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EXPERIMENTAL INVESTIGATION ON TRUSSES MADE OF GLULAM AND BIRCH PLYWOOD GUSSET PLATES

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ABSTRACT: This paper investigates the load-carrying capacity of trusses consisting of glulam elements joined through birch plywood plates by means of either adhesively gluing or mechanical fasteners. A total of 6 trusses with a span of 7 meters were tested, three trusses for each connection type. Furthermore, the thickness of the plywood plates varied between 9 and 21 millimetres (mm). The main purpose of this research was to gain a better understanding of the failure mode of birch plywood subjected to a multi-axial stress state with loads from multiple directions. Therefore, the truss specimens were designed so that failure occurred in the central plywood plate, which was subjected to a multi-axial stress state. All specimens with mechanical connectors, as well as the bonded specimen with the thinnest plywood plate (9 mm), failed in the plywood plates. In contrast, bonded specimens with 12 and 21 mm thick plywood failed at the bonded interface between plywood and glulam. For specimens that failed in the plywood plates, the experimental results showed an increase in load-carrying capacity with increasing plywood plate thickness. Furthermore, glued specimens generally exhibited higher load-carrying capacity and elastic stiffness than those with mechanical connectors. For both glued and mechanically connected specimens, the thickness of the plywood plate did not show a significant influence on the stiffness. The analytical load-carrying capacity estimations slightly overestimated the experimental results of specimens that showed plywood failure, but they generally showed good agreement. The overestimation was attributed to the size effect of birch plywood's mechanical properties.

KEYWORDS: timber-to-timber connections, birch plywood gusset plates, mechanical connections, glued connections

1 – INTRODUCTION

The importance of sustainability has grown significantly in response to the challenges of climate change. The construction industry is a major contributor to global emissions, responsible for approximately 40% of worldwide carbon dioxide emissions [1]. Consequently, there is an urgent need to minimize emissions within this sector.

Birch is widely distributed across the Eurasian continent, particularly in northern Europe. Despite possessing mechanical properties superior to softwoods, lower environmental impact and lower costs than other structural materials such as steel, birch plywood is rarely used for structural applications. In timber structures, the connections between different elements, such as glulam beams, are usually the weakest part of the structure. Fasteners and connection systems affect the overall behaviour of timber structures and take most of the design efforts [2].

Previous studies have thoroughly investigated the mechanical properties of birch plywood, such as tensile, compression, shear and bending strength, by conducting small-scale tests at varying load-to-face grain angles and moisture content [3-4]. Moreover, the potential of birch plywood plates as a substitute for steel plates in connections of timber structures has also been investigated. Connections with mechanical fasteners and birch plywood plates were experimentally investigated to assess the failure modes and to define the behaviour of such connections at varying load-to-face grain angles and plywood thickness [5-7]. Furthermore, the influence of different adhesive types, pressing methods and load-to-face grain angle on the bonding strength was investigated for adhesively bonded connections with birch plywood plates [8-9].

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However, in these studies, the plywood plates were subjected to simple stress states, such as uniaxial tension, and the size of the specimens was relatively small compared to full-scale structures. Yet, in a typical connection node, loads come from multiple directions causing a complex stress state in the plywood plate.

In this investigation, full-scale trusses consisting of glulam elements joined at the nodes through birch plywood plates on the sides were built and tested. This study aimed to gain a better understanding of the failure modes of birch plywood plates subjected to complex stress states.

2 – MATERIALS AND METHOD

2.1 – MATERIALS

A total of six trusses were tested in this study. The connection between the glulam beams and the plywood plates at the nodes was made either with Melamine-urea-formaldehyde (MUF)-based glue (Kauramin from BASF) for three specimens, while for the remaining three smooth dowels with a diameter of 8 millimetres (mm) were used. All the specimens were designed in such a way that failure always occurred in the central (lower) plywood plate (Fig. 1).

