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MECHANICAL CHARACTERIZATION OF TIMBER STRUCTURAL ELEMENTS USING INTEGRAL MECHANICAL ATTACHMENTS

Julien Gamerro[1,2], **Ingebrigt Lemaître**[3], **Yves Weinand**[2]

ABSTRACT: Automation is increasingly present in the construction industry, whether at the design, manufacturing or assembly stage. Thanks to new technologies, such as robotics, new ways of designing structural elements can be imagined and implemented. Complex methods and sequences of assembly can be set up quickly as well. Numerous studies have been carried out in this direction at the laboratory for timber constructions IBOIS (EPFL) especially on wood–wood connections called Integral Mechanical Attachments (IMA). This paper is focused on the mechanical characterization of a prefabricated structural element entirely made of Oriented Strand Board (OSB) panels produced by a fully robotized line. In order to avoid bonding process due to cost, ecological and time reasons, IMA using OSB have been chosen to connect each prefabricated element. Experimental tests and numerical models have been developed to determine the mechanical response of such structural elements.

KEYWORDS: Timber Construction, Connections, Structural Performance, Digital Fabrication, Orientated Strand Board

1 INTRODUCTION

For construction applications, Oriented Strand Board (OSB) panels are generally used for roof, wall and floor sheathing. They are also used in timber construction as structural elements like diaphragm, shearwall, web for prefabricated I-joist and skin material for structural insulated panels [1, 2]. The present research, which was performed in collaboration with a timber construction company, *MOBIC SA*, is focused on the development of a prefabricated structural element fully composed of OSB. To achieve this objective there are many problems to solve, especially the connections between different parts considering the OSB edge mechanical properties. However, nowadays, thanks to digital fabrication and new technologies like robotics, automation is increasingly present in the construction industry. In this context, improved timber plate structure connections, previously achieved with fasteners, were proposed by C. Robeller. He developed an innovative wood–wood connection inspired by traditional joinery [3]. Such connections particularity is that they are an integral part of the panel, therefore they require a customized automated prefabrication: connectors are cut with the panels in a single operation thanks to CNC (Computer Numerical Control) machining [4]. Similar work was carried out by T. Schwinn et al. [5], where a pavilion made of timber plates was connected with finger joints. These types of connections are called Integral Mechanical Attachments (IMA). This paper is focused on the mechanical characterization of IMA using OSB panels. It investigates the structural response of this type of element for which experimental tests and numerical models have been developed.

1.1 CONNECTION BEHAVIOR

Knowledge of the connection behavior between the different layers of the structural element is essential. For characterization of timber connections there are rules in European standards [6, 7] and also a different approach proposed by the Swiss Society of Engineers and Architects for timber construction [8]. These rules define the way to performed the tests and analyse the experimental data. Regarding the IMA behaviour in shear, M. Dedijer et al. studied the shear resistance and failure modes of the Multiple Tab-and-Slot Joint (MTSJ) using Laminated Veneer Lumber (LVL) panels [9]. The shear behavior of such connections has also been investigated for the Segmental Timber Plate Shell for the Landesgartenschau Exhibition Hall [10]. Another experimental study for digital fabrication strategies for timber thin-walled sections has been done in 2016 [11].

1.2 ANALYSIS OF INTERCONNECTED TIMBER ELEMENTS

The main parameter of interconnected wooden elements is the slip modulus of the connection between different parts, as a certain continuity between layers is required in order to use it for structural application. Usually in timber construction, bonding is the most preferred option,

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[1] Corresponding author:julien.gamerro@epfl.ch

[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory for Timber Constructions (IBOIS),1015 Lausanne, Switzerland

[3] Ecole Nationale Supérieure de Techniques Avancées (ENSTA ParisTech), 828 boulevard des Marchaux, 91120 Palaiseau, France

