber–Steel Hybridisation

In the literature, bolts and screws are the most common types of fasteners used in timber–steel hybridisation, securing timber and steel elements together [16,82,94–104]. Note that due to their small diameters and low withdrawal capacity, nails would be rather inefficient in creating composite action for hybrid structural elements. Dowels would only be efficient for embedded plates (i.e., positioned inside the timber) and not for outside-connected steel plates. A bolted connection is made of a bolt consisting of a threaded fastener with a head and a nut on the other end, typically installed with washers [105]. Screws are similar but do not require a separate nut, as they form their own threads in the material they are driven into [106]. These fasteners are available in a range of sizes, typically measured by diameter and length, with the ISO metric sizing representing one of the commonly used systems for standardisation purposes [107–110] in many countries.

3.3. Structural Performances of Mechanical Fasteners in Timber–Steel Hybrid Components

The use of mechanical fasteners in timber–steel hybridisation has been explored in the literature, highlighting their efficacy in terms of the load-carrying capacity and stiffness of connections. To further enhance these properties, some researchers have investigated the use of nail plates [21,82] and toothed plates [111], depicted in Figures 5a and 5b, respectively, in conjunction with bolts or screws. Nail plates, when placed around the screw or bolt hole, have been shown to significantly enhance the load-carrying capacity and stiffness of connections. For instance, Hassanieh et al. [82] conducted push-out tests on steel–CLT composite joints, examining the load–slip behaviour and failure modes of three types of steel–timber composite connections: high-strength bolts, coach screws, and a combination of adhesive and coach screws, with the adhesive results detailed in Section 2.4. The tests revealed that installing nail plates around the screw holes could enhance the connection load capacity by at least 28% and the stiffness by 70% to 226%. However, while nail plates did not alter the failure mode of screwed joints, they reduced the joint ductility. Hassanieh et al.'s [21] research supported these findings. Their study demonstrated that while nail plates improved the stiffness of screwed connections, their impact on the peak load capacity of steel timber composite beams was less. Conversely, toothed plates were observed by Chybiński et al. [111] to only enhance the load-carrying capacity without improving the stiffness. Their work demonstrated this finding by showing that the use of toothed plates in

aluminium-to-LVL beam connections resulted in up to a 35% increase in the load-carrying capacity but had no effect on the stiffness.

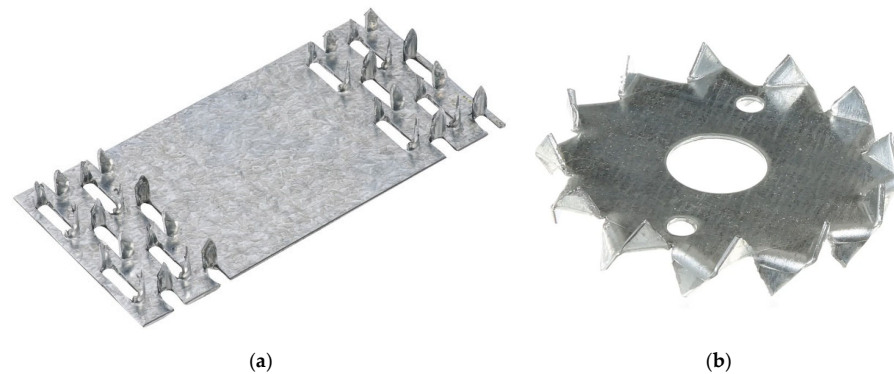


Figure 5. (a) Nail plate; (b) toothed plate.

In steel–timber composite connections, the development of plastic hinges in the fasteners enhances the connection ductility. The greater the number of plastic hinges, the higher the connection strength [112,113]. To ensure the formation of double plastic hinges in the mechanical fasteners and thereby increase the connection ductility and peak load capacity, Zhao et al. [114] and Wang et al. [115] proposed anchoring the screw with mortar or adhesive. Zhao et al. [114] conducted a four-point bending test to investigate the efficacy of using mortar and epoxy resin as filler materials to increase the anchorage of screw tips connecting steel I-beams and Douglas fir GLT. These filler materials replaced the timber around the screw tip. Their approach proved effective, as double plastic hinges were formed on the screw in both cases, as seen in Figure 6a,b, increasing the slip stiffness by 48.4% and 18.8% for the mortar and epoxy, respectively, compared to screw connections without anchorage (Figure 6c). Wang et al. [115], through push-out tests, used a fast-curing epoxy resin to increase the anchorage of composite floors composed of I-steel and timber panels. The epoxy resin was found to increase the initial shear stiffness and capacity by 60.0% and 22.8%, respectively, compared to ordinary screwed connections. This concept of anchoring screw tips with filler material to improve the performance was also demonstrated by Zhao et al. [116], where grout was used to anchor the screw tip connecting GLT and I-steel, resulting in increases of 25.2%, 55.9%, and 33.6% in the peak load, initial stiffness, and ductility, respectively. These findings underscore the importance of designing the connection so that the plastic hinge(s) can develop for an enhanced performance in steel–timber composite connections.

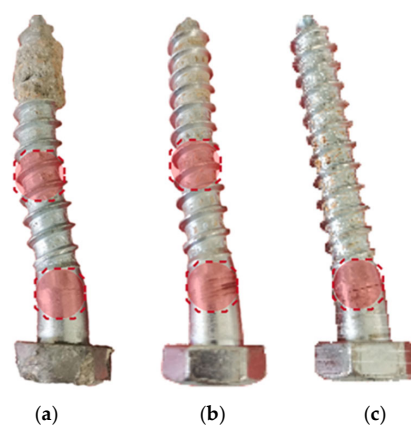


Figure 6. Plastic hinges on screws anchored at the tip with (a) mortar, (b) epoxy, and (c) no anchorage (from Zhao et al. [114]).

