EXPERIMENTAL INVESTIGATION OF GLUED LAMINATED TIMBER BEAM TO BEAM CONNECTIONS

Tomas Gečys, PhD student*
Department of Steel and Timber Structures
Vilnius Gediminas Technical University
Vilnius, Sauletekio av. 11, Lithuania
Email.: tomas.gecys@vgtu.lt

Professor Alfonsas Daniūnas, PhD
Department of Steel and Timber Structures
Vilnius Gediminas Technical University
Vilnius, Sauletekio av. 11, Lithuania
E-mail.: alfonsas.daniunas@vgtu.lt

* Corresponding Author

ABSTRACT
In this article semi-rigid timber connections which are used as beam-to-beam connections, are analysed. These connections also may be implemented as beam-to-column or column-to-foundation connections. The main analysis and design principles of existing semi-rigid beam-to-beam connections are discussed. An innovative timber semi-rigid beam-to-beam connection construction is proposed and investigated experimentally. The analyzed connection is composed using welded steel details which are anchored into timber elements. Steel details are anchored into the timber element by a back T-shaped steel plate. Welded steel details are anchored into tension and compression joint zones. This creates the possibility of using such connections for elements in which acting bending moments and axial forces. Initial slip between timber and steel is eliminated by filling the gap between the timber and steel with filler. Two different types of fillers are used to fill the gap between the timber and steel: two component polyurethane and cement-based fillers with polymer fibres. Laboratory experiments on five joints with the same geometrical parameters are performed.

KEY WORDS: beam-to-beam glued laminated timber joints, fillers for timber joints, semi-rigid joints.
1. INTRODUCTION
While analyzing timber joints’ classification according to strength and stiffness it may be said that there are no ideally rigid or pinned connections in timber structures, since all joints, where more than one connector is used, may be treated as semi-rigid [1]. Semi-rigid joints in timber structures are connections that are assembled fully on construction sites, and have necessary rotational stiffness and strength [2]. The need for new types of mounting joints in timber structures is obvious because of large-scale glued laminated timber elements. This type of structure is shown in Fig. 1, where the main constructional curved longitudinal axis bearing element is made of glued laminated timber. This constructional element is cut into necessary parts and assembled fully on the construction site after transportation.

![Fig. 1. The implementation of semi-rigid mounting joints in glued laminated timber structures](image)

When using semi-rigid joints in glued laminated timber frames, there is the possibility of designing a frame with the necessary stiffness [3]. The behaviour of semi-rigid joint is characterized by a moment-rotation curve [4-9]. The analysis procedure for semi-rigid timber joints is the same as for steel joints; a component method is used to form the joint’s mechanical model and bearing capacity, and the stiffness of each component is analysed. In the joint’s behaviour axial force may be evaluated by modifying the moment-rotation curve [10].

Before choosing the structure of the analyzed connection, other patented joints were looked at. For this purpose espa@cenet world’s patent base was chosen where 81 connections were found which may be treated as semi-rigid timber mounting joints. One of the main purposes in designing semi-rigid mounting joints is the reliable anchoring of steel detail in a timber element. To review the patent analysis data, several different steel detail’s anchoring methods can be distinguished: use of steel plates and dowels of bolts; use of glued-in steel rods; use of wedges and fillers; and use of large diameter steel rods.

The simplest method for joining separate timber elements into one is to use steel plates and dowels, or bolts. Such connections have free initial slip because of the diameter difference between the hole in timber element and the dowel. Various scientists investigated such connections, implemented as semi-rigid knee joints of the frame [5] or beam-to-beam connections [4]. Joints with steel details and dowels or bolts also may be implemented in tension timber elements [11]. When using such types of connections, the most dangerous collapse form is timber element splitting in the outer most stressed layers. While putting steel dowels with the minimum required spacing between them, timber element may be reinforced...
additionally perpendicular to the grain, using self-tapping screws or thin metal plates, which may be implemented as fasteners, and help to avoid the premature splitting of timber [12, 13].

