Research status of glued-in rods connections in wood structures

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Abstract: Glued-in rods connections are widely used as a post-anchoring reinforcement technique in timber structures. The rods are inserted into boreholes with adhesive and then cured to form a whole with high strength, stiffness, and aesthetic properties. Although the glued-in-bar connections have been applied successfully, there are still some problems in the research of these connections in wood structures. There is still no unified standard for glued-in connections in wood structures. In this paper, the state of the art in glued-in-rod connections in wood structures is presented, the main influencing factors, failure modes glued-in rod, and the design methods of glued-in rod connections are summarized. The study provides a reference to bonded bar connections and the development of recommended design methods glued-in rod.

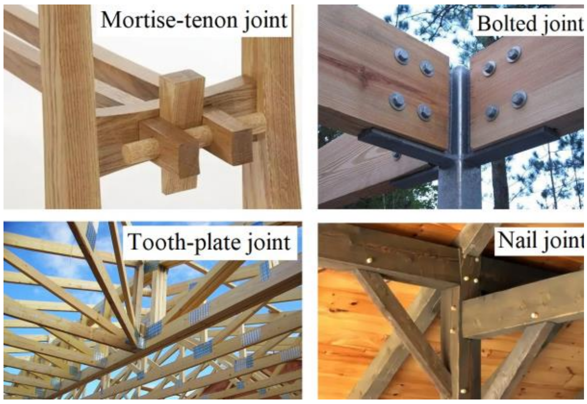
Keywords: Wood structure; glued-in rod; influence factor; design suggestion

1 Introduction

Wooden structures have become increasingly popular and rapidly developed in countries with expanded wood resources [1, 2] and advocates for environmental protection [3]. More than 90% of new structures in the United States, Canada, and North America are made of wood [4]. In Japan, where environmental protection is properly enforced [5], the proportion exceeds 50% [6]. Wood construction is also one of the principal architectural forms in Northern Europe [7], which has a cold weather and abundant forestry resources. China has a long history of timber structures dating back about 3500 years and invented the mortise-and-tenon joint for beam-to-column connections in frame systems [8]. With the development of science and technology, the modern wood structure has formed three main directions: common wood structure [9], glued-laminated timber [10], and light wood frame systems [11]. Today, a series of modern building materials made of wood have emerged internationally, such as Glued laminated timber (Glulam) [12], Parallel strand lumber (PSL), Laminated veneer lumber (LVL), Laminated strand lumber (LSL), and Cross-laminated timber (CLT), as shown in Fig. 1(a). Modern wood structures have been widely used since they ensure comfort, environmental compatibility, heat preservation energy efficiency, structural safety, and durability.

(a) Engineering wood products

(Source: https://graph.baidu.com/)

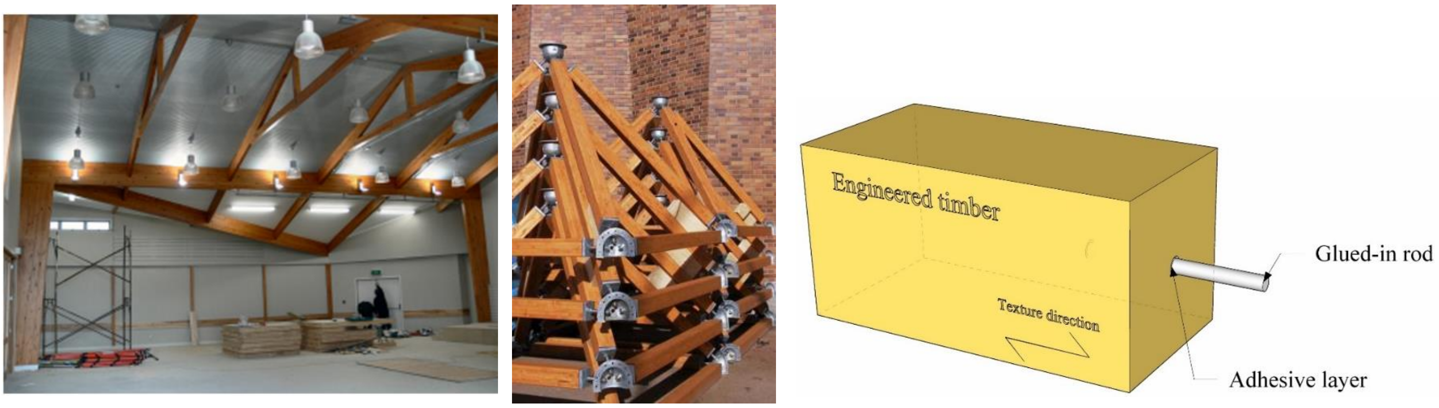


(b) Common wood construction joint types

(Source: https://image.baidu.com/)

Fig. 1 Typical engineering wood and joint formats

Modern wood structures built with the engineered wood often require connections with high strength and stiffness [13]. Traditional wood structures are typically connected using mortise-tenon connections, nails, tooth plates, bolts, pins, and glued-in rods. Fig. 1(b) illustrates the four types of connections mentioned above. The mortise-tenon joint is the typical connection form of Chinese ancient wooden structures, but due to the small stiffness and the high processing accuracy of the mortise-tenon groove, it is less used in modern wooden structures. Nail connection is suitable for light wood shear wall, building and roof cover, and NLT structure, etc. While tooth plate connection is mainly used for connections in light wood truss structure, which is characterized by simplicity and high construction efficiency. However, the tooth connection cannot effectively withstand the pressure, and the durability of the connections is usually poor due to the bare air leakage of the tooth plate [1]. The two most popular connection forms, the bolt connection and pin connection have the high bearing capacity and deformation capability. Glued-in rod connection is a new type of reliable moment-resist anting node connection that has emerged in recent years by bonding the reinforcement in wood with a special adhesive. The application of glued-in reinforcement (known as Glued-in Bolts in Europe and Glued-in rod in North America) to strengthen wood originated from Sweden, Denmark, and other Nordic countries [6], has been developed for more than 40 years. One instance is the 2003-built Eastview Baptist Church in Auckland, as depicted in Figure 2(a); another example is the space truss construction in Spain, in which the hollow glulam elements were connected using the glued in rod method, as presented in Fig. 2 (b). The practice is to insert reinforcing materials (such as steel bars, bolt rods, FRP bars, etc.) into pre-drilled holes of wood using adhesive, and to form a unified member when the glue is cured[6] , as shown in Fig. 2(c).



(a) Eastview Baptist Church Auckland [125]　(b) A space truss structure [43]　(c) Schematic diagram of single GIR connection

Fig.2 Diagrams of the GIR connection and actual application

The Glued-in rod connection, which can be used to create new structures or to reinforce existing ones, is widely welcomed [10, 14, 15]. This treatment can be applied in parallel or perpendicular to the grain direction of the wood, which provides excellent strength and stiffness properties for the structure, as well as an effective load-bearing capacity [16], being a lightweight and strong joint [17], which eliminated the use of steel intermediate connectors. It is surrounded by wood and has good fire resistance and good appearance. As structural reinforcement, the placement of reinforcing bars in areas of high stress along the grain or in the shear zone can prevent structural cracks in materials, such as tapered or curved glulam beams and notched end beams [14, 18-20].

Early studies of glued-in rod connections used adhesive bolts or tendons that were screwed into smaller-sized holes [21, 22]. Glued-in rod connection was first used for cross-grain implantation into the ends of wood beams to enhance the beam's shear and local compression capacity. Due to the advantages of high strength-to-weight ratio, high stiffness, aesthetic appearance and good fire resistance, the glued-in rod connections are well suited for the construction of modern wood buildings and bridges. Although a lot of researches has been conducted on glued-in rod connections at home and abroad, there are still some problems and a lack of systematization in the research, such as the divergent views among different scholars on some influencing factors of connection performance. Therefore, it is necessary to summarize the research status of the glued-in rod connections.

2 Factors influencing the performance of wood structure glued-in rods connections

The first wood structural reinforcement technology appeared in Northern Europe. In the past 20 years, wood structural reinforcement technology has developed particularly rapidly, especially in 1998, when a research project on the performance of glued-in rod connection (referred to as the GIROD project) was initiated in Switzerland and other European countries, which provided design recommendations on wood structural reinforcement for the

European Code of Design for Wood Structures EC5 [23]. Numerous studies have shown that many parameters affect the bonding performance of GIR connections, which can be summarized into the following three categories: geometric parameters, material parameters, loads, and boundary conditions. As shown in Fig. 3, the number of inserted rods can be another parameter for the analysis of the bonding capacity of a reinforced connection; however, there are almost no experimental studies on multiple GIR connections because there are so many factors that affect the bonding and anchoring performance of this reinforced connection; the damage mechanism and load transfer mode are also complex and therefore difficult to evaluate.

In addition, there is a lack of theoretical studies related to the experimental research on the bonding performance of glued-in rods connection when subjected to many different types of loads at a time, such as simultaneous shear and bending loads [24-26], which is of great importance in engineering In the following, several main influencing parameters shown in Fig. 3 will be discussed.

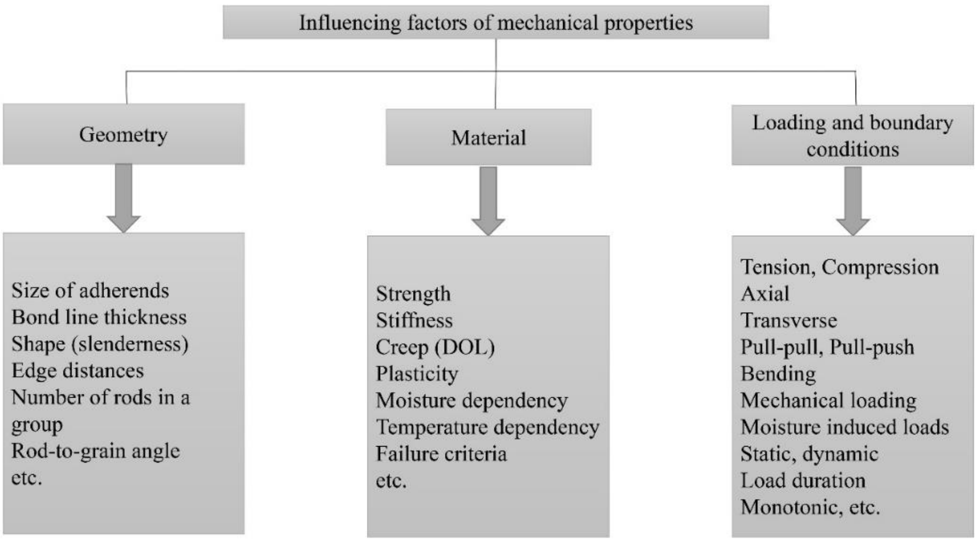


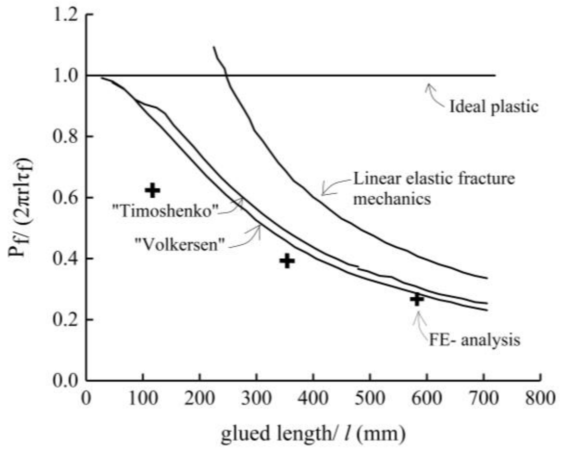
Fig.3 Influencing factors on the bond performance of glued-in connection [27]