As described in Section 2.4, it has been recognised that adhesives provide higher stiffness in connections compared to mechanical fasteners inserted at 90 degrees. However, the stiffness of connections with fasteners can be improved by inserting screws at an angle. Wang et al. [104] highlighted this importance by joining timber and steel with inclined self-tapping screws. Their study examined the load–slip behaviour and failure modes for screws of different sizes inserted at different inclinations (0° , 30° , and 45°) into CLT. The study observed 12% and 28% increases in the shear capacity for the screws at 30° and 45° , respectively. Regarding the stiffness, it increased by 71% and 47%, respectively, for the screws inclined at 30° and 45° . To obtain these improvements in performance in Wang et al. [104], the screws were best used with tapered washers. Santis et al. [117] argue that the mechanical advantage of inclined screws is that the load is resisted axially, allowing them to engage more effectively under the load, and surpassing that of connections with purely transversely loaded fasteners loaded in shear and bending. Along this line, Romero et al. [118] conducted an experimental assessment of novel shear connections for demountable timber–steel composite beams through push-out tests, focusing on three different connection designs: one using a round steel plate, another featuring a Geka-type connector, and a third incorporating a rectangular steel plate with inclined screws at a 60° angle for added reinforcement. The results revealed that the design with the rectangular steel plate and inclined screws outperformed the other two in terms of stiffness (by up to 43.3%) and ductility (by up to 25.6%).

While the use of inclined screws seems important to improve the composite action in steel–timber composite beams, the utilisation of longer screws increases the embedded depth in timber, resulting in higher withdrawal resistance [104]. Wang et al. [104] also outlined the importance of selecting screws with sufficiently long, smooth shanks. Such a design consideration ensures that the transition from the smooth shank to the threaded part of the screw occurs away from the steel–timber shear plane, thereby mitigating the risk of shear failure.

Although mechanical fasteners offer simplicity and versatility, their application in timber–steel hybrid structures can present challenges. Traditional fasteners, through boring, may damage the timber components and create localised stress concentrations [18]. Issues such as free slip due to clearance gaps and the influence of the hole size on installation can affect the connection stiffness and integrity and must be carefully managed [99]. As highlighted by Li et al. [119], clearance gaps in drilled bolt holes can lead to reduced rotational stiffness and an insufficient moment-resisting capacity. Screws have the advantage of less slip over bolted connections.

3.4. Concluding Remarks

Studies on mechanical fasteners in timber–steel hybridisation have highlighted their distinct advantages over adhesives, particularly in terms of their ease of assembly and disassembly. While adhesives result in high stiffness between the steel and timber materials, greater than for mechanical fasteners, as seen in Section 2, the stiffness for mechanical fasteners can be improved through the use of inclined screws, potential anchorage at the screw tip, or the use of metal plate fasteners. When selecting mechanical fasteners for connections in timber–steel hybrid structures, the following key aspects should be considered:

- **Improved performance with inclined screws:** Research indicates that screws inclined at angles from 30° to 60° offer enhancements in the shear capacity and stiffness compared to screws inserted at 90° . The use of tapered washers with inclined screws further boosts these benefits.
- **Advantages of longer screws:** Utilising longer screws increases the embedded depth in the timber, which enhances the withdrawal capacity of the screws and potentially

the timber–steel hybrid connections, depending on the failure mode. Additionally, selecting screws with sufficiently long, smooth shanks is important. This design feature ensures that the transition from the smooth shank to the threaded shank occurs away from the shear plane.

- **Enhanced performance through anchorage techniques:** Integrating anchorage methods, such as using mortar or adhesive to secure screw tips, has been shown to enhance the overall performance of timber–steel hybrid connections. These techniques contribute to improved connection stiffness, peak load capacity, and ductility.
- **Utilisation of metal plates:** Metal plates, including nail plates and toothed plates, can potentially enhance the connection performance in timber–steel hybrid structures. Nail plates, with their embedded nails or spikes, are effective at increasing both the load-carrying capacity and stiffness, though they may reduce ductility. Conversely, toothed plates, featuring teeth designed to interlock with timber, have shown potential for improving the load-carrying capacity, though their impact on stiffness is less certain based on the current research.

4. Timber–Steel Hybrid Configurations for Composite Beams

4.1. General

As mentioned in the Introduction, in timber–steel hybridisation, timber and steel are combined, with the weakness of the one material being compensated by the strength of the other, to enhance the structural performance of the overall section, and tailoring the composite element to meet the engineering design requirements. This hybrid approach takes advantage of timber’s high strength-to-weight ratio and pairs it with the high strength, stiffness, and ductility of steel. Steel, being approximately 17.5 times stiffer than timber, reinforces the timber, contributing to a balanced and effective structural design [4,5,7].

In a beam, steel can be positioned in the tension zone, where it can assist in delaying the brittle failure mode of timber in tension, increasing the overall stiffness, providing ductility, and resisting tensile forces [21,27,33,34,38]. In other configurations, steel can be added in the compression zone to enhance the overall stiffness, the bearing capacity under point loads, and the fire performance of the composite element [5,29,30,34,120–122]. When steel is used on the sides of the timber, it provides balanced reinforcement that improves the stiffness and lateral stability [33,34]. Furthermore, steel components may be embedded within the timber, creating a composite section with improved structural and fire performances [6,34,123–125]. Examples of popularly adopted reinforcement configurations are depicted in Figure 7.

In reference to the discussions in the following sub-sections, the advantages and disadvantages of different types of reinforcement are summarised in Table 1.

Table 1. Advantages and disadvantages of different locations of reinforcement in timber–steel hybrid beams.

Reinforcement Location	Advantages	Disadvantages
Top Reinforcement	- Improves the bearing capacity under concentrated loads, as well as the bending stiffness, bending strength, and fire resistance. - Suitable for preserving the aesthetics of heritage buildings.	- Strengthens the ductile compression zone of the timber material, not utilising steel ductility for the brittle tension zone of the timber material. - Shifts the neutral axis towards the compression zone, potentially leading to brittle tensile failure in timber.
Bottom Reinforcement	- Improves the bending stiffness, bending strength, and potentially ductility. - Delays brittle failure in the tension zone of the timber material.	- Exposed steel can be vulnerable to fire unless adequately protected with coatings, for instance. - May alter the original aesthetics of heritage buildings.

Table 1. Cont.

