

A Review of Shear Connectors for Glulam-Ultra-High Performance Concrete Composite Beams

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How to cite this paper: Han, Y. (2026). A Review of Shear Connectors for Glulam-Ultra-High Performance Concrete Composite Beams. *Advances in Engineering Research : Possibilities and Challenges*, 5(1), 8–19. ISSN Print: 3079-5192, ISSN Online: 3079-5206.
<https://doi.org/10.63313/AERpc.9122>
Published: 2026-09-10

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Abstract

Timber-concrete composite (TCC) beams combine the lightweight high strength-to-weight ratio of timber with the favourable compressive behaviour of concrete, and have been widely used in bridges and buildings. However, conventional concrete slabs suffer from large self-weight, significant creep, and pronounced cracking, which restrict the spanning capacity and durability of the composite system. Glued laminated timber (glulam) is an engineered wood product with excellent strength and dimensional stability, while ultra-high performance concrete (UHPC) offers ultra-high strength, high elastic modulus, and extremely low creep. The combination of glulam and UHPC to form glulam-UHPC composite (GUCC) structures is expected to overcome the performance bottlenecks of traditional TCC. The key to realising this advantage lies in the rational design of the shear connectors. This paper systematically reviews the development history and mechanical properties of shear connectors for TCC and GUCC systems, with emphasis on typical types including dowel-type connectors, notched connections, steel plate connectors, adhesively bonded connections, and hybrid connections. The load-carrying capacity, slip modulus, and failure modes of these connectors are analysed, and the influences of anchorage method, inclination angle of rebar, notch geometry, fibre reinforcement, and interface conditions on connection performance are summarised. Research indicates that inclined crossed arrangements, the synergistic use of notches with metallic fasteners, and epoxy-assisted anchorage can significantly improve initial stiffness and ductility. However, purely adhesive connections exhibit brittle failure, while purely mechanical connections are limited by local crushing of timber. The introduction of UHPC shifts the failure mode of connectors from concrete crushing to steel shear or timber shear, and the slip modulus can be increased by about 18%–30%. Current research has moved from conceptual validation towards quantitative design, but further investigations are still needed on high-stiffness-high-ductility hybrid connection configurations tailored for GUCC, long-term performance evolution, and standardised test methods. Based on the identified research gaps, this paper proposes a novel hybrid connection concept comprising X-shaped rebars, epoxy resin, and glued-in notches in glulam, aiming to provide a theoretical basis and design reference for

the development of high-performance shear connectors for GUCC structures.

Keywords

Glued laminated timber (glulam); Ultra-high Performance Concrete (UHPC); Timber-Concrete Composite (TCC) Beams; Shear Connectors; Slip Modulus; Ductility; Epoxy resin anchorage; Notched connections

1. Introduction

1.1. Research Background

1.1.1. Development of Timber-Concrete Composite Beams

Timber-concrete composite (TCC) structures originated in the 1930s USA with Richart and Williams' first tests, followed by bridges in the 1940s and adoption in Australia/New Zealand in the 1950s. After a lull, TCC revived in Europe in the 1990s and expanded globally in the 21st century; over 85% of 75 surveyed TCC bridges were built in the last two decades, over 50% between 2000 and 2010.

A TCC beam consists of a timber beam, a concrete slab, and shear connectors; concrete is in compression and timber in tension. Compared with pure timber, it offers higher capacity, stiffness, fire resistance, and sound insulation; compared with pure concrete, it is lighter and more seismic-resistant. However, concrete slabs are heavy, shrink and creep, and crack easily, causing poor durability and excessive long-term deflection.

Using UHPC thin slabs reduces floor weight, decreases slab thickness by about 20%, and raises natural frequency; lightweight aggregate concrete weighs 70–75% of normal concrete. Birdsmouth connections are easier to make than rectangular notches; multi-angle beveled notches improve ductility but cost more. At 40% ultimate load, high-strength/low-shrinkage concrete with appropriate fibers can increase stiffness by 30% (excessive fibers may reduce it). Concrete properties most affect connection performance, followed by notch geometry, then fibers (15–30% improvement). Triangular notches with inclined and vertical screws outperform rectangular notches with only vertical screws.