Another method to obtain a quite stiff connection is to use glued-in rods for anchoring steel details into the timber element. Using these types of structures, a rigid contact between timber and steel is obtained, and deformation between steel and timber is about 0.5-1.0 mm at failure moment [2]. Steel rods may be glued into the timber at various angles to the fibre orientation [14, 15]. Glued-in threaded steel rods are used widely for corner beam-to-column connections in portal timber frames [16, 17], as well as for beam-to-foundation connections where glued-in rods are used as reinforcing bars in reinforced concrete structures [18]. Instead of glued-in threaded steel rods, glued-in hardwood dowels may be used for rigid frames in glued laminated timber houses [19]. In joints where glued-in rods are used to create a tight contact between the timber and the steel, the collapse of such a connection usually occur suddenly, with the timber splitting along the fibre grain. Analogous with glued-in rods, there may be large diameter screws which also may be screwed into the timber, parallel to the fibre direction [20]. Plastic behaviour and the ductile collapse of such connection types are reached by allowing plastic deformations in outer steel parts [21].

In semi-rigid timber connections, initial slip causes free rotation of the joint when initial contact between elements is not ensured. To eliminate initial free slip, the joint’s components should, initially, be in-filled, or gaps between timber and fasteners must be filled with filler. For initial infilling, different sizes of wedges may be used to create initial contact between different materials [22]. The hardwood wedges were implemented in semi-rigid timber connections for the portal frame construction as beam-to-column and column-to-foundation connections [23]. It has been determined numerically and in the laboratory that the wedge size which influences the level of initial infill directly has an influence on the joint’s stiffness, but has no significant impact on its bearing capacity [24]. Another method of eliminating the gap between timber and steel is to use a filler. Some authors implemented fillers for semi-rigid timber mounting joints combined with steel details and dowels [25].

Summarizing patent database review results, it was noticed that most connections in timber structures are designed by traditional methods, using steel plates and dowels, large diameter rods or glued-in rods. There has been little attention paid to connections where fillers may be used, and also where the contact between timber and steel would be ensured by compressing the timber while anchoring the steel detail.

In this article, the analysed and experimentally investigated connection is composed of three different materials: glued laminated timber, steel and filler. The development of such type of connection, sought to eliminate the initial movement of the joint by filling in the gap between timber and steel with filler. For this purpose, a floating texture filler is used which fills the gaps between the timber and the steel well. Also, the connection should be assembled easily on construction site, and there should be the ability to choose different thicknesses of plates or the anchoring length of the timber, to obtain the necessary strength and stiffness of the connection.

2. ANALYSED SEMI-RIGID BEAM-TO-BEAM CONNECTION
In this article, analysed construction of connection consists of welded steel details, which connect separate glued laminated timber elements, as shown in Fig. 2.
The welded steel detail is the same in the joint’s lower tension part and in the upper compressive part. In this case, this type of joint construction may be implemented for tension, compressive bending and also eccentric tension and compressive elements. Steel details are anchored into the timber elements using a back T-shaped part. The contact between the timber and steel is ensured by compressing the timber element in the contact zone. To centre the steel detail in the timber element, there is a groove in the timber element 5.0 mm larger than the thickness of the steel plate. The thickness of the groove in the timber element was assumed, taking into account technological tolerances and the minimal thickness of the filler. After assembling constructive bolts and centring the steel detail in the timber element, the contact zone is filled with filler. In this experimental study two different types of fillers were used: two component polyurethane and cement-based with polymer fibres. Fillers that are used do not expand while drying, so there are no additional stresses for the timber elements. The timber element with steel detail is assembled fully in a factory, an easily assembled on the construction site.
Fig. 3. Glued laminated timber element with assembled steel detail (left); welded steel detail (right); contact zone between timber and steel filled with cement based filler (below)

3. LABORATORY EXPERIMENT OF CONNECTION
The main aim of laboratory experiments is to determine the joint’s bending bearing capacity and rotational stiffness. Laboratory experiments on the joints are performed at Vilnius Gediminas technical university. For the bending test, a 1 000 ton capacity test stand was used.

In total, five connections with the same geometrical parameters were tested experimentally. The main experiment is four-point bending, as shown in Fig. 4. The analysed connection is in the middle of a 3.20 m span beam with pinned supports. Load is applied at two concentrated points. Glued laminated timber element is made of GL24h strength class timber, according to EN1194 standard. Cross-section of glued laminated timber element is 200x400, composed of 40 mm thickness lamella. Steel details are made of S275 strength class steel, according to EN10025 standard.

