Structural Analysis of Historical Constructions, New Delhi 2006
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Strengthening Techniques of Portuguese Traditional Timber Connections

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ABSTRACT: Different strengthening solutions with metal elements have been experimentally evaluated with tests on full-scale connections. Attention has been focused on the birdsmouth joints, due to its common use in practice. Even if unstrengthened, these types of connections reveal significant moment resistance. Experimental results show that structural response of birdsmouth connections under cyclic loading cannot be represented by common constraint models, like perfect hinges or rigid joints, but with semi-rigid and friction based models. Thus, the rotational behaviour of the birdsmouth joints is analysed.

1 INTRODUCTION

The most common joint in existing timber roof structures is the “birdsmouth joint with a single tooth”, 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 do not transmit forces directly; they were 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 but 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 behaviour of traditional roof trusses can result in unacceptable stresses in the members as a consequence of inappropriate joints strengthening (in terms of stiffening). Joints 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 has unique consequences in terms of the joint final strength, stiffness and ductility. Although being widely used, the number of studies on the mechanical performance of existing traditional carpentry joints and possible strengthening techniques is not worldwide. With few exceptions, see e.g. Bulleit et al. 1999, Seo et al. 1999 and Parisi and Piazza 2000, timber joints research has been oriented towards new engineering configurations. A research program has been developed by the authors with the purpose of investigating the monotonic and cyclic behaviours of old timber connections and identifying and evaluating suitable strengthening techniques. This research concerns both unstrengthened and strengthened connections under monotonic and cyclic loading. Test data of original connections have been gathered with the purpose of characterizing their behaviour as well as to allow the calibration of numerical models. The tested specimens could not cover all the possible ranges and combination of parameters (as geometry, compression level, loading test velocity, etc.) that are of practical interests. The experimental analysis can be extended by numerical models in the next research step. Beyond this, experimentation gave an insight of the joint behaviour for the calibration of the models. It was particularly important to observe the post-elastic behaviour and the failure mode of the connections. Observing the behaviour of strengthened connections under cyclic loading gave straight indications on the positive and negative characteristics of the different strengthening techniques that have been analysed.

2 EXPERIMENTAL CAMPAIGN

The experimental research was carried out at the Laboratory of Structures of the University of Minho (Portugal), and includes monotonic and cyclic tests of full-scale birdsmouth joints; see Branco et al. (2005a). A series of tests on unstrengthened specimens were performed in order to characterize the original behaviour of joints representative of existing timber systems. Subsequently, a set of joints were strengthened with metal devices and tested under monotonic and cyclic loading. Tests on assembled connections were preceded by accurate material characterization, in terms of the mechanical properties of the timber elements used for all full-scale models. Table 1 summarises the test campaign conducted on birdsmouth joints.

Table 1 : Tests on birdsmouth joints.

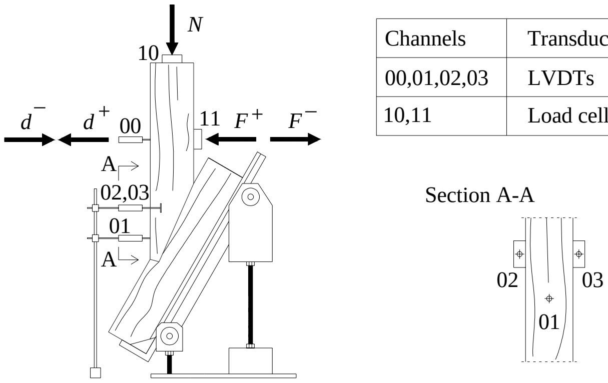
Specimen	Type of connection	Loading Method	Rafter compression stress
A1, A2, A3	Unstrengthened	Monotonic +	1.4 MPa and 2.5 MPa
A4, A5, A6	Unstrengthened	Monotonic -	1.4 MPa and 2.5 MPa
A7, A8, A9	Unstrengthened	Cyclic	1.4 MPa and 2.5 MPa
S1, S2, S3	Stirrup	Monotonic +	1.4 MPa
S4, S5, S6	Stirrup	Monotonic -	1.4 MPa
S7, S8, S9	Stirrup	Cyclic	1.4 MPa
B1, B2, B3	Bolt	Monotonic +	1.4 MPa
B4, B5, B6	Bolt	Monotonic -	1.4 MPa
B7, B8, B9	Bolt	Cyclic	1.4 MPa
BS1, BS2, BS3	Binding Strip	Monotonic +	1.4 MPa
BS4, BS5, BS6	Binding Strip	Monotonic -	1.4 MPa
BS7, BS8, BS9	Binding Strip	Cyclic	1.4 MPa