1.1.2. Glued Laminated Timber Composite Beams

1.1.2.1. Development History of Glued Laminated Timber

Glued laminated timber (Glulam) is an engineered wood product made by bonding dried laminations (typically 20–50 mm thick) with grain parallel to the member axis, using finger jointing and laminating to eliminate natural defects and realize “using small timber for large members and inferior timber for superior purposes.”

The history of glulam as a structural material dates back to the late 19th century: the auditorium of King Edward College, Southampton, England (1860) is among the earliest recorded glulam structures. In 1893, the Basel Music Hall in Switzerland used glulam arches. In 1901, Otto Hetzer of Germany obtained the first glulam

patent in Switzerland, and in 1906 a German patent, marking the beginning of curved glulam structures. By 1907, glulam structural technology was formally established in Germany. It spread to Denmark in 1914, Norway and Sweden in 1918, and the United States in 1934, where the first U.S. glulam building—the Peshtigo School Gymnasium—was built in Wisconsin. In the same year, the U.S. Forest Products Laboratory began systematic research on glulam strength, publishing a systematic report in 1949. By the mid-1940s, glulam had become an important branch of modern timber structures.

In China, glulam application began in the 1950s: the first glulam building was constructed in Beijing in 1957, and the first 44 m span glulam highway bridge was built in Fujian in 1959. In 1989, the Kanglegong recreation center in Beijing used a 60 m span glulam roof. Recent representative cases include the Taiyuan Botanical Garden exhibition greenhouse (maximum span 89.5 m), its waterside restaurant (21 m), the Dishui Lake landscape pedestrian bridge in Shanghai (48 m), and the Tacoma Dome in the United States (diameter 162 m).

Glulam is lightweight with a very high strength-to-weight ratio, making it highly suitable for long-span spatial structures. Under China's "dual carbon" goals, glulam long-span structures have advantages, and the Taiyuan Botanical Garden greenhouse with its novel "shell" shape provides a basis for innovation and promotes the development of glulam long-span spatial structures in China.

1.1.2.2. Advantages of Glulam

Mechanical properties are significantly improved. By optimally combining laminations of different grades, glulam effectively avoids defects in natural wood and provides members with relatively high strength. Glulam has a very high strength-to-weight ratio, and its load-carrying efficiency is higher than that of steel. Dimensional stability is excellent. The laminations used in glulam are dried to a uniform moisture content (typically controlled at 6%–15%), resulting in good dimensional stability of the finished members. Glulam breaks through the limitations of natural size and realizes the principle of "using small timber for large members." It can be made from short or small-diameter timber through end jointing and laminating to form large-span, large-section structural members. At the same time, it is the only engineered wood product that can be manufactured in curved shapes, meeting the design requirements of various irregular structures. Design flexibility and material utilization efficiency are high. Glulam allows laminations of different strength grades to be arranged at different positions within the member cross-section, thus making full use of lower-grade timber. This optimized combination not only improves structural performance but also greatly increases wood utilization. Fire resistance is superior. When large-section glulam members are exposed to fire, a char layer forms on the surface, effectively slowing the burning rate of the wood. Tests show that the charring rate of wood is usually about 0.7 mm/min. Glulam structures are typically used for large load-carrying members, and

fire resistance can be extended by controlling member dimensions. Glulam is environmentally friendly and supports sustainable development. Wood is a renewable resource. The production of steel and cement emits large amounts of CO₂. Glulam can utilize fast-growing plantation timber, and its processing energy consumption is far lower than that of steel and concrete, which is in line with the strategic requirements of green buildings and low-carbon development.