2.1 Geometric parameter

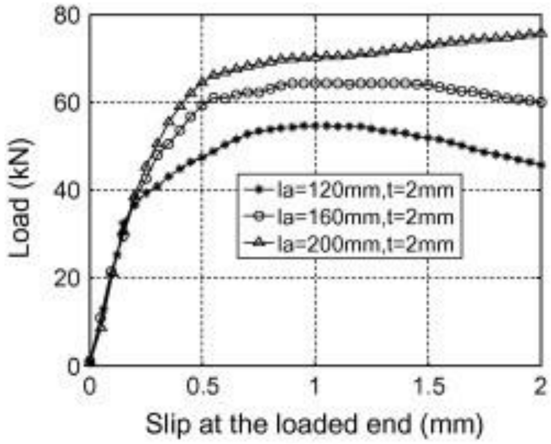
2.1.1 Anchor length and diameter

The anchorage length of the glued-in rod is one of the main parameters affecting the pullout and bond performance of the glued-in rod connections as well as the damage mode of the nodes. Tang et al. [28] pointed out that HRB235 rebar glued in connections with epoxy resin showed rod yielding when the anchorage length reached 12.5*d* (*d* is the diameter of the rod, same below), therefore, it can be defined as the critical anchorage length. For the use of high-strength bolt rods of M8.8 grade and above, Steriger et al. [10] considered ductile damage of the connection by weakening part of the cross-section of the rod near the loading end. The results of Otero Chans D et al. [29] showed that the damage strength increased with the increase of the insertion depth, but not in a significant linear relationship. In the study by Malczyk [30], 10 mm steel rods were inserted into Douglas fir glulam, the damage load increased with increasing anchorage length, the failure mode of the specimens was pull-out damage of the rods at an anchorage length of 130 mm, while when the anchorage length depth was longer than 300 mm, the tensile failure of the rods themselves was observed. Lorenzis et al. [31] showed that the anchorage pullout resistance and ductility of the members increase with increasing anchorage length. Gonzales et al. [32] conducted a pull-out test of a low yield point bolt bar glued-in rod connection and the results showed that the rods yielded to failure when the anchorage length reached 10*d*, thus showing that the GIR connections could achieve ductile failure through a reasonable design. Advent [33] investigated the factors affecting the strength of GIR connections in wood structures and showed that the shear bond strength increased with the increase in wood shear strength. It was also determined that the main factors affecting the strength are the ratio of bond length to member thickness and the direction. Ayansola et al. [34] conducted uniaxial quasistatic monotonic tension tests on 220 CLT glued-in rods joints of two thicknesses to investigate the effect of different diameters and anchorage lengths on the loading capacity and the failure mode, respectively. The results showed that the loading capacity of the specimen increased with increasing bar diameter and anchorage length when $l_a < 14d$, but did not change when $l_a < 14d$. Sofi et al. [35] discovered a non-linear positive correlation between the axial pull-out capacity of the CLT GIR connections and the bond length when $10d \le l_a \leqslant 15d$, the bond length was primarily responsible for the pull-out strength. Zhu et al. [36] demonstrated that when the anchorage length exceeded 200 mm, the bonding performance of single reinforced timber joints with GFRP rod no longer increased with increasing bonding length. However, it has also been previously shown [21, 29, 37-42] that although the ultimate load of the glued-in rod increases with increasing anchorage length, the stress distribution at both ends of the anchorage zone is not uniform, which leads to a decrease in its nominal shear strength.

As shown in Fig. 4(a), the effects of anchorage length are predicted using different theoretical approaches. The two limiting cases are the perfect plastic behavior where the pull-out load is proportional to the anchorage length, and the linear elastic fracture mechanics approach where the anchorage length does not affect the pull-out load (the linear elastic fracture) at all. Ling et al. [44] investigated the effect of pullout strength and anchorage length on GIR connections in Glulam. The results showed that when the anchorage length spanned from 120 mm to 200 mm, the relationship between pullout strength and anchorage length was generally linear, while the initial stiffness was essentially unaffected by the anchorage length, as shown in Fig. 4. (b).



(a) Comparison of different methods (according to GIROD engineering model) [47]



(b) Curves of load-deformation with different anchorage lengths [44]

Fig.4 Effect of anchorage length of GIR connections on their tensile strength

In general, the pull-out load capacity of the GIR increases with an increase in the anchorage length [10, 16, 37, 43], and there is no obvious linear proportionality between them; when the anchorage length reaches a certain requirement, the pull-out load capacity of the GIR connections equals or even exceeds its yield strength, and the inserted rod yields [30, 45, 46].

To sum up, the influence of anchorage length on the distribution of adhesive shear stress at the bar interface is mainly manifested as follows: for short anchor specimens (anchorage length is generally less than 5*d*), the distribution of adhesive stress at the bar interface is relatively uniform along the anchorage length; as the anchorage length increases, the concentration of adhesive shear stress at the bar interface near the two ends of the anchorage interval becomes more obvious.

2.1.2 The diameter of the rod

It has been shown [21, 41, 47-51] that the diameter of the inserted bars (or the diameter of the borehole when damage to the wood occurs) is related to the pullout strength. The diameter (*d*) of the inserted bar is also an influencing factor. It has been shown that screws anchored in wood depend on the compression mechanism resulting from the lateral circumferential contact between the wood and the screw so that the pullout strength of screws in glued-in rod connections is related to their surface. If the nominal diameter of the rod is very close to the diameter of the hole, the bonding performance of the GIR connections will be better due to compression and close contact [41, 52]. On the contrary, according to Otero Chans D et al. [29] and Broughtong and Hutchinson [16], there is no significant relationship between the pullout strength and the diameter of the insert rod, but an increase in the diameter of the bar can increase the contact area between the adhesive and the bar and reduce the shear strength.

Table 1 The comparison test results of GIR connection in different references

Ref.	Diameter (mm)	λ	*e*	Bond anchoring property		Basic information of the test
				F_u / kN	Stress/ MPa	
Steiger[10]	12	7.5	2.29	43.8	14.5	Test method: pull-pull test; Direction of reinforcement: parallel to the grain; Type of engineered wood: glulam of Norway spruce lamellas; Type of rod: steel rod
	16	7.78	2.34	77.2	13.7	
	20	7.96	2.50	110	12.2	
Malczyk [30]	20	10	-	76.5	-	Test method: pull-out test; Direction of reinforcement:parallel to the grain; Type of rod: steel rod
Lorenzis [31]	12	4.17	13.3	6.2	2.86	Test method: pull-out test; Direction of reinforcement: parallel to the grain; Type of engineered wood: European first-quality spruce glulam; Type of rod: CFRP rod
		8.33	13.30	6.2	4.17	
		12.5	13.30	6.2	5.3	
		16.67	13.30	6.5	4.52	
Gonzales [32][32]	12	5	3	29.1	—	Type of adhesive: 2C PUR (CR-412); Direction: parallel to the grain.
		10	3	45.3		
		20	3	45.5		
		5	3	29.9		Type of adhesive: 2C EPX (Gel Magic): Direction: parallel to the grain.
		10	3	43.9		
		20	3	45.4		
Ayansola [34]	12.7	6	8	35.3	—	Test method: pull-pull test; Direction of reinforcement: parallel to the grain; Type of engineered wood: CLT (5-ply panels, 139 mm and 175 mm thick); Type of rod: steel rod.
		10	8	51.4		
		14	8	65.2		
		18	8	75.5		
	19.1	6	8	71.5		
		10	8	99.3		
		14	8	88.5		
		18	8	146.8		
Sofi [35]	12	5	11.3	25.5	9.7	Test method: pull-distributed configuration; Direction of reinforcement: parallel to the grain; Type of engineered wood: CLT (3-ply, 105 mm thick panel); Type of rod: Grade 4.6 threaded M12 rods; Type of adhesive: two-component epoxy.
		10	11.3	21.2	8	
		15	11.3	40.6	5.1	

Note: Parameter *e* is the ratio of the edge margin to the diameter of the inserted rod, thus $e = a_1 / d$.

Some scholars [28-30, 38, 40] also considered the anchorage length and the diameter of the inserted bar together, defined as slenderness ratio λ (i.e. the ratio of the depth to the diameter of the bar or the hole) ,and established a prediction formula for the pullout load capacity. The results of the bonded anchoring capability of GIR connections under various anchoring lengths l and diameters d are compared in Table 1 across various references. Steiger et al. [10] analyzed the effects of the slenderness ratio of the inserted bar, and the results showed that as the rod depth increased, the final load increased and the shear strength decreased; the ultimate breaking load of the connection increased as the diameter of the inserted rod increased, but the relationship between the shear strength and diameter was not obvious. The relationship between pullout strength and length to slenderness ratio was power exponential, and it was recommended that the diameter of the threaded rod was between 12 and 20 mm.

2.1.3 Thickness of adhesive layer

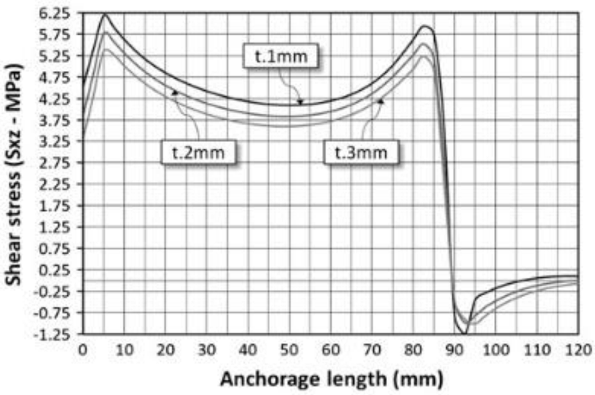
The thickness of the adhesive layer is also considered to be an important parameter affecting the performance of glued-in rod connections in wood structures. Some researchers have analogized the glued-in connection to a combination of two connection methods, namely, gluing, and mechanical connection [37, 53, 55]. For example, in the case of bars inserted into the smaller holes, the strength of the connection depends on the mechanical occlusion between the wood and the side of the inserted bar [20]. The influence of the thickness of the adhesive layer on the performance of the glued-in rod connection mainly occurs when damage appears at the wood/adhesive interface and grows with an increase in the thickness of the adhesive layer. This, in turn, increases the elasticity of the adhesive layer, which facilitates the uniform distribution of shear stress. Different adhesives have different changes in mechanical strength as the thickness of the adhesive layer increases.