Reinforcement Location	Advantages	Disadvantages
Side Reinforcement	- Increases the lateral stability and shear capacity. - Balances the stress profile across the beam.	- Less efficient for increasing the bending stiffness and bending strength compared to top and bottom reinforcement. - Structural benefits may not be as pronounced as in other configurations.
Embedded Reinforcement	- Offers improved fire protection and thermal insulation of the embedded steel. - Integrates steel components within the timber beam, preserving the aesthetic integrity, such as in the restoration of heritage buildings.	- More complex manufacturing process due to the need for integrating steel into timber. - Potential complications in repair and maintenance if embedded components are damaged.



Figure 7. Examples of steel–timber hybrid reinforcement configurations: (a) top flat plate; (b) top U-shaped; (c) top Y-shaped; (d) embedded top; (e) bottom flat plate; (f) bottom U-shaped; (g) embedded bottom; (h) side flat plates; (i) embedded sides; (j) C-shaped sides; (k) embedded middle; (l) embedded I-shape; (m) combined top and bottom flat plates; (n) combined top and bottom U-shaped; (o) combined top, bottom, and embedded; (p) combined top bottom and sides.

4.2. Comments on the Fire Performance and Thermal Insulation

In timber–steel hybrid structures, timber offers notable fire resistance and energy efficiency benefits, largely attributed to its inherent thermal insulation properties. Its cellular structure effectively traps air, which reduces heat transfer, while its relatively low thermal conductivity, particularly in the longitudinal direction, further supports its temperature-regulating capabilities across various climates [3,126,127]. When exposed to fire, timber forms a protective char layer that serves as a natural thermal barrier, insulating any embedded steel components and slowing down the rate of heat transfer. This characteristic helps to prolong the structural integrity of the hybrid element during fire events [38,128,129].

Studies, such as those conducted by Le et al. [130], have highlighted the importance of this protective char layer, recommending that encasing steel with approximately 15–16 mm of timber can ensure at least one hour of fire resistance. Embedding steel within timber not only protects the steel itself but also shields the adhesives used in bonding the two materials (if bonded), helping to reduce the risk of delamination under fire exposure [131]. The use of top reinforcement is particularly beneficial in this regard, as the timber below shields the steel from direct fire exposure, improving the fire resistance of the hybrid beam. Furthermore, covering timber–steel connections, including mechanical fasteners, with timber improves fire protection and reduces the risk of fastener failure at high temperatures [132,133].

In cases where the steel cannot be embedded or insulated with timber, studies have suggested coating the exposed steel with intumescent, a fire protection coating that expands significantly when exposed to high temperatures, forming an insulating char layer [134]. For instance, a study by Malaska [35] examined the effect of fire on an exposed steel section acting as bottom reinforcement in a slim-floor-type timber–steel hybrid system. In the study, the steel was coated with intumescent material, and the results revealed that the intumescent fire protection significantly reduced the steel temperatures and charring depths.

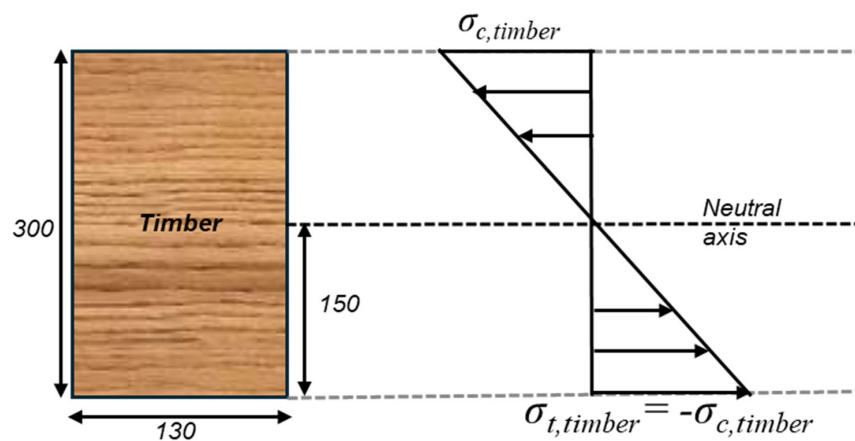
4.3. Structural Performances and Other Advantages of Various Timber–Steel Hybrid Configurations

4.3.1. Top Reinforcement (Compressive Zone)

Top reinforcement in timber–steel hybrid systems typically involves the addition of steel plates or channels, for instance, to the upper surface of timber beams, loaded in compression, as depicted in Figure 7a–d. This configuration is primarily designed to enhance the bearing capacity under a concentrated load at the top of the beam, as well as the bending stiffness, bending strength, and fire resistance of the composite beam (see Section 4.2). Moreover, the discreet placement of the reinforcement makes it especially suitable for reinforcing heritage or historic buildings, as it preserves the original aesthetics and appearance of the structure, ensuring that the visual and architectural character are conserved [131,135,136].

However, top reinforcement primarily strengthens the ductile compression zone of the timber rather than takes advantage of the ductility of the steel to reinforce the more brittle tension zone of the timber material [137]. Additionally, this reinforcement shifts the neutral axis toward the compression side, thereby increasing the maximum tensile stress in the timber relative to its maximum compressive stress. Using the Euler–Bernoulli theory and a perfect composite action between steel and timber, and assuming moduli of elasticity for steel and timber of 210,000 MPa and 12,000 MPa, respectively, Figures 8a and 8b plot the stress distribution for an illustrative example of a 300 mm deep $\times$ 130 mm wide timber beams unreinforced and reinforced with a 10 mm thick steel plate at the top, respectively. The bending stiffness of the composite beam and the stress values under an arbitrary bending moment of 100 kNm are also presented in the figure. In the example, the steel

plate significantly increases the bending stiffness of the timber beam by a factor of 2.2. In the top reinforced beam (Figure 8b), due to the shift in the neutral axis, the maximum tensile stress in the timber ($\sigma_{t,timber}$) is 2.23 times greater than the maximum compressive stress in the timber ($\sigma_{c,timber}$). Additionally, when compared to the unreinforced beam, the maximum compressive and tensile stresses in the timber of the reinforced beam are 3.5 times and only 1.6 times lower, respectively. These values illustrate both the influence of the steel in reducing these stresses and unbalancing the tensile and compressive stresses. If the steel grade is high enough, the steel will not yield before brittle failure develops in the timber, leading to no or little ductility of the composite beam [137]. To maintain some level of ductility, it is essential for the designer to carefully select the steel cross-sectional dimensions and yield stress to ensure that the steel yields before tensile failure occurs in the timber.