1.1.3. Glulam-UHPC

Ultra-high-performance concrete (UHPC), formulated based on the principle of maximum packing density, exhibits an order-of-magnitude improvement over normal concrete (NC). Its compressive strength can reach 120–150 MPa or higher, its tensile strength generally exceeds 5 MPa, and its ultimate tensile strain capacity is 20–50 times that of NC, showing strain-hardening behavior and multiple cracking rather than brittle failure. UHPC has a porosity of about 9%, a chloride ion diffusion coefficient below $0.30 \times 10^{-12} \text{ m}^2/\text{s}$, impermeability 1–2 orders of magnitude better than NC, resistance to more than 300 freeze–thaw cycles, a creep coefficient only 0.2–0.3 times that of NC, and an elastic modulus of at least 49 GPa.

Glued laminated timber (Glulam) is lightweight, high-strength, renewable, and low-carbon. However, in traditional timber–concrete composite (TCC) structures, the normal concrete slab is thick and heavy, and concrete shrinkage and creep superimpose on timber creep, so long-term deflection can exceed 50% of the initial elastic deformation. Introducing UHPC into TCC systems creates glulam-UHPC composite structures (GUCC), which reduce slab thickness and self-weight, control long-term deflection, and improve overall stiffness and durability.

The performance of GUCC structures depends critically on the shear connectors. Wang et al. designed a horizontal steel plate + stud (HS) connector. Push-out tests showed that the slip modulus reached 134.9–165.6 kN/mm and the shear capacity reached 167.6–200.3 kN. Short studs failed by stud shear, while long studs failed by shear parallel to the grain in glulam. The UHPC slabs did not crack, and compared with NC slabs, the UHPC slabs increased the connector slip modulus by about 18%. A load–slip constitutive model and a shear capacity design formula were also proposed. Research on UHPC–NC interface bonding indicates that steel fiber bridging in UHPC and interface treatments such as chiseling, sandblasting, grooving, and stud implantation can significantly enhance interface performance.

Current research on GUCC connectors has progressed to quantitative design. Future work should focus on comparative studies of multiple connector types, long-term performance, fatigue behavior, and optimized design methods to promote the practical application of GUCC systems in long-span bridges and green buildings.

1.1.4. Evolution of Shear Connectors

Shear connectors determine the stiffness and load-carrying capacity of timber–concrete composite (TCC) structures. Rodrigues et al. reviewed the

development of TCC connectors. Their evolution includes four stages: (1) 1930s–1970s, initial mechanical fasteners (nails, bolts), with slip stiffness identified as key; (2) 1980s–1990s, diversified connectors and notches, including Finnish X-type steel bars, German notches, and Swiss glued rigid connections; (3) 2000s–2010s, combined connectors, where notches plus screws increased strength by 3 times and stiffness by 8.5 times, along with steel plate–stud and HBV continuous plate systems; (4) 2010s–present, connectors for UHPC and prefabrication, such as steel plate/shear pins, flat plate–studs, inclined bars, and demountable modular connectors.

Connector types include metal dowels, notches, steel plates, and adhesives. Steel bar connectors are common; inclined bars are stiffer than straight ones, and epoxy fixing increases stiffness and strength. Notches provide high initial stiffness and capacity through concrete interlock, especially when combined with metal dowels.

Deam et al. found that a rectangular concrete plug reinforced with a coach screw gave the best overall performance (peak 54.9 kN, initial stiffness 297 kN/mm, ductile failure), enabling only 16 connectors over an 8 m span. However, purely mechanical connectors suffer large slip and delayed stiffness due to timber bearing, and chemical bonding was unexplored, motivating the present X steel bar + epoxy + glulam notch design for ultra-high initial stiffness and controllable ductility.

Miotto and Dias tested perforated steel plates bonded with epoxy; they achieved average initial slip modulus 339.4 kN/mm but failed by brittle concrete cracking with almost no ductility, required expensive irreversible fabrication, and severely reduced the glulam cross-section. The proposed discrete X-bar notch scheme aims to offer better ductility, lower cost, and less timber damage while maintaining capacity.

Yeoh et al. reported that rectangular and triangular notches with screws provide good ductility; failure was concrete shear in the notch with the screw bridging after peak, whereas toothed plates failed brittly by tearing. Otero-Chans et al. found that discrete perforated steel plates bonded with epoxy are strong and stiff but ultimately fail by brittle timber shear along the glued interface, with capacity limited by timber shear strength and size effect. The X-bar notch design shifts the weak link from timber to confined concrete plus yielding steel, enabling gradual crushing rather than sudden fracture.

