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BEHAVIOUR OF GLUED-IN ROD CONNECTIONS IN MASS TIMBER STRUCTURES - A STATE-OF-THE-ART REVIEW

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ABSTRACT: In high-rise buildings, beam-to-column connections are one of the most critical components; thus, their failure can lead to a catastrophic collapse of the entire structure. Accordingly, in tall wood buildings, careful consideration for the design of connectors used in connections is critical for the overall structural integrity of such buildings. Using glued-in steel or FRP rods as connectors in mass timber frame connections can enhance the performance of such connections in mid and high-rise timber buildings. Although innovative types of glued-in rod connections have been successfully utilized in mass timber construction, a lack of consistency remains in their design approaches. This hinders their use in broader applications, particularly concerning their behaviour as moment-resisting connections and in fire conditions. This paper presents state-of-the-art research on glued-in rod connections and the structural behaviour of various connection configurations utilizing glued-in rods at ambient and elevated temperatures.

KEYWORDS: mass timber structures, high-rise buildings, connections, glue-in rods, fire conditions

1 – INTRODUCTION

Environmental compatibility, heat preservation, energy efficiency, structural safety, and durability are the primary reasons behind the increasing construction of tall buildings made of mass timber in North America and worldwide [1].

Fires in wooden buildings, particularly those in large construction projects, have become a significant safety challenge due to the widespread use of wooden structures. This poses a risk to the safety of occupants and could result in substantial financial and environmental losses. This issue is particularly significant in large residential and commercial buildings that are under construction. The following are examples of such fires (Fig. 1).

(a)

(b)

Figure 1. Real-world examples: (a) Large-scale fires at wood-framed apartment buildings in Boston, Massachusetts, USA, August 2017, (Photo: Johanna Knapschaefer); (b) Richmond House engulfed in flames, Canada, September 2019 (Photo: London Fire Brigade).

As with other structures, connections with high strength and stiffness are the most critical components of the structure. Thus, different wood connections with various types of connectors, such as those utilizing slotted-in steel plates [1], external steel plates [2], self-tapping screws [3], and dowels [4], have been investigated experimentally and analytically. Alternatively, Glued-in Rods (GIRs) provide robust connection mechanisms for various types and configurations of connections in mass timber structures. GIRs provide strong connections

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between beams and columns in mass timber structures, as they can maintain the structural integrity of their connections. Glued-in rods have been commonly used in Europe and North America for several decades to enhance the strength and stiffness of wood connections [5]. These connections are well-suited for modern wooden buildings due to their advantages, including a high strength-to-weight ratio, high stiffness, aesthetic appearance, and good fire resistance [6].

Given the importance of utilizing this type of connection in high-rise buildings, which has recently garnered significant attention from several engineers and designers, identifying research gaps in this area is crucial. Therefore, a technical and scientific investigation of these connections is essential. One of the primary gaps in research on mass timber structures is the lack of experimental data on high-rise buildings in fire conditions, as most tests have been conducted for only 30 to 60 minutes at high temperatures with small sample sizes [7]. Wood loses its compressive strength when it chars at a temperature of 300°C [7]. Despite the existence of several international standards, gaps remain in these codes that need to be addressed. The International Building Code (IBC) provides criteria for low- and mid-rise buildings but lacks specific guidelines for high-rise buildings [8]. Additionally, TR-10 addresses fire resistance in timber connections, emphasizing the impact of charring rates and connector cover on structural performance during fire exposure [9]. Due to the importance of moisture content in timber connections, some codes highlight related concerns. For instance, at temperatures above 100 degrees Celsius, some of the moisture inside the wood evaporates. In contrast, the remaining moisture migrates to cooler parts of the wood, as outlined in Eurocode 5 [10].

This paper investigates the effects of key parameters on wooden GIR connections. Several concerns exist regarding the mechanical and thermal properties of connection components used in buildings, particularly under critical conditions such as fire. Experimental and analytical research on GIR connections suggests that adequate fire resistance can be achieved if sufficient wood cover is provided [6]. Most notably, the ease of installation and potential for prefabrication of GIR connections contribute to more efficient construction processes, potentially reducing project timelines and labour costs.

2 – BACKGROUND

Several researchers worked on the mechanical properties of GIR connections, including their failure modes, design methods, curing techniques, and the type of adhesive. Some GIR connections were tested under static axial load [11], shear [12], and bending forces [13] as well as cyclic loadings [14]. The moment-resisting capacity of connections and pull-out tests were the main criteria. Additionally, geometric parameters such as the embedded length of rods, rod size, number of rods in a group, edge distance, spacing, and rod-to-grain angle are also important parameters. A study indicates that the minimum required rod embedded length for GIR connections is 10 to 15 times the diameter of the rod [13]. The thickness of the adhesive layer, which ranges from 0.2 to 6 mm, is a crucial parameter that can significantly impact the performance of GIR connections [15].

Table 1 presents the factors that influence the performance of wood structures with GIR connections. Additionally, the minimum edge distances and hole spacing in connections, as specified in different standards, are listed in Table 2, in relation to Fig. 2.

Table 1. Mechanical factors that affect the performance of glued-in rod timber connections

(1) Geometric parameter			
(a) Rod length, diameter and number	(b) Edge distance and spacing	(c) Thickness of adhesive layer	(d) Rod-to-grain angle
(2) Material parameters			
(a) Strength and Stiffness of wood, rod and adhesive	(b) Moisture and temperature dependence	(c) Creep and Plasticity	(c) Failure criteria
(3) Loads and boundary conditions			
(a) Axial loads: Tension, Compression, Bending and Shear forces	(b) Types of loads based on their nature: Static, Dynamic	(c) Types of loading based on their variation over time: Monotonic, Cyclic	(d) Types of loading scenarios: Pull-Pull; Pull-Push
(4) Influence of manufacturing process			
(a) Wood preparation and direction	(b) Adhesive application	(c) Rod insertion and alignment	

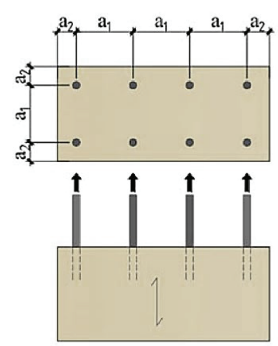

Figure 2. Definition of rod edge distances and spacing per the most applicable codes and standards.