2.1 Material properties

A mechanical characterization of the timber used in the joints (*Pinus Pinaster* Ait.) was performed. In the carpentry where the joints were fabricated, all timber pieces used were classified as belonging to quality class EE as result of a visual strength grading according the Portuguese National Standard NP 4305 (IPQ, 1995). At the laboratory, over some samples collected during the fabrication of the joints, the local and global Young's modulus and strength, both in bending and compression parallel to the grain, were estimated following the prEN408 (CEN, 2000).

2.2 Test setup and instrumentation

A steel test-hand able to accommodate specimens with various skew angles was built within a larger steel loading frame of the laboratory (Fig. 1). The arrangement allows independent control of two hydraulic jacks. One jack, aligned with the rafter, induced constant compression throughout the test. The other, a double-acting jack, positioned at a height of 70 cm above the center of the joint, applied a transversal force, with a programmed load cycle, and generated a moment at the joint. Force (*F*) versus displacement (*d*) curves were measured. The two jacks have a maximum loading capacity of 50 kN and 100 kN and a maximum stroke of 160 mm and 50 mm, respectively. Type and location of instrumental channels, including load cells and linear voltage differential transducers (LVDT), are shown in Fig. 1. Tests were performed under displacement control for the typical birdsmouth joint skew angle of 30º. For all the specimens, the cross sections of the elements were 80 x 220 mm^2, the notch depth was 45 mm and the notch length was 422 mm as represented in Fig. 2. The first step of the loading procedures in both the monotonic and cyclic tests was the application of an axial compression force on the rafter. The axial force, simulating the effect of the self-weight and dead load presented in the structure, was kept constant during the test. In the subsequent loading steps, a transversal force, F, acts perpendicular to the rafter axis. When the skew angle increases, it is defined as the positive direction and when the skew angle decreases, it is defined as the negative direction.



Channels	Transducers
00,01,02,03	LVDTs
10,11	Load cells

Figure 1 : Testing apparatus and instrumentation layout.

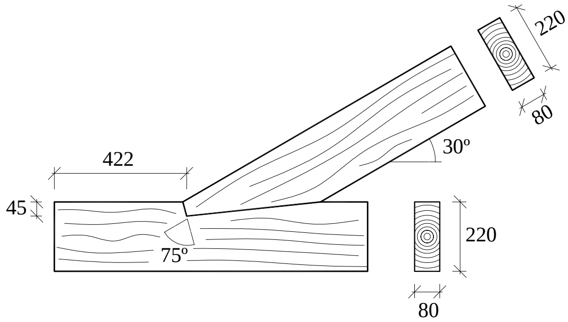


Figure 2 : Connections geometry (dimensions in millimeters).

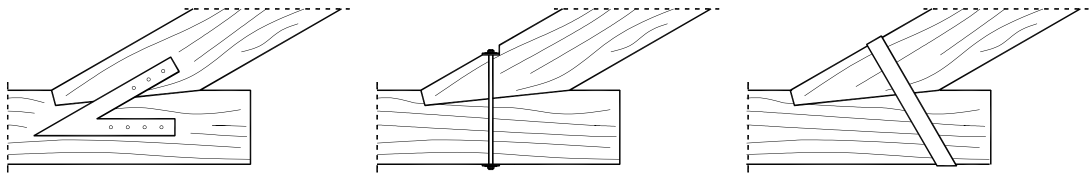
Monotonic tests were performed to determine the elastic behaviour, in particular, the apparent elastic limit displacement d_e^+ and d_e^-. Under displacement control at channel 00, a maximum displacement value of 50 mm, was imposed under a velocity of 0.028 mm/s.