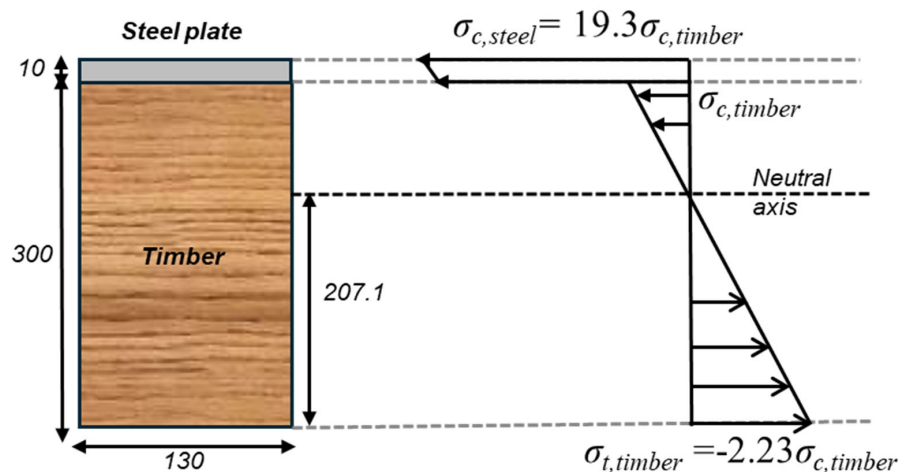
Bending stiffness = 3510 kNm²

Under a 100 kNm moment:

$\sigma_{c,timber} = -51.3$ MPa

$\sigma_{t,timber} = 51.3$ MPa

(a)



Bending stiffness = 7660 kNm²

Under a 100 kNm moment:

$\sigma_{c,timber} = -14.6$ MPa

$\sigma_{t,timber} = 32.6$ MPa

$\sigma_{c,steel} = -281.8$ MPa

(b)

Figure 8. Cont.

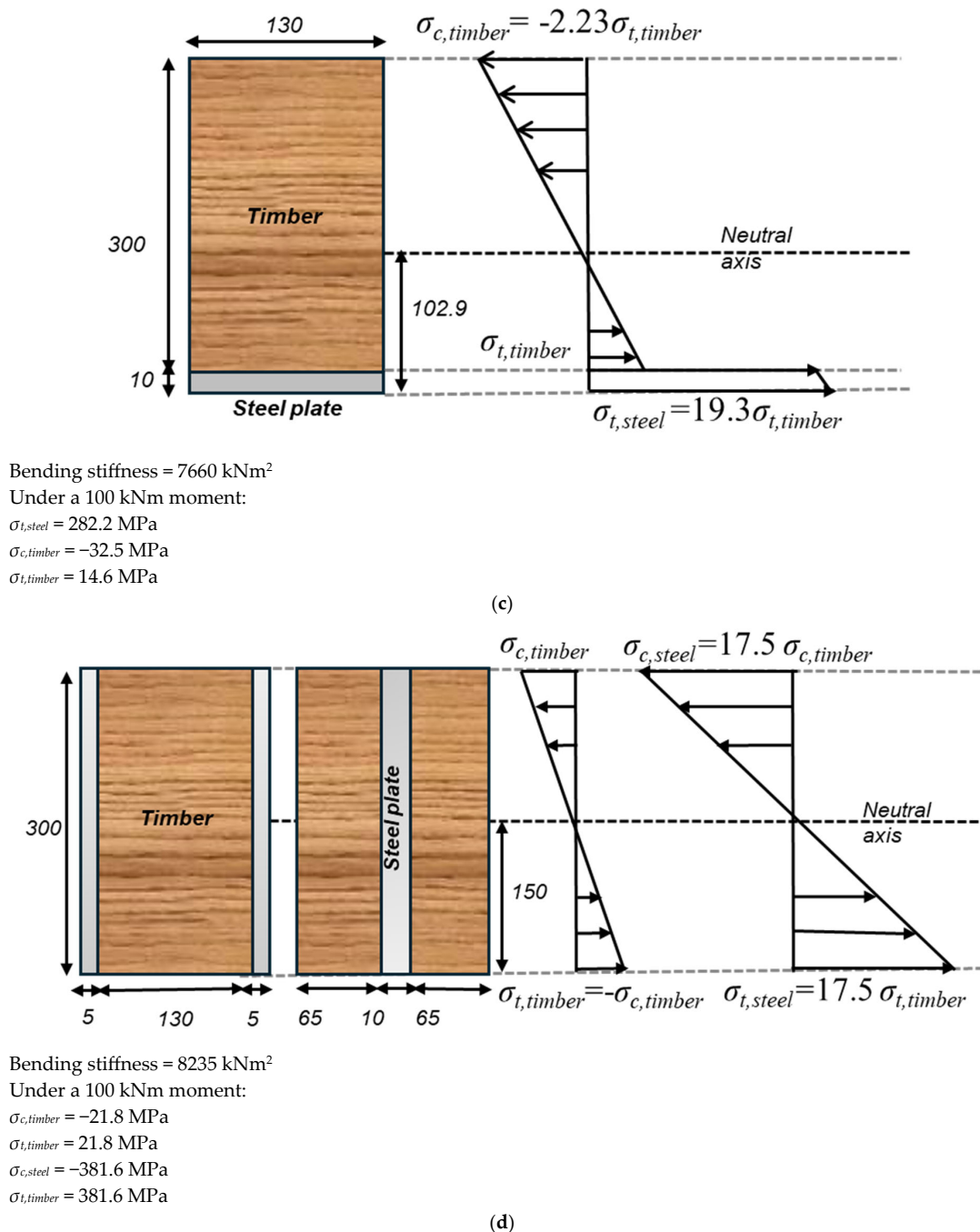


Figure 8. Stress distributions and bending stiffnesses of timber beams: (a) unreinforced; (b) reinforced at the top; (c) reinforced at the bottom; (d) reinforced on the sides and embedded only, not at the top and bottom (all units in mm).