Table 2. Minimum rod edge distances and spacing in different design standards concerning Figure 2 [6]

Different Standard Recommended Values	a_1	a_2
PrEN 1995:2001	4d	2.5d
DIN 1053:2004-08	5d	2.5d
STEP1	2d	1.5d
French Professional Guide	3d	2.5d

Wood connections are categorized based on their rigidity (according to the strength and stiffness classification) into three types: ductile, semi-rigid, and fully-rigid connections [16]. Typically, a ductile failure mode is a reliable design consideration for beam-to-column

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connections in wood structures. However, those ductile connections are not repairable after deforming [5]. Semi-rigid beam-to-column GIR connections have been investigated through full-scale experimental tests and 3D finite element (FE) models in ANSYS software [17]. Accordingly, most investigated timber connections were pinned and could transfer shear and axial loads using several braces. However, in mid- and high-rise buildings, rigid connections are necessary to transfer moments, such as semi-rigid or fully rigid connections without the use of braces. Thus, one efficient method for connecting mass timber beams to columns is to use GIR connections.

Most of the GIR connections have been tested using small samples, except in a few research studies, where the mechanical properties of full-scale GIR beam-to-column connections were tested [18]. In that study, five specimens were tested using M20 grade 8.8 threaded rods with an embedded length of 800 mm (40 times the diameter of the rod) in a pull-out test configuration. The epoxy adhesive used in those connections was WEVO-EP 32S (density: 1.18 g/cm³, viscosity: 12,000 mPa·s). The pull-out load applied was 500 kN, as specified in the EN 26891 standard. The minimum edge distance used was 2.5 times the diameter of the rod. The pull-out load applied was 500 kN, as specified in the EN 26891 standard. Upon applying the maximum pull-out load, several failure modes were observed, including adhesive failure, where the adhesive bond between the rod and wood failed; cohesive failure, where the adhesive itself failed internally; and wood failure, where the wood surrounding the embedded rod exhibited splitting or fracture [6].

In addition to experimental studies, some researchers developed analytical models to predict the behaviour of GIR connections [19, 20]. In these studies, several parameters, including viscosity, adhesive hardening (which can lead to shrinkage), glue line thickness, and adhesion to wood or steel, were investigated. Results show that the wood section was found to be the weakest part in each connection due to fractures in the wood; however, the interface between the wood and adhesive was found to be critical, with more localized stresses observed in pull-out tests. In those studies, researchers investigated various geometrical parameters that affect the performance of GIR connections, including the rod embedded length, diameter of the rods and drilled holes, edge distance and spacing of rods, and the angle of the applied load relative to the wood grain. It was also found that the embedded rod length directly influences the pull-out strength; however, the connection shear strength was not influenced by the embedded rod length or hole diameter. Meanwhile, the hole diameter affected the ultimate load of the GIR connection. Regarding the edge distance and rod spacing, it was found that there are limitations to achieving optimum performance. For instance, the edge distance should be between 2.5 and 3 times the rod diameter, and the rod spacing should be between 1.5 and 5 times the rod diameter [6].

In other studies, wood splitting was the primary concern for GIR connections [21]. It was also concluded that the ultimate load can increase by increasing the rod diameter and number [6]. The angle of the applied load with respect to the wood grain is another critical parameter that can affect the GIR connection behaviour [22]. According to the available literature, several theories exist regarding adhesive behaviour in GIR connections [19]. Linear elastic stress and fracture mechanics are two theories that are suitable for the numerical analysis of GIR connections. Additionally, the nonlinear and quasi-nonlinear fracture mechanics of adhesives is another theory that has been explored in several research studies [19]. In the context of linear elastic stress theory, the relationship between stress and strain is critical in determining the load-bearing capacity of GIR connections, as it directly influences the material's ability to withstand applied loads without failure. Table 3 summarizes basic information from several related studies reviewed to highlight the most critical parameters investigated in small-size GIR connections.

Table 3. Basic information from several studies on small-sized GIR connections

Ref.	Basic Information of the Test
Baroth et. al., (2004) [23]	**Test method:** Bending tests on beam connections. **Type of wood:** Glulam timber cross-sections (GL28h); **Type of rod:** Steel rods; **Type of adhesive:** An epoxy glue.
Widmann et. al. (2007) [22]	**Test method:** Pull-pull tests; **Type of wood:** Glulam of Norway Spruce lamellas; **Type of rod:** Steel rods; **Type of adhesive:** An epoxy-type adhesive utilizing the GSA system.
Fava et. al. (2013) [24]	**Test method:** Pull-out tests; **Type of Wood:** Glulam (density = 380 kg/m^3); **Type of rod:** CFRP rods; **Type of adhesive:** An epoxy adhesive.
Javier et. al., (2013) [25]	**Test method:** Pull–push tests; **Type of wood:** Laminated wood (density = 425.62 kg/m^3); **Type of rod:** Multi-bulb anchors, threaded steel rods; **Type of adhesive:** Hilti Hit Re-500 epoxy adhesive.
Raftery et. al., (2015) [26]	**Test method:** Four-point bending tests; **Type of wood:** Plain sawn timber (C16 graded); **Type of rod:** BFRP rods; **Type of adhesive**: Phenol-resorcinol-formaldehyde (PRF) adhesive.
Gonzales et. al., (2016) [27]	**Test method:** Pull-out tests; **Type of wood:** Glulam (density = 530 kg/m^3); **Type of rod:** Steel rods; **Type of adhesive:** 2C PUR (CR-412); 2C EPX (Gel Magic).
Zhu et. al., (2017) [28]	**Test method:** Pull-out tests; **Type of wood:** Glulam timber (density=562 kg/m^3); **Type of rod:** GFRP rods; **Type of adhesive:** Two-component PUR structural adhesive.
O'Neill et al., (2018) [13]	**Test method:** Pull-bending tests; **Type of wood:** BS EN 338 (C16 graded; density = 310 kg/m^3); **Type of rod:** BFRP rods; **Type of adhesive:** An epoxy adhesive.
Stamatopoulos and Malo (2018) [29]	**Test method:** Pull-push tests; **Type of wood:** Glulam (density = 400 kg/m^3); **Type of rod:** Threaded steel rods with 15° angle; **Type of adhesive:** No adhesive.
Sofi et. al., (2021) [11]	**Test method:** Pull-distributed configuration tests; **Type of wood:** CLT (3-ply, 105 mm thick panel); **Type of rod:** Grade 4.6 threaded M12 rods; **Type of adhesive:** Two-component epoxy.

