Mechanical Behaviour of Traditional Timber Carpentry Joints in Service Conditions – Results of Monotonic Tests

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1. Background

The structural safety assessment of ancient timber structures requires the evaluation of the mechanical properties of their elements and joints. As Building Codes focus mainly in common modern industrialized joints [1], they usually provide little guidance to designers regarding traditional timber carpentry joints, being necessary to establish reliable behaviour models, set detailing rules and provide useful recommendations for future rehabilitation or strengthening interventions in timber structures.

Carpentry joints connect timber elements, usually subjected to compressive axial loads, often without any other devices but notches in the connected members. These joints rely on the compression internal forces to keep facing surfaces in close contact and seldom in metal fasteners (more common in Western cultures than in Oriental joint craft [2]).

A widespread classic connection at the heel joint in timber trusses is the front notched joint, with a single tooth in the strut, a notch in the top face of the bottom chord and, frequently, some metal fasteners. This joint directs the horizontal component of the internal compression force in the strut to the bottom chord, through compression of the front notch and a shear surface in the toe of the chord.
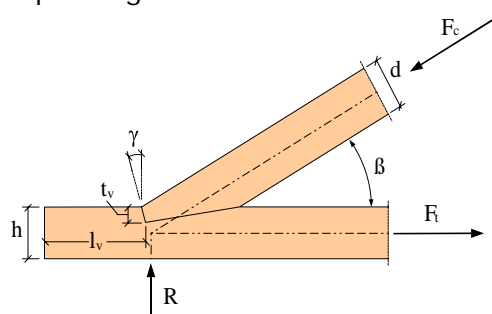

Figure 1. Free body diagram of the heel joint

In the absence of metal parts, this joint is sustained only due to the friction developed between the timber elements in the front notch, which is highly dependent on the compression level in the strut, and cannot support alternating connection forces. Eurocode 8 [3] states that compression members with carpentry joints should "be designed in such a way that they are prevented from separating and remain in their original position", therefore the employment of metal parts is necessary to comply with the safety requirements, assuring the contact between friction surfaces and stabilizing the performance under cyclic actions. On the other hand, often the metal parts are used to strengthen the joints, without adequate knowledge on the consequences of such actions on the joint and on the overall structural behaviour.

The heel joint is usually considered as hinged and the internal forces acting in the connection are the axial compression in the strut, the tension in the chord and the vertical support reaction. The widespread method, commonly presented in the
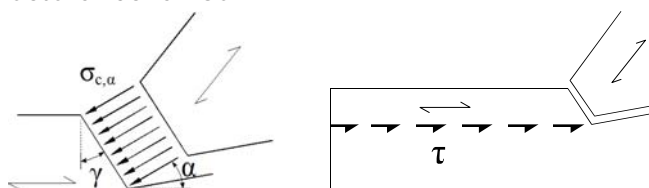

Figure 2. Stresses in the heel joint

related literature [4] [5] [6] [7], to asses the strength of this type of joint relies on this assumption. It implies checking the compression stresses at an angle to the grain in the frontal notch surface (if $\gamma \neq \beta/2$ or if the strut and the chord timber belong to different strength classes, this must be done in both the strut and the chord) and shear stresses in the timber beyond the notch.

Other failure modes are also mentioned [6] [8]: tension in the reduced cross section at the notch; combined stresses due to bending induced across that same section by eccentric load paths; bending stresses derived from the chord being supported beyond the notch cross section (eccentric support reaction).

As previous research works have shown [9] [10] [11], these joints exhibit a semi-rigid behaviour, with influence over the internal forces (primarily in asymmetric load configurations and/or structures) and in the failure modes to consider (mainly in the connection area).
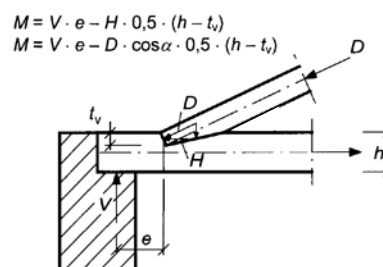
$$M = V \cdot e - H \cdot 0,5 \cdot (h - t_v)$$
$$M = V \cdot e - D \cdot \cos\alpha \cdot 0,5 \cdot (h - t_v)$$

Figure 3. Other failure modes [6]

2. Test program

The experimental research currently being conducted at LNEC comprises monotonic and cyclic tests of full size front notch joints without and with different metal parts, moisture contents of 12 and 20 %, sound timber and timber with biological degradation and different loading steps. It includes both monotonic and cyclic tests, based in EN 12512:2001/A1:2005 [12]. The monotonic tests allow determining the yield slip of the joints (necessary to define the procedure for cyclic testing), initial stiffness, strength, ductility and failure mode in quasi-static conditions. For each joint configuration (geometry, moisture content and metal fasteners), three different joints are tested solely opening the skew angle, other three exclusively closing the skew angle and, finally, other three will be tested cyclically in both directions.