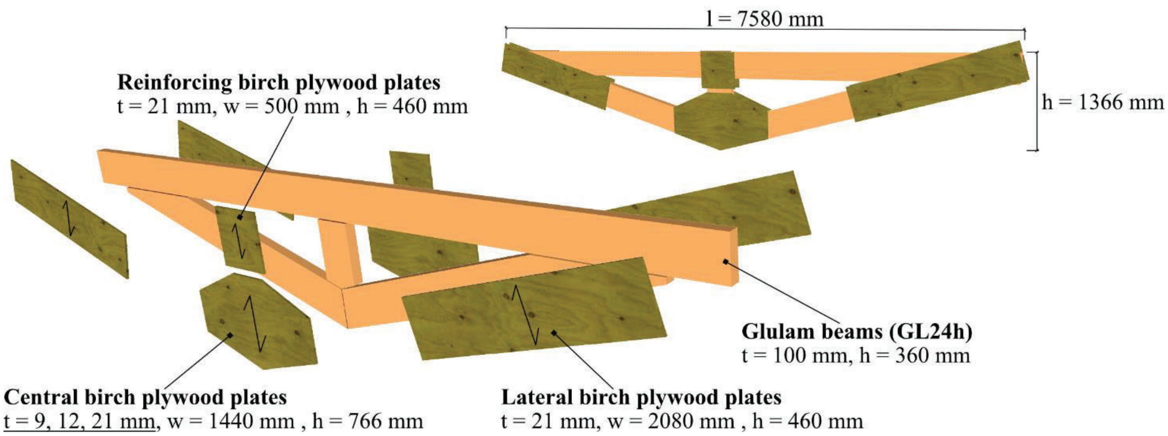

Figure 1. Specimens geometry.

The investigated thickness of the central plywood plate was 9, 12 and 21 mm, respectively (Table 1), while the thickness of the other plywood plates was maintained at 21 mm. Each specimen was labelled as the type of connection used (GLU for adhesively glued and DOW for smooth dowels) and the thickness of the central plywood plate in millimetres. One replicate was tested for each configuration.

Table 1: Specimens overview and denotations.

Connection type	Central plywood plate thickness (mm)	Denotation
Glued	09	GLU09
	12	GLU12
	21	GLU21
Smooth dowels	09	DOW09
	12	DOW12
	21	DOW21

The plywood plates used in this study were produced by Koskisen Oy (Järvelä, Finland). The total number of veneers in each plate, corresponding to plate thicknesses of 9 mm, 12 mm, and 21 mm, was 7, 9, and 15, respectively. The thickness of each inner veneer was approximately 1.5 mm, while the outer veneers were about half as thick as the inner veneers. The thickness of each inner veneer was approximately 1.5mm, while the outer veneers had a thickness that was about half that of the inner veneers.

The span of each truss was 7 meters, and the height was 1366 mm. The glulam beams had a cross-section of 100x360 mm and a grade of GL24h, while the central plywood plate had a height of 766 mm and a width of 1440 mm. A gap of 10 mm was kept between the glulam beams to have an unambiguous load path through the plywood plates, except between the vertical post and the horizontal glulam beam. For specimens with thicker plywood, support timber elements were attached on the sides of the vertical post to increase the contact area with the horizontal glulam beam and avoid the risk of failure due to compression perpendicular to the grain (Fig. 2). Furthermore, rectangular plywood plates were glued on the horizontal glulam beam to restrain out-of-plane movements of the vertical post and reinforce against compression perpendicular to the grain where the load was applied.