Studies have investigated the performance of top reinforcement in timber beams. For instance, a study by Jasienko et al. [34] explored the impacts of various steel plate reinforcement configurations, similar to those depicted in Figure 7a,e,h,i, on the bending capacity and stiffness of solid timber beams. The results showed that reinforcing the top of the 200 mm deep beam with a 4 mm thick steel plate led to up to a 58.7% increase in the bending capacity and up to a 31% improvement in the stiffness compared to unreinforced specimens. Aside from using flat steel plates for the top reinforcement, U-shaped steel cross sections (Figure 7b,f) have also been found to increase the stiffness and bending capacity of timber beams. This was demonstrated in a study by Bravo et al. [30], where the hybridisation of timber beams made from either spruce GLT, sawn Scots pine (*Pinus*

sylvestris), or solid pine beams with U-shaped steel cross sections screwed to the timber resulted in increases in the bending capacity of 27–58% and stiffness improvements of 45–98%. While the U-shaped steel section used by Bravo et al. [30] faced with the flanges upwards, i.e., away from the timber element, Ghanbari et al. [29] employed a U-shaped steel section facing downward (Figure 7b), almost like a cap. Notably, in Ghanbari et al.'s [29] study, the specimen with top steel reinforcement was also reinforced at the bottom using composite fibre-reinforced polymer (CFRP). This innovative configuration, as described in their study, combined steel and CFRP to reinforce machine-graded pine (MGP10 in AS 1720.1 [138]), leading to 373% and 294% increases in the bending strength and stiffness, respectively. One of the advantages of U-shaped sections over flat plates in reinforcing timber beams is that, for the same overall depth, more material is positioned away from the neutral axis, which, in turn, enhances the beams' flexural capacity. More studies and more detailed outcomes on top reinforcement can be found in Table 2.

4.3.2. Bottom Reinforcement (Tension Zone)

Reinforcement at the bottom of timber beams is typically achieved by attaching or embedding either a steel plate, a channel, or another cross-sectional shape to the underside of the timber beam, as depicted in Figure 7e–g. This configuration has the advantage of improving the following key structural performance criteria: increasing the bending stiffness, enhancing the bending strength, and demonstrating the high potential to improve the ductility [21,27,33,34,38]. Bottom reinforcement overcomes the brittle nature of timber in tension by placing a stiff and ductile material in the tension zone. The neutral axis of the beam is then shifted towards the tension side influencing the stress distribution within the beam. To further illustrate this and demonstrate their similarity to the top reinforcement assumptions, the bending stiffness and stress pattern for the 300 mm deep timber beam reinforced at the bottom by a 10 mm thick steel plate are shown in Figure 8c. The same comments as for the top reinforcement can be drawn but with the stress pattern reversed, i.e., with the maximum compressive stress in the timber now being 2.23 times greater than the maximum tensile stress. This helps delay the onset of brittle failure in the timber. The stress pattern shows that if designed so that yielding develops in the steel (for instance, in the case in Figure 8c, with a steel yield stress (f_y) = 250 MPa, which would typically lead to the yielding of the steel before the tensile stress in the timber is reached), combined with the ductile behaviour of the timber in compression, the incorporation of steel has significant potential to enhance the overall ductility of the beam [137].

One potential limitation of bottom reinforcement is that the steel could experience high temperatures when subjected to fire as the heat rises, leading to the faster degradation of its mechanical properties, and could therefore be vulnerable to fire [36]. This would require the steel to be embedded, hidden, or coated with intumescent for adequate fire protection, as discussed in Section 4.2.

Studies have highlighted the performance of this configuration. For instance, bottom reinforcing a timber beam with a steel plate similar to the depiction in Figure 7e has been shown to increase the bending capacity and stiffness by up to 41.2% and 20%, respectively, according to Jasieńko et al. [34]. Beyond enhancing the structural performances of individual beams, bottom reinforcement has proven effective at connecting shorter timber elements to form longer structural components. For instance, shorter GLT timber beams were successfully connected and reinforced using a system of splices, steel rods, and steel shear keys [27], similar to Figure 9. This innovative approach, as described by Wang et al. [27], allows for the prefabrication of smaller timber elements and steel devices at a low cost, which can be easily assembled on site to create longer structural elements. Furthermore, this system has demonstrated the potential for retrofitting existing timber

elements, enhancing their strength, stiffness, and ductility. In the study, three types of specimens were tested: a full simple GLT beam (unreinforced), a joint hybrid GLT beam using splices to connect sections of the GLT, and a full hybrid GLT beam without any joining. Timber beams connected and hybridised using splices and steel rods at the bottom exhibited a 20% increase in stiffness compared to the simple GLT beam (i.e., without any joining or reinforcement). In contrast, hybrid beams with a full timber section (i.e., not assembled from shorter elements) demonstrated up to a 60% increase in stiffness over the unreinforced beams.