Scholars have carried out a great deal of research based on the above problems. Bengtsson and Johansson [56] studied the effect of adhesive layer thickness on the strength of glued reinforcement with three types of adhesives, and with the increase of adhesive layer thickness (0.5-2 mm), the pullout strength of epoxy (EPX) and polyurethane (PUR) adhesives increased slightly, while the strength of resorcinol adhesives decreased. This is mainly due to the large shrinkage of resorcinol adhesives during the curing process, which leads to many voids between the adhesive media and thus generates significant adhesive layer stress. Feligioni et al. [57] investigated the effect of adhesive layer thickness on the bearing capacity of glued-in rod connections based on pull-out tests, and the results showed that the pull-out capacity of glued-in rod connections increased with an increase in both ductile and brittle adhesive layers. Harvey and Ansell [17] used glass fiber reinforced plastic (GFRP) as a reinforcing bar material and studied the influence of the thickness of the adhesive layer when using epoxy adhesive. The ultimate failure load increased when the thickness of the adhesive layer increased in the range of 0.5~6 mm, the maximum shear stress changed slightly. With an increase in the thickness of the adhesive layer, the possibility of the bar being pulled out from the wood increases. The results showed that the thickness of the adhesive layer was 2mm. According to experimental research by Broughton and Huchinson [16] on GIR specimens with adhesive layer thicknesses of 2 mm and 6 mm, the failure load was linearly related to the thickness of the epoxy resin adhesive layer, as indicated in Table 2. Ling [49] investigated the effect of adhesive layer thickness on the strength and stiffness of glued-in rod connections using tensile tests of laminated wood, and the results showed that the connections' pullout strength and initial stiffness tended to increase gradually as the adhesive layer thickness increased from 2 mm to 6 mm, as Table 2 showed.

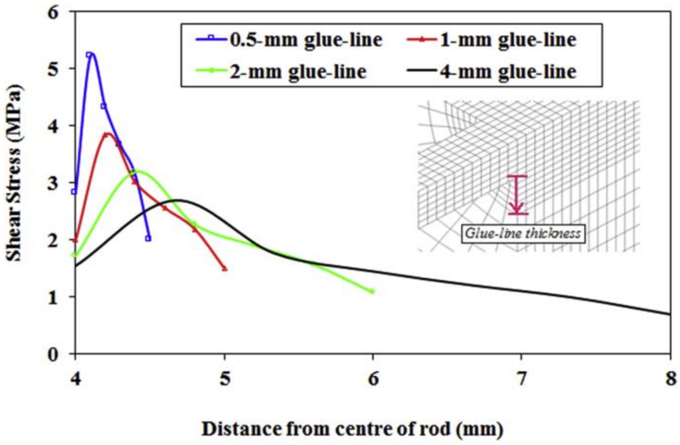
Table 2 The effect of layer thickness on the mechanical properties of GIR connections in different references

Ref.	Adhesive thickness (mm)	Diameter (mm)	Anchorage length (mm)	Ultimate load (kN)	Type of engineered wood	Type of adhesive
Broughton [16]	2	10	60	17.3	LVL	epoxy (EPX)
	6	10	60	23.3		
Lin [49]	2	16	200	81.37	glulam	2-component EPX
	4	16	200	84.08		
	6	16	200	92.81		

The effect of adhesive layer thickness on the mechanical properties of GIR connections has been studied using the finite element analysis, and the conclusions reached are not uniform. Martin et al. [58] improved the distribution of bond stress of the adhesive layer using local reaming. The results showed that the local reaming at the loading end or the anchorage end of the glued-in rod connection increased the local thickness of the adhesive layer, and the peak value of bond stress of the adhesive layer could be reduced, as shown in Fig. 5(a). On the contrary, as shown in Fig. 5(b), Madhoushi and Ansell [59] found that when the rod was loaded in tension, the distribution of stresses in LVL, adhesive, and GFRP rods was relatively similar for the four glue-line thicknesses of 0.5, 1, 2, and 4 mm but more sensitive to loading rate, and the stress concentration at the bar/adhesive and adhesive/wood interfaces decreased with increasing adhesive layer thickness, while shear stress increased to a peak value within 20-30% of the anchorage length.



(a) Different adhesive thicknesses [58]



(b) Different loading rate [59]

Fig. 5 Shear stress distributions

To sum up, considering the influence of construction precision and the surrounding environment on the properties of the adhesive, it is suggested that the thickness of the glue should be 2 ~ 6 mm. The difference in failure location and failure mode has a decisive influence on the load-bearing capacity of the glued-in rod connections, and the adhesive can be selected according to the requirements of geometric properties and use scenarios when designing connections to avoid its brittle failure s and to ensure that the adhesive does not become the weakest link [59].

2.1.4 Margin and spacing of bars

The margin and spacing of the bar are important factors that affect the failure mode of the glued-in rod connection, but different scholars have different views. Serrano et al. [18] pointed out that a small distance between the implanted bars could lead to splitting damage of the wood and thus affect the strength of the connection. According to Steriger [10], when the edge distance was less than 2.3 times the diameter of the screw, the fracture mainly occurred in the specimens, and the anchorage pull-out distance of the specimens increased.

In practical engineering, multiple reinforcement bars are usually planted on the same end of the component to enhance the bearing capacity of the connection. For multiple rod connections, the spacing between rods is an important factor affecting the bearing capacity of the connections. Blass et al. [60] investigated the spacing between rods and recommended that the minimum distance between rods and the spacing between rods should be not less than 2.5d and 5d respectively (d was the diameter of the rods). The study of Broughton and Hutchinson [16] was consistent with the previous conclusion and showed that the bearing capacity of the doubled glued-in rods connection could increase twice compared to a joint with a single rod, provided that the former met the minimum spacing requirement. Hans [61] compared the influence of different bar spacing on the anchorage pull-out strength, the specimens were all embedded with three bars in the same position. The results showed that there was mutual influence among the bar spacing, but when the screw spacing was greater than the screw diameter by 2.5 times, the interaction could be neglected. The draft European Code (EC5 2003) [23] suggested the following values for the spacing and edge distance: in the perpendicular to grain direction, the insert spacing and end distance are not less than 4d, and the edge distance is not less than 2.5d; in the parallel to grain direction, the insert edge distance is not less than 2.5d, and the insert spacing is not less than 4d. However, Muciaccia [62] suggested that a single value of spacing should not be provided in design standards if the full capacity of the adhesive was to be exploited.

The failure model of the glued-in rod connection is related to the distance between the wood boundary and the bar. Steiger [10] showed that the pull-out strength of the glued-in rod connections decreased significantly when the edge distance was less than 2.3d. Serrano [18] showed that the boundary distance was too small and cracking failure of the wood often occurred and played a decisive role in the strength of the connection. Blass and Laskewitz [60] studied the effect of boundary distance and spacing of glued reinforcement on axial pullout strength. It was suggested that the edge should not be less than 2d to avoid the inevitable error in the process of drilling, and the results showed that the strength of the connection would decrease when the edge was less than 2.5d. The edge distance and spacing specifications for GIR in various standards are shown in Fig. 6 and Table 3.

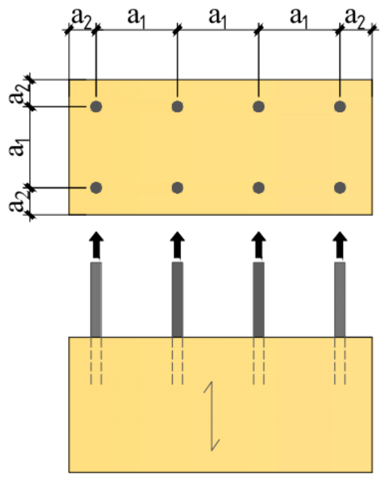


Table 3 Margin and spacing requirements under different standards

Different standard recommended values	a_1	a_2
PrEN 1995:2001 [23]	4*d*	2.5*d*
DIN 1053:2004-08 [63]	5*d*	2.5*d*
STEP1 [20]	2*d*	1.5*d*
French Professional Guide [64]	3*d*	2.5*d*

Fig. 6 Comparison of insert bars edge distance requirements under different specifications

2.2 Material parameters

2.2.1 Types of reinforcement

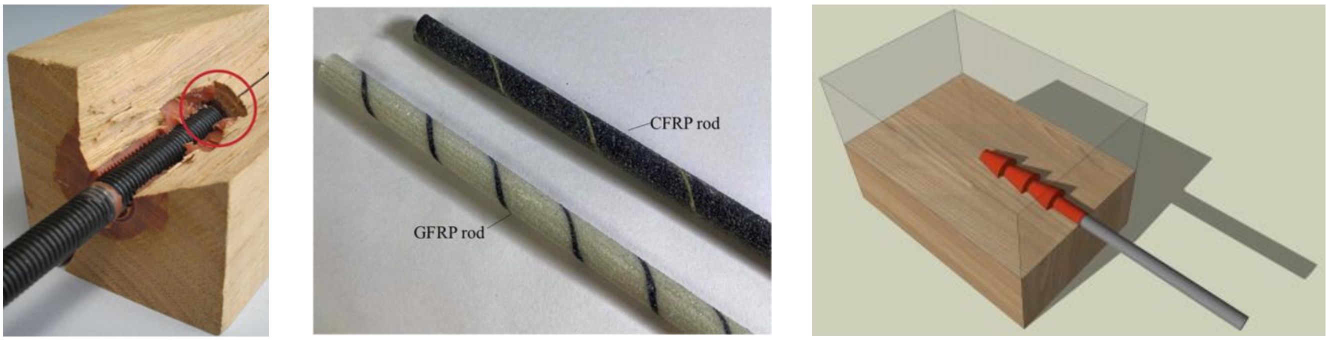
Various types of bars can be used for reinforcement planting, including ordinary rebar, bolt bars, FRP bars/plates, and steel plates. Due to the differences in the material properties and surface conditions of different types of bars, the adhesion properties between them and wood are different. In some countries, experimental studies of glued-in rod connections have been conducted for LVL structures using different reinforcement materials [14, 65], as well as investigations on embedded connections and flexural connections for LVL using GFRP bars for reinforcement [17, 53]. Besides, Jung et al. [66] used maple compression lumber as a pin bar for reinforcement planting in Japan. It can be concluded that there are many types of materials used as reinforcement inserts. Table 4 shows the influence of different kinds of reinforcement on the mechanical properties of GIR connections.