2.1.   Tested configurations, materials and geometry

The configurations tested so far include all the monotonic tests (opening and closing the skew angle) of joints with a moisture content of 20 % and almost every monotonic tests of the 12 % moisture content joints, shown in Figure 4.

The joints were built with Maritime Pine (*Pinus pinaster* Ait.) and comprised the geometries presented in   Figure 5. The skew angle (β) is 30°, which is a very common roof slope in Portugal, and both strut and chord specimens have a length of 1.00 m and cross sections dimensions of 15.5 × 7.5 cm². The notch depth (t_v) is 4.5 cm for every joint configuration, though some unreinforced connections with a notch depth of 3.0 cm were also tested. The shear length in the chord (l_v) is 45.0 cm, which is intentionally overvalued to prevent this type of failure from occurring.

Front notch joints with mortise and tenon were also tested. In the related literature there are many graphical representations of these joints geometry (Figure a)), but the criteria in which such geometries are based is, most of the times, not discussed. In the tested joints the following geometric principles were adopted [13]: the tenon width is 1/3 of the wood element thickness; width and depth of the mortise are equal to the width and depth of the tenon. Tests made in beam to column mortise and tenon joints [14] showed that the fitting between the tenon and the mortise plays a major role in the strength and stiffness of these connections.
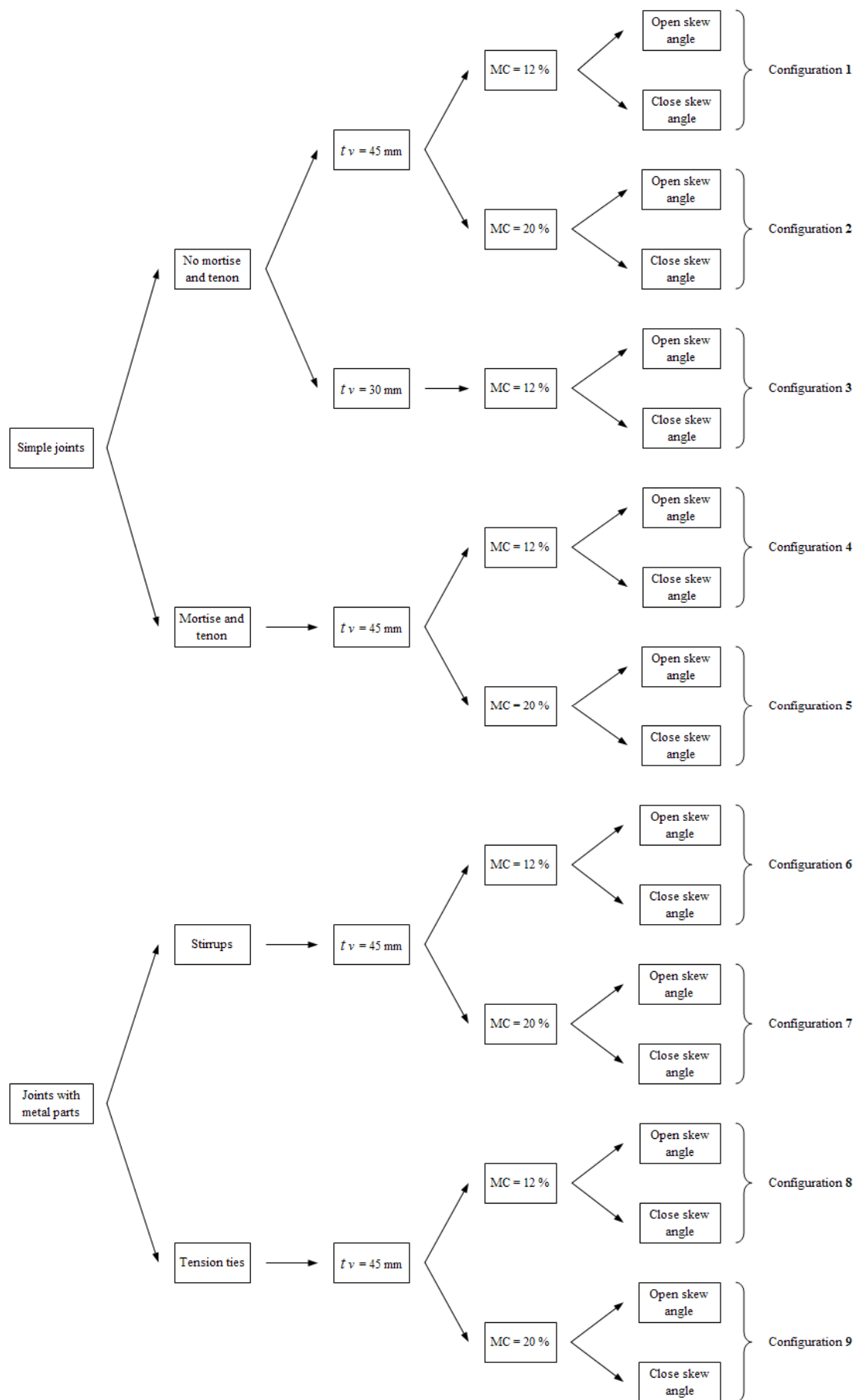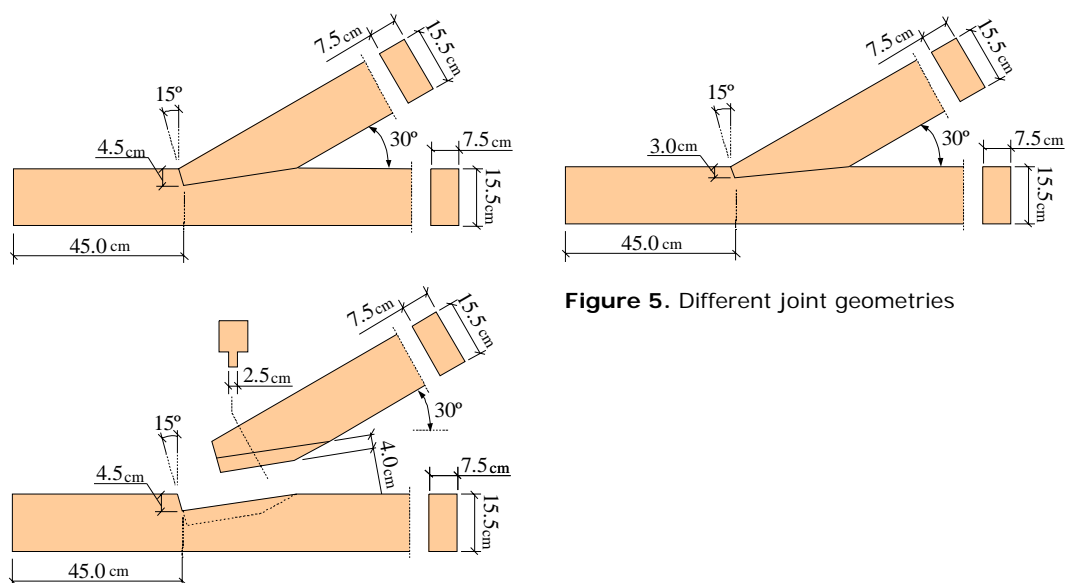
Figure 4. Situations tested so far