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Bouchard et. al., (2021) [30]	**Test method:** Pull-pull tests; **Type of wood:** Glulam (density = 497 kg/m^3); **Type of rod:** Steel rods; **Type of adhesive: A** two-component polyurethane adhesive (Henkel Purbond CR 421).
Ayansola et. al., (2022) [31]	**Test method:** Pull-pull tests; **Type of wood:** CLT (5-ply panels, 139 mm and 175 mm) **Type of rod:** Steel rods; **Type of adhesive:** PUR adhesive.
Valentina et. al., (2017) [37]	**Test method:** Pull-out tests at the cold state. **Type of wood:** Solid timber (Douglas-Fir C16 class) and glulam (Spruce GL24 class); **Type of rod:** Steel rods; **Type of adhesive:** Resins with different viscosity values.
Luo et. al., (2020) [36]	**Test method:** Pull-out tests; **Type of wood:** Douglas-Fir glued-laminated timber; **Type of rod:** Steel rods; **Type of adhesive:** Phenol-resorcinol-formaldehyde.
Verdet et. al., (2016) [34]	**Test method:** Pull-compression tests; **Type of wood:** Glulam timber produced from Black Spruce (Picea Mariana Mill); **Type of rod:** Steel rods; **Type of adhesive:** Polyurethane (PUR) and Epoxy (EPX).
Lahouar et. al., (2018) [15]	**Test method:** Pull-out tests at high temperature on GIRs. **Type of wood:** GL-24 spruce glulam timber; **Type of rod:** Steel rods; **Type of adhesive:** Melamine-Urea-Formaldehyde glue.

Another concern for GIR connections is their fabrication procedure. Several methods have been proposed, with the most common being to drill a hole in the wood that is 1-4 mm larger than the rod diameter [20]. The hole is then thoroughly cleaned, and any remaining wood dust is removed using air pressure. A specific amount of glue is poured into the hole, and then the rod is inserted, (Type 1) Fig. 3. The second method is to drill one or two holes perpendicular to the main hole to insert the glue from these holes to remove cavities, (Types 2 and 3) Fig. 3.

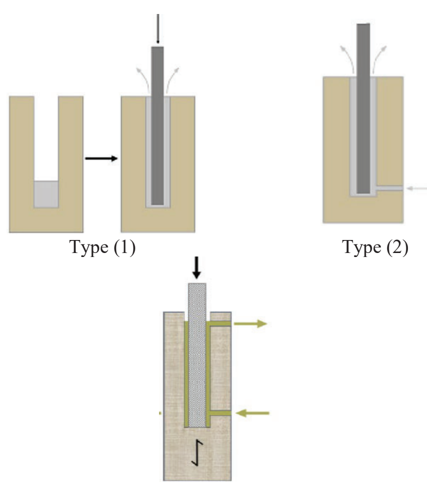

Figure 3. Fabricating GIR connections [20].

Some researchers have investigated the different failure modes of conventional GIR connections under tensile forces, as illustrated in Fig. 4. Others have explored various new configurations of GIR beam-to-column connections, as shown in Fig. 5.

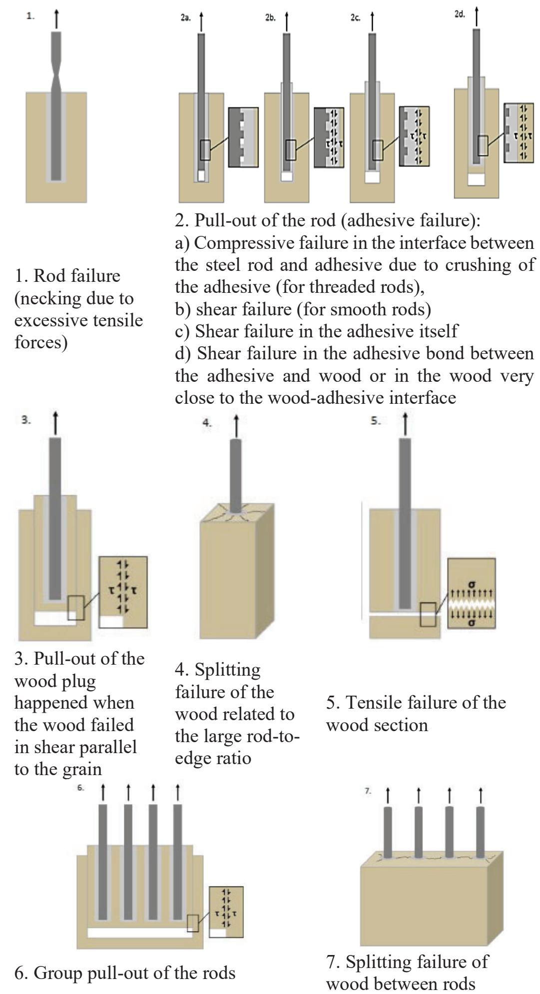

Figure 4. Failure modes of GIR connections under tensile forces [19].