Table 4 Mechanical properties of GIR inserted with different types of reinforcement

Ref.	Type of reinforcement	*d* (mm)	*l* (mm)	*t* (mm)	F_u (kN)	Ultimate stress (MPa)	Additional details

Wiktor [68]	HRB400 rebar	16	405	1.5	128.8	2.95	Pullout test; the epoxy glue "IFC-SP"; rebar yielding
Raftery [69]	BFRP rods	12	3610	2	-	28.7 (bending)	Four point bending test; A phenol resorcinol formaldehyde (PRF) adhesive
	GFRP rods		3610	2	-	26.2 (bending)	
Neill [70]	BFRP rods	12	80	2	29.71		Pull-bending test; parallel-to the grain
			180	2	59.72	-	
			280	2	74.57		Wood species is BS EN 338 (C16 graded; density=310 kg/m^3);
			600	2	93.12		
Zhu [36]	GFRP rods	12.7	50	1.5	14.2		The single sided tests;
			100	1.5	22.1		Two-component PUR structural adhesive;
			150	1.5	26.6	-	
			200	1.5	32.9		Glue-laminated timber
			250	1.5	34.9		(density=562 kg/m^3)
Fave [75]	CFRP plates	25×3 (cross sectional dimensions)	50	2	52.9	10.58	Pullout test;
			100	2	84.22	8.42	Plane weave textile reinforcements;
			150	2	106.3	7.09	
	GFRP plates	25×3 (cross sectional dimensions)	50	2	52.18	10.44	Parallel to the grain;
			100	2	65.88	6.59	Glulam (density=380 kg/m^3)
			150	2	63.6	4.24	
Javier [79]	Multi-bulb anchors	12 (with 2 bulbs)	90	1	31.25		Hilti Hit Re-500 epoxy adhesive;
		12(with 3 bulbs)	120	1	44.27		Laminated wood (density=425.62 kg/m^3.);
		12 (with 4 bulbs)	150	1	57.17		
	Threaded steel rods	12	90	1	49.56		
			120	1	63.92		
			150	1	75.37		

In some studiess, steel bars (often referred to as ribbed bars) have been used in place of threaded rods as the reinforcing insert material, as shown in Fig.7 (a). In Finland, an oblique cross-angle steel bonded connection, called V-joints or V-connections [40, 50], was developed and has proved to be an effective alternative to threaded rods. The material used for inserting rods is usually steel, where metric threaded rods are commonly used [6, 67, 68], mainly because threaded rods increase the gluing area and mechanical embedding in the wood connection process and are suitable for connections between steel and wood. Lin [49] carried out tensile tests on glued laminated wood rebar and bolt rod rebar specimens, and the results showed that for rebar inserting, the yield failure of rebar would occur when the anchorage length reached a certain value, and because the surface of rebar was relatively rough, it was easy to produce oblique extrusion to the surrounding wood in the process of rebar. Due to the fine and uniform distribution of the external screw thread, the bolt rod only generated shear stress along with the interface during the pull-out process. Without the oblique extruding action similar to that of the rebar, the failure mode of bolted bar-embedded joints was mainly interfaced or circumferential shear failure of wood. Javier et al. [79] investigated a novel type of anchorage as shown in Fig. 7(c). The multiple widenings or bulbs along the length of the bore, and the test results showed that using multi-bulbs anchors was superior to using straight anchors for specimens with pushout strength increases ranging from 32% to 59%.



(a) Ribbed rebar [58] (b) GFRP and CFRP rods with helical wrapping [77] (c) Multi-bulb anchor [79]

Fig. 7 Several illustrations of reinforcement in GIR connections

In addition, FRP materials such as glass fiber reinforced plastic (GFRP) [17, 71] and carbon fiber reinforced plastic (CFRP) [69, 71] can be used in glued-in rod connections, since according to Muller and Roth [73] they have the advantages of easy processing, light weight, and good corrosion resistance. Other scholars had also done related experiments [16, 17], and the results showed that these materials also perform well in terms of ease of fabrication, light weight, and statically efficient connections. Yeboah et al. [74] conducted pull-out tests on BFRP rods glued-in laminated wood specimens, and the results showed that the pull-out load of the inserted reinforcement increased slightly when the anchorage length reached 15d and above, and increased linearly with the anchorage length less than 15d. Fave et al. [75] investigated the pull-out performance of glued-in FRP plates bonded in laminated wood, and the results showed that the typical failure mode was either glue layer/ FRP interface failure or glue layer/ laminated wood interface failure, and fracture failure of FRP occurred when the anchorage length reached 15cm. Zhu et al. [76] tested the bonding properties of GRFP reinforced glulam specimens, and the test results showed that the ultimate load of the specimens gradually increased with an increase in the anchorage length; some specimens experienced interface damage and wood splitting damage. Toumpanaki and Ramage [77] conducted monotonic and cyclic loading tests on timber GIR joints with GFRP and CFRP rods, respectively, and the surface morphologies of the two bars are as shown in Fig. 7(b). found that the CFRP rods had an 11% higher uplift loading capacity than the GFRP bars under monotonic loading, but with better bonding of the GFRP bars to the timber matrix. Besides that, cyclic loading had no effect on the bonding performance of the wood GIR joints. Zhang et al. [78] investigated the bond-slip performance between the embedded CFRP reinforcement and wood, and the results showed that the improved BPE simulation could better simulate the local bond-slip relationship curves between wood and CFRP reinforcement. Raftery et al. [69] conducted an experimental study on the flexural performance of low-grade glued laminated timber beams inserted with BFRP rods, demonstrating that the flexural performance of timber beams inserted with BFRP rods was comparable to that of beams reinforced with GFRP rods, and obtaining that a modest reinforcement rate of 1.4% resulted in the highest flexural performance.

2.2.2 Types of adhesives

During the axial drawing of the glued-in rod connection, the adhesive is used to carry out the load transfer between the wood and the inserted reinforcement, so the bonding performance of the glued-in rod connection depends on the shear resistance of the adhesive. However, in some cases, it is more reasonable to consider the bond between the threaded rod and the adhesive as a mechanical connection based on the surface characteristics of the rod and its surface treatment [80, 81]. There are many types of adhesives used for glued-in rod connections. Kemmsies [67] examined 12 alternative adhesives and sealants for GIR connections, and they were divided into three grades, as shown in Table 5. An adhesive with good working and high-strength characteristics was represented by grade A. Grade B was the adhesive that makes the appropriate working claims; however, it was unclear whether the adhesive has cohesive issues. Grade C stands for this kind of adhesive, which shouldn't be employed going forward. Broughton and Hutchinson [16] considered several adhesives, namely epoxy resin (EPX), polyurethane (PUR) acrylics (AC), and phenol-resorcinol-formaldehyde (PRF) in LVL structure for gluing reinforcement performance. The results showed that, the damage pattern of the EPX specimen was different from other adhesives and characterized by the wood failure near the wood/adhesive interface, and the average shear strength of 4.6-7.1 MPa. AC, PRF, and PUR adhesives failed at the wood/adhesive interface and had lower pull-out strength than EPX. Serrano [18] showed that the strength of glued-in rod connections with different adhesives was PRF＜PUR＜EPX, and the load-deformation curves showed that PRF adhesives had better toughness behavior, and synthetic EPX adhesives was the best for use in reinforcement connections.

Table 5 Comparison of the mechanical characteristics and grading of 12 adhesives [67]

Typr of adhesive		Anchorage length/adhesive thickness				Grade
		160/0.5		160/1		
		Mean shear strength (MPa)	Stiffness (kN/mm)	Mean shear strength (MPa)	Stiffness (kN/mm)	
Epoxy	EP1	7.78	-	8.53	-	Grade A, used in GIROD

	EP2	7.76	142	8.24	157	Grade A, used for steel-wood structure
	EP3	8.47	173	8.67	188	Grade A, used for steel-wood structure
Polyurethane	PU1	7.33	-	7.5	-	Grade A, used in GIROD
	PU2	8.65	141	8.16	141	Grade A, used for steel-wood structure
	PU3	5.37	71	5.72	82	Grade B, for structural timber adhesion
	PU4	3.41	84	4.56	42	Grade C, for structural timber adhesion
Sealant adhesive	SA1	2.39	13	1.77	7	Grade C, for non-load-bearing applications
	SA2	2.59	13	1.79	8	Grade C, for non-load-bearing applications
	SA3	3.32	17	2.49	13	Grade C, experimental
	SA4	1.93	9	1.41	14	Grade C, experimental
PRF	PRF	7.93	-	6.44	-	Grade B, used in GIROD

Besides, temperature and humidity affect the durability of adhesives in wood GIR joints and research on the thermal moisture effects of adhesives has been conducted [82, 83]. The heating and cooling phases of the adhesive inside the wood structure have been shown to be consistent with the structure's external temperature variation [84, 85], whereas the bonding process of the adhesive used in the GIR joints is time-consuming, and the external temperature and humidity variation also affect the adhesive's bonding performance. Aicher and Dill [86] revealed that when the epoxy resin adhesive reached an intrinsic critical temperature (also known as the glass transition temperature T_g), the internal structure of the adhesive underwent irreversible changes, significantly reducing the loading capacity of the GIR joints. Lartigau et al. [87] found that when the test temperature was higher than 601°C ($T_g = 581$℃), the stiffness of the GIR joints was significantly reduced. As a result, the adhesive's inherent mechanical properties have a significant influence on the mechanical properties of the wood GIR joints, and the durability of the GIR is primarily determined by the thermomechanical properties of the chosen adhesive.

Furthermore, the GIR adhesive's sluggish rate of curing is likely to cause issues like alignment flaws, therefore the issue of how to speed up the adhesive's curing is one that needs to be resolved. Ratsch et al. [88, 89] conducted a series of studies to solve the problem above; the first step was through the controlled induction heating of the two-component adhesives (2K-EPX and 2K-PUR, respectively) to hasten the curing process; in the second step, methods including inductive and resistive heating were used to accelerate curing; and the results demonstrated that both of the above methods accelerated the negative effect of processing defects (wood moisture, oil contamination of the threaded rod, adhesive voids, and rod corrosion) on the mechanical properties of the joints; and the results demonstrated that both of the above, and the epoxy resin could be obtained with better durability to some extent. Voß and Vallée [90] demonstrated that using Curie-Particles (CP) exposed to a high-frequency (HF) alternating electromagnetic field (EMF) method, the adhesive curing speed for the GIR joints of GLT could be reduced from

1-10 days to 10 minutes.

In conclusion, the two-component PUR and EPX are the most used adhesives in Sweden, UK, Switzerland, German [18], and New Zealand [65].

2.2.3 Species of wood

The properties of wood vary widely, and the physical and mechanical properties of wood have an impact on the connection bond properties. The main factors include wood density, moisture content, strength grade, and dimensional specifications, among which the effects of wood density and moisture content have been studied more.

Different scholars have different views on the effect of wood density on the performance of glued-in rod connections. Glued-in rods connections can be used to reinforce the old timber structures [29], which were widely built of hardwood, but existing design experience formulas are primarily based on low-density softwoods, with little research on high-density hardwoods. Kemmsies [67] concluded that the pullout resistance of the glued-in rod connections with the same species of glulam did not depend on the wood density. The results of Bengtsson and Johansson [56], Bernasconi.[91] and Serrano [18] showed that the correlation between wood density and the pullout resistance of glued-in rod connections was small. Aicher and Gustagsson [38] obtained a power exponential model for the relationship between the pullout strength of the reinforcement and the wood density.