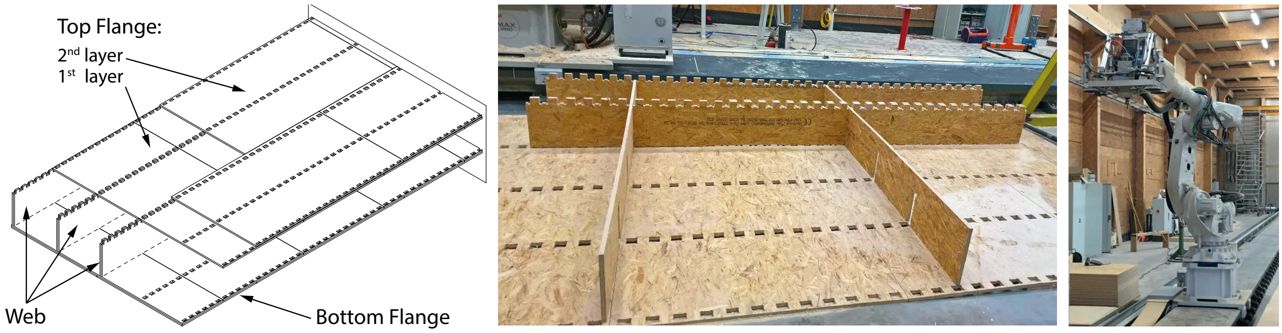

Figure 1: *(a) Axonometry of the OSB prefabricated element (b) Photo of the OSB prefabricated element under fabrication (c) Robotic line equipped with special tool for OSB panel [credit photo : Cedric Moutschen, MOBIC SA]*

for example Glued Laminated Timber (GLT) or Cross Laminated Timber (CLT), because it can be considered as having perfect continuity. However, many elements are assembled with fasteners such as nails and bolts and in those cases, connection is not perfectly rigid. This phenomenon is called semi rigidity.

For the calculation of interconnected timber elements, there are three analytical models that take into account the semi rigidity of the connections. B. Heimeshoff developed the gamma method [12] for reconstituted elements up to three layers. This method is still relevant and serves as a basis for the Eurcodes 5 for this type of calculation [6]. More recently, U. A. Girhammar developed a simplified analysis method for composite beams with interlayer slip [13]. This method allows to calculate for different types of support and loading but only for 2 layers as it is a simplified case of the gamma method. Another model was developed by H. Kreuzinger with the possibility of calculating a composite beam for various loading cases and a layer number higher than 3 [14, 15]. Such method is accurate for two layers and afterwards becomes an approximation due to the simplifying assumptions. Kreuzinger model is used in German standards for timber construction [16] and is also in the form of a report published by the European Organisation for Technical Approvals [17].

From the second half of the 20th century, computers and Finite Element Model (FEM) allowed the development of other calculation methods for reconstructed sections. In 1994 M. Hoeft developed a finite element method for the calculation of multiple layer beams [18] which has been deepened by P. Krawczyk et al. with Felina software [19, 20]. In the same time, another model was developed with Sofistik software by T. Gollwitzer et al. [21]. During his thesis C. Pirazzi compared different analytical and numerical approches [22]. Other works were performed on multiple layer beams and construction elements made from timber with Castem software [23, 24]. More recently S. Roche et al. studied the semi rigidity of the dovetail joint for a beam on two supports with a numerical model developed with Matlab [25]. All these works were performed in two dimensions not considering the non-linear behaviour of the connections except for the work of S. Girardon [26]. A three dimensional model was developed for timber beams connected with wood dowels [27] and others more specific to timber-concrete composite [28, 29, 30].

For this research, it was chosen to use a FEM due to the geometric complexity of IMA connections as well as to be able to implement a parametric model.