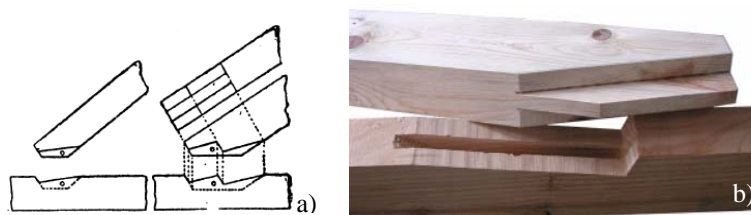**Figure 5.** Different joint geometries

Figure 6. a) Mortise and tenon joint (XIX century book) [15];
b) mortise and tenon of the tested joints

2.2.   **Metal fasteners: stirrups and tension ties**

Metal fasteners have been widely applied in timber joints since the 19th century. They can improve the performance concerning out-of-plane actions in the carpentry joints and definitely change their mechanical response. The metal parts used in the tested joints are examples of very common typologies and are intended to provide the basic behaviour model of each typology.

Metal stirrups are a quite frequent reinforcement in timber trusses and are also widely applied to strengthen old joints. The metal stirrups used in this testing campaign were made of two welded steel flat bars (cross section of 3×50 mm^2) with 9 mm diameter holes to the 8 mm diameter dowels made from a threaded bar.

Figure 6. Stirrups and tension ties

Another commonly used metal parts, mainly in ancient roof structures, are ties which embrace the two timber members in the connection area. A relative displacement between strut and chord stresses the lateral ties, which in turn compress the thick metal plates against the outer surface of both members, therefore restraining the movement.

The simplest way to reproduce this effect is with two lateral bars (tension ties) attached to thick metal plates that rest on the strut's upper surface and chord's lower surface, being normal to the longitudinal axisof the strut.

2.3. Moisture contents

To evaluate the influence of timber moisture content on the joints' mechanical behaviour, each joint configuration was tested with moisture contents of 12 and 20 %. The elements tested with 20 % moisture content were previously dried until moisture content reached 8 %.