Table 6 Effects of wood density on the mechanical characteristics of GIR connections

Ref.	Type of wood	Density (kg/m^3)	*d-l-t* (mm)	Ultimate load (kN)	Stiffness (kN/mm^2)
Jung [66]	Compressed wood (CW0)	330	12-120-0.5	2.504	15.8
	Compressed wood (CW50)	660	12-120-0.5	2.627	18.3
	Compressed wood (CW57)	767	12-120-0.5	2.65	17.2
	Compressed wood (CW63)	892	12-120-0.5	2.178	14.5
	Compressed wood (CW67)	1000	12-120-0.5	2.86	18.5
Otero [95]	spruce (Picea abies)	443.86	12-120-1	29.01	5.49
	Eucalyptus (Eucaliptus globulus)	795.07	12-120-1	44.57	8.44
Cimadevila [96]	Tali wood	856.36	24-200-1	152.99	10.15
			27-200-1	160.84	9.48

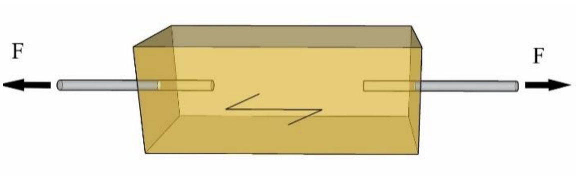
On the contrary, it has also been shown that wood density may have some influence on the mechanical properties of the GIR connections [52, 92-94], with softwoods and high-density hardwoods exhibiting significant differences. The use of different densities of wood also has a certain influence on the bonding and anchoring performance of GIR connections, as shown in Table 6. Otero et al. [29, 95] compared the densities of two types of glued laminated timber: eucalyptus(density=734.93kg/m^3) and spruce (density=443.86kg/m^3). The results showed that the higher the wood density, the less the slenderness ratio affected the mechanical properties of the joints, and the higher the pullout strength of the joints. According to Steriger et al. [10] and Widmann et al. [37], the relationship between tensile strength and wood density was 0.55 and 0.25. Cimadevila et al. [96] used a two-component Hilti HIT-RE 500 resin to insert reinforcement into Tali wood, which is a high-density hardwood rather than a low-density softwood, and performed push-out tests as well as a comparison with existing theoretical formulations (including the one in the EC5 informative appendix [23]), and the results showed that the bond performance of hardwood GIR joints was better than softwood. In order to investigate the moment-rotation behavior of hardwood and softwood GIR connections. Ogrizovic et al. [97] used columns subjected to shear and bending for three types of wood (including hardwood and softwood) separately to simulate column foundations in frames. The results showed that both types of GIR connections could withstand repeated loading cycles at increasing rotational amplitudes without losing strength or stiffness, but hardwood connections outperformed softwood connections. Molina et al. [98] compared the bonding performance of Eucalyptus citriodora wood and Pinus taeda wood GIR connections under fatigue loading and showed that the former was superior.

Changes in moisture content of wood can cause dry shrinkage and wet rise, which can lead to stresses in the adhesive layer and reduce the bond performance. Also, the degree of influence of moisture content on the mechanical properties of glued-in rod connections is related to the type of adhesive. Aicher and Dill-Langer [86] found that the use of EPX glued reinforcement under long-term and short-term loading conditions was largely unaffected by humid environments. However, resorcinol glued reinforcement significantly reduced strength in high humidity environments and was sensitive to humidity and variation of load. The short-term strength of PUR glued reinforcement also decreased under high humidity conditions. Wiktor [68] studied the effect of moisture content variation on the strength of glued-in rod connections under the conditions of laminated wood using EPX reinforcement and showed that the effect of moisture content variation on glued reinforcement was is less than the effect of the properties of the wood itself. Harvey and Ansell [17] studied the effect of moisture content on the strength of LVL after implantation with GFRP rods, when the moisture content increased, damage often occurred at the wood/adhesive contact surface and the pullout strength was low. Shekarchi et al. [99] conducted a pull-push test on 324 single reinforcement joints immersed in seawater from 0 to 90 days. The results showed that specimens with GFRP rods and steel rods had a significant reduction in ultimate load at the initial stage of exposure and pull-out load capacity reduced by 39% and 55% respectively.

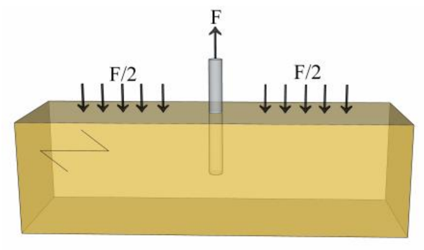
In conclusion, the mechanical properties of the glued-in rod connections showed a decreasing trend with an increase in wood moisture content; the effect of wood density on the mechanical properties of the glued-in rod connections was not uniformly concluded, and further research was needed.

2.3 Loads and Boundary Conditions

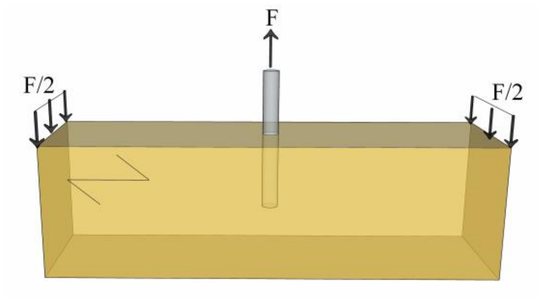
Fig. 8 shows several typical loading and boundary conditions for the pull-out test of glued-in rod connections in wood structures [99]. Among them, the two-end tensile mode (Fig. 8(a)) can reflect the actual stress state of the glued-in rod connections more realistically, but the specimen fabrication is difficult, especially for the alignment of the reinforcement at both ends; the pull-out mode (Fig. 8(b)) is the most simple and effective, and the most commonly used test device in the concrete bond-anchorage test, but the disadvantage of this test method is that the stress field generated by the loaded end block can affect the distribution of adhesive shear stresses between the insert interfaces. It has been shown that the pull-out load obtained from the two-end pull-out test is about 42% higher compared to that obtained from the pull-out test under the same conditions [16]. The beam pullout model (Fig. 8(c)) and pile anchorage pullout model (Fig. 4(d)) are considered as an improvement to the pullout model (Fig. 8(b)), which can effectively mitigate the effect of loaded end block on the distribution of adhesive shear stress at the interface.



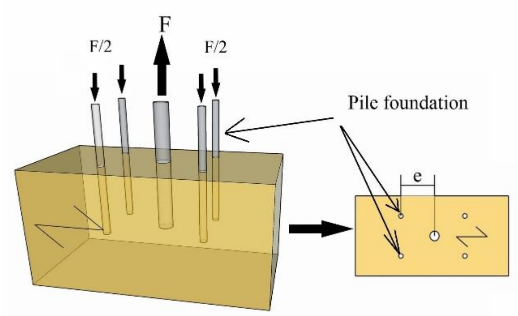
(a) Pull-pull



(b) Pull-compression



(c) Pull-beam



(d) Pill-pile foundation

Fig.8 Several loading and boundary conditions

The insert directions include parallel to the grain, perpendicular to the grain, and oblique insert. The early studies were done in parallel to grain or perpendicular to the grain direction. Planting bar along the oblique direction was first proposed by Tlustochowicz et al. [100] to enhance the shear capacity of the laminated timber beams and later developed into a connector capable of transmitting bending moments. Oblique glued reinforcement requires the full use of the ultimate strength of the steel to ensure that the load-bearing capacity of both the steel and the wood is matched. It was generally believed that the strength of the bar planted parallel to the grain was the highest, but the strength of the bar planted perpendicular to the grain was the lowest, which was confirmed by the tests carried out in the GIROD project [41]. However, some studies [37, 101] showed the opposite, the strength was higher in the perpendicular to grain direction than in the parallel. In addition, Harver and Ansell [17] inserted GFRP bars in LVL members and conducted an experimental study, which showed that the par-grain and cross-grain directions of the insert did not have a significant effect on the strength. Rorbert Malczyk [30] glued oblique rebars with epoxy into Douglas-fir glulam at angles of 15°, 30°, and 45°, and the results showed that the best strength was for the 30°.

Gattesco et al. [102] first conducted a flexural experimental study on timber beams with threaded steel rods under monotonic loading to investigate the effects of transverse screw restraint, different rod arrangements and different rod force characteristics on the performance of the GIR joints; the study yielded negligible effects of transverse screws on node ductility, while the selection of a reasonable steel type for rods could result in better ductile The tests were then extended to a cyclic loading, which was used to simulate the effects of seismic action. The results showed that the GIR joints had a high dissipation capacity at the beginning of the test, but after a few cycles, the dissipation capacity was greatly reduced due to the longitudinal splitting of the timber, which led to the lateral instability of the joints. Madhoushi and Ansell [103, 104] performed static load testing, fatigue tests, and simulated seismic tests on L- shaped and U-shaped LVL joints with GFRP bars. The findings demonstrated that under displacement control mode, the joints could withstand reverse cyclic loading with good ductility and energy dissipation capacity, but that under static loading, linear elasticity was mostly responsible for damage to the joints. Toumpanali and Ramage [105] investigated the axial loading capacity and stiffness of timber with CFRP and GFRP bars under cyclic loading. When the anchorage length was $5d$, the axial loading capacity of GFRP rods was 23% higher than that of CFRP rods, while the axial tensile stiffness was 20% lower. The axial loading capacity of GFRP rods tended to stabilize as the bond length increased when the anchorage length was greater than $10d$.

2.4 Influence of manufacturing process

The fabrication process of glued-in rod connections requires strict quality control of the production process of glued-in connections by ensuring specific curing conditions of the adhesive (i.e., temperature and moisture content) and precise control of the geometry of the connections [53]. The high requirements of the production process make the use of glued-in rod connections on construction sites difficult, which limits the possibility of using them to strengthen existing structures. There is still no method of strict control over the production process in many countries, even at domestic production plants [64]. In addition, processing defects can also affect the mechanical properties of the GIR connections, such as the degree of filling of the adhesive, the presence of bubbles in the adhesive layer and the alignment of the bars.

Xu et al. [106] carried out experimental on two types of positional defects of the rod in the joints (eccentric position of rod and inclined setting of the rod) to investigate the effect of pullout mechanical properties of the joints under the influence of three different adhesive layer thicknesses. As the adhesive thickness increased, the loading capacity and stiffness increased for the vertically eccentric position (similar to the findings for the centrally positioned insert), while there is no significant relationship for the specimens inserted in an inclined manner. Furthermore, Gonzales et al. [107] demonstrated that the effect of the position of the inserted rod on the mechanical properties could be negligible if the anchorage length was sufficient. The above discussion demonstrates that the effect of the reinforcement's position deviation on the mechanical properties of the glued-in rods connections can be ignored.