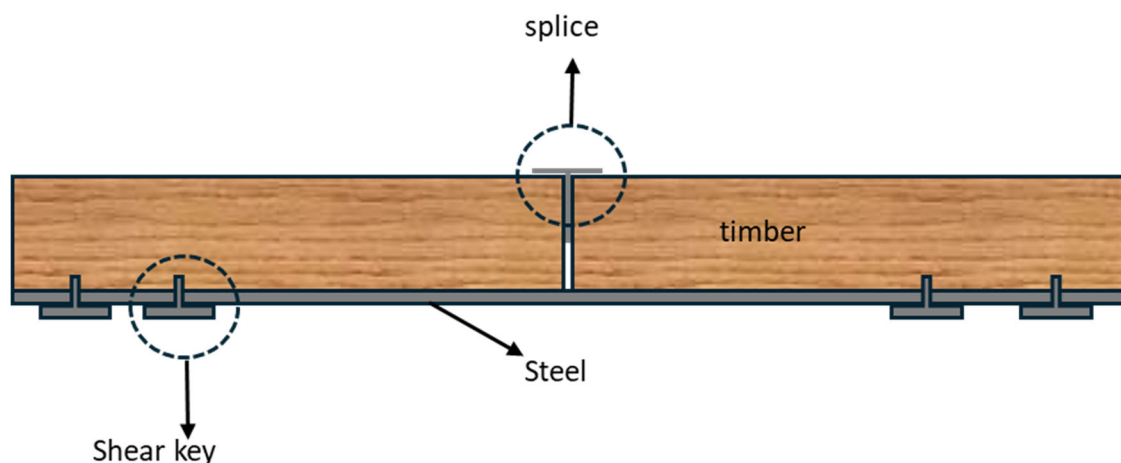


Figure 9. Joining GLT timber elements using steel rods, splice, and shear key (adapted from Wang et al. [27]).

Similar to top reinforcement configurations, the use of U-shaped steel sections for the bottom reinforcement of timber elements has also been explored by Ghanbari et al. [29]. Their study on MGP10 beams [138] showed that reinforcing the bottom with a 2 mm thick U-shaped steel section increased the bending strength and stiffness by 123% and 202%, respectively. The U-shaped steel reinforcement not only delayed the typical brittle failure of solid timber beams but also enhanced the overall structural performance by allowing for higher ductility. The reinforced beam failed at a deformation of approximately 4.0 times the elastic deformation, compared to about 1.5 times for the unreinforced beam. More studies and detailed outcomes on bottom reinforcement can be found in Table 2.

4.3.3. Side Reinforcement

Steel reinforcement on the sides of timber beams typically involves attaching steel plates or channels vertically along the beam's sides, as depicted in Figure 7h–j. While less commonly used than other reinforcement methods, side reinforcement offers distinct advantages. It significantly improves the lateral stability, increases the shear capacity, and balances the stress profile across the beam [139]. To further illustrate this, Figure 8d provides the stress pattern and bending stiffness of the 300 mm deep timber beam reinforced with 2×5 mm thick steel plates on its sides. The bending stiffness is just 1.08 times higher than when the beam was reinforced either at the top or bottom while using 2.3 times the amount of steel. When compared to the unreinforced beam, the maximum stresses in the timber decreased by a factor of 2.4. The maximum stress in the steel is 1.4 higher than that for either the top or bottom reinforcement, reflecting some inefficiency in the use of the material.

Side reinforcement has been shown to increase both the bending capacity and stiffness. For example, Jasienko et al. [34] investigated the use of steel plates to reinforce solid timber beams by applying the plates to the sides. This side reinforcement resulted in a

91.3% increase in the bending capacity and a 62% improvement in the stiffness compared to unreinforced beams, significantly enhancing their structural performance. Another study that examines the impact of side reinforcement is the work by Gomez et al. [33]. However, unlike traditional steel plate reinforcement, metallic fibre meshes were used in this case. The side reinforcement was found to significantly enhance both the flexural and shear capacities, with the flexural capacity increasing from 65 MPa to 91.2 MPa, a 40.9% improvement, and the shear capacity rising from 4.9 MPa to 6.8 MPa, marking a 38.8% increase. These findings demonstrate the potential of metallic fibre meshes as an alternative for boosting the structural performance of timber beams, particularly in enhancing their load-bearing capacities. However, this exposed side reinforcement may not be suitable for heritage rejuvenation projects where aesthetics is paramount, as the visible steel plates could compromise the historical appearance of the structure. More studies and detailed outcomes on side reinforcement are highlighted in Table 2.

4.3.4. Embedded Reinforcement

Embedded reinforcement integrates steel components within the timber beam itself. This approach may include top, bottom, side, middle, or combined configurations (as further discussed in Section 4.3.5), as shown in Figure 7d,g,i,k,l. While embedding the steel may not necessarily affect the strength and stiffness compared to exposed reinforcements (see Figure 8d to illustrate), it offers additional benefits, such as improved fire protection and thermal insulation, thanks to the natural properties of timber [130,140,141], as discussed in Section 4.2. However, embedding steel within timber can involve a more complex manufacturing process, as it requires integrating the steel into the timber structure rather than simply attaching it to the timber surface.

A study conducted by Jasienko et al. [34] found that embedding two steel plates in a timber beam (Figure 7i) led to substantial enhancements in both the bending capacity and stiffness when compared to an unreinforced beam, achieving increases of up to 100% and 51%, respectively. Similar to the idea highlighted by Khorasani et al. [142], Nabati et al. [58] embedded a thin vertical steel plate into a timber beam, as shown in Figure 7k, to assess its flexural response under a four-point bending test. The inclusion of the steel plate led to a 100% increase in the ductility and a 191% increase in the stiffness.

Additionally, and as discussed in Section 4.1, this method of reinforcement also preserves the aesthetic and historical integrity of structures, making it ideal for both new construction and the restoration of heritage buildings. Metelli et al. [131] successfully employed this technique for the non-invasive repair of ancient wooden floors by embedding steel plates into grooves in the timber, secured with epoxy resin and high-strength steel nails. This approach restored the structural performance of the floor, with deflection levels comparable to those of the undamaged floor.

4.3.5. Combined Reinforcement

Beyond the individual reinforcement configurations of top, bottom, side, and embedded, it is important to highlight that the research has also explored combining two or more of these methods [29,34,139,143]. This approach aims to leverage the strengths of each configuration to potentially enhance the overall structural performance, offering a more balanced and effective reinforcement strategy. For instance, a study by Song et al. [144] explored a novel approach of wrapping a timber beam with steel, similar to Figure 7p, effectively combining reinforcement on the top, bottom, and sides to create a timber-filled, steel, tubular composite beam [145]. This design showed significant improvements in structural performance compared to unreinforced timber beams. Specifically, the reinforced beam achieved a maximum load 223% higher than that of the unreinforced timber beam.