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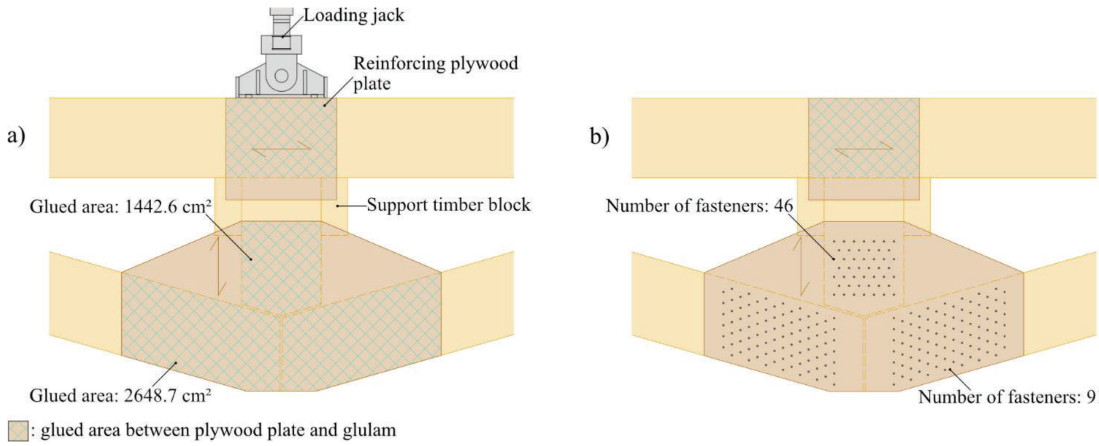

Figure 2. Details of the central node for: a) glued trusses and b) doweled trusses.

The bonded trusses were assembled using clamps to apply the required pressure for the curing process of the glue (Fig. 3). This method was chosen to allow reproducibility in other facilities. The approximate pressure applied from the clamps was 0.3 N/mm^2, and the curing time for the glue was 32 hours in an indoor environment with controlled temperature and relative air humidity.

Figure 3. Assembly of a glued truss.

The mean moisture content (MC) of the timber elements was calculated according to EN 13183-1 [10] by taking small timber samples from the tested specimens. The mean density was estimated by dividing the mass of each sample measured before drying by its volume. The mean MC and density of glulam were 15.5% and 524.2 kg/m^3, respectively, and those of birch plywood were 11.1% of 722.8 kg/m^3.

Further research will present more information regarding adhesively bonded trusses.

2.2 – TEST SETUP

Each truss was supported by two short vertical glulam colums with a height of 1.1 metres and was laterally braced against out-of-plane movements at approximately one-third and two-thirds of the span (Fig. 4). The load was applied on the top of the horizontal glulam beam at a constant rate of 6 millimetres per minute.

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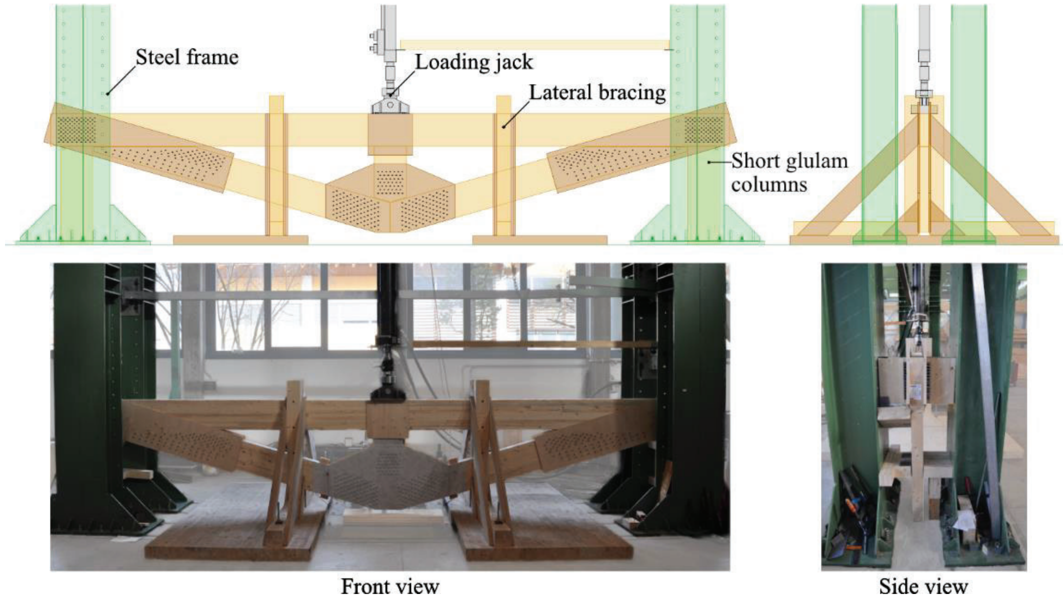

Figure 4. Test setup.