Grunwald [108] used numerical methods to investigate the effect of construction defects on the mechanical properties of GIR connections and discovered that connections with a 50% adhesive loss could still reach 70%. Bengtsson et al. [56] came to a similar conclusion, claiming that when the adhesive lost 50% compared to normal, the loading capacity of the connections was only reduced by 20-39%. The above results show that bond void defects and glue loss defects have a much smaller effect on the loading capacity of the nodes than is commonly believed.

Different fabrication processes for glued-in rod connections have been described [134]. Johansson [54] proved the possibility of inserting bars laterally to create the connections. But this way led to an uneven distribution of the adhesive and a significant reduction of the pullout strength of the glued-in rod connection. Syme [109] proposed a method to screw rods into smaller holes, which required that the bottom of the hole was first filled with adhesive half the length of the hole, and the rod has a notch distributed along the length of the rod, allowing the adhesive to be filled evenly all the way through and can spill out. However, it was not possible to avoid this effect by inserting non-horizontally or horizontally inclined bars. If the drill hole is larger than the diameter of the bar, a simple solution is to apply a small amount of adhesive to the bottom of the hole and insert the bar (rotating at the same time to ensure a uniform expansion). This method usually requires some equipment to insert the rebar, because if the rebar connection has a long bonding length, then the force of the screw-in is too large to be manually operated.

One possible method of rebar placement is to drill a small hole perpendicular to the end of the insertion hole and fill it with adhesive, as shown in Fig. 7. In addition, a hole is drilled near the free end of the drill pipe, which is used to fill the pre-embedded hole evenly with an adhesive and to remove air bubbles. After the parallel rod is inserted, the hole is filled if the adhesive overflows. In addition to this method, several other methods can be used, such as using a hollow rod of smaller diameter through which the glue can be inserted [110]. The fabrication of glued-in rod connections requires a high level of the production process. An effective method for good reinforcement adhesion is to clean the surface of the inserted rod and the hole. However, cleaning the inner surface of the borehole and making it flat is difficult. Therefore, for economic reasons, the surface cleaning of the inner wall of the hole is not usually carried out.

As shown in Fig. 9, one possible method of planting reinforcement is to drill a small hole vertically near the end of the embedded hole and fill it with adhesive. In addition, a hole is also drilled near the free end of the drill rod, which serves to fill the pre-embedded hole completely and evenly with adhesive and remove air bubbles. After inserting and spinning the rod, if the adhesive overflows it indicates that the entire hole has been filled. In addition to this approach, some other fabrication methods should be used, such as the use of smaller diameter hollow rods into which the adhesive can be injected through this central hollow hole [110].

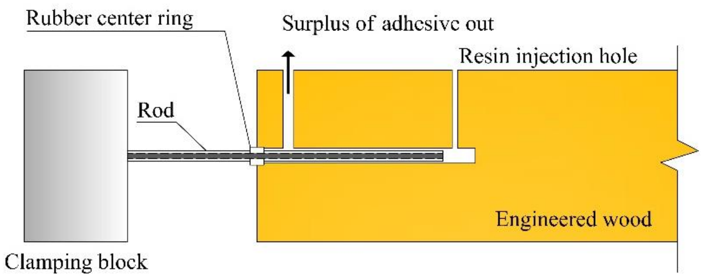


Fig.9 One of the available methods of gluing-in rods [99]

There are also glued-in rod connections where the size of the hole is smaller than the diameter of the inserted bar. In this case, the diameter of the hole is usually equal to the nominal diameter of the threaded rod minus the depth of the threads. This type of glued-in rod connection is formed by applying an adhesive to the hole and the rod, which is then screwed into the hole. The advantage of this method was that the adhesive was better retained in the hole before curing, but the disadvantage was that it was hard to ensure that the adhesive could uniformly cover all parts of the rod. Therefore, if the hole diameter was less than (or equal to) the bar diameter of the glued-in rod connection, it was recommended to cut slots in the threaded rod to ensure the diffusion of the adhesive inside [111].

2.5 Multiple rods connection

Turkovsky [101] first proposed that when a glued-in rod connection had multiple bars inserted, the uneven stress distribution between different bars should be considered. The literature [25, 112] presented some applications of multiple rod connections. In Fig. 8(a), schematic diagram of the test of a wood-steel connection with multiple reinforcement bars inserted according to different insertion methods under monotonic transverse loading was shown, and a cyclic loading test was performed on one of the glued-in rod connections with the highest bearing capacity. Three types of connections were made using M20 bars inserted in glulam timber in the direction of the grain (Fig. 10(a)); at an angle of 20° (Fig. 10(b)) and with transverse ties (Fig. 10(c)). It was found that the specimens reinforced parallel to grain exhibited the best performance and good seismic resistance under monotonic and cyclic loading. Parida et al. [113] investigated the effect of strength, diameter, and number of reinforcement bars on the mechanical properties of GIR connections, as shown in Fig. 8(d) for a group of 12 high strength small diameter specimens (group GS) and Fig. 8(f) for a group of four lower strength larger diameter specimens (group GB). The tensile load capacity of the GB and GS groups was 425kN and 422kN, respectively, according to the results. The GB group's load capacity was similar to the theoretical value, but the GS group's load capacity was lower than the theoretical predicted value, indicating that the GIR connection was not suitable for high strength reinforcement.

Table 7 Comparison of the mechanical behavior of GIR connections with different implantation bar numbers

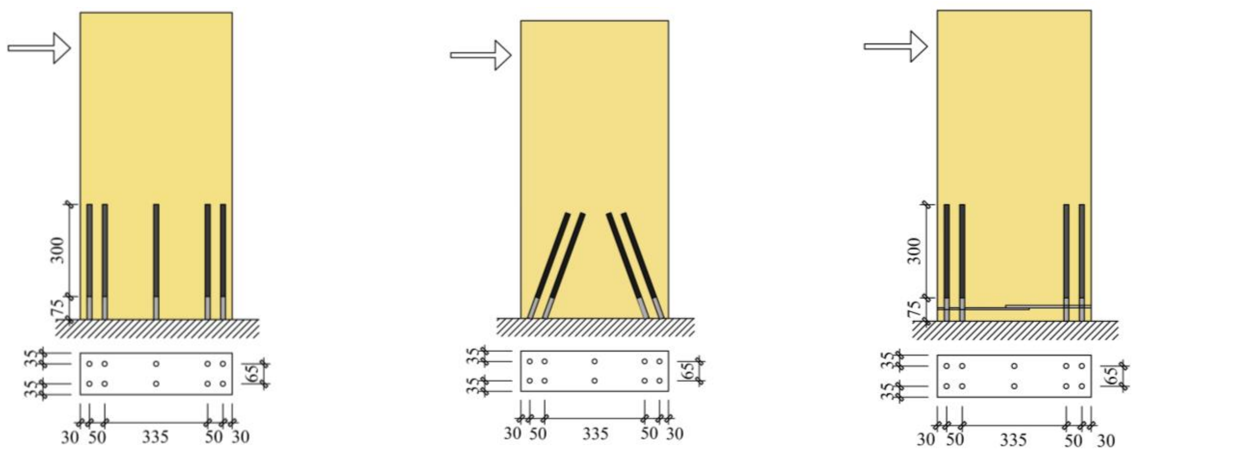
Ref.	No.	a_1 (mm)	a_2/mm	$d-\lambda-d_h$	Bearing capacity/kN	Stress /MPa	Detailed description
Baroth [116]	2	125	62.5	12-40-16	Not given	194.3[a]	Bending tests on beam connectionsparallel to the grain
	2	125	100	12-40-16		176.7[a]	
	8	60	30	25-40-30		238.3[a]	
Stamatopoulos [117]	2	40	50	20-22.5-15	235.5 (1.72[b])	Not given	The 'remote' pull-push test; glulam (400 kg/m^3); threaded rods with 15°
	2	80	30	20-22.5-15	258.9 (1.89[b])		
Gonzales [118]	1	-	More than 36mm	12.7-5-16	29.1	Not given	Pullout tests parallel to the grain; Glulam (530 kg/m^3); The failure type is bond failure
	2	26			14.9		
	2	48			18.3		
	2	60			24.8		
	3	26			18.5		
	3	48			19.5		
	3	60			22.7		
	4	26			17.7		
	4	48			17.6		
	4	60			24.7		
Bouchard [133]	4	63.5 (4d)	37.8 (2.38d)	15.8-25-19	277	Not given	Pull-pull tests; Glulam (497 kg/m^3)
	6	63.5 (4d)	40.5 (2.55d)	15.8-25-19	418		
	8	63.5 (4d)	43.8 (2.76d)	15.8-25-19	679		

10	63.5 (4d)	46.5 (2.92d)	15.8-25-19	876

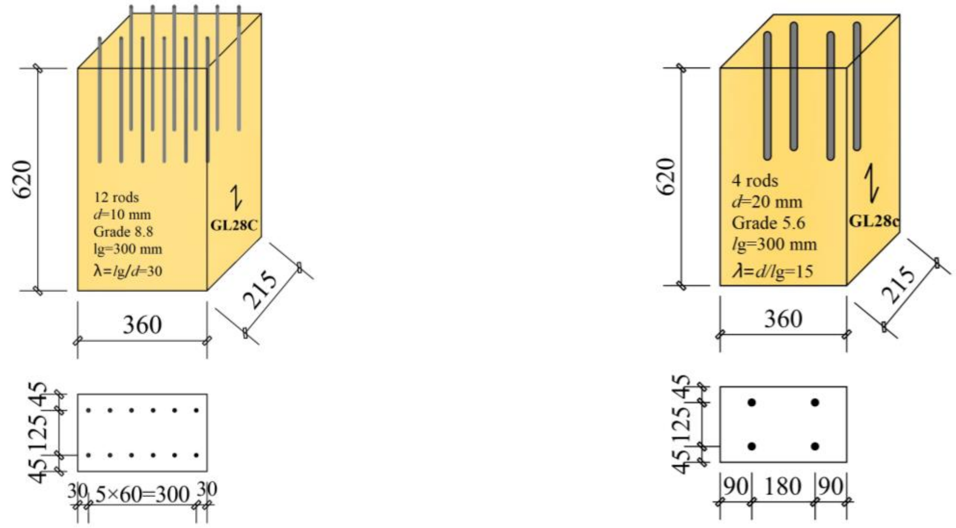
a: Bending bearing capacity;

b Mean capacities of specimens with single rods as measured experimentally [114]

The differences in bonding mechanical properties of the GIR connections inserted with various numbers of rods are summarized and compared in Table 7. Gattesco and Gubana [115] carried out an experimental study on different glued-in bars connections with 2-4 rods. It was shown that ductile failure could be achieved by selecting appropriate parameters such as edge distance, anchorage length, and reinforcement material. Baroth et al. [116] explored methods to improve the ductility of the span in the glued-in rod connections. In conclusion, compared to a single rod connection, when brittle damage occurs, the failure of one rod may cause the failure of the entire connection even if the load does not undergo plastic redistribution. Stamatopoulos and Malo [117] conducted pullout tests on 324 glued-laminated timber specimens with two threaded rods to evaluate the interaction effects (group effect), and the effective number of rods was 1.72-1.94. Gonzalez et al. [118] investigated the tensile strength of laminated timber with multiple glued-in steel rods (two, three, and four). The result showed that ductile failure occurred when the distance between rods equaled 5d and the bonding length was larger than 10d. But some studies have come to the opposite conclusion. Bouchard et al. [133] conducted an experimental study of GIR nodes (with and without transverse reinforcement) inserted with 4, 6, 8, and 10 steel threaded rods and found no significant relationship (group effect) between the number of glued in rods and the reduction of tensile strength and ductility.