2 STRUCTURAL SYSTEM

OSB panels are mainly combined with other materials to compose structural elements like joist component and timber frame wall. The challenge here is to use only OSB material for all the elements within the structural system. For economic, ecological and industrial reasons bonding process was avoided and fasteners were minimized. The proposed prefabricated roof (or slab) component is composed of beams (web) connected by a top and bottom panel layers (flange) with Through Tenon (TT) joints as shown in Figure 1 (a,b). The material used is OSB type 4 with a size of 1,25 by 2,5m and a thickness of 18 and 25mm [31]. The fiber orientation (FO) of the panel is along their length. Thanks to the robotic line of *MOBIC SA* (see Figure 1 (c)), TT joints were machined directly in the OSB panels to connect all the different parts.

3 SLIP MODULUS OF OSB JOINTS

The first challenge of this project was to find a way of connecting the different parts, especially the web to the flange (i.e. edge to face of the panel) because the local embedment of OSB panel is very weak at the edge. Standard values for mechanical resistance of nails in OSB panels concern only face to face connections. Several preliminary tests were performed with nailed connections, however the results showed that they were not appropriate for structural application. This was the starting point of the implementation of IMA techniques for the assembly of the web to the top and bottom flange of the prefabricated element.

3.1 EXPERIMENTAL CAMPAIGN

In order to characterize the mechanical properties of the chosen assembly, an experimental campaign was realized, following the protocols described in standards for timber joints made with mechanical fasteners [7]. Seven series of different geometries consisting of three replicates were tested. The sample properties are listed in Table 1 and visible in Figure 2. As you can see in Figure 2 (c), the top and bottom assemblies do not have the same

Table 1: *Sample characteristics for shear tests*

ID	Nbr	Thickness (mm) 2nd layer	Thickness (mm) 1st layer	Thickness (mm) Web	Fiber Orientation (°) 2nd layer	Fiber Orientation (°) 1st layer	Fiber Orientation (°) Web	Spacing (mm)	Assembly type
M1	3	18	18	18	90	0	90	50	top
M2	3	18	18	18	90	0	90	50	bottom
M3	3	18	18	25	90	0	90	50	top
M4	3	18	18	25	90	0	90	50	bottom
M5	3	18	18	25	90	0	90	100	top
M6	3	18	18	25	90	0	90	50	top & bottom
M7	3	18	18	18	90	0	90	50	top & bottom

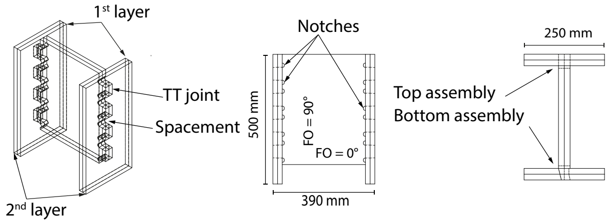

Figure 2: *Sample geometry (a) Axonometry (b) Side view (c) Top view*

Figure 3: *(a) Experimental Setup (b) Failure mode, web part (c) Failure mode, flange part*

geometry. The top one has a basic rectangular geometry in order to transmit shear strength while the bottom one is also able to keep in position the bottom flange. This assembly is made possible by the fact that the web is composed by two panels side by side. It is possible to insert one first and after the other to block the assembly. The traction behavior of the bottom assembly was not studied during these investigations, only shear behavior was considered. The studied TT joint length was 50mm for each sample and only the spacing between joints was variable. The OSB panel fibers were oriented according to the prefabricated structural element shown in Figure 1 (a). Due to the cylindrical shape of CNC tools, concave angles are machined with a notch as it shown in Figure 2 (b). Notch size depends on the tool radius used during the fabrication process and additionaly reduces a high stress concentration when compared to a right angle.

Samples were tested using an experimental setup designed for shear tests (see Figure 3 (a)). A 300 kN cylinder is pressing on the web which transmits the stress by the TT joints to the top and bottom flanges. Displacements and loads were recorded by the cylinder sensors. The loading procedure was carried out by following the standard for timber joints [7]. A total of 19 specimens were tested.