Additionally, the bending stiffness of the reinforced beam increased by about 440%. These substantial enhancements highlight the effectiveness of integrating multiple steel reinforcement configurations in improving the structural performance of hybrid timber–steel composite beams.

While the use of U-shaped steel sections for top and bottom reinforcement has been discussed in previous sections, these U-shaped steel cross sections can also be used to reinforce the timber, as depicted in Figure 7j [146]. This has the advantage of combining top, bottom, and side reinforcements. Cold-formed, steel, thin-walled sections were favoured by Karki D [147] for their strength-to-weight ratio, especially in applications where lightweight construction is essential. This approach was also explored by Chen et al. [139], who reinforced a fast-growing radiata pine beam with cold-formed, steel, U-shaped sections positioned on the sides of the beam (as in Figure 7j). While direct comparisons with unreinforced beams were not reported by Chen et al. [139], the study indicated the potential effectiveness of combined reinforcement when combining suitable connection techniques in hybrid timber–steel structures.

Nabati et al. [58] investigated the flexural responses of innovative steel–timber-FRP composite beams, with 18 test specimens created in different configurations and different thicknesses of steel (3 mm and 6 mm) (Figure 7e,f,k,m,o), tested to their ultimate capacity. The results showed that the specimens reinforced with the 6 mm steel web achieved the highest average capacity increase, up to 4.5 times that of the reference specimens, while those with the 3 mm steel web had the second highest strength. Beams reinforced with steel at both the top and bottom, along with a steel web, exhibited the highest stiffness, up to 7 times higher than that of the reference specimens. In terms of ductility, beams with bottom steel reinforcement resulted in higher ductility, the ultimate displacement being 8 to 9.3 times higher than that of the reference specimens. More studies and detailed outcomes on combined reinforcement are highlighted in Table 2.

4.4. Concluding Remarks

Research into the performances of various reinforcement configurations in timber–steel hybrid beams has demonstrated significant improvements in the bending capacity, bending stiffness, fire resistance, and overall structural performance. Each reinforcement method offers distinct benefits, highlighting the importance of selecting the most appropriate strategy based on specific needs and objectives. Key considerations for each approach are outlined below:

- **Top reinforcement (compressive zone):** This configuration increases the load bearing under concentrated load, bending capacity, and bending stiffness. It is also a better option for fire resistance. This configuration is particularly suitable for heritage buildings where aesthetics must be preserved. While it primarily reinforces the ductile compression zone of the beam material, it fails to utilise the strength and ductility of the steel to strengthen the brittle tension zone of the timber. Additionally, this reinforcement shifts the neutral axis toward the compression side, increasing the tensile stress in the timber at the bottom of the beam relative to the compressive stress, and the ductility of the composite beam may be limited. The existing work indicates performance improvements with the configuration, especially with U-shaped steel cross sections.

Table 2. Summary of the literature investigating timber–steel hybrids with different configurations.

References/ Study Title	Authors	Hybridisation Configuration	Testing and Analysis Methodology	Materials Used	Surface Treatment	Results
[34] Solid timber beams strengthened with steel plates—Experimental studies	Jasieńko J, Nowak TP	Timber beams reinforced with steel plates in various configurations, including on the top, bottom, sides, and embedded within	Bending tests	Sawn timber (softwood), steel plates, epoxy adhesive	Steel plates were sandblasted and degreased.	Embedding two steel plates into the beam on the sides provided the best performance, with up to 100% increase in strength and up to 51% increase in stiffness compared to unreinforced beam. For surface reinforcement, top reinforcement was found to limit delamination.
[146] Experimental investigation on the flexural and shear behaviour of LVL I-beam strengthened with steel channels	Wang X, Zhang J, Wu P, Li Y	I-shaped LVL beam strengthened with cold-formed, thin-walled steel channels	Bending tests, shear tests	LVL, cold-formed steel channel, and structural adhesive (unspecified)	Stains and galvanised layer on the bonding surface of the steel were removed and polished with alcohol.	For shear and bending tests, the peak loads for specimens with the largest steel sections, were 1.45 times and 2.9 times higher, respectively, than those with thinner steel sections.
[8] Long—Term testing of timber-steel bar hybrid beams	Kiyoto S, Shioya S	GLT timber reinforced with deformed steel rebar and epoxy resin adhesive at both the top and bottom	Long-term bending creep test	Japanese cedar, deformed steel bar (rebar), epoxy resin adhesive	Unspecified	The hybrid beam had an increase in bending creep stiffness and strength by 3–4 times compared to the timber beam alone.
[30] Bending reinforcement of wooden beams with steel cross-sections	González-Bravo C, Arriaga-Martitegui F, Díez-Barra R.	U-shaped steel cross sections connected to timber from upper side	Bending tests	GLT, sawn timber, old solid timber beams, and U-shaped steel plates	Unspecified	Reinforced beams showed increased bending stiffness (by 45–98%) and strength capacity (by 27–58%).
[131] On the delamination phenomenon in the repair of timber beams with steel plates	Metelli G, Preti M, Giuriani E	Reinforcement of ancient wooden floors with steel plates into a groove	Experimental analysis using Moiré interferometry for stress observation and long-term deflection monitoring over 14 years	Steel plates, epoxy resin, high-strength steel nails	Timber grooves were cleaned and brushed while the steel plates were sandblasted.	Steel reinforcement effectively repaired the beam with deflection increases similar to those of undamaged beams. Delamination occurred at 1.64 times the service load, and deflection rose by 7 mm over 14 years (0.5 mm/year).

Table 2. Cont.