(a) Multiple GIR in the grain direction [25] (b) Multiple GIR at an angle of 20° [25] (c) Multiple GIR with stirrups [25]



(d) Multiple GIR with higher-strength rods [113] (e) Multiple GIR with larger diameter rods [113]

Fig.10 Bar arrangements for testing of moment-resistant joints

3 Study on the performance of the glued-in rod connections in wood structure

3.1 Study on mechanical properties of glued-in rod connections in wood structure

Glued-in connections can be used as load-bearing connections for structures, typically between timber-timber and timber-steel connections. Fig. 11 showed the application of the glued-in rod connections in frame structures and foundations and analyzes its static bearing capacity. The results showed that the glued in bolt bars exhibited excellent mechanical properties in many aspects [109, 119, 120]. The main advantage of wood-wood glued-in rod connection is that the reinforcement is embedded in the wood member, which allows the structure to be aesthetically pleasing and meet the load-bearing capacity requirements. In addition, this type of glued in rods provides better protection of the connections from fire and corrosion (such as indoor swimming facilities), and the timber members can be used as kink protection for the inserted reinforcement.

Usually, glued-in rod connections are used instead of corners in frame structures, when larger bending moments occur, for example with corners made of steel profiles, which can be easily attached to wooden frame members using glue-laminated bars. However, this solution may be prone to corrosion and requires the application of appropriate surface protection or the selection of special quality steel. Due to the design errors of large-scale components, the damp deformation of wood is easy to be caused. As a result, moisture cracks can develop and radically weaken the performance of the connections.

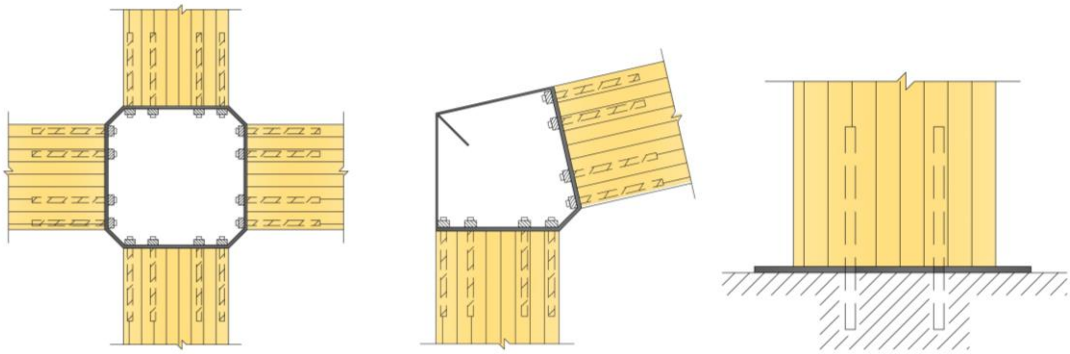


Fig. 11 Examples of applications of connections with glued-in rod [109, 119, 120]

As shown in Fig.12, the connection of planting bar in the wood structure includes the connection of timber bent frame and beam-column connections of the wood frame. Since the 1990s, many scholars have experimentally studied these two types of connection [24, 119, 121-126] focusing on the strength, stiffness, hysteresis performance, displacement ductility, and energy dissipation capacity under low reversed cyclic load. The results show that the flexural reinforcement connections with low yield point inserts (such as rebar) will yield and destroy the inserts under reciprocal loading, and the connections show better ductility and energy dissipation capacity; while for flexural reinforcement connections with strong bolt bar inserts, the ductility, and energy dissipation are relatively poor. It should be noted that for purely reinforced connections, the planting bar cannot be replaced after yielding. Parida et al. [127] installed steel connection boxes at the foot of shear walls and connected the steel boxes to the wood shear walls as a whole by means of reinforcement, and did experiments under horizontal load. The test results showed that the wood wall with planting bar as the anchor has higher bearing capacity and stiffness, but the ultimate failure mode of the connection was the shear failure of the wood around the planting bar, which belonged to the brittle failure mode. Lin [49] combined energy dissipative components with glued-in rod connections in laminated wood structure glued-in rod which allowed them to yield before the reinforcement bars. The results showed that the ductility and energy dissipation capacity of the combined glued-in rod connections with energy dissipation components were greatly improved compared with the purely reinforced connections.

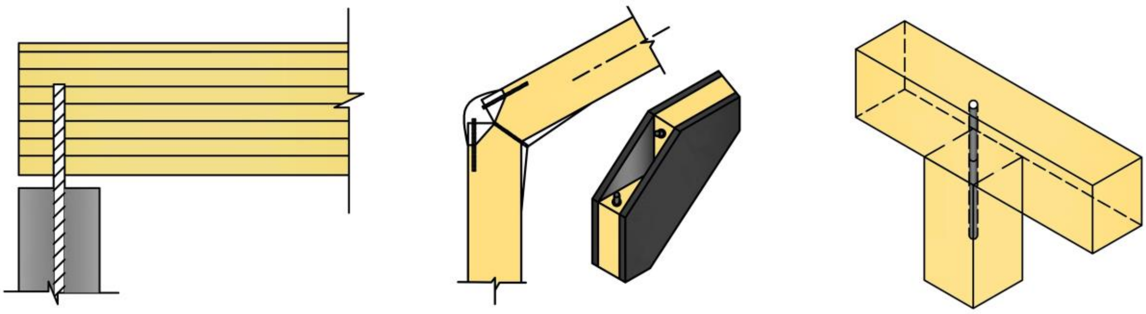
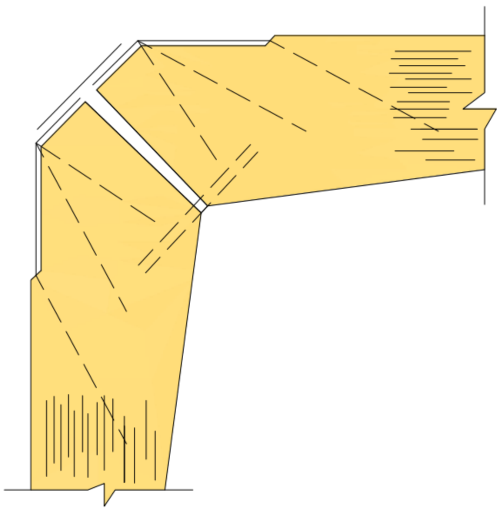
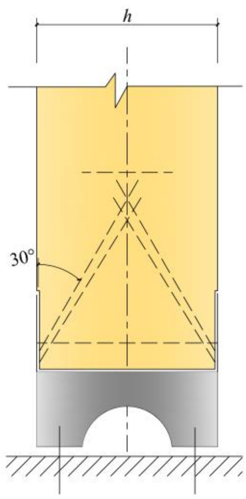


Fig.12 Examples illustrating some of the possible connection methods employing bonded-in rods

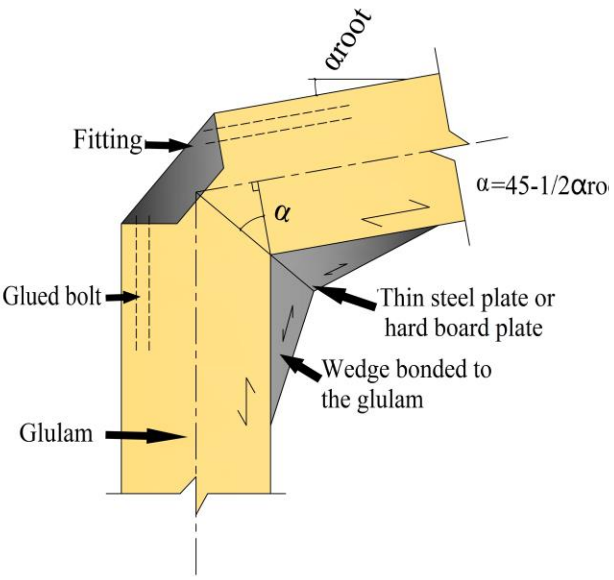
Many scholars had developed the application of glued-in rod connections in wood structure. The use of such connections was first developed in Russia in the mid-1970s [128], and a rod was inserted at the end of the wooden beam so that the force can be distributed along the inserted rod to solve the problem of excessive force on the wooden beam. Turkovskij [128] conducted tensile, compression, bending and shear tests on bending resistant glued-in rod connections with an empirical angle of 30°, and the results showed that GIR can improve the mechanical properties of bending resistant connections, and applied to reinforcing glue-laminated structures in Russia [127] (as shown in Fig. 13(a) and Fig. 13(b)). Gopu [129] studied the behavior of unreinforced Douglas-fir beams, the results showed that the ratio of the strength of the repaired beam to that of the beam without inserted bars was 1.6, indicating that the original load-bearing capacity could be restored by reinforcing the beam with inserted bars. Riberholt [39] performed tensile and shear tests on glued inserted reinforcement at the ends of glued timber beams and presented empirical equations for the load bearing capacity and strength of the glued-in rod connections. When the GIROD connections are used in door frame knee joints, there are two methods of connection see Fig. 13(a) [128] and Fig. 13(c) [39], respectively; when applied in the connection between superstructure and foundation, the connection is shown in Fig. 13(d) [109]; when applied in the reinforcement of glulam beams, in Australia Law and Yttrup [130] proposed a reinforcement method as in Fig. 13(e) for the reinforcement implantation; when applied in the connection of joists, the connection is shown in Fig. 11(f) [109].



