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TESTING OF THE SEISMIC BEHAVIOUR OF A TRADITIONAL JOINT IN A WOODEN ROOF STRUCTURE

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Abstract

The roof timber constructions are and have been used extensively to support floors and roofs, nowadays as well as traditionally. They consist of plain timber elements and carpentry joints that work together mainly by contact pressure and friction. The structural response of roof frameworks (especially those in historical buildings) is highly dependent on the behaviour of their joints, particularly, their capacity for rotation and energy dissipation. Nevertheless, the seismic response in newly designed timber structures relies on the mechanical behaviour of connections. In historical timber structures, carpentry joints transmit forces between timber elements by direct contact and friction, whereas metal connectors, when present, only safeguard the connection against exceptional actions that could relieve contact and separate parts. Carpentry joints are built based on traditional practice based on empirical rules, or at most designed with extremely simplified models that are not supported by sufficient experimental and analytical evidence and consequently they may not comply with the safety levels that are now imposed, particularly for seismic action.

With that in mind, a small research program has been carried out by the authors for characterizing the mechanical behaviour of carpentry joints. The so called bird-mouth joint typology most frequently used in simple timber structures, with special attention to roof trusses, have been considered in the study. In the paper, some results are presented, with special attention to the rotational behaviour of these joints and to the effects of possible seismic strengthening operations in the elastic and post-elastic field.

Keywords: wooden roofs, carpentry joints, mechanical seismic behaviour, experimental testing.

1. Introduction

Traditional carpentry joints, which make up the majority of joints in historic timber structures, transmit forces primarily through direct contact and friction. Traditional timber connections are most often constructed with notches, wedges, bearing surfaces, grooves. These joints are often supplemented with metal parts, some of which were added during construction to enable the joints to withstand tensile forces, or to increase their strength or stiffness, while some are added later, to repair or reinforce joints that have deteriorated. Metal elements are extremely important in rehabilitation, i.e. subsequent reinforcement of the joint. The need for reinforcement arises for several reasons, e.g. deterioration due to poor maintenance, change of purpose of the building and the need for greater strength due to cracks, etc. Metal elements in the joint, when present, prevent the joint from separating in exceptional situations and can thus reduce pressure or act outside the plane of the joint. Given the brittleness of wood, it is important to ensure that the wooden elements remain elastic. Under critical conditions, the post-elastic behavior of joints, which involves the interaction between metal and wood, is crucial for meeting modern safety standards, [1].

The vast majority of regions around the world are located in seismically active areas, and earthquake damage can be catastrophic. Therefore, it is important to understand how different building structures, including roofs, respond to seismic forces.

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Seismic damage in old wooden roof structures can mainly be attributed to inadequate joint performance until significant damage to the wooden elements occurs. Damage also occurs due to poor connection of the main load-bearing structure and secondary elements. Often, in seismic strengthening of existing buildings, wooden structures were removed and replaced with new elements of industrial origin, which would often lead to poor outcomes because the interaction of new structures, with high stiffness and mass, with the surrounding walls, often of modest quality, would result in poor seismic performance, or even greater damage or even collapse.

The key issues when it comes to traditional wooden roofs are the weight of the material and weak connections. Since traditional roofs often use materials such as tiles and wood, they increase the load on the structure. During an earthquake, this load can cause greater forces to act on the walls and foundations. Traditional roofs have less effective connections, which can lead to the roof separating or collapsing during an earthquake. Another important factor is stiffness, as reduced stiffness can cause the building to not adapt to the vibrations caused by the earthquake, which can increase the risk of damage.

In their research paper, Parisi et al. [2] consider the quality of the wood-to-wall connection, the type and quality of the wood-to-wood connection, and the general state of preservation for seismic loading. They developed a procedure for assessing the seismic vulnerability of wooden roof structures. They divided it into two steps. In the first part, data on the structure is collected based on a visual inspection, and in the second step, specific vulnerability indicators are determined by analysis.

Kasal and colleagues [3] conducted research that focused on investigating the behavior of glulam frames under dynamic loading simulating an earthquake. They tested two types of frames, one without reinforcement and one of a new design with glass fiber reinforcements to improve the durability of the joints. The results showed that the wooden structures, thanks to their low density and high ductility, can withstand heavy loads well while maintaining the load capacity and energy absorption capacity, which makes them very resistant to earthquakes.