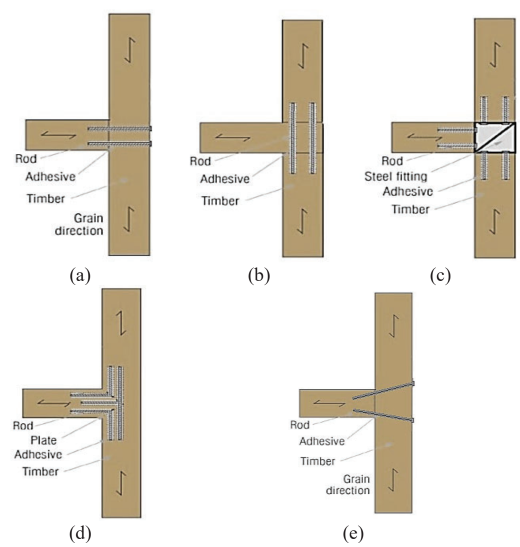

Figure 5. Different configurations of GIR beam-to-column connections: (a) Extended column, (b) Extended beam, (c) Steel fitting, (d) 45º Mitre, (e) Extended column with angled rods [32].

According to the available literature, there is a substantial lack of theoretical studies, particularly design methods for GIR connections. The most significant design aspects lacking improvement include the bonding performance of GIR connections in mass timber structures and the structural behaviour of various connection configurations at both ambient and elevated temperatures. In this paper, emphasis is placed on the different influencing factors and failure modes of these connections, particularly in fire conditions.

3 – GLUED-IN ROD CONNECTIONS IN AMBIENT CONDITIONS

The most recent studies on GIR connections have been conducted in ambient conditions to investigate several geometric parameters, including rod embedment length, diameter, number, spacing, and rod-to-grain angle. Other studies have examined adhesive curing techniques and their various types. Strength, stiffness, creep, moisture, thickness of the adhesive layer, and temperature were also essential parameters investigated [5].

Different types of rods are commonly used in GIR connections, including steel rods and fiber-reinforced polymer (FRP) rods [33]. These types of rods have been used and tested in ambient conditions, exhibiting varying performances in both experimental and analytical studies. In ambient conditions, when rods are bonded with glue in connections, the assumption of uniform stress distribution over short lengths is typically used to model bond stress and slip. However, this assumption becomes less accurate when the rod is embedded in the glue for lengths equal to or exceeding five times its diameter, leading to localized bond weakening [14]. It is also suggested that a total curing rate of the adhesive, achieved through special heat induction, typically takes a few days, whereas it may take several weeks at ambient temperature. The final adhesive curing is another concern of GIR connections, which warrants further investigation [14]. The use of different types of FRP rods (glass, basalt, and carbon) in GIR wood connections under ambient conditions has been investigated by numerous researchers [29, 33]. These types of FRP rods have considerable diversity in their mechanical properties. They also possess several advantages, such as corrosion resistance to Acid and humidity, and a high strength-to-weight ratio. Most importantly, their lower heat conductivity can be favourable in fire conditions.

A few researchers studied the effects of glue thickness (e.g., 0.5, 1, 2, and 4 mm) surrounding rods in pull-out tests for GIR connections using computer modeling [6].

In addition to the glue thickness, bond strength is another critical parameter that significantly affects the overall strength of GIR connections. A study suggested that the average bond strength of GIR can be estimated using Eqn. 1 [33].

$$\tau = \frac{P}{\pi * d * l_a} \tag{1}$$

Where P is the maximum applied load, d is the diameter of the rod, and la is the length of the rod embedment.

Also, Eurocode 2001 [10] provides Eqn. 2 to determine the pull-out capacity of FRP glued-in rods in wood sections.

$$P = \pi * d * l * f_v * \sqrt[3]{\frac{E_{FRP}}{E_W}} \tag{2}$$

Where f_v is wood shear strength, and E is Young's modulus for FRP and wood materials.

4 – GLUED-IN ROD CONNECTIONS AT ELEVATED TEMPERATURES

Glued-in rods represent a versatile connection system with advantages such as high load transfer, appropriate behaviour in the event of fire, easy application, combined with a high level of prefabrication for fast installation, and an aesthetically pleasing appearance of the finished connection. Due to the advantages of good fire resistance in mass timber sections, GIR connections are well-suited for constructing modern mass timber buildings.

The high degree of prefabrication facilitates rapid installation, making GIR connections advantageous in modern mass timber construction. Moreover, mass timber sections inherently possess good fire resistance due to the charring layer that forms on the surface when exposed to high temperatures, which acts as an insulating barrier protecting the inner core [9].

However, thermally induced effects on the mechanical characteristics of GIR connections are crucial issues that influence the fire behaviour of those connections. Thus, a few researchers experimentally examined the fire behaviour of GIR connections [34]. The spacing in beam-to-column connections is a key factor influencing heat transfer. The exposed metal parts in each connection can directly impact the charring rate. Multi-story buildings require a fire resistance rating of at least 60 to 120 minutes, depending on the building's height and floor area, as specified in applicable building codes. Low- to medium-rise buildings, up to six stories, should sustain applied loads in fire conditions for at least 60 minutes. In contrast, high-rise buildings with a height of 22.9 m or more should have a fire resistance rating of 120 to 180 minutes. These criteria are established by the International Building Code (IBC) and other building codes for low- and mid-rise buildings; however, specific guidelines do not exist for high-rise buildings [8]. Another key issue is wood charring, which can be influenced by the cover of metallic connectors used in timber connections subjected to fire. Another key issue is wood charring, which can be influenced by the cover of metallic connectors used in timber connections subjected to fire. According to TR-10 [9], a minimum wood cover of 38.1 mm is recommended, while Eurocode 5 [10] specifies a minimum cover of 49 mm. These cover thicknesses generally correspond to fire resistance ratings of up to 30 minutes, depending on factors such as timber density and fire exposure conditions. For fire resistance

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periods exceeding 30 minutes, additional measures such as increased member dimensions or protective claddings are required.

Two key aspects must be considered when investigating the performance of GIR timber connections at elevated temperatures: the charring rate of wood and the specific parameters that affect GIR behaviour. Specific parameters influencing the behaviour of GIR timber connections at elevated temperatures include the adhesive thermal effects and the bond line temperature. The charring rate determines the rate at which the cross-sectional area of wood is reduced, directly impacting the load-bearing capacity during a fire event.