2.3 Cyclic test procedures

Full-scale connections, similar to the specimens of monotonic loading, were tested with a quasi-static cyclic loading. In particular, the test program included one cycle in the range [0.25 d_e^+; 0.25 d_e^-]; one cycle in the range [0.50 d_e^+; 0.50 d_e^-]; three cycles in the range [0.75 d_e^+; 0.75 d_e^-]; three cycles in the range [(1+n) d_e^+; (1+n) d_e^-] with n = 0, 1, 2, …. until joints failure. This sequence is in accordance with the proposal in reference (CEN, 2001). The values used for the elastic limit displacements, for both positive (d_e^+) and negative (d_e^-) directions, came directly from the results achieved by the monotonic tests.

2.4 Strengthening solutions studied

Metal connectors have been applied occasionally in timber joints since very ancient times. However, this practice became common only in the 19th century, when the development of industrial production methods made bolts, rivets, and other metal elements easily available. Metal devices were intended to counteract out-of-plane actions, which could not be resisted by the assemblage itself. Nowadays, strengthening also concerns the behaviour of the friction-based connection in its own plane, and is intended to avoid the detachment of the connected members. Particularly in seismic areas, strengthening can prevent loss of capacity and possible separation of friction surfaces due to the decrease of compression forces, and, under cyclic loading, the application of strengthening solutions can maintain a stable structural behaviour Parisi and Piazza (2000). The three basic types of intervention considered in this study are modern implementations of traditional strengthening techniques: the stirrups, the internal bolt and the binding strip (Fig. 3).



(a) Stirrup (b) Bolt (c) Binding Strip

Figure 3: Traditional strengthening techniques evaluated.

Metal stirrups placed in pairs at two opposite sides of the joint were very popular in the past and are still considered adequate and frequently adopted. The effect of the large increase of in-plane stiffness connection is particularly important and should be investigated. In this study, each stirrup was composed of two steel plates welded in a V-shape. Each prong was 50 mm wide and 5 mm thick. They were parallel to the rafter or to the chord, and bolted to it with seven bolts of 10 mm diameter. The use of a steel rod, with 12 mm diameter, was also considered. The rod was fixed by a nut at both ends and secured by using a special rectangular-shape washer (70 x 30 mm^2 and 5 mm thick). A suitable seat area was formed within the timber element for accommodating it, which allows perfect contact between surfaces. The rod was located at the mid-joint and normal to the axis of the rafter. Metal binding strips, considered obsolete today, were very frequently adopted in the 19^{th} century roof structures, particularly to strengthen the lower rafter and chord connection in configurations which had skew angles typically of 30º, see Branco et al (2005b). An updated version of this layout was considered here: the joint was bound with a hollow steel ribbon, 50 mm wide and 5 mm thick, located at mid-joint, normal to the chord.

3 TEST RESULTS

3.1 *Efficiency evaluation of the strengthening techniques*

Comparing the tests results in terms of force-displacement curves for the unstrengthened and strengthened connections (Fig. 4), it is recognized that all the strengthening schemes analysed increase the stiffness, in particular, in the positive direction and the maximum resistance for both directions.