Many factors, such as urbanization, excessive tourism, climate changes, people’s neglect and loss of traditional knowledge, affects this tangible heritage. Additionally, the vulnerability of historic buildings is greater in seismic prone regions as earthquakes pose a big treat to the stability of the buildings and may cause irreversible damage.

2. Typical carpentry joints

The most frequent layout of roof structures is given by a series of parallel trusses, usually connected by simple purlins or, seldom, by more elaborated transversal elements. Depending on the surface to be covered, trusses may reach considerable size and complexity. The rafter-to-tie beam connection has always been considered the most important node of a truss, as may be seen, for instance, consulting traditional design manuals. Figure 1 presents the forms of this joint that are most frequently found.

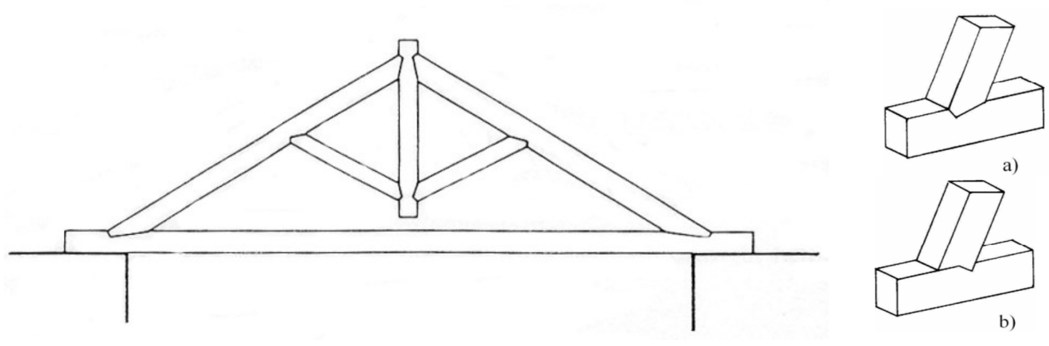

Figure 1. Typical roof truss (left), (a) birdsmouth joint; (b) its reversed form.

The most common joint in existing timber roof structures is the "birdsmouth joint with a single tooth", (a) in Figure 1, usually presenting a skew angle of about 30° between the tie beam and the rafter,

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although geometry varies with joint location in the truss, and the joint bearing capacity is function of skew angle, notch depth and length of the toe. The load transmission relies on direct contact and friction between facing surfaces. Metal ties or fasteners are not mean to transmit forces directly; they are mainly used for positioning and maintaining the functionality of the joint in adverse or unpredictable conditions.

Common timber roof structures are usually modelled with perfect hinges at the extremities of each element. However, these joints offer a significant moment resistance and may be better classified as semi-rigid. The lack of practical though realistic models for the joints in old traditional timber structures generally leads to very conservative retrofits and upgrades to satisfy new safety and serviceability requirements. Moreover, the misunderstanding of the global behavior of traditional roof trusses can result in unacceptable stresses in the members as a consequence of inappropriate joint strengthening (in terms of stiffening). Joint strengthening can be done in a number of possible ways: from simple replacement or addition of fasteners, to the use of metal plates, glued composites or even full injection with fluid adhesives. Each solution presents unique consequences in terms of the joint final strength, stiffness and ductility.

3. Testing and numerical analysis

The behaviour of carpentry joints in historical timber structures plays an important role in their overall structural response to applied loads, especially during seismic events. This has been the subject of several research projects, mostly in countries with high seismic activity. In these countries, roof framework joints employ a typical birdsmouth connection for joined timber elements, as shown in Figure 1.

The birdsmouth joint has been studied most extensively, because of its preminence among possible connection solutions. Its rotational behavior has been characterized by numerical analysis and experimentally in monotonic conditions, in the elastic and post-elastic field up to failure. Monotonic tests were performed on unreinforced joints and on strengthened ones. During the tests a constant pressure is applied to the rafter, while a lateral force is applied to generate moment and rotation at the node. The experimental setting permits load reversal.