4.1 CHALLENGES OF WOODEN GIR CONNECTIONS IN FIRE CONDITIONS

With the growing use of GIRs in timber structures, there is a strong need to identify the factors that contribute to the loss of mechanical performance at elevated temperatures, as this is a regulatory requirement for most buildings. The mechanical behaviour of GIRs appears to be influenced by several parameters, including temperature changes in fire conditions. According to the available literature, existing research on the fire resistance of GIR connections has primarily focused on those with traditional and commercial epoxy resins. Only a few heat-resistant modified adhesives have been proposed. In a study, different types of adhesives have been investigated. This research has highlighted that adhesives, such as epoxy and polyurethane, exhibit different thermal behaviours, with epoxy adhesives experiencing a more rapid degradation in mechanical properties compared to polyurethane adhesives at temperatures above 40°C [35].

An experimental study has been conducted using two types of adhesives, as well as two different shapes for the internal hole surface (cylindrical and threaded), to evaluate whether different geometrical properties of the hole could affect the performance of the connection subjected to elevated temperatures. The study shows that the load-bearing capacity of GIRs is highly dependent on the adhesive's temperature. Results show that an increase in the temperature of the bonding layer causes a significant decrease in the bond shear strength of the adhesive. Additionally, the strength of the adhesive at elevated temperatures exhibits a clear dependence on the adhesive type and a negligible dependence on the hole geometry [36].

In another experimental study, which involved testing GIR timber connections at elevated temperatures to evaluate their fire performance, test specimens consisted of timber elements with embedded steel rods bonded using epoxy resin adhesives [37]. To enhance the adhesive's thermal resistance, specific inorganic additives were incorporated into the epoxy mixture. The study investigated multiple parameters, including edge distance, adhesive type, and failure modes. Test results indicate that the modified epoxy resin has significantly improved the fire resistance of the connections, thereby enhancing their load-bearing capacity at elevated temperatures. In contrast, the unmodified epoxy resin exhibited rapid degradation at elevated temperatures, resulting in premature bond failure. Additionally, edge distance was found to influence failure mechanisms, where greater distances contributed to enhanced fire resistance by reducing thermal stress concentration near the bonded interface. These findings highlight the effectiveness of adhesive modification for improving the fire performance of GIR connections in timber structures. Another study was conducted to investigate the performance of adhesives in GIR timber connections at high temperatures [34]. To analyze the adhesive properties at elevated temperatures, dynamic mechanical analysis (DMA) tests were conducted on an epoxy (EPX) and a polyurethane (PUR) adhesive. The former adhesive exhibited a faster decline in stiffness and strength compared to PUR at elevated temperatures. However, no direct correlation was found between the glass transition temperature (T_g) and the performance of the timber connections utilising those adhesives [34]. Another critical factor that can influence the fire resistance of GIR connections is the degradation of the wood material beneath the char layer. The charring rate of wood at the connections is another critical factor that can significantly influence the thermal and mechanical behaviours of GIR connections [15]. Since timber connections exhibit considerable strength degradations in fire conditions, the following three separate but related assessments need to be made to determine the fire resistance of timber connections [7].

1. The reduction in wood cross-sectional area due to charring.

2. The reduction in strength behind the char layer through thermal penetration.

3. The impact of thermal transfer from exposed metallic connecting components into the timber sections.

A few researchers have investigated how the adhesive lines within timber structural members respond to the outer temperature regime during both heating and cooling phases. This phenomenon was confirmed by a Finite Element Analysis [38]. Fig. 6 illustrates the relationship between ambient and adhesive temperatures through a finite element analysis. For GIR tests in timber at elevated temperatures, two different methods were frequently used. The first method is generally referred to as the “residual capacity test” and involves using an oven to heat the connection to a selected temperature. The connection is typically left in an oven overnight to allow the sample to reach a homogeneous temperature throughout its entire volume. Subsequently, the sample is removed from the oven and cooled to room temperature, and a tensile test is performed to assess its pull-out capacity. The other method used to study GIRs at elevated temperatures involves the use of a gas oven (furnace), where the sample is heated, usually following the standard time-temperature curve, while subjected to a constant tensile load [39].

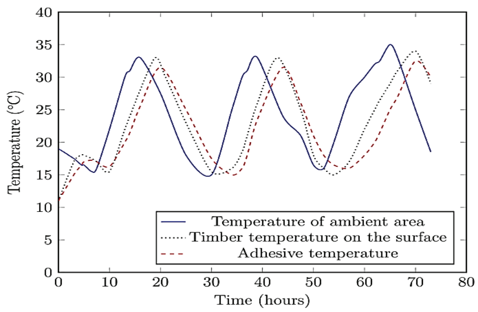

Figure 6. Relation between ambient and adhesive temperatures through a finite element analysis [39].

To investigate the performance of two types of PUR and EP adhesives at elevated temperatures, an experimental study has been conducted. For verification, the thermo-mechanical behaviour of the shear modulus of both adhesives was determined using a relaxation spectrometer according to ASTM D 4065, with a frequency of 1 Hz, in the temperature range of –20 to 120°C [40]. The results for the shear modulus are depicted in Fig. 7. The graph shows that for PUR, the glassy region ends at approximately 25°C, with a subsequent catastrophic decrease in the modulus between 30 and 45°C. For EP, the glassy region ends at approximately 45°C, with an extreme reduction in the temperature range of 45°C to 60°C [40].

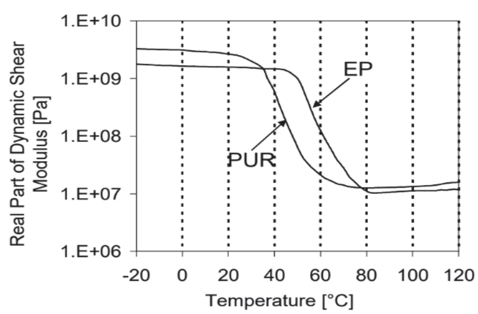

Figure 7. Results of thermo-mechanical tests according to ASTM D4065: shear modulus vs. temperature for PUR and EP [40].