Bolts of the joints with metal parts were tightened when moisture content reached its lower values, so that later, when wood swelled, the metal parts were fitted tight to the wood. In the joints tested at 12 % moisture content, the bolts were manually tightened just before testing.
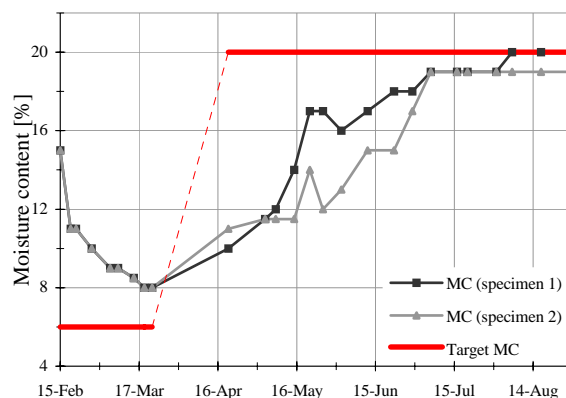

Figure 7. Moisture content variation

3. Equipment, procedure and loading
3.1. Test description

The evaluation of the mechanical behaviour of traditional timber carpentry joints in service conditions requires that during the test the joint is subjected to the internal forces which would act in normal circumstances. As mentioned above, the internal axial compression forces play a major role in carpentry joints, especially those which do not employ any metal fasteners, by maintaining the joint integrity and significantly influencing its rotational capacity. Therefore it is essential to apply this load in the strut and simultaneously impose relative rotations between both members, by applying a transverse force (perpendicular to the longitudinal axis of the strut). To establish the $M - \theta$ behaviour of the joint, it is also necessary to know, in each instant, the position of the instantaneous centre of rotation. Due to the great number of tests to be performed in a relatively short period of time, only one test of each configuration will be monitored with LVDTs (linear variable differential transformers), placed in predefined locations, to ascertain the rigid body motion of the strut, thus determining the position of the instantaneous centre of rotation.
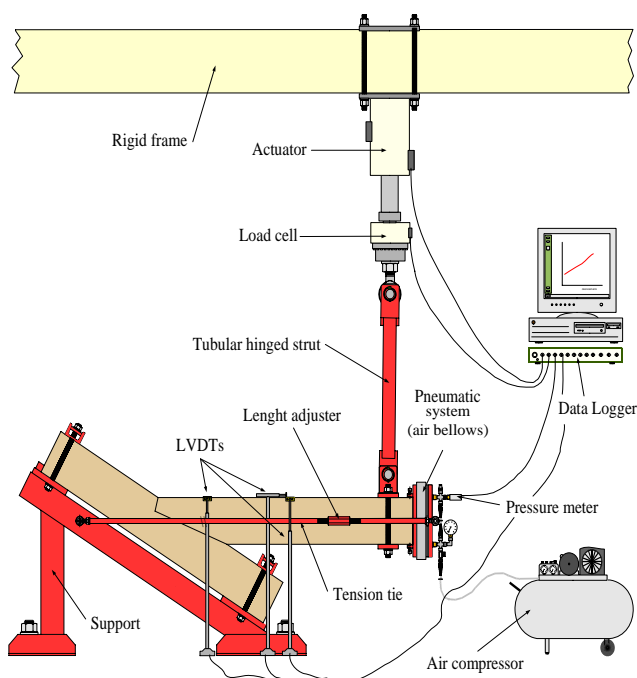

Figure 8. Test setup and instrumentation [16]

3.2. Equipment and instrumentation

Special equipment (Figure 9) was developed by the authors in collaboration with the LNEC Scientific Instrumentation Centre. The equipment is composed of a metal base, where the connection rests, a pneumatic system, to apply the compression force in the strut, and two pinned tension ties parallel to the strut, holding the pneumatic system against the top of the strut and to the metal base. It allows keeping a constant compression level in the strut, while the actuator imposes the transversal displacements. The test setup is reasonably quick, comparing to the average test duration.

Figure 9. Test setup

3.3. Procedure and loading

A compression force of 15 kN in the strut is applied by the pneumatic actuator and kept constant during the entire test. This load represents the self-weight and the dead loads applied in a timber roof truss with common dimensions and the consequent compressive stress in the strut is 1.3 MPa. Transversal displacements are imposed at a speed of 0.2 mm/s, to the hinge above the strut's upper surface, at a distance of 0.950 m from the theoretical centre of the joint (intersection of the members' axis), along the strut.

The adopted test procedure includes the following steps: i) restraining the chord member to the metal base; ii) placing the strut and adjusting the length of the two lateral pinned tension ties; iii) adjusting the height of the air bellows; iv) increasing the pressure in the air bellows to obtain the adequate compression force in the strut; v) positioning and clutching the metallic tubular hinged strut to wood strut member; vi) positioning of LVDTs; vii) imposing the displacements transversely to the strut.