3.1 Test specimens

An experimental research was carried out at the Laboratory of Faculty of Civil Engineering and Architecture Osijek, including monotonic tests of full-scale traditional timber connections. A series of monotonic tests on unstrengthened specimens was performed in order to study the primary behaviour characteristics of the connection, as well as its sensitivity to a few parameters. Subsequently, connections strengthened with basic metal devices were tested under monotonic loading. The purpose of these tests was to uncover any advantages and deficiencies in the behaviour of the connection and the device itself, as well as to determine a need for different types of strengthening. Tests on assembled connections were preceded by accurate material characterization, determining the mechanical properties of the timber elements used for all full-scale models

A total of 6 tests were performed. Three (3) models were made with varying angles between the rafter and the beam (30°, 45°, 60°). First, an unreinforced joint (carpenter's joint) was tested, which was held in place by a single screw, then a reinforced joint with a metal plate and screws was tested. Monotonic tests were applied in 4 steps, being 2 in each loading direction (positive and negative) under a compression level in the rafter of 5.0 MPa corresponding to the Service Limit State conditions.

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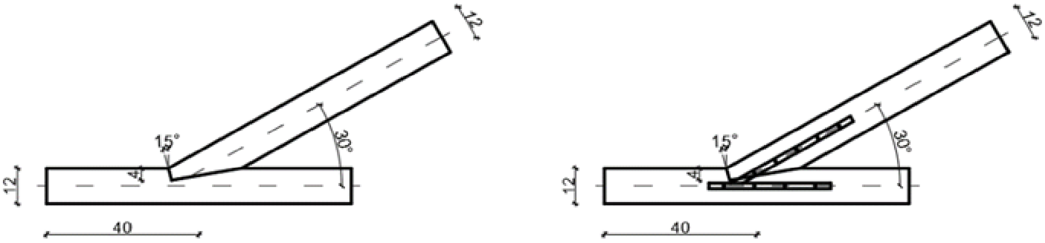

Figure 2. Geometrical scheme of the joint at an angle of 30°: basic unreinforced (left) and strengthened (right).

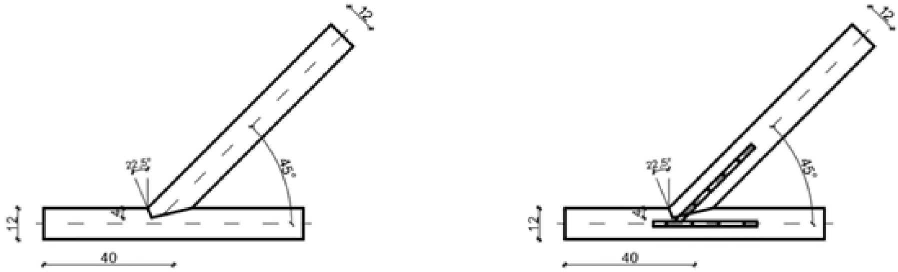

Figure 3. Geometrical scheme of the joint at an angle of 45°: basic unreinforced (left) and strengthened (right).

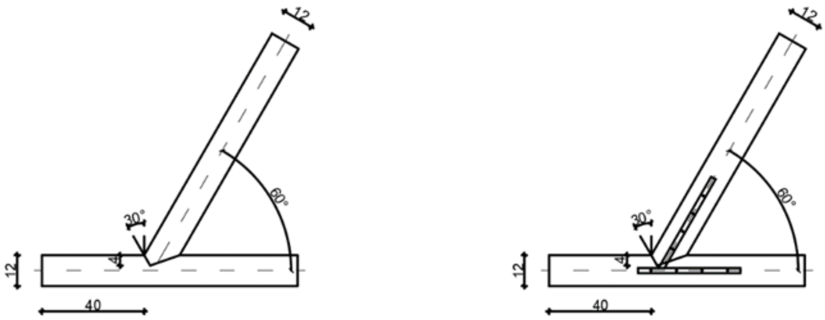

Figure 4. Geometrical scheme of the joint at an angle of 60°: basic unreinforced (left) and strengthened (right).