Fig. 4. Testing scheme of beam-to-beam connection: 1-analysed connection; 2-timber element; 3-crossbeam; 4-load application points; 5-pinned supports; 6-dynamometer
A four-point bending test is performed according to EN26891:1991 standard requirements. The load is applied gradually, at first till 40 per cent of maximum theoretical load, than decreased to 10 per cent; after that till ultimate [26]. While testing, joint’s displacements and deformations are recorded. Nine displacement gauges are fixed on the connection, as shown in Fig. 5. 1-5 displacement gauges are set for measuring vertical displacements; 6-9 displacement gauges are set for measuring total deformations of timber, steel detail and filler in contact zones. The base of the contact deformation measuring is 80 mm. Tenzo sensors are used to measure deformations in the timber surface, in the contact area of timber and steel. 16 tenzo sensors are fixed to each connection, as shown in Fig. 5.

One beam was tested with a polyurethane-based filler, while for the remaining four connections a cement-based filler with polymer fibres was used. Mechanical and physical properties of fillers declared by manufacturers are shown in Table 1. The first filler used in the investigation was polyurethane-based filler PURBOND CR 421, which creates a tight contact between timber and steel, and does not shrink if used up to 8.0 mm thickness. The second filler is cement-based with polymer fibres EMACO Nanocrete R4 Fluid, which contains of Portland cement, graded sand, specially selected polymer fibres and special additives, which compensate for shrinkage strains. The cement-based filler, depending on the quantity of water, may range from a floating to casting texture. In this study, a casting texture was used because the thickness of the gap varied from 3 to 8 mm.
Table 1. Manufacturers’ declared physical and mechanical properties of fillers

<table>
<thead>
<tr>
<th>Filler name</th>
<th>Tension strength, MPa</th>
<th>Compressive strength, MPa</th>
<th>Modulus of elasticity, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>PURBOND CR 421</td>
<td>25.0-30.0</td>
<td>79.9</td>
<td>1.56</td>
</tr>
<tr>
<td>EMACO Nanocrete R4 Fluid</td>
<td>–</td>
<td>55.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

4. LABORATORY EXPERIMENTAL INVESTIGATION RESULTS

Displacements and deformations are recorded according to the location scheme of displacement sensors shown in Fig. 5. In Fig. 6, load-central point displacement curves are presented for joints with polyurethane filler (J-1-PUR) and cement-based filler (J-2-CEM, J-3-CEM, J-4-CEM, J-5-CEM). Curves indicate that the behaviour of joints is very similar, but although the geometrical and physical parameters are the same, the bending bearing capacity and stiffness of joints differ by about 1.40 times. Comparing joints with the same cement-based filler, results only vary 1.07 times. It should be marked that joints reveal high stiffness, because even at the moment of failure, the serviceability limit state is satisfied.

![Fig. 6. Joints’ load-middle point (displacement gauge No. 1 according to Fig. 5) vertical displacement curves](image_url)

In Figs. 7 and 8, the joints’ load-deformation curves of contact zone in tension (below) and compression (above) are presented. While applying load, general deformations of timber steel and filler are recorded. From Fig. 7 it is obvious that different fillers in the compressive zone act differently while loading. The cement-based filler’s contact deformations are about 2.5 times greater than those of the polyurethane-based filler at the same level of loading. In the compressive zone, irreversible deformations occur when the joint reaches 50 percent of ultimate loading. These should be evaluated additionally for structures where acting cyclic loading or changing efforts which create tension and compression.

![Fig. 7. Joints’ load-compressive contact zone deformation curves (displacement gauges nos. 6 and 7, according to Fig. 5)](image_url)
In Fig. 8, load-contact global tension deformations are presented. The joints’ tension zone behaviour is very similar, although the difference in the curves’ slope angles is not so pronounced as in compressive zone. Distribution variation of deformations in tension zone is greater than in the compressive zone.