3.2 RESULTS AND DISCUSSIONS

The main aim of the performed experiments was to understand the shear behavior of these joints, especially the slip modulus which plays a major role in the global displacement of the assembled element. From the test resutls two values have been exploited. First the applied ultimate force (F_{max}) before the sample failure occurred and second the slip modulus (shear stiffness), called K_{ser} according to Eurocode 5 [6], which is defined by a linear regression from 10 to 40% of F_{max}. In order to exploit these values the stress distribution was considered equal in each joint. Therefore in order to have the K_{ser} of one TT joint, the total K_{ser} was divided by the total number of TT joint of the specimen (n_{tot}) (1). The same principle was applied for F_{max} (2).

$$K_{ser,i} = K_{ser,exp} \div n_{tot} \tag{1}$$

$$F_{max,i} = F_{max,exp} \div n_{tot} \tag{2}$$

The failure mode is a shear rupture in each TT joint of the specimen as visible in Figure 3 (b,c). The failure occurs in all the specimen joint at the same time . At the end of the test the web is totally detached from the flange. All the specimen curves are represented in Figure 4 and all the results are listed in Table 2. The $K_{ser,exp}$ is displayed in Figure 5 and 6 for each specimen. The behavior of the TT joint with OSB is defined by three parts. First, there is an initial slip due to the fabrication process and assembly constraint. This part will be assessed and taken into account in future research, considering the optimum gap for IMA assembly. Secondly there is an elastic part until the brittle failure when F_{max} is reached. There is no plastic part for this material compared to the shear test with LVL [9].

The joint spacing considered is 50mm for this first comparaison. The influence of the web thickness is negligible as the difference between M1 and M3 maximum force and the shear stiffness is 1% and 3% respectively, even though M3 is 49% thicker than M1. The reason can be that OSB material is denser towards the surface than in the middle of the panel so increasing the thickness does not significantly affect the shear properties of the TT joint. By comparing the top and bottom assembly, there is a difference of 5% and 18% for the $K_{ser,exp}$ and $F_{max,exp}$ in 18mm and a difference of 12% and 22% for the $K_{ser,exp}$ and $F_{max,exp}$ in 25mm. The bottom assembly geometry is less resistant than the top one because the contact surface is reduced and the dense area is machined in both sides of the joint. This difference should be take into account for the global model of the prefabricated element.

Another spacing of 100mm between joint was tested for the top assembly geometry. The $K_{ser,exp}$ and $F_{max,exp}$ respectively decrease of 6% and 22%. If these results are reported for a single connection, the interpretation is different. For the same length assembly for M5 sample there is only 6 TT joints compared to 8 with M3 sample. Therefore $K_{ser,i}$ and $F_{max,i}$ for M5 is higher by 20% and 9% than M3. Increasing the number of joints and reducing the distance between them affects the resistance almost proportionally but not really the shear stiffness. The reason for this can be that above a certain number of joints for a given distance, an optimum shear stiffness is reached, same as the effective number for mechanical fasteners (nails, bolts etc.). Shear tests on single connection are further needed for better understanding of this behavior and to verify the assumption made for the equations (1)(2).

Finally, the comparison of shear stiffness in Figure 6 shows the relative homogeneity for the different variations of TT joint with OSB. The key findings resulting from the presented experimental campaign are as follows:

- The TT joint behavior is elastic and brittle.
- The panel thickness does not significantly influence the resistance and stiffness, but the machining of the panel does.
- The joint spacing affects the shear stiffness up until an effective number of joints is reached.

Table 2: *Experimental results for each sample*

ID	n_{tot}	$K_{ser,exp}$ (kN/mm)	$K_{ser,i}$ (kN/mm)	$F_{max,exp}$ (kN)	$F_{max,i}$ (kN)
M1	8	18.32	2.29	90.92	11.37
M2	8	17.41	2.18	77.17	9.65
M3	8	19.05	2.38	92.35	11.54
M4	8	17.04	2.13	75.49	9.44
M5	6	17.89	2.98	75.73	12.62
M6	8	17.49	-	73.89	-
M7	8	18.17	-	85.36	-