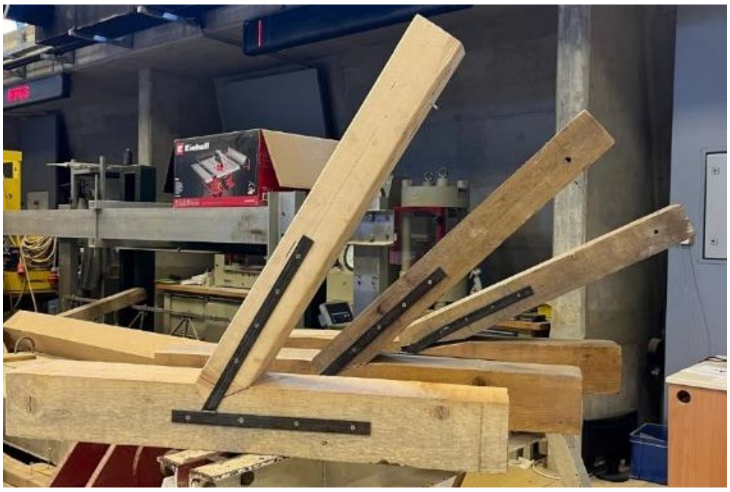

Figure 5. Test specimens of the joint at an angle of 60°, 45° and 30°.

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The notch lengths t_v and the length l_v (length of timber outside the notch - heel) are given as functions of the angle of inclination and the cross-sectional dimensions. The general design procedure assumes a hinged connection and involves defining the load paths between the members, resolving the pressure from the rafters into components perpendicular to the notch surfaces (a) and defining the corresponding shear surfaces to accommodate these stresses (b) [4].

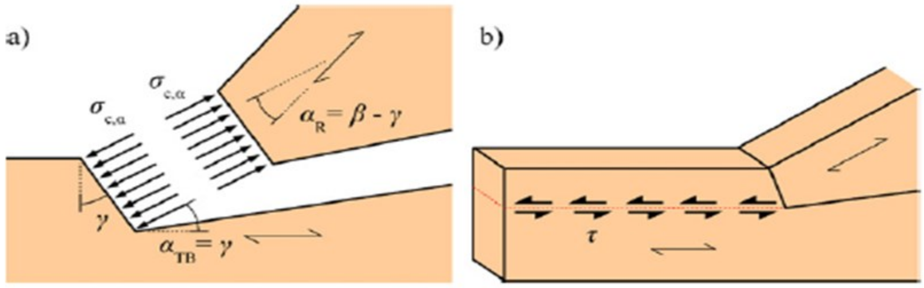

Figure 6. (a) Compressive stresses in the notch, (b) Shear stresses in the heel [4].

Regarding the rotational behavior of the horn-beam joint, Parisi and Piazza [2] presented two simplified physical models (for rotations in both directions) to predict the moments of simple butt-joints without metal parts. These models are based on equilibrium considerations and are shown in the figure below.

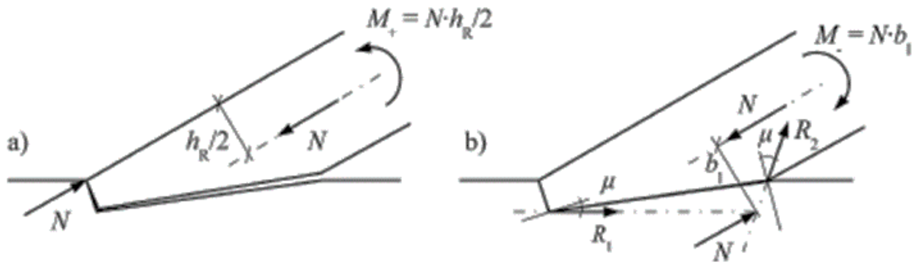

Figure 7. Prediction of moments of simple front mortise joints without metal parts [2].

When opening the tilt angle (a), the maximum moment M_{max} is given by the equation:

$$M_{max+} = N \frac{h_R}{2}$$

where N is the compressive force in the horn, and h_R is the horn height (max moment does not depend on the depth of the notch, but on the level of compressive load in the horn).

When closing the bank angle (b), the maximum moment M_{max} is given by the equation:

$$M_{max-} = N \cdot b_l$$

where N is again the compressive force in the horn, and b_l is the lever arm between N and the intersection of the lines of action of the corresponding notch reactions. The lever arm b_l depends on the geometric parameters of the joint (depth, length and angle of the notch) and on the coefficient of friction.

A groove is a cutout in a wooden beam that allows a tongue to be inserted into another component. This form of connection provides a larger contact surface between the two elements, which increases the strength of the connection. The groove can be of various dimensions and shapes, depending on the needs of the structure and the size of the wooden elements. It is usually made in such a way that the tongue fits tightly into the groove, minimizing movement and oscillation.