Linear variable displacement transducers (LVDTs) were used to record relative and absolute displacements around the central node (Fig. 5a). In addition, the central plywood plate on the other side was painted with a white background and random black dots that create a speckle pattern. This was done in order to use the digital image correlation (DIC) method, in which a camera is used to capture photos of the surface of interest at a set time interval during the tests (Fig. 5b), which in this study was every three seconds. This method can give displacements and strains after processing the photos with a surface.

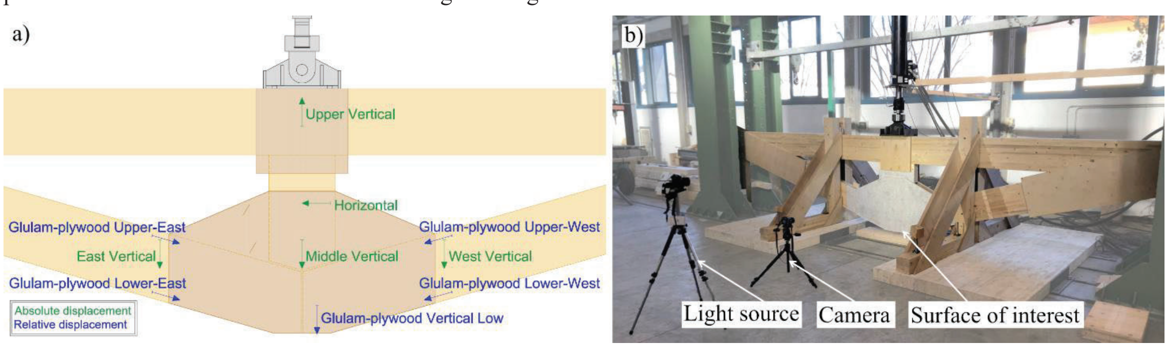

Figure 5. Measuring instruments: a) LVDTs and b) DIC.

2.3 – ANALYTICAL ESTIMATIONS

Trusses with mechanical fasteners were assumed to behave as trusses with hinged connections, while bonded trusses were considered trusses with rigid connections. Furthermore, the spreading angle effect within the plywood plate was considered for all trusses. This was previously investigated in [6-8] for both bonded connections and with mechanical fasteners. The value of the spreading angle used in this study was $\beta_t = 15°$ was used, as shown in Figure 6. The axial force was assumed to act within the spreading angle height ($h_{bp\_sa\_DOW}$ for mechanically connected trusses and $h_{bp\_sa\_GLU}$ for glued trusses), while the shear force and bending moment were acting on the entire plywood height.

Mechanically connected trusses

To simplify the calculations, the load was assumed to be applied to the vertical post, which was not connected to the horizontal glulam member. This simplification was possible since the vertical load carried by the horizontal glulam beam was not significant. As a result, in the analytical calculations, the glulam beams were subjected only to axial forces, as shown in Figure 6a. The axial force in the glulam beam was decomposed into the components parallel and perpendicular to the grain direction of the central plywood plate. The verification of the central plywood plate was done through the following interaction formula that combines the actions of tension and shear:

$$\frac{N}{R_N} + \frac{V}{R_V} = 1 \tag{1}$$

where

$$R_N = f_{t\_bp\_90} * n * t_{bp} * (h_{bp\_sa\_DOW} - 8 * d) \quad (2)$$

$$R_V = f_{v\_bp\_0} * n * t_{bp} * (h_{bp} - 11 * d) \quad (3)$$

where $f_{t\_bp\_90}$ and $f_{v\_bp\_0}$ are, respectively, the tensile and shear birch plywood strength with a 90° and 0° load-face grain angle [3], t_{bp} is the plywood thickness, d is the fastener diameter, $(h_{bp\_sa\_DOW} - 8 * d)$ and $(h_{bp} - 11 * d)$ are the effective heights of the plywood plate for tension and shear, respectively, and n is the number of shear planes.