4. Monotonic tests results

The following results concern the monotonic tests performed to determine the yield slip, necessary for the forthcoming cyclic tests. These are preliminary results and, for the time being, some of them lack the consistency that a greater number of tests would provide. Nevertheless, they represent a valid first approach to the behaviour model of each configuration.

To simplify the analysis of test results, all the *F-d* curves are plotted in the same global axis, although there is no continuity between the curves in the first and in the third quadrants (opening and closing the skew angle tests, respectively). Positive and negative values for displacements and forces have the meaning represented in Figure 11
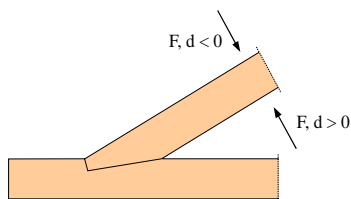
F, d < 0

F, d > 0

Figure 10. Adopted signal convention, concerning the direction of forces and displacements

4.1 Simple joints
4.1.1. Notch depth of 45 mm (configurations 1 and 2)

The simple joint with a notch depth of 45 mm displayed an asymmetric behaviour, in respect to opening or closing the skew angle (Figure 13). When opening the skew angle, the joints followed a fairly elastic-plastic behaviour and both 12 and 20 % moisture content joints showed approximately the same strength and a ductile performance (typical of wood in compression).

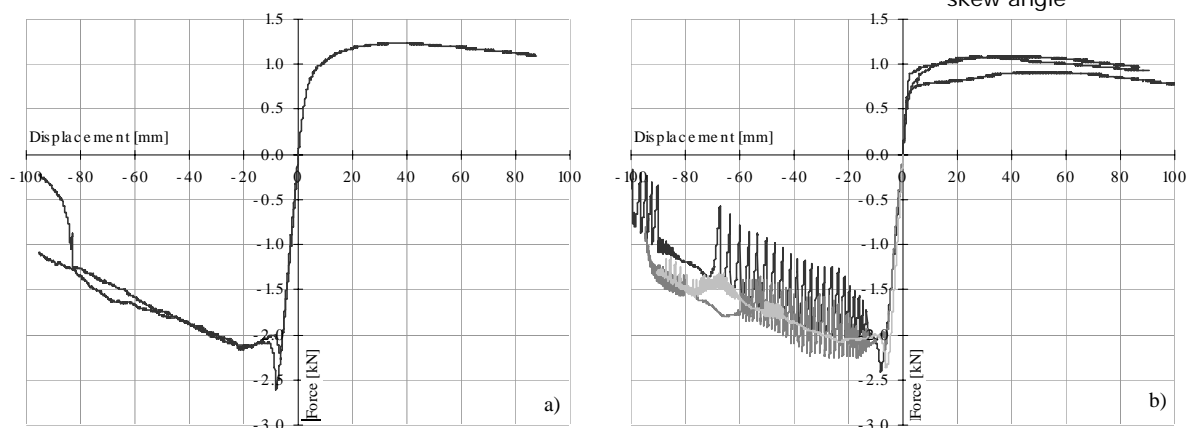**Figure 11.** Joint with t_v = 45 mm: opening skew angle

Figure 13. Simple joints, tv = 45 mm: a) 12 % MC; b) 20 % MC

The behaviour when closing the skew angle was quite different regarding both moisture contents. Although their strength and initial stiffness was approximately the same, after the first slip the 20 % moisture content joints *F-d* curves exhibited a "sawtooth" appearance. This is apparently a consequence of higher slips between the two elements, due to changed friction owing to the increase in moisture content **Errore. L'origine riferimento non è stata trovata.**. In both cases, after an initial elastic stage, the transverse force decreased rapidly. Figure 12 and Figure 14 show the failure modes and deformed shapes identified during the tests.
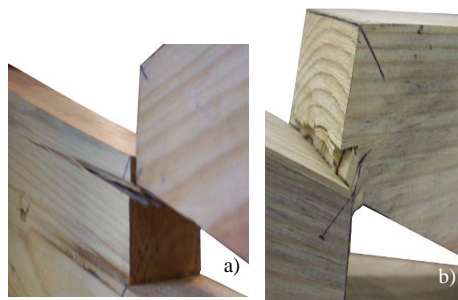
Figure 12. Joints with t_v = 45 mm: closing skew angle, 12 % MC: a) failure due to stresses perpendicular to the grain; b) compression of strut's tooth

4.1.2. Effect of notch depth (configuration 1 versus 3)

As shown in Figure 15, there were no significant effect of the notch depth, 35 or

45 mm in the opening mode performance of the joint. In both cases, the contact area in the front of the notch decreased progressively until it had no capability of opposing the relative movement between the elements.