Tannert et al. showed that full-surface epoxy bonding gives high short- and long-term composite efficiency with no degradation after 4.5 years, but construction is demanding and debonding can cause brittle failure without redundancy. Hybrid connections combining self-tapping screws and epoxy strips achieved stiffness close to pure adhesive (1159 vs 1224 kN/mm) and ultimate load 2.45 times higher, providing “stiff yet tough” behavior through two-stage failure.

Lukaszewska et al. found that prefabricated dry connectors can perform satisfactorily, but pure epoxy connectors (SM/GSP) have high stiffness with brittle

failure and no plastic stage, while ST+S+N has high strength but complex construction. He et al. derived Johansen-based formulas for bolted connectors; capacity increased linearly with diameter and stiffness with diameter squared, but larger bolts caused brittle concrete splitting, revealing the inherent trade-off between high stiffness and high ductility.

Marchi et al. showed that inclined self-tapping screws under compression cause brittle conical concrete failure and limited stiffness due to timber bearing collapse, especially in lightweight concrete; reverse screws did not improve stiffness. Mai et al. found that inclined connectors at 45° outperform vertical ones, but failure is controlled by local crushing and brittle connector fracture, limiting capacity. Du et al. reported that crossed inclined screws had the highest stiffness and cyclic capability; failure involved concrete cone expulsion and screw pull-out with plastic hinges. Khorsandnia et al. confirmed the superiority of crossed inclined connectors (SFS) in stiffness stability and of notch-screw combinations in capacity/ductility, though with dispersion. Di Nino et al. modeled inclined screws on elastic foundations and found optimal inclination 45°–60°; OSB interlayers reduced stiffness, supporting direct notching.

Further studies reinforced these findings. Molina et al. found epoxy-bonded steel bar connectors superior to pre-drilled unglued ones. Hehl et al. showed pure notches have stress singularities causing sudden timber splitting. Jiang and Crocetti noted floor stiffness is insensitive to notch depth between 15–35 mm. Jiang et al. found notch connectors with screw reinforcement improve strength, ductility, and post-peak behavior. Fong et al. recommended 150 mm rectangular notches for strength and triangular notches for constructability. Xie et al. derived formulas for stud-notch connectors with errors within 8%.

Overall, prior mechanical and purely bonded connectors exhibit limitations: brittle timber/concrete failure, stress concentration, large slip, high cost, or cross-section weakening. The proposed X-shaped steel bars embedded in epoxy-filled notches combine mechanical interlocking with chemical bonding and lateral confinement. This shifts failure to confined concrete and yielding steel, achieving ultra-high initial stiffness, controllable ductility, reduced timber damage, and lower construction cost, filling the gap in chemical-mechanical hybrid TCC connections.

1.1.5. Glulam-UHPC Shear Connector Composite Beams

With the proposal of GUCC structures, how to establish a reliable and efficient shear connection between glulam and UHPC has become a key scientific issue. Compared with normal concrete, UHPC has higher strength and elastic modulus, which brings new opportunities and challenges to the design of connectors. At present, research on glulam-UHPC shear connectors is still in its initial stage, and systematic research on connector types, design parameters, and failure mechanisms is urgently needed.

1.2. Domestic and International Research Status

Recent years have seen significant progress in experimental and numerical studies on rebar-type connectors. Fernandes et al. (2023) used epoxy-bonded ribbed rebars and compared the effect of triangular notches. Push-out tests showed that the inclined 45° bonded rebar (RB) connection had an average capacity of 51.27 kN and a slip modulus of 75.54 kN/mm, with failure characterised by plastic hinge formation in the rebar (ductile). Adding a triangular notch (NRB) increased capacity by 172% to 139.84 kN, but slip modulus increased by only 27.8%, and failure became brittle shear of the concrete in the notch, with a rapid post-peak drop.