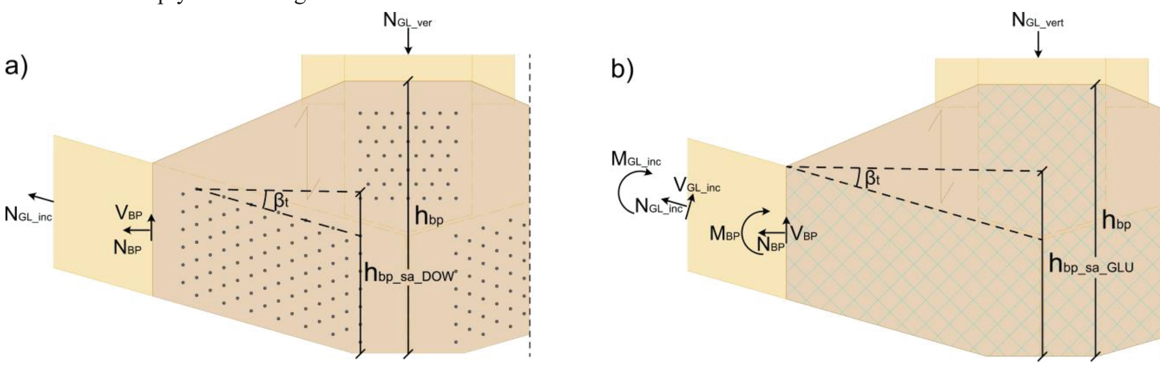

Figure 6. Verification of the central plywood plate: a) doweled trusses and b) adhesively bonded trusses.

Adhesively bonded trusses

The load-carrying capacity of the central plywood plate was estimated through the following formula that considers the interaction between normal force, shear force and bending moment [11]:

$$\frac{N}{R_N} + \left(\frac{M}{R_M}\right)^2 + \frac{V}{R_V} = 1 \quad (4)$$

where

$$R_N = f_{t\_bp\_90} * n * t_{bp} * h_{bp\_sa\_GLU} \quad (5)$$

$$R_V = f_{v\_bp\_0} * n * t_{bp} * h_{bp} \quad (6)$$

$$R_M = f_{m\_bp\_90} * \frac{n * t_{bp} * (h_{bp} * \cos(\alpha))^2}{6} \quad (7)$$

where $f_{m\_bp\_90}$ is the birch plywood bending strength with a 90° load-face grain angle [4].

3 – RESULTS AND DISCUSSION

3.1 – EXPERIMENTAL RESULTS

All specimens with mechanical connectors and the bonded specimen with 9 mm thick central plywood plates (GLU09) showed failure of the central birch plywood plate (Fig. 7). Failure for the bonded specimens with 12 and 21 mm thick central plywood plates (GLU12 and GLU21) occurred at the bonded interface between plywood and glulam. More details about bondline failure will be presented in future works.

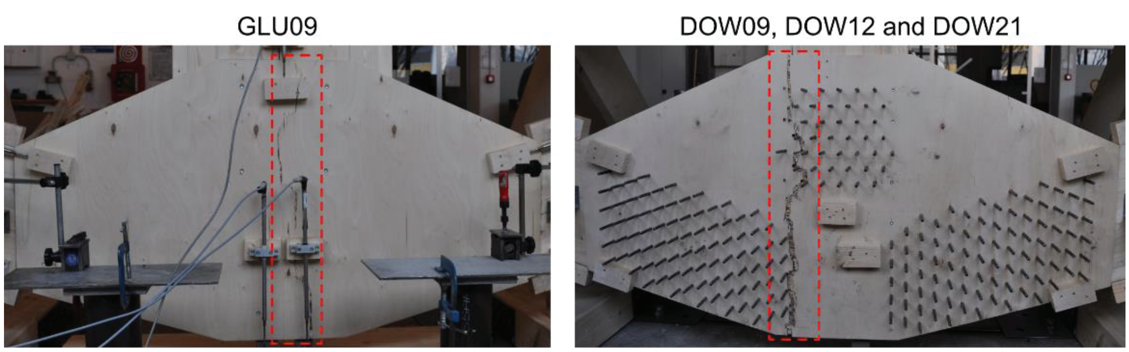

Figure 7. Typical plywood failure modes.