On the other hand, the closing mode performance increased with notch depth, in particular the maximum displacement. As expected, a smaller notch depth will induce an earlier loss of equilibrium, completely separating both elements.
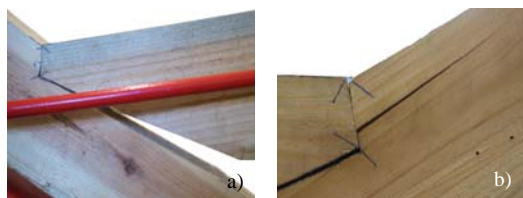
Figure 15. Joints with t_v = 30 mm: a) deformed shape (opening skew angle); b) failure due to stresses perpendicular to the grain (closing skew angle)
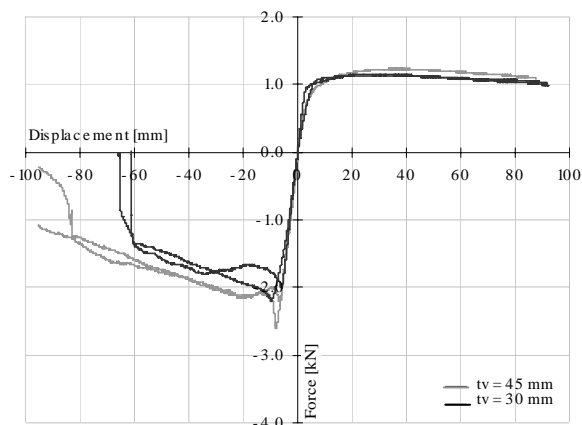
Figure 14. Comparison between different notch depths, 12 % MC

4.2. Mortise and tenon joints (configurations 1 and 2 versus 4 and 5)

The mortise and tenon had a great influence when closing the skew angle, but not so much when opening it (Figure 17). The tenon extinguished the "sawtooth" appearance of the curve at 20 % moisture content, increased strength and enhanced ductile behaviour after the first slip between the elements.
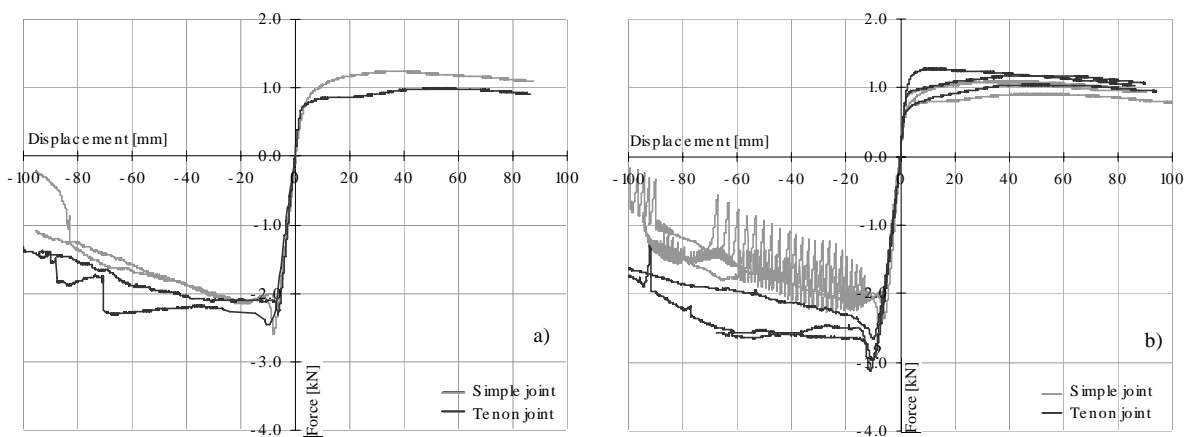
Figure 16 - Comparison between simple joint and tenon joint: a) 12 % MC; b) 20 % MC

The joints were assembled with 12 % moisture content, so when the 20 % moisture content was reached the mortise and tenon were tightly fitted. On one specimen, failure occurred in the tenon when closing the skew angle (Figure 18), significantly reducing the ductility of the joint.

Figure 17. a) Failure in the tenon (opening skew angle); b) deformed shape (opening the skew angle)

4.3.   Stirrups (configurations 6 and 7)

The stirrups were assembled before any compression force was applied to the strut. The obtained *F-d* curves (Figure 21) exhibit an initial elastic stage, followed by a non-linear behaviour. Although the behaviour of the joint in closing and opening modes is not symmetric, they are more similar to each other than in the case of simple joints.

When closing the skew angle, the increase in moisture content led to a significant increase in strength, as the stirrups were more tightened to the timber elements.

Failures modes (Figure 20) were the fracture of the weld (opening the skew angle) and yielding/buckling of the stirrups near the notch area (closing the skew angle).