1.2.1. Interface Shear Research on Timber–Concrete Composite Beams

Shear connectors are the core element for composite action in TCC structures; stiffness, strength, ductility, and fatigue are key indicators. Connectors evolved from nails/screws to dedicated systems: studs (high stiffness, poor ductility), X-bars (good ductility, improved with notches), notches (high stiffness, brittle), HBV plates (ductile), and others (CHS, UCS, HSP, PSP).

Reported properties: nails ~9 kN, ~12 kN/mm; screw+spring ~8 kN/mm; studs ~119 kN, ~68 kN/mm; X-bars ~122 kN, ~140 kN/mm; notches ~263 kN, ~387 kN/mm (brittle); HBV ~919 kN, ~66 kN/mm. Ultimate slip is 1–3 mm, while service slip is ~0.05 mm, so safety reserve is sufficient. Slip modulus ranges from 8 to >400 kN/mm.

Stiffness increase has diminishing returns: beyond a threshold, further stiffness adds little; below another threshold, composite action is negligible. Fatigue tests show X-bars degrade rapidly under cyclic loading; notches improve strength by 30% and stiffness significantly, but unified fatigue verification is lacking. Other gaps include no unified test standard, unclear creep–fatigue long-term behavior, and need for accurate numerical models.

Connector design must balance stiffness, strength, ductility, construction, and economy. In GUCC, UHPC changes local stress and confinement, posing new challenges for connector selection and optimization.

1.2.2. Interface Shear Research for Glulam–UHPC

Timber–concrete composite (TCC) structures achieve the cooperative work of timber and concrete through shear connectors, and the type, geometric configuration, and installation method of connectors directly affect the load-carrying capacity, stiffness, and failure mode of the structure. In recent years, experimental and numerical research on steel bar connectors has made significant progress, especially the work of the University of São Paulo team in Brazil and the ZIE Institute team in Burkina Faso, West Africa, which is the most representative. Fernandes et al. (2023) used epoxy resin to bond ribbed steel bars and systematically compared the influence of the presence or absence of triangular notches on connection performance. Push-out tests showed that the average load-carrying capacity of connections with only 45° inclined bonded steel bars (RB)

was 51.27 kN, and the slip modulus was 75.54 kN/mm. The failure mode was characterized by steel bars embedding into the timber and forming plastic hinges, showing ductile behavior. After adding triangular notches (NRB), the load-carrying capacity increased significantly by 172% to 139.84 kN, but the slip modulus increased by only 27.8%, and the failure changed to brittle shear of concrete at the notch, with the load-carrying capacity dropping rapidly after the peak. The ABAQUS three-dimensional finite element model established by the team, using the Hill yield criterion to describe the orthotropic behavior of timber, the concrete damaged plasticity (CDP) model, and the cohesive zone model to simulate the adhesive layer, predicted the load-carrying capacity and stiffness of RB connections with errors within 3.3%, but overestimated the stiffness of NRB connections by 36.2%, reflecting the complexity of simulating concrete failure in the notch region.

In contrast, the 2iE team in Burkina Faso focused on the context of developing countries and was committed to developing low-cost connection technologies that do not require adhesives and rely only on locally available ordinary threaded steel bars. Tako et al. (2023) used push-out tests to investigate the performance of plain round bars (installed by hammering), threaded bars (installed by screwing), threaded bars with hooked ends, and plain round bars combined with U-shaped steel sections. The results showed that threading reduces the net cross-section of the steel bar, slightly reducing load-carrying capacity and stiffness, but hooked anchorage can effectively enhance the concrete side grip, increasing load-carrying capacity by about 16%. The U-shaped steel section combined connector (HA12U) performed outstandingly, with a load-carrying capacity of 40 kN, which was 93.6% higher than that of plain round bars of the same diameter (HA12S), and the slip modulus increased from 13.48 kN/mm to 37.23 kN/mm, an increase of 168.5%, while maintaining a ductile failure mode. The team also compared various configurations of threaded bars without notches, pure notches, and their combinations (Djoubissie et al., 2018). The results showed that the plain threaded bar without a notch inclined at 120° (S120-HA12) had a load-carrying capacity of 25 kN and a slip modulus of 15.4 kN/mm, far superior to the vertical 90° configuration (load-carrying capacity 23.8 kN, slip modulus only 2.92 kN/mm), indicating that inclined arrangement can significantly improve stiffness. When notches were combined with threaded bars (CTS120-HA12), the load-carrying capacity jumped to 66.5 kN and the slip modulus reached as high as 115.1 kN/mm, but the failure mode changed to brittle (ductility parameter $\nabla = 45\%$). In addition, the team investigated the weakening effect of an interlayer plywood formwork (10 mm thick) on connection performance (Djoubissie Denouwe et al., 2018): with a single threaded bar and an interlayer, the load-carrying capacity decreased by about 17%, and the slip modulus at the serviceability limit state dropped sharply by 81%, revealing the significant adverse effect of a formwork layer on anchorage stiffness. In terms of numerical simulation, Tako et al. (2023) used the simplified concrete damage