The experimental results showed increasing load-carrying capacity with increasing thickness of the central plywood plate (Fig 8). Furthermore, the load-carrying capacity of glued trusses was higher than those using mechanical connectors. This is presumably due to the reduced cross-section in the mechanically jointed specimens caused by the holes for the dowels. In addition, the global stiffness did not show a significant influence on the thickness of the plywood plates. Yet, glued specimens showed almost double stiffness compared to mechanically jointed specimens.

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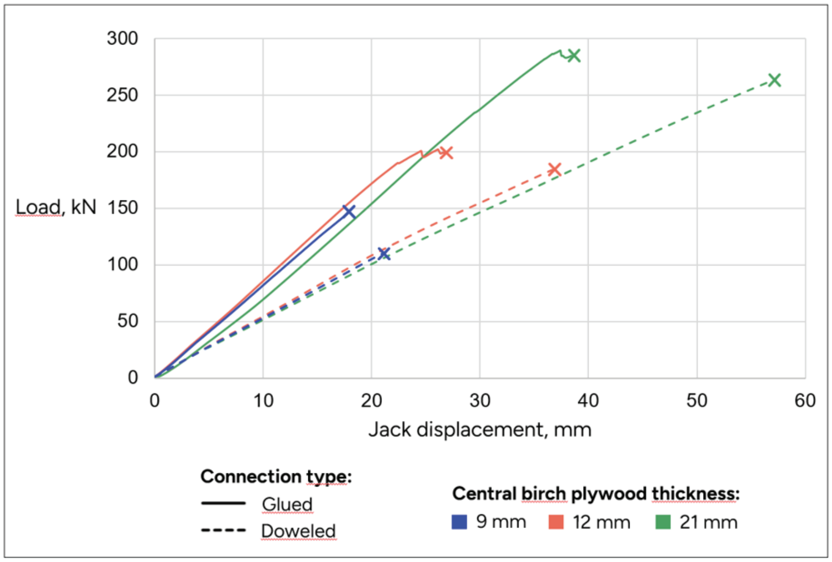

Figure 8. Load-displacement curves for all specimens.

3.2 – ANALYTICAL ESTIMATIONS

Analytical estimations generally showed good agreement with experimental results, as shown in Table 2. The predicted failure mode for all specimens with mechanical connectors and bonded trusses with 9 and 12 mm thick plywood (GLU09 and GLU12) was in the central plywood plate, while for the bonded truss with the thickest plywood (GLU21) was in the bondline between the plywood and the inclined glulam beam. However, as shown in Figure 7, specimen GLU12 showed bondline failure and not failure in the plywood plate.

The analytical estimations for specimens that showed plywood failure are generally slightly overestimating the experimental capacity but this was expected due to the size effect, as the strength values used in the analytical estimations are from small-scale tests on birch plywood.

Table 2: Analytical estimations and experimental results, the values in bold are the expected failure modes.