4 GLOBAL BEHAVIOUR

In order to assess the global behavior of the entire structural element, a Finite Element Model was created. The geometry of the model was taken considering a planned full scale prototype as shown in Figure 1 (b). The results of the presented experimental campaign have been implemented into the FEM model to represent the behavior of IMA connections. Furthermore, automation was the key factor that made possible to produce easily the elements with very large number of connections. Also tools have been developed for the automatic generation of the final 3D, simplified geometry and fabrication

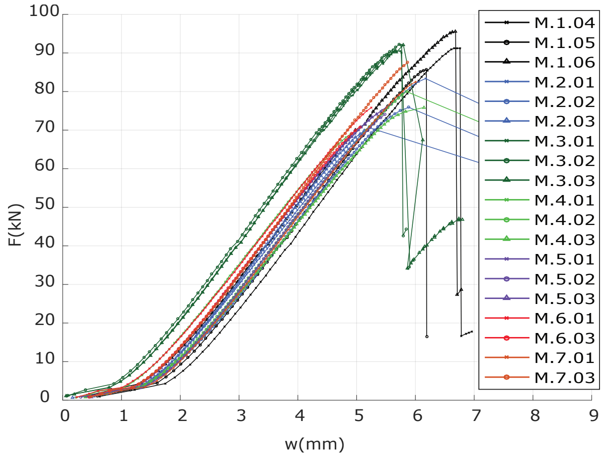

Figure 4: *Force as a function of displacement for each specimen. Full experimental curves*

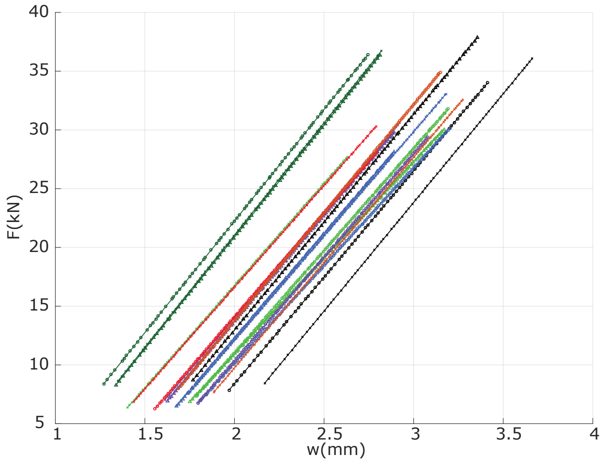

Figure 5: *Force as a function of displacement for each specimen. Fit from 10% to 40% $F_{max,exp}$*

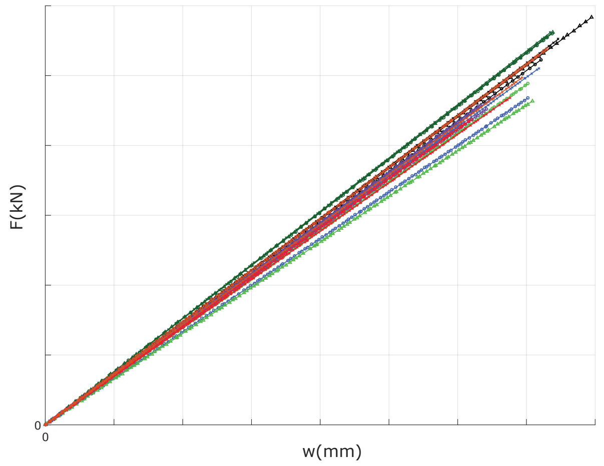

Figure 6: *Force as a function of displacement for each specimen. Comparison of slip modulus $K_{ser,exp}$*