Fig. 8. Joints’ load-tension contact zone deformation curves (displacement gauges nos. 8 and 9, according to Fig. 5)

The semi-rigid joint’s behaviour is characterized by bending moment-rotation dependence, as shown in Fig. 9. Rotation angles are determined by the difference between displacements between the middle point and load application points.

Fig. 9. Joints’ bending moment-rotation scheme (above) and bending moment-rotation curves

Joints’ bending bearing capacities and maximum deformations are summarized in Table 2. Joint J-2-CEM’s bending bearing capacity and rotation angle is about 1.425 times greater than other tested joints: J-1-PUR; J-3-CEM; J-4-CEM and J-5-5CEM. The reason for such a decrease in bending bearing capacity and stiffness may be explained by the technological longitudinal drying crack which was noticed in a sudden cross-section change area, as shown in Fig. 10. Before, the loading crack’s width was 1.58 mm, length 300 mm. While loading crack did not grow in a longitudinal direction, it did widen. The coefficient of variation is about 1.07, when comparing joints’ bending bearing capacities with the same fillers.
### Table 2. Joints’ bending bearing capacities and maximum deformation at failure moment

<table>
<thead>
<tr>
<th>Joint name</th>
<th>Experimental bending bearing capacity, kNm</th>
<th>Rotation angle, deg</th>
<th>Joint’s middle point displacement, mm</th>
<th>Maximum deformation in compressive contact part, mm</th>
<th>Maximum tension deformation in tension contact part, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>J–1–PUR</td>
<td>66.24</td>
<td>0.0084</td>
<td>10.78</td>
<td>0.23</td>
<td>0.97</td>
</tr>
<tr>
<td>J–2–CEM</td>
<td>46.48</td>
<td>0.0144</td>
<td>14.52</td>
<td>1.35</td>
<td>1.44</td>
</tr>
<tr>
<td>J–3–CEM</td>
<td>59.96</td>
<td>0.0143</td>
<td>15.76</td>
<td>1.12</td>
<td>1.24</td>
</tr>
<tr>
<td>J–4–CEM</td>
<td>56.16</td>
<td>0.0130</td>
<td>14.42</td>
<td>0.59</td>
<td>1.58</td>
</tr>
<tr>
<td>J–5–CEM</td>
<td>55.56</td>
<td>0.0137</td>
<td>14.77</td>
<td>0.67</td>
<td>1.70</td>
</tr>
</tbody>
</table>

**Fig. 10. Initial longitudinal drying crack of joint J-2-CEM in the lower tension zone near sudden cross section change**

All joints tested experimentally collapsed in the same failure mode, with the timber splitting in the lower tension zone of the joint, as shown in Fig. 11. During failure, the full shear block which anchors the steel detail split off.

**Fig. 11. Experimental failure mode, splitting of shear block: 1 (J-1-PUR); 2 (J-2-CEM); 3 (J-2-CEM); 4 (J-4-CEM); 5 (J-5-CEM)**
Short-term static loading experimental results show that analysed joints have high rotational stiffness behavior. According to moment-rotation curve angle, curves are very similar to hybrid steel timber connections with glued-in threaded steel rods [16]. Hybrid timber steel connection with glued-in threaded steel rods, implemented for beam-to-column joints, rotate between 0.009 and 0.015 rad at failure moment, while in this article, analysed connections are in the range between 0.0084 and 0.0137 rad. In this article, comparing connections investigated experimentally with traditional dowel type connections with steel plates, it is obvious that this new type of joint construction is several times stiffer than traditional dowel type connections, which represents rotation between 0.009 and 0.043 rad at the moment of failure.

5. CALCULATION OF JOINTS ACCORDING TO EUROCODE5

When designing timber structures according to Eurocode5, linear stress distributions are assumed. Normal stresses from bending moment are presented in Fig. 12 where $\sigma_n$ stresses in Section 1-1 are shown. Shear stresses in the anchoring area of the steel detail are also presented. Shear stresses are distributed unevenly along the steel detail’s anchoring length. There are authors who investigated empirical equations for the determination of shear strength, taking into account the uneven distribution of shear stress in length, and concentrations of these stresses in peak areas [27]. Maximum shear stresses occur in the steel detail’s back T-shaped plate’s tight contact with timber. In the contact area where high shear and tension stresses occur perpendicular to the grain, stress concentrations should be avoided.