The tongue-and-groove joint provides greater stability and resistance to horizontal forces, which is especially important in areas prone to earthquakes or winds. This type of joint is relatively simple to

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make, which makes the carpenter's work easier and reduces construction time. This joint must be properly protected to prevent moisture from penetrating, which can cause the wood to rot or warp over time. The tongue-and-groove joint can allow for some flexibility in the structure, which is important for resistance to earthquake forces. This flexibility helps to reduce the transfer of forces to other parts of the structure.

For the purpose of testing, a carpenter's joint, or the connection of a rafter and a beam, known as a groove joint, was performed. More precisely, the rafter rests on a groove in the beam, which is additionally (in this case) fastened with a single screw. This connection relies exclusively on compressive forces and friction forces that are generated and transmitted on the contact surfaces. The main force transmitted through the rafter is compressive force. As the rafter supports the weight of the roof and loads (e.g. snow, wind), these loads create a compressive force along the axis of the rafter. This compressive force is transmitted through the groove to the beam, thus ensuring the stability of the connection. For the purpose of testing, this compressive force was introduced into the rafter as a prestressing force of 5 kN.

Tensile forces occur because the beam, as a horizontal element, must maintain the tendency of the rafter to move apart or separate from the structure due to the horizontal component of the load on the rafter. Shear forces occur on the contact surfaces between the rafter and the beam. These forces act parallel to the surfaces of the connection and are caused by the weight that the rafter transfers to the beam. Bending forces also occur due to the load that the rafter transfers to the beam.

3.2 Test arrangement and procedure

The arrangement allows independent control of two forces (Figure 8). First, aligned with the rafter, induced constant compression throughout the test by prestressing. The other, a double-acting jack, positioned above the center of the connection, applied a transversal force, with a programmed load cycle, and generated a moment at the connection. Force (F) versus displacement (d) curves were measured. Tests were performed under displacement control for the typical birdsmouth connection skew angle of 30º , 45 º and 60º. For all the specimens, the cross sections of the elements were 10x120 cm^2, the notch depth was 40 mm and the notch length varied according to the skew angle.

The first step of the loading procedures was the application of an axial compression force on the rafter, which was kept constant during the test. In the subsequent loading steps, a transversal force (F) was employed, acting perpendicular to the rafter axis. When the skew angle increased, it was defined as the positive direction and when the skew angle decreased, it was defined as the negative direction. Monotonic tests were performed to determine the elastic behavior, in particular, the apparent elastic limit displacement d_{e+} and d_{e-}. Under displacement control, a maximum displacement value of 50 mm was imposed.

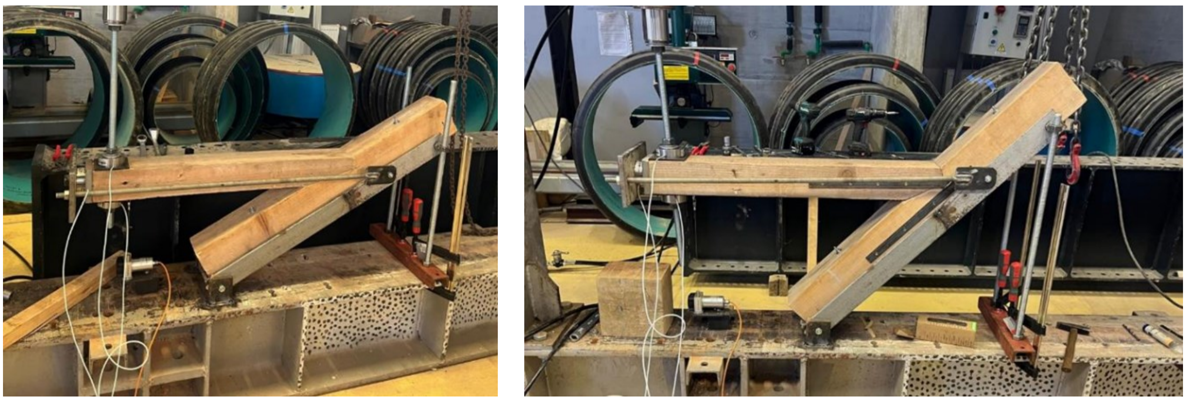

Figure 8. Test setup of joints without (left) and with metallic strengthening parts (right).