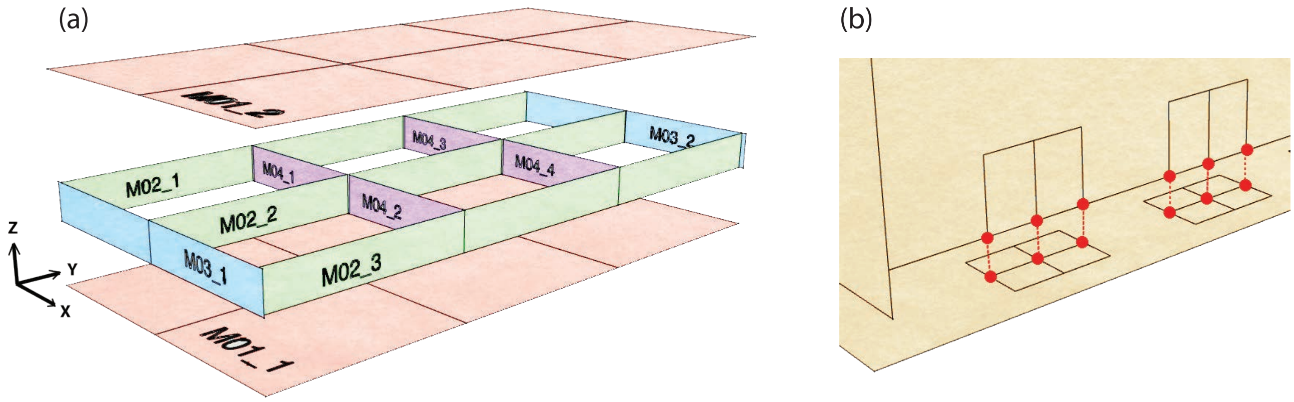

Figure 7: *(a) Simplified geometry of a smaller element with all the IMA coordinates (b) Anchor points to model the springs for the TT joints. Red dots are the Vertices to connect*

files. The software Rhinoceros® and its scripting interface were used for the automatic generation of the geometry while Grasshoper® was used for the user interface and Abaqus® for numerical model. Python was the common coding language used within this research. The timber construction company, *MOBIC SA*, has developed its own tool, for designing and producing the structural elements in order to build the first full scale prototype on their robotic machining line.

4.1 GEOMETRY

The prefabricated element (see Figure 1 (b)), is a rectangular parallelepiped reinforced by a grid of transversal beams, to be placed upon 2 supports. The overall dimensions that were used are $6.15 \times 2.5 \times 0.3$m. The element consists of 5 longitudinal beams and 9 transversal ones, all evenly spaced along their specific direction. Transversal beams are not directly connected to the flange, but are interlocked with the longitudinal ones using slots (see Figure 1 (b)). Their goal is to prevent lateral displacement and buckling of the longitudinal beams.

In order to build an efficient and reliable model some features were discarded or simplified. All elements composed of several OSB panels , the top and bottom flanges and the longitudinal beams, were represented as one continuous element. Transversal beams were represented as single element cut at the slot position and rigidly connected to the longitudinal elements. The elements were represented by surfaces lying in the mid-plane of the panels (see Figure 7 (a)).

Finally, TT joints were not explicitly drawn. It was chosen to model the IMA connections as *Springs*. This assumption followed from the results presented by A. Stitic et al. [32] concerning simplified modeling of IMA. Anchor points for the *Springs* were added for providing the necessary vertices where TT joints are positioned as represented in Figure 7 (b).

This simplified geometry is built through the scripting interface of Rhinoceros® and transferred via CAD exchange format to Abaqus® in order to run the numerical calculation.

4.2 NUMERICAL MODEL

The numerical model follows the same logic in order to be modified easily. It consists of a group of Python script files that are executed one-by-one from the geometry import to the final calculation. Different choices have been made for the FEM.

For OSB material modeling, engineering constants were used: E_1, E_2, ν_{12}, G_{12}, G_{13} and G_{23}, where 1 is the principal direction parallel to the fiber orientation (FO), 2 the direction perpendicular to the fiber orientation and 3 the normal of the panel plane. The values for elastic and shear modulus (E_i and G_{ij}) were chosen according to the supplier [31] and according to characteristic properties for OSB defined by the NF EN 12369-1 [33]. The Poisson coefficient ν_{12} was chosen based on the results of J. N. Lee et al. [34]. All the values are listed in in Table 3.