Fig. 12. Normal stresses from bending moment in section 1-1 and shear stresses in steel detail’s anchoring length

The joint’s theoretical banding bearing capacity is determined by the equilibrium of internal forces. In Fig. 12 $\sigma_m$ are the maximum normal stresses from bending moment in outer surfaces, and $\sigma_{m1}$ are normal stresses near the groove. When calculating theoretical bending bearing capacity, all possible failures modes are analysed.

In Eurocode5 there are no methods for how to determine a semi-rigid timber joint’s rotational stiffness. Also, there are no equations for the determination of separate components’ stiffness.

6. EVALUATION OF EXPERIMENTAL RESULTS AND THEORETICAL CALCULATION

The joint’s bending bearing capacities are summarized in Table 3. Joint J-1-PUR’s experimental bending bearing capacity is 1.574 times higher than the theoretical one calculated by taking the characteristic values of timber strengths. Joint J-2-CEM’s bending bearing capacity is 1.104 times higher, which may be explained by the fact that a longitudinal drying crack was noticed before the experiment. These experiments showed that technological imperfections, such as longitudinal drying cracks, have a strong influence on the behaviour of the joint. The influence of drying cracks should be investigated in further experiments, but this article does not include that.
It is very difficult to design connections with high bending bearing capacity because of timber anisotropy, since physical properties differ in several ways compared along the grain and perpendicular to the grain direction. While calculating the theoretical bending bearing capacity of the joint, all possible collapse forms are analysed: timber compression; timber tension; shear of timber; tension of bolts; bending of steel plates. Theoretical bending bearing capacity of analysed connection is $M_{Rk} = 42.09\, \text{kNm}$ taking into account the characteristic material properties.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Experimental bending bearing capacity, kNm</th>
<th>Theoretical bending capacity taking into account characteristic material values, kNm</th>
<th>Ratio between experimental and theoretical bending bearing capacities</th>
</tr>
</thead>
<tbody>
<tr>
<td>J–1–PUR</td>
<td>66.24</td>
<td>42.09</td>
<td>1.574</td>
</tr>
<tr>
<td>J–2–CEM</td>
<td>46.48</td>
<td>42.09</td>
<td>1.104</td>
</tr>
<tr>
<td>J–3–CEM</td>
<td>59.96</td>
<td>42.09</td>
<td>1.425</td>
</tr>
<tr>
<td>J–4–CEM</td>
<td>56.16</td>
<td>42.09</td>
<td>1.334</td>
</tr>
<tr>
<td>J–5–CEM</td>
<td>55.56</td>
<td>42.09</td>
<td>1.321</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

In this article, the semi-rigid timber beam-to-beam connection is analysed experimentally. Timber elements are joined together using welded steel details which are anchored into the timber with back T-shaped steel plates. To eliminate initial movement between the timber and the steel, two types of different fillers are used: two-component polyurethane and cement-based. Five joints with the same geometrical parameters are tested experimentally, and the bending bearing capacities theoretically determined. The main conclusions formed as follows:

1. The analyzed connection is easily assembled using mounting bolts while all steel details of the connection are fixed to timber in the factory.
2. Experimentally determined that two component polyurethane and cement-based fillers may be used as filling material, to ensure initial contact between timber and steel, and eliminate initial movement between these elements. Fillers’ mechanical and physical properties are not inferior to timber properties. Fillers’ consistency allows filling gap between timber and steel in range of 2.0-8.0 mm.
3. Experimental investigation showed that ratio between experimental results and theoretical calculation, according to Eurocode5, taking into account characteristic strength values is in the range between 1.321 and 1.574 for joints’ J-1-PUR; J-3-CEM; J-4-CEM; J-5-CEM, while for joint J-2-CEM it is 1.104.
4. Experimental results show that investigated joints have high rotational stiffness, which may be compared to hybrid timber steel connections with glued-in threaded steel rods. In this article, investigated connections are several times stiffer than traditional connections with steel plates and dowels.
5. Technological imperfections, such as longitudinal drying cracks, have a strong influence on bending bearing capacity and rotational stiffness. The impact of drying cracks should be evaluated in further investigations.
REFERENCES