ID	Analytical estimations, kN			Maximum experimental load, kN
	Glulam failure	Plywood failure	Bondline failure	
GLU09		**166.3**	264.0	146.7
GLU12	307.6	**221.7**	264.0	202.0
GLU21		388.0	**264.0**	289.4
DOW09		**127.7**	-	111.3
DOW12	369.1	**170.2**	-	183.7
DOW21		**297.9**	-	264.4

3.3 – DIC ANALYSIS

Figure 9 shows the horizontal and vertical displacements of the central plywood plate and the surrounding glulam beams from the DIC analysis of specimens DOW12 just before failure. The displacements from the DIC analysis were compared to the reading from the LVDTs, and good agreement was shown. As shown in Figure 9a, the upper part of the plywood plate shows almost no horizontal displacements. In the lower part of the plate, where the connectors to the inclined glulam beams are placed, the plate moves horizontally due to the tensile force from the glulam beams. In addition, as shown in the figure, the horizontal displacement of one fastener in the bottom fastener row (lower dowel) is approximately 1 mm greater than one fastener in the upper fastener row (upper dowel) (Fig 9a). This means that, although the analytical estimation showed good agreement with the experimental results, the assumption that connections with mechanical fasteners behave as a perfect hinge is an idealisation. However, the tensile force is more severely loading the plate than the bending moment, even for glued trusses. Further investigation will study the influence of the bending moment on the structural behaviour and load-carrying capacity of such connections.

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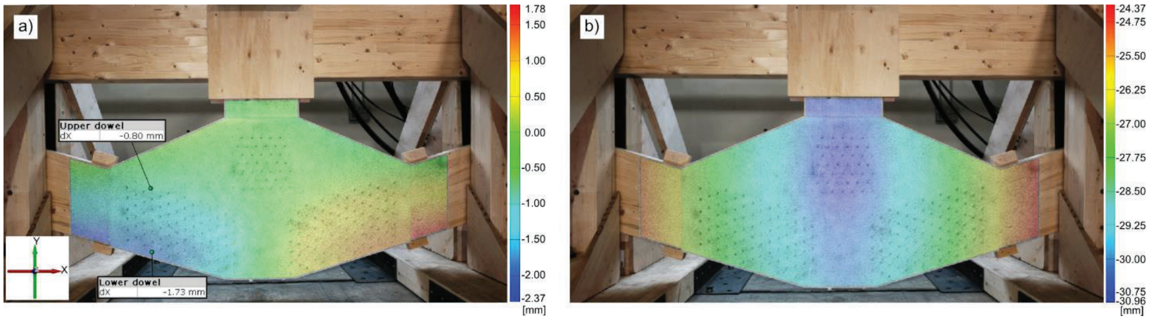

Figure 9. DIC analysis for DOW12 just before failure: a) horizontal displacements and b) vertical displacements.

4 – CONCLUSIONS

This study investigated the load-carrying capacity and failure modes of full-scale glulam trusses connected through birch plywood gusset plates, either bonded or mechanically fastened. Six tests were conducted to assess the structural behaviour of these trusses. The central plywood plate, where failure was designed to occur, was subjected to multi-axial stress conditions.

Analytical estimations were performed and compared to the experimental results; furthermore, results from the DIC analysis were discussed.

All mechanically connected trusses and the glued truss with the thinnest plywood plate (9 mm) showed failure in the central plywood plate, while glued trusses with thicker plywood (12 and 21 mm) showed glueline failure. The load-carrying capacity was proportional to the thickness of the central plywood plate, while the global stiffness depended on the connection type but not on the plywood thickness. Trusses with bonded connections exhibited higher load-carrying capacity and almost double stiffness compared to mechanically connected trusses.

The analytical load-carrying capacity estimations showed generally good agreement with the experimental results for specimens that showed plywood failure. The slight overestimation of the experimental capacity was attributed to the size effect, as the strength values of the plywood plate used in the analytical estimations were obtained from small-scale tests.

Furthermore, the results of the DIC analysis showed that fasteners on the lower and upper fastener rows exhibited different horizontal displacement values, indicating that the assumption of hinged connections for mechanically connected trusses is an idealisation. The analytical estimations showed good agreement with the experimental results because the tensile force was significantly more severe than the bending moment in this specific truss geometry.

Further investigations will perform numerical analysis on the specimens tested in this study and compare the results to the DIC analysis. In addition, more information regarding experimental results and analytical estimations of bondline failure will be presented in future works. Further research should investigate the size effect of birch plywood's mechanical properties.

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