Semi rigid connections were modeled with *Springs*. The Abaqus® *Spring* links two *Vertices* (see Figure 7 (b)), by establishing the dynamics of a spring, with a user-defined stiffness. In the X and Z directions, *Springs* with an almost infinite stiffness were used to model rigid connections, while the experimental $K_{ser,i}$ was used as stiffness for the *Spring* in the Y direction.

Finally, the load applied to the OSB prefabricated element was chosen accordingly to the Eurocode 5 [6] considering the location of a potential project of the partner company *MOBIC SA*. In timber building construction, dimensions and design are often determined by the Serviceability Limit States (SLS) so calculations were focused on displacements. Dead loads were taken into consideration and the SLS loads were applied uniformly on the structural element.

4.3 RESULTS AND DISCUSSIONS

The presented investigations were performed taking into consideration the project perspective in order to see if an OSB prefabricated element using IMA is a viable solution. Results were only examined with a single criterion, the maximum vertical displacement of the structure w_{max}, which is the usual design criteria for interconnected timber element because of large displacements occurring due to the semi rigidity of the connection. The results calculated with the model for different assembly methods

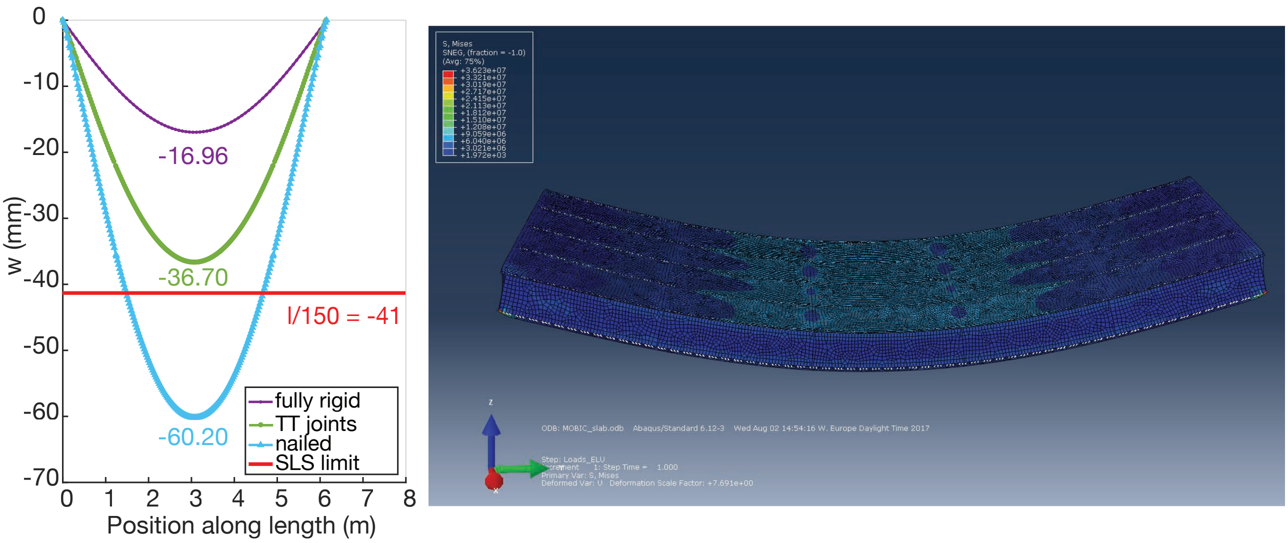

Figure 8: *Vertical displacement at SLS of an element on 2 supports with only 18 mm OSB/4*

Table 3: *Chosen engineering constants for OSB/4 panels, between 18 and 25mm thick*