References/ Study Title	Authors	Hybridisation Configuration	Testing and Analysis Methodology	Materials Used	Surface Treatment	Results
[5] Timber-steel hybrid beams for multi-storey buildings: Final report	Winter W, Tavoussi K, Parada FR, Bradley A	I-beam, grade S355, cold-formed or hot-rolled steel, embedded in GLT beams	Bending test	GLT bolted with I-shaped steel	Unspecified	Hybrid beams showed minimal buckling in the steel web and flange. Hot-rolled profiles, while 3% stiffer than cold-formed ones, presented some assembly challenges.
[6] Experimental and analytical study of hybrid steel-timber beams in bending	Jurkiewicz B, Durif S, Bouchair A, Grazide C	Steel I-beam connected to ungraded timber beams with knots and defects, fastened using bolts or screws on the sides of the web	Bending test and numerical modelling	Steel beams, ungraded wood beams, bolts, screws	Unspecified	Wood elements provided lateral support to the steel profile, reducing the local instability and lateral torsional buckling, resulting in an over 80% increase in strength for the studied configurations.
[114] Experimental and finite element analysis of flexural performance of steel-timber composite beams connected by hybrid-anchored screws	Zhao Y, Yuan Y, Wang CL, Meng S	Steel timber composite beams connected by hybrid-anchored screws with different filling materials	Experimental testing, finite element simulation	Hybrid-anchored screws, epoxy resin, mortar	Unspecified	Hybrid-anchored screws effectively improve flexural performance of steel timber composite beams. Mortar increased slip stiffness by 48.4% and capacity by 15.1%. Epoxy improved stiffness by 18.8% and capacity by 10.1%.
[103] Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms	Loss C, Frangi A	Steel placed in hybrid floor diaphragms with CLT panels	Monotonic and cyclic shear tests	Steel, timber, bolts, screws	Unspecified	Shear stiffness increased by up to 56%. Residual displacement was reduced from 9.4 mm to 2.0 mm.

- **Bottom reinforcement (tension zone):** This configuration enhances the structural performance by directly addressing the brittle nature of the timber material in tension. By shifting the neutral axis toward the tension side, it reduces the tensile stress in the timber relative to the compressive stress and delays brittle failure. This also has the potential to improve the ductility if the beam is designed for the steel to yield. The use of bottom reinforcement has been shown to increase bending stiffness and strength. However, considerations regarding the exposure of steel to heat generated by fire remain essential. While intumescent coatings offer effective protection, designers must remain vigilant about the implications of this reinforcement approach on the overall structural integrity and aesthetics, especially in heritage applications.
- **Side reinforcement:** The incorporation of vertical steel plates for rectangular beams enhances the structural performance by improving the lateral stability and shear capacity. This configuration balances the stress profile across the beam. However, side reinforcement is not the most efficient way of using steel for increasing the bending stiffness and capacity, as the placement of steel near the neutral axis does not fully optimise the material location.
- **Embedded reinforcement:** This approach enhances the fire protection and overall performance by integrating steel components within the timber beam. The insulating properties of timber shield the embedded steel from heat, helping to maintain the structural integrity during fire exposure. While this method preserves the aesthetic appeal of structures—particularly of heritage buildings—it also adds complexity to the manufacturing process.
- **Combined reinforcement:** This approach incorporates two or more reinforcement methods (top, bottom, side, or embedded) to enhance the structural performance of timber beams. By optimising the stresses across the beam, these configurations combine the advantages of the other methods. Therefore, reinforcing all sides may represent the most structurally effective option, offering maximum strength, stiffness, and ductility. However, this approach is often less favourable when considering costs, sustainability, and fire due to the extensive use of steel, aesthetic considerations, and exposed steel, respectively.

5. Overall Conclusions

This paper has explored key aspects of timber–steel hybridisation, focusing on connection methods between the two materials and reinforcement configurations that enhance the structural performance. Based on experimental studies, adhesives, particularly epoxy and polyurethane (PUR), have demonstrated superior strength and stiffness when bonding timber and steel together, outperforming mechanical fasteners in terms of the load-bearing capacity and stiffness. The importance of proper surface preparation, such as shot blasting for steel, has also been highlighted for achieving an optimal adhesive performance.

While adhesives show significant advantages in stiffness, mechanical fasteners, particularly bolts and screws, offer ease of assembly and disassembly and flexibility during construction. The use of inclined screws, long screws, and anchorage techniques have been shown to improve the shear capacity, stiffness, and ductility of timber–steel connections. The inclusion of nail plates and toothed plates further enhances the structural performance, although it could potentially have a negative impact on the ductility.

Regarding timber–steel hybrid beam configurations, the placement of the steel in the compression zone has been shown to improve the bending stiffness and strength. Bottom reinforcement has been proven effective at addressing the brittle nature of timber under tensile loads, enhancing both the stiffness and ductility when designed accordingly. Side reinforcement improves the lateral stability and shear capacity but offers less efficiency in

improving the bending stiffness compared to bottom or top reinforcement. Considerations for the fire performance remain critical for exposed steel elements. Embedded reinforcement, while more complex to manufacture, offers enhanced fire resistance and preserves the aesthetic integrity of timber structures.

Among the various configurations, combined reinforcement, where the steel is placed in multiple zones, may offer the highest structural performance by balancing strength, stiffness, and ductility. However, it may not always be the optimal choice when considering the cost, weight, and construction complexity. Among the configurations reviewed, bottom-embedded reinforcement may present an optimal solution in terms of efficiency and practicality, particularly for simply supported beams, as it targets the tension zone where the timber is brittle. This allows for the effective use of a relatively low amount of steel while also improving fire protection by insulating the steel within the timber. The findings of this review paper point to the importance of the material preparation, connection methods, and reinforcement configurations in optimising the structural efficacy of timber–steel hybrid systems. By strategically combining these elements, engineers can enhance the performance of composite beams, balancing strength, stiffness, and ductility while considering the fire performance, aesthetic integrity, and ease of construction.

6. Future Studies

This review has identified a significant gap in studies addressing the long-term performance of timber–steel hybrid connections, particularly under environmental conditions such as moisture and thermal variation. Only one study has been found that investigated this phenomenon [18]. Future research should focus on evaluating the durability of these hybrid systems over time, involving both mechanical fasteners (such as screws) and commonly used adhesives like polyurethane (PUR) and epoxy.

In addition, while PUR and epoxy are the most widely investigated adhesives in timber–steel hybridisation, further studies are needed to explore the performances of other adhesive systems, such as phenol formaldehyde (PF) [58], which could offer competitive alternatives in structural applications.

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