plasticity (SCDP) model and Hill criterion in ABAQUS/Explicit to achieve a good fit of the load–displacement curves of HA12S and other connections within a 15 mm slip range, with load-carrying capacity prediction errors between 7% and 13.5%.

In summary, the mechanical properties of connectors are jointly regulated by anchorage method, steel bar inclination angle, notch coordination, and interface conditions. Bonded steel bars provide the best load-carrying capacity and stiffness performance, but they are demanding in construction and show a certain brittleness; mechanically anchored inclined threaded steel bars, although of moderate performance, have both good ductility and construction convenience, and are especially suitable for resource-limited regions; U-shaped steel section composite connectors show potential as high-performance ductile connectors. The addition of notches can increase load-carrying capacity and stiffness severalfold, but at the cost of ductility, so design should weigh this trade-off according to structural ductility requirements and safety redundancy. The weakening effect of interlayer formwork on stiffness needs to be fully accounted for in practical engineering. Current finite element models are relatively mature in simulating the elastic stage of bonded and mechanically anchored connections, but accurate prediction of notch connection stiffness and brittle failure remains a challenge. Future research can further explore new low-cost ductile connection configurations, long-term performance under multi-factor coupling, and standardized design methods oriented toward material characteristics in different regions.

3.1. Design drawings

The following content includes 3D images and fabrication drawings related to my push-out specimens. As shown in Figures 1, 2, and 3.

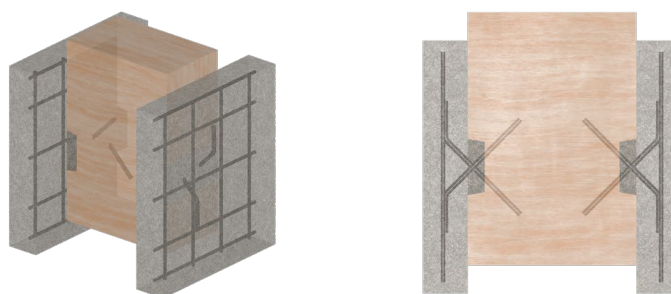


Figure 1. 3D drawing of the component.

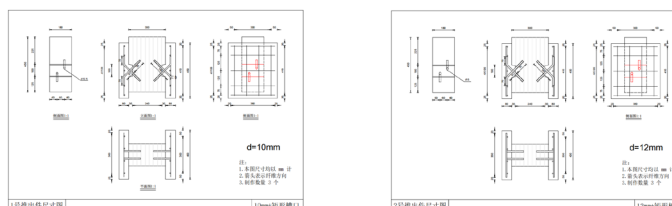
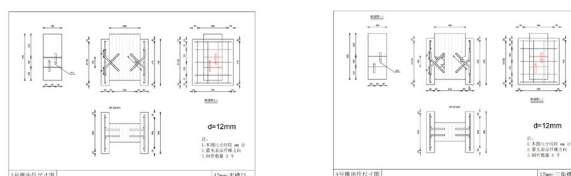


Figure 2. Shop drawings.**Figure 3.** Shop drawings.

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