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3.3 Some test results

In the seismic response of timber structures, joints are the key elements because they may either contribute to fragility, or develop, to some extent, a dissipating behavior. In the perspective of seismic strengthening of timber structures, general criteria for strengthening the connections to resist the effect of seismic action are needed, considering that traditional intervention methods in timber construction are generally conceived in view of a static behavior under vertical loads. The results of an experimental and numerical research program on the behavior of carpentry joints have been outlined here focusing on the semi-rigid behavior of carpentry joints. The measurement is carried out in four (4) steps and was based on the pushover analysis principle, i.e. the method of gradual pushing until a certain level of deformation is reached.

Table 1. Test results, steps #1 and #2

Test sample		Step #1			Step #2	
		Force [N]	Displacement [m]	Joint stiffness [kN/m]	Force [N]	Displacement [m]
30°	basic	1000	0,0293	34,095	1601	0,0298
	strengthened	1000	0,0163	61,538	1938	0,0161
45°	basic	1000	0,0314	31,888	1409	0,0255
	strengthened	1000	0,0255	39,154	1210	0,0261
60°	basic	1000	0,0347	28,794	1851	0,0301
	strengthened	1000	0,0263	38,037	2301	0,0263

Table 2. Test results, steps #3 and #4

Test sample		Step #3		Step #4	
		Force [N]	Displacement [m]	Force [N]	Displacement [m]
30°	basic	1931	0,0502	1688	0,0501
	strengthened	2051	0,0502	2956	0,0502
45°	basic	1872	0,0530	2986	0,0502
	strengthened	1852	0,0525	3566	0,0501
60°	basic	2000	0,0510	2122	0,0502
	strengthened	2182	0,0516	2991	0,0501

The results of the pushover analysis are shown graphically below. They are shown graphically in relation to force/displacement (curve F/d) and in relation to moment/turning angle [curve M/φ]. The curves in the first quadrant (d>0 and F>0) correspond to the tested joints opening the curvature angle. The curves in the fourth quadrant (d<0 and F<0) represent the tested connections where the curvature angle closes. The M/φ curve will only be shown for the first test step since it is crucial to obtain the stiffness input to the model.

Before the actual analysis and processing of the data, it is important to note that the reinforcements were placed on previously tested non-strengthened models and that they had already acquired certain defects there.

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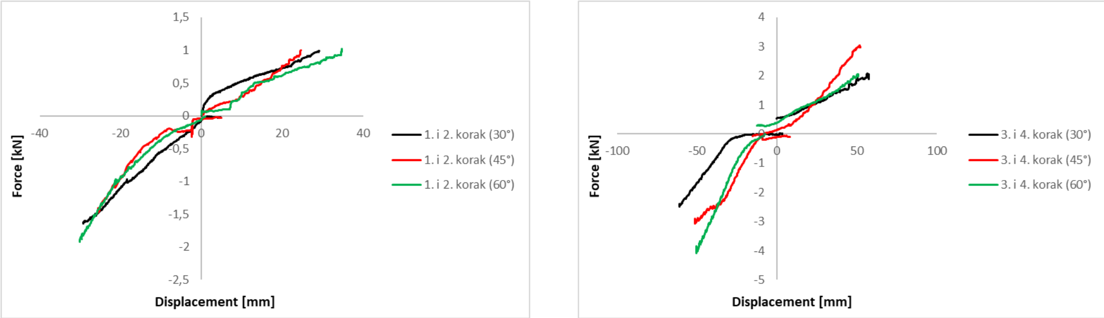

Figure 9. Force – displacement curves obtained for non-strengthened joints and various skew angles.