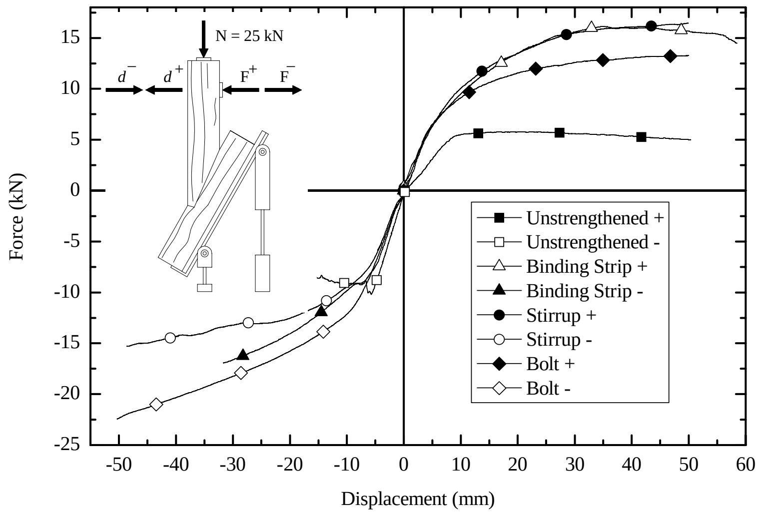


Figure 4 : Force-displacement diagrams for unstrengthened and strengthened connections under monotonic loading.

The elasto-plastic behaviour with limited ductility evidenced by the unstrengthened connections is substituted by full non-linear curves exhibiting high ductility in the strengthened connections. Comparing the strengthening techniques evaluated, the less efficient, in terms of maximum resistance, is the internal bolt, while the elastic stiffness is similar. Connections strengthened with stirrups and binding strip attained the same range of maximum force, however, this later scheme has a lower ductility capacity. In particular, the maximum resistance for the strengthened connections with stirrups and internal bolt is achieved near the end of the test. However, in the strengthened connections with binding strip, when the tests were interrupted, the force value was already decreased. Therefore, between the internal bolt and the binding strip, the first one is more efficient in terms of ductility capacity with the goal to assure a better seismic behaviour of the joints. The effect of the strengthening schemes in the negative direction of the monotonic tests is obvious: the increase of maximum moment resistance and the ductility capacity. The benefits to the stiffness are not significant. However, the brittle behaviour exhibited by unstrengthened connections disappears in the strengthened specimens. Therefore, the main profit of adding a metal device to the joints is the improvement of ductility with clear advantages in their seismic behaviour. Only the binding strip showed limitations in terms of maximum displacement. Fig. 5 shows the common failure modes and principal damages detected in the cyclic tests on the strengthened connections. Table 2 summarises the main results of the cyclic tests on the strengthened joints.

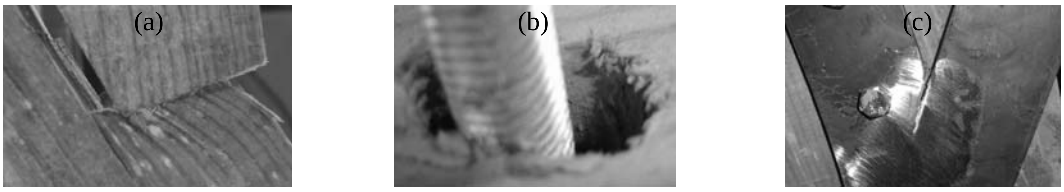


Figure 5 : Failure modes and damages detected during the cyclic tests on the strengthened connections: (a) Compression in the joint with the binding strip, (b) Bending of the bolt with local embedment and (c) Stirrup failure.

Table 2 : Main results for the cyclic tests on the original and strengthened joints (average values).

Joint	Dissipated Energy (kJ)	*Veq.* (%)	d_{max}^{+} (mm)	d_{max}^{-} (mm)	F_{max}^{+} (kN)	F_{max}^{-} (kN)
Unstrengthened (σ_c=1.4 MPa)	230	2.45	16.49	-15.83	6.20	-11.57
Unstrengthened (σ_c=2.5 MPa)	380	3.96	9.15	-21.17	9.45	-17.00
Binding Strip	2874	6.85	18.38	-39.63	23.38	-25.47
Bolt	1877	11.28	13.30	-35.30	15.29	-21.08
Stirrup	1859	14.57	28.68	-21.75	18.09	-15.60

Fig. 6 collects the force-displacement diagrams for cyclic loading on the strengthened and original unstrengthened joints with a rafter compression stress level of 1.4 MPa.