4.2 CHARRING IN WOOD CONNECTIONS

The process of thermal decomposition of wood directly refers to a charring procedure in wood connections when exposed to high temperatures, resulting in the formation of a carbonized layer on the surface. This layer acts as an insulating barrier, slowing further heat penetration and combustion. In wood connections, charring can weaken structural integrity by reducing the effective cross-sectional area of the wood and affecting the performance of metal fasteners. The charring rate of wood and the performance of metal fasteners in fire conditions are closely related. Metal fasteners and connecting components are good heat conductors; therefore, they can lose their strength at elevated temperatures. Metal fasteners can accelerate localized charring around them, reducing the load-bearing capacity of the connection. Additionally, as temperature rises, metal fasteners lose strength, especially in steel. Fig. 8 shows heat transfer flow for bolts, dowels, and timber at elevated temperatures [41]. From this figure, it can be observed that at the same distance, mainly those away from the fire-exposed surface of a timber connection, the temperatures exhibited by metallic bolts and dowels are greater than those of the timber section. Accordingly, metallic components, such as bolts and dowels used in timber connections, can increase the charring rate and thus negatively influence the strength and fire resistance of timber connections.

The heat transfer and fire behaviour of GIR connections are critical considerations in timber construction, as elevated temperatures can significantly impact their structural integrity. Several studies have investigated these aspects, focusing on the performance of adhesives and the overall behaviour of GIR connections subjected to fire.

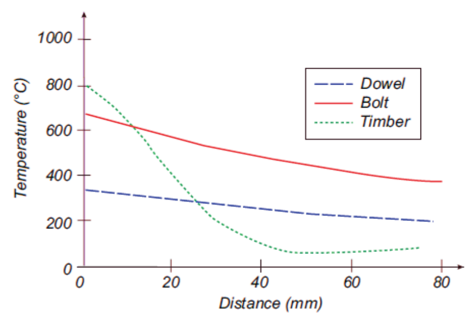

Figure 8. Connection heat flow with different elements [41].

To ensure the fire safety of GIR connections, it is essential to select adhesives with higher glass transition temperatures (T_g) and consider protective measures such as fire-resistant coatings. Designing connections with sufficient cross-sectional dimensions can also help maintain lower temperatures at the adhesive bond line during a fire, preserving the connection's load-bearing capacity. For instance, increasing the size of the timber member can provide additional thermal insulation, reducing the rate at which heat reaches the adhesive layer [35].

Another essential aspect for the fire resistance of timber connections is that the wood material loses its strength behind the char layer. In GIR connections, it is essential to sustain the excessive pull-out forces in fire conditions for the targeted fire resistance times required by applicable building codes. It is important to note that, for each connector and timber design methodology, heat flow and penetration depth must also be considered, as these designs are typically developed solely for the required capacity at ambient temperature. To satisfy this requirement, careful determination of the actual thickness of the char layer developed is crucial to ensure that GIRs are still away from the heat penetrating the wood section [42]. Concerning this, Eq. 3 can be used to

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determine the temperature (T) at depth (x) in timber sections at the connection.

$$CapT(x) = 20 + 180 * \left(\beta.\frac{t}{x}\right)^{a(t)} \quad for \leq 300\,^{o}\mathrm{C} \tag{3}$$

Where

a (t) = 0.025t +1.75

T(x) = temperature at depth (x) ^{o}C

β = charring rate (mm/minute)

x = depth (mm)

t = time (minutes)

Fig. 9 shows the temperature variation in timber sections behind the char layer during short-duration standard fire exposure in glulam [7].

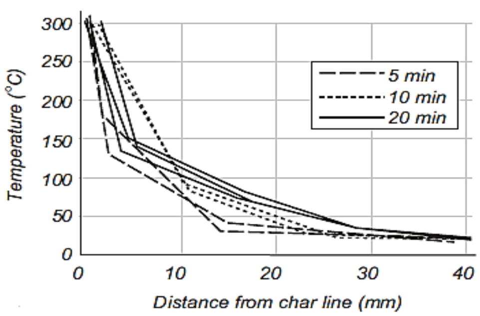

Figure 9. Temperature distribution in timber sections behind the char layer during short-duration standard fire exposure in glulam [7]

Due to the importance of charring rate in designing timber connections, design approaches for fire resistance of connections are limited to a few available methods: (1) charring-rate method, (2) acceptance criteria. For the charring-rate method, the minimum wood cover for embedded GIRs shall be 1.14 times the maximum char depth that can be developed during a specified fire exposure time [9]. According to engineering wood design standards, connectors should be protected with wood to a depth that is at least equal to the adequate depth of charring. By the acceptance criteria outlined in the American Wood Council publication [9], defined temperature limits have been established to ensure the adequacy of protection during the fire resistance period. The prescribed average and maximum allowable temperatures are 140°C and 180°C, respectively.

5 – SUMMARY

This paper discusses key factors influencing the behaviour of this type of connection and summarizes the available design approaches for such connections. GIR connections offer reasonable fire resistance while maintaining rigid beam-to-column connections for mass timber structures. The rods subjected to high stress exhibit strong mechanical performance, effectively mitigating the risk of cracking or shear failure in areas of concentrated stress. Thermally induced effects can significantly alter the mechanical properties of both the adhesive and the timber, influencing the overall fire behaviour of these connections. Experimental studies have shown that the type of adhesive used has a significant impact on the fire resistance of GIR connections. Timber connections that utilize exposed metal connectors (i.e., steel plates and bolts) are influenced considerably by heat in fire conditions, as they can increase the wood charring rate within their connections due to the high thermal conductivity of these materials. Thus, using concealed GIRs in mass timber connections with sufficient wood cover thicknesses offers a robust connecting mechanism with enhanced fire resistance. The following are some key findings.