A significant issue is the contact between the members in the notch surfaces. Two 20 % moisture content joints were poorly assembled and had a gap between the strut and the chord (Figure 19). Their behaviour (Figure 21b)) clearly shows lower stiffness and strength when comparing with the other properly assembled joints.
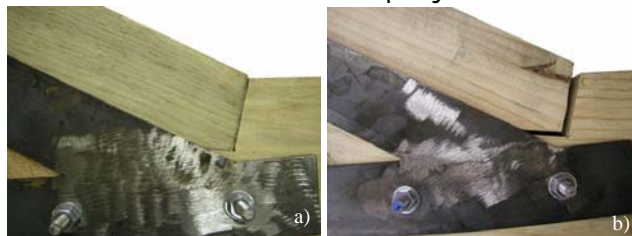

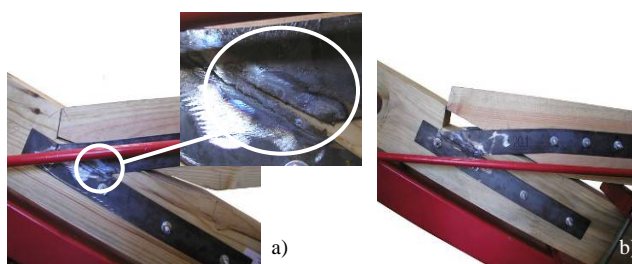**Figure 18.** Joints with stirrups: a) good fit in the notch surfaces; b) initial gap due to assembly problems

Figure 19. a) Weld failure (closing skew angle); b) deformed shape (closing skew angle)
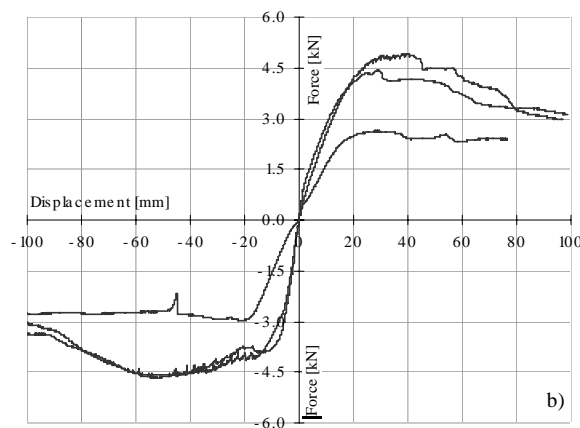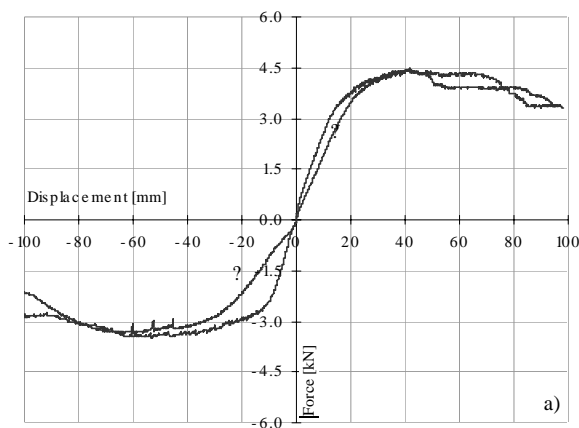

Figure 20. Stirrups: a) 12 % MC; b) 20 % MC

4.4.   Tension ties (configurations 8 and 9)

As opposed to the joints with stirrups, where rising moisture content seemed to increase strength and stiffness (due to a closer tight between the timber and the metal parts), the joints with lateral tension ties saw their performance decrease with increasing moisture content. In fact, the small contact area beneath the thick metal plates lead to higher deformation of the wood with the higher moisture content, thus

Figure 21. Joints with tension ties: a) contact loss on the front surface (closing skew angle); b) failure due to stresses perpendicular to grain (opening skew angle)
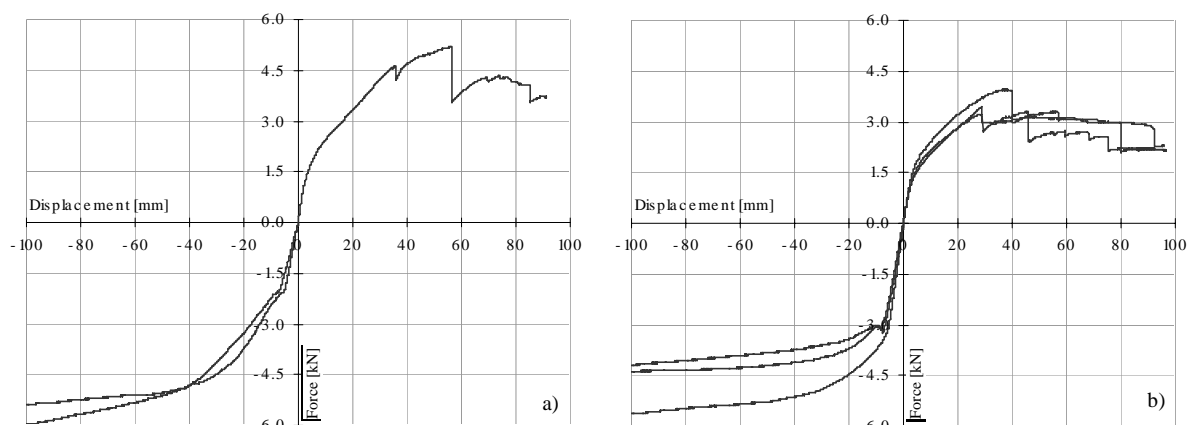
increasing the tension in the ties.