Const	Description	Unit	Value
ρ	Density	$kg \cdot m^{-3}$	620
E_1	Elastic modulus // FO	$N \cdot mm^{-2}$	4800
E_2	Elastic modulus ⊥ FO	$N \cdot mm^{-2}$	1900
ν_{12}	Poisson coefficient	–	0.25
G_{12}		$N \cdot mm^{-2}$	1090
G_{13}	Shear modulus	$N \cdot mm^{-2}$	60
G_{23}		$N \cdot mm^{-2}$	60

Table 4: *Maximum vertical displacement for a structural element on 2 supports under SLS loads*

Long. beam thickness	Model type	Max. vertical disp. (mm)	SLS limit (%)
18mm	Fully rigid	16.96	41.4
	TT joints	36.70	89.5
	Nailed	60.20	146.8
25mm	Fully rigid	17.32	42.2
	TT joints	38.38	93.6
	Nailed	61.87	150.9

are compared to a general limit for structural elements on 2 supports defined in Eurocode 5 [6] :

$$w_{max} < w_{lim} = L/150 \tag{3}$$

where L is the total length of the structure.

Three horizontal structural element models of 6,15m length on two supports were analyzed: fully rigid, with TT joints using the experimental shear stiffness ($K_{ser,i}$) and with nails using shear stiffness ($K^{nail}_{ser,i}$, determined during preliminary tests). Each configuration was tested with different panel thickness, 18 and 25mm. For the semi rigid model with TT joints, shear stiffness values were as shown in Table 2, according to longitudinal beams thickness: M1 and M2 for 18mm, M3 and M4 for 25mm. The nailed model used nails spaced by 50mm, with a shear stiffness of 0.37kN/mm per nail. All results are listed in Tables 4 and the displacement of a prefabricated element is shown in Figure 8.

The impact of the connection rigidity can be observed in Figure 8. The stiffer it is, the smaller the displacements are. The fully rigid model represents a perfect structural bonding which is really difficult to achieve, especially with thin OSB panels. Compared to the rigid model, the TT joint model maximum displacement is 54% higher and 72% higher with nailed connections. Despite this observation, the TT joint model satisfies the SLS limit and the maximal displacement is 39% smaller when compared to nailed connections.

Finally, there is a very small difference for the global displacements using 18 or 25mm thickness panel for the web. This can be explained by the experimental results concerning the rigidity of TT joint using different panel thickness (see Table 2). The connection stiffness and the web inertia considering rectangular cross section do not increase with the panel thickness. On the other hand, the self-weight increases which can explain the bigger displacement of the prefabricated element using 25mm thickness.

5 CONCLUSION

Constraints and regulations related to new buildings evolved considerably in recent decades. Many factors must be considered such as thermal, waterproofing and structural performance. Moreover, economic constraints and an increasingly competitive environment push manufacturers to find new constructive solutions to meet all these requirements more easily.

In this context that prefabricated, timber elements have been developed in the past 15 years by different manufacturers. They can serve different functions: structural but also insulation and waterproofing in one element directly delivered on the construction site. All these elements are factory-produced with industrial processes using timber engineered products and structural bonding. These production methods involve significant investments in the production and assembly process. Structural bonding is really difficult to achieve and an important quality control must be executed. The production line is dedicated completely to one standard element and cannot be changed easily.

Integral Mechanical Attachments for structural timber element offer an alternative to structural bonding. Fabrication process and geometries are more flexible and can be used to design others timber construction products. Moreover, there is no need of a drastic quality control.

The results has shown that IMA are less rigid than a structural bonding (rigid model) but still relevant for structural applications considering the Serviceability Limit State. Moreover, TT joints have a better mechanical response that mechanical fasteners due to the thin thickness and the local properties of OSB panels for face to edge connections. Some assumptions were made for the experimental campaign and the numerical model because investigations were oriented for a project perspective, and it is the early stage of research. Future works are still required regarding the gap and the stress distribution in the connections.

This research was concentrated on OSB panels, a cost efficient timber engineered product with poor mechanical properties especially in bending. The implementation of IMA for prefabricated timber element has shown good results and thus a great perspective for higher quality engineered wood products.

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