- ➢ GIR connections offer a versatile joint system that provides high load transition, good fire resistance, and ease of installation, making them suitable for modern wood construction.
- ➢ In timber connections, the charring layer enhances fire resistance by acting as an insulating barrier, protecting the inner core.
- ➢ The strength of adhesives at elevated temperatures depends on adhesive type but has a negligible dependence on hole geometry. The bond shear strength of adhesives decreases significantly as the temperature of the bonding layer increases.
- ➢ The failure mechanisms of GIR connections can be influenced by geometric parameters, such as edge distance, where greater distances enhance heat resistance by reducing thermal stress concentration.
- ➢ Metal fasteners and connectors lose strength at elevated temperatures, acting as weak links in timber connections in fire conditions.
- ➢ Metallic components, such as bolts and dowels, increase the wood charring rate, negatively affecting the strength and fire resistance of GIR connections.
- ➢ Selecting adhesives with higher glass transition temperatures (T_g) and using fire-resistant coatings can increase the fire resistance of GIR connections.
- ➢ Increasing the cross-sectional dimensions of timber members provides thermal insulation, reducing heat penetration to the adhesive layer and improving fire resistance.
- ➢ The strength of wood behind the char layer is a critical factor in sustaining pull-out forces for the required fire resistance time.
- ➢ Heat flow and penetration depth must be considered in the design of GIR connections.

In summary, while GIR connections offer numerous benefits in timber construction, their performance under fire conditions is influenced by factors such as the charring rate of the timber and the thermal stability of the adhesives used. Ongoing research and experimental evaluations are crucial for optimizing these connections to enhance fire resistance in modern timber structures.

6 – CONCLUSIONS AND RECOMMENDATIONS

According to the reviewed research articles, various factors can affect the performance of GIR connections, including the adhesive's performance, the geometry and configuration of the connections, the moisture content of the wood, and the rod embedment length, among others, particularly in fire conditions. Generally, using GIRs as connectors offers a practical solution for constructing new mass timber structures and effectively retrofitting deteriorating timber buildings. In mass timber structures, the GIR connections have the advantage of acceptable fire resistance because their connecting components (i.e., rods) are concealed within large timber sections. However, there is still a high demand for further research on their behaviour under different load ratios, particularly in a setup of full-size moment-resisting beam-to-column timber connections in fire conditions, to verify high fire resistance ratings (i.e., 120 and 180 minutes) for high-rise timber buildings, as per most applicable building codes.

7 – REFERENCES

[1] L. Hu, L. Qin, D. Wu, H. Xu, & Z. Yang, “Radial variation in bonding performance of preservative-treated wood within Pinus elliottii trees and its relationships with wood density and adhesive penetration” Bioresources 16, no. 2 (2021): 2204.

[2] Z. Shu, Z. Li, X. Yu, J. Zhang, and M. He. “Rotational performance of glulam bolted joints: Experimental investigation and analytical approach.” In: Construction and Building Materials 213 (2019), pp. 675-695.

[3] O. Salem. “Experimental testing of steel-wood-steel glulam frame bolted connections.” In: Proceedings of the 14th World Conference on Timber Engineering (2016), Vienna, Austria.

[4] L. Fang, L. Wang, W. Qu, and S. Zhang. “Mechanical performance of glulam beam-column moment-resisting connections with self-tapping screws as fasteners.” In: Journal of Building Engineering 54, (2022).

[5] H. Min-juan, and L. Hui-fen. “Comparison of glulam post-to-beam connections reinforced by two different dowel-type fasteners.” In: Construction and Building Materials 99 (2015), pp. 99-108.

[6] H. Zhang, H. Li, A. Dauletbek, R. Lorenzo, I. Corbi, and O. Corbi. “Research status of glued-in-rods connections in wood structures." Journal of Building Engineering 65 (2023): 105782.

[7] D. Barber, A. Abu, A. Buchanan, Ch. Dagenais, M. Klippel, “Timber connections, Book, Fire Safe Use of Wood in Buildings”, (2017), Edition1st Edition. ImprintCRC Press, Pages40, Book ISBN9781003190318

[8] International Code Council., International Building Code (IBC). Washington, D.C. (2021): International Code Council. Available from https://codes.iccsafe.org/s/IBC2021P1/chapter-6-types-of-construction/IBC2021P1-Ch06-Sec602.4

[9] TR-10, “Fire Design Specification for Wood Construction”, American Wood Council, (2021), https://awc.org/codes-standards/publications/fds-2021.

[10] Eurocode 5, “Design of Timber Structures”, prEN 1995-2(Second Draft), EC5-2004, November, (2004), pp. 28–31.

[11] M. Sofi, E. Lumantarna, R. Hoult, M. Mooney, N. Mason, J. Lu, “Bond strength of GIR in cross-laminated timber: a preliminary study,” Construct. Build. Mater. 301 (2021) 123864, https://doi.org/10.1016/j.conbuildmat.2021.123864.

[12] P. Palma, A. Frangi, E. Hugi, P. Cachim, and H. Cruz, "Fire resistance tests on timber beam-to-column shear connections", In Journal of Structural Fire Engineering, 7(1), (2016), pp. 41-57. https://doi.org/10.1108/JSFE-03-2016-004

[13] C. O'Neill, D. McPolin, S. E. Taylor, T. Martin, A.M. Harte, (2018), “Glued-in basalt FRP rods under combined axial force and bending moment: an experimental study”, Compos. Struct. 186 (2018) 267–273, https://doi.org/10.1016/j.compstruct.2017.12.029.

[14] E. Toumpanaki, and M. Ramage. “Glued-in CFRP and GFRP rods in block laminated timber subjected to monotonic and cyclic loading.” In: Composite Structures 272 (2021).

[15] M. A. Lahouar, J. F. Caron, G. Foret, K. Benzarti, and R. Mege. “Temperature effect on the mechanical behavior of glued-in rods intended for the connection of timber elements.” In: Construction and Building Materials 186 (2018), pp. 438-453.

[16] G. Iovane, C. Noviello, F. M. Mazzolani, R. Landolfo, & B. Faggiano, “A Proposal for the Mechanical Classification of Beam-to-Column Joints for Timber Structures”, (2023).

[17] M. Vašek, R. Vyhnalek, “Timber semi-rigid frame with glued-in–rods joints”, In World Conference on Timber Engineering, (2006), Conference Proceedings, p. 275, Portland Oregon State University, Portland.