Figure 22. Lateral tension ties: a) 12 % MC; b) 20 % MC

When closing the skew angle, after a displacement of 5 to 10 mm, there was a loss of contact in the front surface of the notch and a significant increase in the compression of the wood in the rear of the notch (at a greater angle to the grain), with a consequent loss in stiffness (visible in the *F-d* plots). In the 20 % moisture content specimens the yield strength is higher than in the 12 % moisture content joints, but the latter have a higher ultimate strength.

Opening skew angle exhibited a clearly non-linear behaviour and is marked by perpendicular to grain failures in the timber between the tension ties and the frontal notch surface.
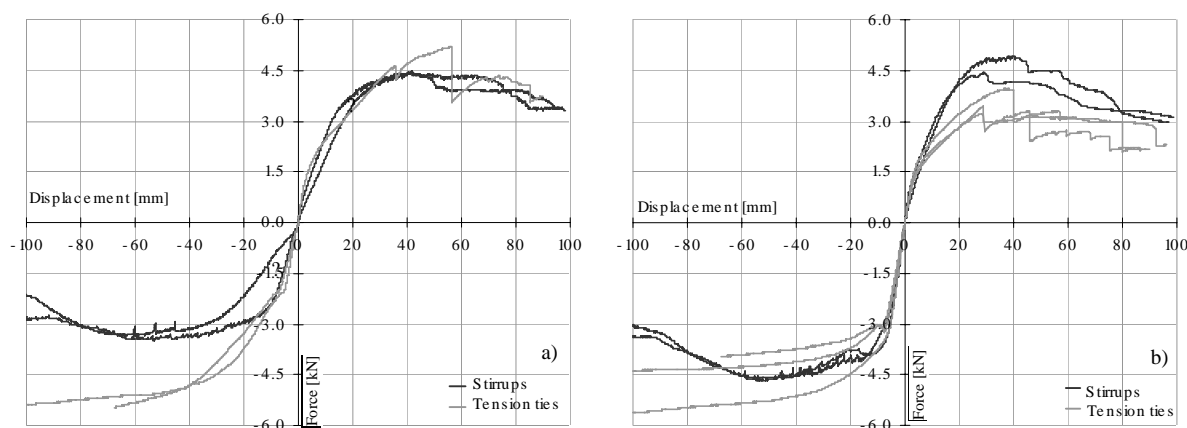
Figure 23. Comparison between stirrups and tension ties: a) 12 % MC; b) 20 % MC

The comparison between the use of stirrups and tension ties (Figure 24) confirms the abovementioned aspects: increased moisture content led to higher stiffness and strength in the joints with stirrups and to a lower strength in the joints with tension ties. When closing the skew angle, at 12 % moisture content, the tension ties generally lead to a much higher strength than the stirrups, though when opening the skew angle there is not much difference in the overall behaviour.

5. Conclusions

Despite the limited number of test results available so far, some preliminary conclusions can be drawn, as follows:

- There seems to be no influence of notch depth, at least for the compression level adopted in the tests, in the opening mode performance of the joint.
- Mortise and tenon improve the ductility of the joints when closing the skew angle.
- Stirrups had a clear effect on the behaviour of the joint, by increasing its strength and ductility and by bringing a more symmetrical behaviour to joints (in opening and closing modes).
- A significant issue is the importance of a perfect match of the members in the notch surfaces, since a poor assemblage with a gap between strut and chord seems to lead to much lower stiffness and strength of the joint.
- The effect of tension ties on the joints performance is not so consistent. They also increase joints strength and ductility, as compared to simple joints, but in the opening mode the progressive displacement of contact areas between strut and chord and failure in compression perpendicular to grain lead to a highly irregular *F-d* diagram.

In the tested joints, stirrups were assembled before compression loading was applied to the strut and, therefore, the matching between the members in the notch surface might not have been completely perfect. Additional tests will be made where the compression force is applied before the stirrups are assembled, in order to clarify this issue.

Further monotonic and cyclic tests are necessary to allow a more reliable analysis of the behaviour of the joints.

Acknowledgements

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