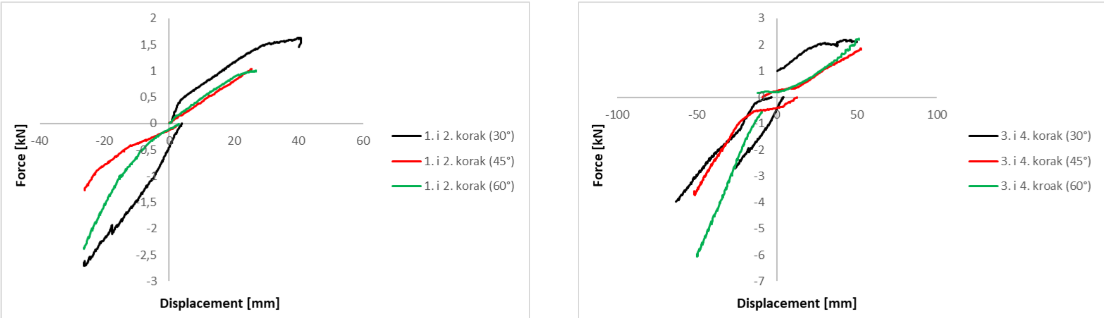

Figure 10. Force – displacement curves obtained for strengthened joints and various skew angles.

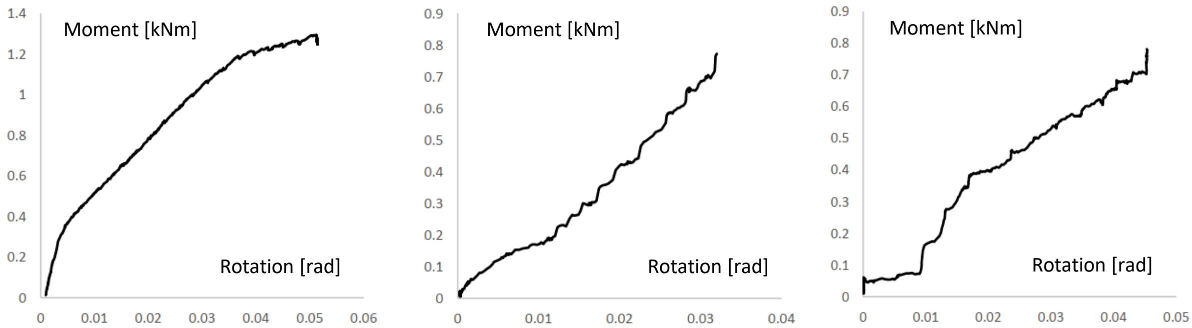

Figure 11. M – φ diagrams for non-strenghtened rafter to tie beam joints with skew angle of 30°, 45° and 60°.

Figure 12. Final deformed shapes of non-strengthened / strengthened joints for 30° skew angle.

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4. Conclusion

With this work, we paid attention to traditional wooden roofs, which are mostly represented in our area and are made of ordinary wooden elements, and the joints are usually carpentry with or without reinforcement.

A total of six tests were conducted where the joints were exposed to monotonic loading, observing their behavior, the influence of the reinforcement itself and the angles between the rafter and the tie beam.

By analyzing the data, it was determined that the reinforcement itself in this case of loading, where the behavior of the joint under seismic load was analyzed, did not prove to be effective. The reason for this is that the connection to the groove itself works on the principle that the horn is wedged when the force acts downwards, while in the case when the force acts upward, the horn comes out of the connection and this reinforcement that we used does not sufficiently prevent it. For such a load case, it would be necessary to put a thicker metal plate or even better to make a screw connection through both elements in order to connect the elements in that direction as well.

Also, from the tests, we come to the conclusion that roofs with a greater slope are more suitable for this type of load, since they have a better distribution of forces and reduce horizontal loads during an earthquake. That was noticed during this test champagne since the model with an angle of 30° responded in the same way during the test in the case with/without reinforcement, that is, the rafter rose out of the tie beam and when the downward force was applied, it did not form a wedge again, which was not the case with the other two models proving their better performance.

In any case, it is necessary to additionally examine the behavior of classic wooden joints, since their stiffness plays an important role in the calculation of the global structure. This is important in order to know how to carry out the reconstruction or assessment of safety and remaining service life in the correct way.

Traditional timber connections, even without any strengthening device, usually have a significant moment-resisting capacity. Therefore, they should not be represented by common constraint models, like perfect hinges, but should be considered semi-rigid and friction based. The test results performed by the authors show that this capacity is function of the compression stress applied to the rafter and of the skew angle, the height of the rafter cross section and the friction angle The experimental analysis has been of fundamental importance in order to understand the real behavior, by pointing out some important aspects like force transmission mechanisms, failure modes and guidance for appropriate strengthening solutions.

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