[18] S. Navaratnam, J. Thamboo, Th. Ponnampalam, S. Venkatesan, K. Beng Chong, “Mechanical performance of glued-in rod glulam beam to column moment connection: An experimental study”, In Journal of Building Engineering 50 (2022) 104131, https://doi.org/10.1016/j.jobe.2022.104131

[19] P. Feldt, A. Thelin, “Glued-in rods in timber structures finite element analyses of adhesive failure”, master's thesis in Structural Engineering, (2018), Chalmers University of Technology, Gothenburg, Sweden

https://doi.org/10.52202/080513-0352

[20] R. Steiger, E. Serrano, C. O'Neill, & D. Mcpolin, “Reinforcement with glued-in rods”, Aachen: Shaker Verlag GmbH, (2015).

[21] E. Gonzalez, C. Avez, & T. Tannert, “Timber Joints with Multiple Glued-in Steel Rods”. In the Journal of Adhesion, (2016), 92(7-9), pp. 635-651.

[22] R. Widmann, R. Steiger, E. Gehri, “Pull-out strength of axially loaded steel rods bonded in glulam parallel to the grain”, Mater. Struct. 40 (1) (2007) 69–78, https://doi.org/10.1617/s11527-006-9111-2.

[23] J, Baroth, L. Bodé, P. Bressolette, E. Fournely, P. Racher, “Glued-in rod connections in bending: experiment and stochastic finite-element modelling”, in: World Conference, (2004).

[24] G. Fava, V. Carvelli, C. Poggi, “Pull-out strength of glued-in FRP plates bonded in glulam”, Construct. Build. Mater. 43 (2013) 362–371, https://doi.org/10.1016/j.conbuildmat.2013.02.035.

[25] E. C. Javier, D. O. Chans, E. M. Gutierrez, “Adhesive multi-bulbs: a novel anchoring system using threaded steel rods glued into wood”, Construct. Build. Mater. 48 (2013) 131–136, https://doi.org/10.1016/j.conbuildmat.2013.06.079.

[26] G. M. Raftery, F. Kelly, “Basalt FRP rods for reinforcement and repair of timber”, Compos. B Eng. 7 (2015) 9–19, https://doi.org/10.1016/j.compositesb.2014.10.036.

[27] E. Gonzales, T. Tannert, T. Vallee, “The impact of defects on the capacity of timber joints with glued-in rods”, In Internationa Journal of Adhesion Adhesive. 65 (2016) 33–40, https://doi.org/10.1016/j.ijadhadh.2015.11.002.

[28] H. Zhu, P. Faghani, T. Tannert, “Experimental investigations on timber joints with single glued-in FRP rods”, Construct. Build. Mater. 140 (2017) 167–172, https://doi.org/10.1016/j.conbuildmat.2017.02.091.

[29] H. Stamatopoulos, A.M. Kjell, “Withdrawal of pairs of threaded rods with small edge distances and spacings”, Eur. J. Wood Wood Prod 76 (1) (2018) 31–42, https://doi.org/10.1007/s00107-016-1146-7.

[30] R. Bouchard, A. Salenikovich, C. Frenette, B.G. Blanchet, “Experimental investigation of joints with multiple glued-in rods in glued-laminated timber under axial tensile loading”, Construct. Build. Mater. 293 (2021) 122614, https://doi.org/10.1016/j.conbuildmat.2021.122614.

[31] G. S. Ayansola, T. Tannert, T. Vallee, “Experimental investigations of glued-in rod connections in CLT”, Construct. Build. Mater. 324 (2022) 126680, https:// doi.org/10.1016/j.conbuildmat.2022.126680.

[32] Wood Works. (n.d.). Wood Works index of mass timber connections. Wood Works. Retrieved, (2025), https://www.woodworks.org/wp-content/uploads/woodworks-mass-timber-connection-indices.pdf

[33] M. Titirla, L. Michel, and E. Ferrier. "Mechanical behavior of glued-in rods (carbon and glass fiber-reinforced polymers) for timber structures - An analytical and experimental study", In: Composite Structures 208 (2019), pp. 70-77.

[34] M. Verdet, , A. Salenikovich, A. Cointe, J. Coureau, Ph. Galimard, W. Munoz Toro, P. Blanchet, and Ch. Delisee. "Mechanical Performance of Polyurethane and Epoxy Adhesives in Connections with Glued-in Rods at Elevated Temperatures." *BioResources* 11, no. 4 (2016).

[35] F. Diego, Ch. Dagenais, and P. Blanchet. "Characterizing the fire performance of adhesives used in glued-in rods connections.", Word conferenace on timber engineering, Oslo, (2023)

[36] M. Valentina, L. D’Andria, G. Muciaccia, and A. Ianakiev. "Influence of elevated temperature on glued-in steel rods for timber elements." Construction and building materials 147 (2017): 457-465.

[37] L. Luo, B. Shi, W. Liu, H. Yang, & Z. Ling, “Experimental investigation on the fire resistance of glued-in rod timber joints with heat resistant modified epoxy resin”. (2020), In Journal of Materials, 13.

[38] C. Faye, L. Le Magorou, P. Morlier, and J. Surleau. "French data concerning glued-in rods." In Proc., 37th Meeting of the Working Commission W18—Timber Structures, CIB, Int. Council for Research and Innovation. (2004).

[39] S. Harris, “Fire resistance of epoxy-grouted steel rod connections in laminated veneer lumber (lvl)”. Fire Engineering Research Report 04/07, (2004).

[40] Aicher, Simon, and Gerhard Dill-Langer. "Influence of moisture, temperature and load duration on performance of glued-in rods." Proceedings, Rilem PRO, Stuttgart, Germany (2001): 383-392.

[41] M. Audebert, F. Zeman, R. Beaudoin, A. Pery, & J-P. Cravedi. "Comparative potency approach based on H2AX assay for estimating the genotoxicity of polycyclic aromatic hydrocarbons.", Toxicology and applied pharmacology 260, no. 1 (2012): 58-64.

[42] A. Frangi, M. Fontana, “Charring rates and temperature profiles of wood sections”. In Fire Mater. (2003), 27, 91–102.