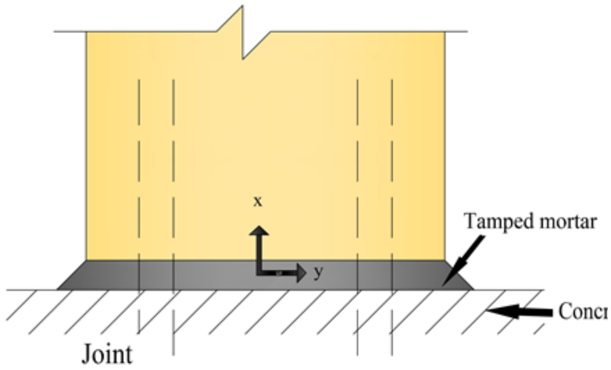
(a) Cornice Joint of frame [128]



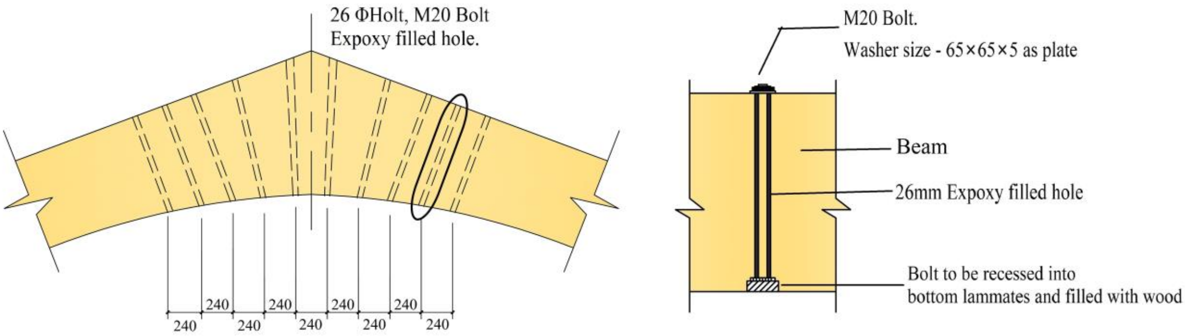
(b) Joint of the column with foundation [128]



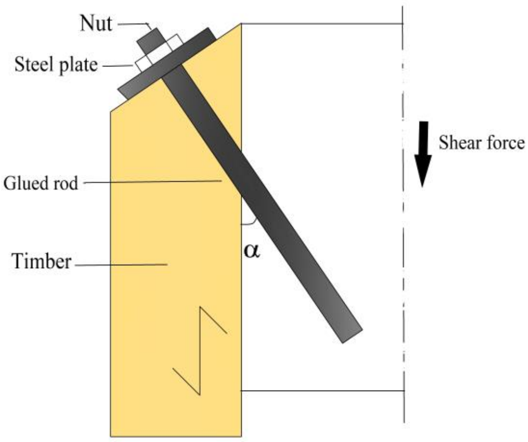
(c) Portal knee moment-resisting connection [109]



(d) Column-foundation joint [109]



(e) Repair of a curved glulam beam with epoxied steel dowels [130]



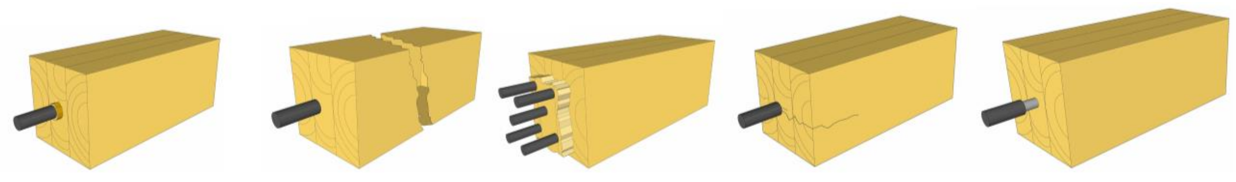
(f) Trimmer joint [109]

Fig.13 Glued-in rod connections in a wood structure

Therefore, the combination of energy-consuming components and glued-in rod connections can be released the real construction of industrial assembly, avoid planting bar on-site, ensure the quality of the connections. Through reasonable design, this kind of connection can have good ductility and energy dissipation ability.

3.2 Failure mode of glued-in rod connection

The wood connection with glued-in rod is a composite connection of three different materials and the properties of the materials determine the different failure modes. Gardelle and Morlier [131] divided the failure of the glued-in rod connections into two modes, brittle failure, and ductile failure, according to the location where the failure occurred. The brittle and ductile failure can be subdivided into two modes, respectively. It is also necessary to add a non-negligible failure mode- the yielding failure of the rod [119]. Since the yielding of the rod is ductile damage, this failure mode is the most desired in the design. It allows a very accurate calculation of the strength of the connections, which can continue to transmit loads even after damage occurs and have a certain degree of energy storage properties. In addition, the insert rod in the ductile design of the glued-in rod connections should be considered as the weakest link of the connection that will result in a stronger structure with the possibility of energy consumption (e.g. under hazardous effects such as earthquakes) [132]. If the inserted bar exhibited tensile failure before the failure occurred in the wood, then it was the yielding failure mode [80]. For this reason, mild steel (strength class: 4.6) is typically used as the material for the inserted bar. Steel with a quality class of 8.8 is typically used for high-strength woods like beech or ash. When brittle damage occurs in the rod, the rapid deformation of the rod breaks the bond between the rod and the wood, but the corresponding strain of the bond cannot occur [132]. As shown in Fig. 14, there are five possible failure modes of glued-in rod connections: (a) shear failure along the rod (bond failure); (b) tensile failure; (c) shear block failure; (d) splitting failure; and (e) yield of the rod. Besides, failure images for both single and multiple GIR connections in the actual test are shown in Fig. 15.

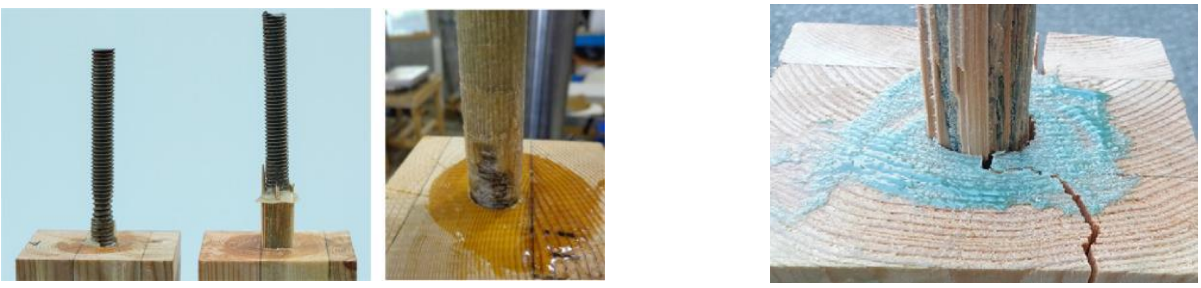


(a) (b) (c) (d) (e)

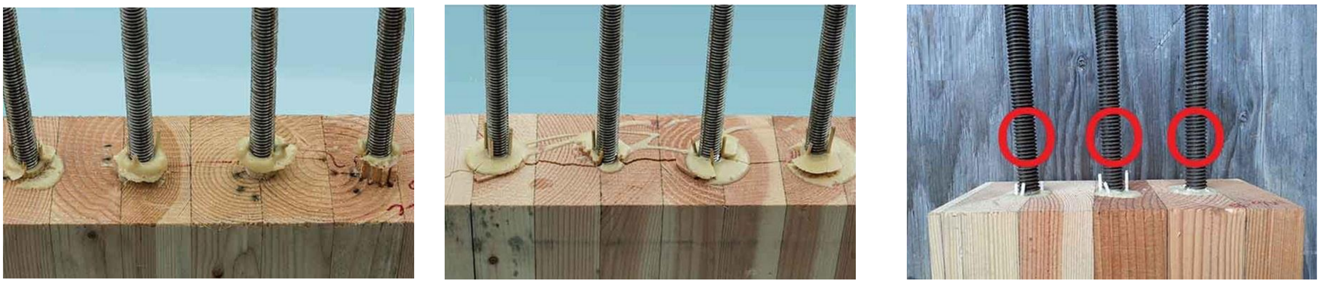
Fig.14 Types of failure modes of glued-in rod connections

(a) shear failure along the rod [32] (b) tensile failure [100] (c) shear block failure [100] (d) splitting failure [131] (e) yield of the rod [119]

Fig. 14 (a) and Fig. 14 (c) both show damage between the adhesive and wood contact surfaces caused by shear, and Fig.14 (b) shows tensile damage to the wood, which depends on the strength of the wood and the strength of the connection, and this damage tends to occur at the end of the reinforcing rod which caused by tensile stress. Fig. 14(d) shows the splitting failure of the wood and, according to Serrano [18, 19], this cracking pattern is mainly caused by too small edge spacing, which is usually the main mode of failure that tends to occur when the edge spacing is 1.5 ~ 2.25 times the rod diameter. As shown in Fig. 14(e), the yield failure of the GIR is a ductile failure mode, and the strength of the connection can be calculated very accurately even after the damage [68]. The ductile failure of glued-in rod connections is mainly designed to make the strength of the inserted steel rod the weakest part so that the wood structure can disperse the energy in hazardous conditions. Achieving ductile failure of the steel part is the best design criterion. Steel has the ductile failure mode and has stable strength and low variability for the same grade compared to wood, as well as proven design guidelines. Since the ductile failure mode of glued-in rod connections needs to occur before the other failure modes, it is advisable to use medium strength steel materials for the insert bars. There is also an important failure mode: the yielding failure of the rod [119].



(a) Single rod yielding (left); shear block failure (middle); bond failure (right) [32]   (b) Splitting of timber (single rod connection) [36]



(c) Multiple rod bond failure [118]   (d) Multiple rod splitting [118]   (e) Multiple rod yielding [118]

Fig. 15 Specimen Sample damage images from real tests

4 Conclusion

The connection of glued-in rod in timber structures provides a feasible scheme for building new structures and strengthening the existing structure. Glued-in rod represent a versatile connection system with advantages such as high load transition, appropriate behavior in case of fire, easy application combined with a high level of prefabrication for fast installation, and aesthetic appearance of the finished connection. They are generally used for large cross-section components (such as Glulam, LVL etc.), construction of large-span, large space venues, and timber bridges. The main results of this study are as follows, and some suggestions for future research are below.

(1) For the wood structures with glued-in rods connections, the strength and stiffness of the wood structures are improved and the wood structures can bear loads while maintaining a good appearance of the structure, regardless of whether the connections are inserted parallel to the grain or perpendicular to the grain. In addition, the

glued-in rod connection also has the advantages of great fire resistance and light deadweight. The inserted bars also exhibit good mechanical properties, which can prevent the joints from cracking or shear failure in high-stress areas.

(2) The results of the review show that various factors are affecting the performance of glued-in rod connections, such as the performance of the adhesive, the geometry of the members, the moisture content of wood, hardwood usage instead of softwood, and the anchorage length. Many scholars suggest that the empirical formula for the design of bearing capacity of wood structure reinforcement should consider the combination of multiple factors, not only the anchorage length, reinforcement diameter, and other factors. However, most scholars have studied the mechanical properties of single reinforcement nodes, and the study on multi-reinforcement connections needs to be further developed.

(3) In the design of beam-column connections of wood structure, it is suggested to adopt the ductile failure mode, but the connections are not repairable after yielding. However, the pull-out strength of the connection cannot be neglected due to the failure of the wood or adhesive. Therefore, for the beam-column joints of wood structure, energy dissipation components and embedded bars can be combined, and the ductile failure of the joints can be realized by yielding the energy dissipation components instead of damaging the embedded bars.

(4) Although a great deal of research has been done since the early 1980s, there are still some unsolved problems. Therefore, it is necessary to further study the effects of wood density, load duration, the fabrication method of glued-in rod connection, and fire treatment on its mechanical properties.

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