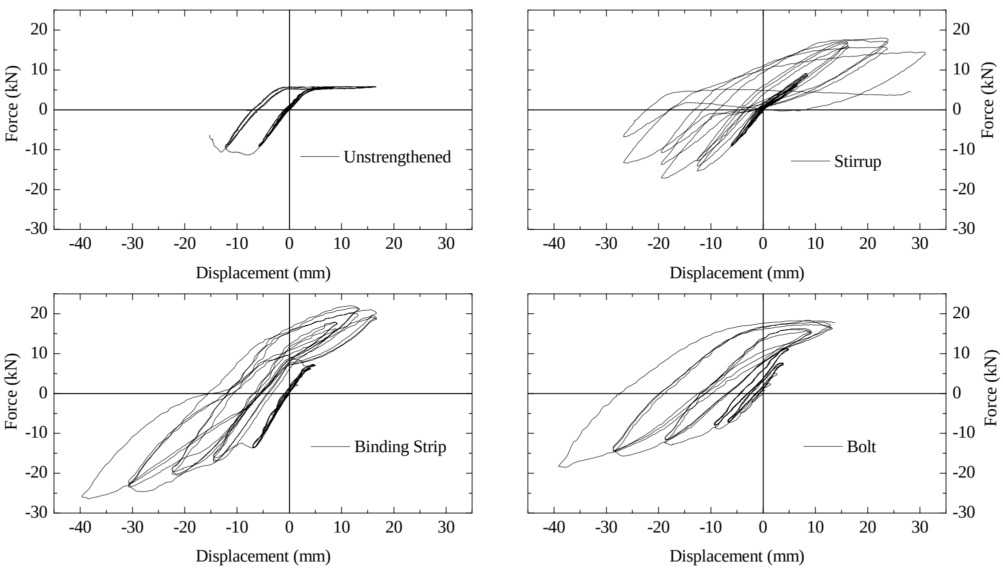


Figure 6 : Force-displacement response for the cyclic loading (rafter compression level of 1.4 MPa).

The failure of the connection is governed by its behaviour that, when closing the skew angle, the final detachment of the notch from the tie-beam has been damaged during the previous cycles. The significant quantity of energy dissipated, illustrated in Fig. 6, is mainly the consequence of the energy needed to cause the failure of the notch. The experimental force-displacement diagrams achieved for all connections are asymmetric, both in term of stiffness and yielding limits.

Without any strengthening device, the joint is not able to prevent the failure causes by load reversals (detachment of the connected elements), the amount of energy dissipated is very small. All strengthening techniques adopted were efficient in the improvement of the hysteretic behaviour of the connections. Hysteretic equivalent viscous damping ratios (*Veq*) evaluated from test results are considerable. With more cycles achieved, more energy is dissipated. The number of cycles achieved is particular important taken into account the Eurocode 8 (CEN, 2003) imposition for the behaviour factor. In this standard, it is defended that the dissipative zones shall be able to deform plastically for at least three fully reversed cycles at a static ductility ratio of 4 for ductility class M structures and at a static ductility ratio of 6 for ductility class H structures, without more than a 20% reduction of their resistance.

4 MOMENT-ROTATION BEHAVIOUR

The behaviour of the connections studied in the experimental campaign can be formulated by the relationship between moment and relative rotation (M-Φ). Indeed, common constraint models, like hinges or full restraint connections, cannot satisfactorily describe their behaviour under cyclic loading. These connections are semi-rigid and friction based. One objective of the general research program in which this work was developed, is the definition of synthetic models that represents the static and dynamic behaviour of timber connections in traditional constructions.

4.1 The monotonic behaviour

For structures under monotonic static loading, the law for the positive and negative rotation describes completely the joint behaviour. An accurate matching of the experimental curve and the model may be feasible by different order curves.

In this case, for the definition of the M-Φ diagrams, the Dolan (1994) procedure was followed. Two methods for the definition of the M-Φ curves are suggested, namely, a bilinear and a trilinear approach. In the presence of a bilinear behaviour, the initial stiffness (k_0) is reported to the range [0.1Mu-0.4M_u] and the post-elastic stiffness (k_u) is given as 1/6 of k_0, as represented in Fig. 7.

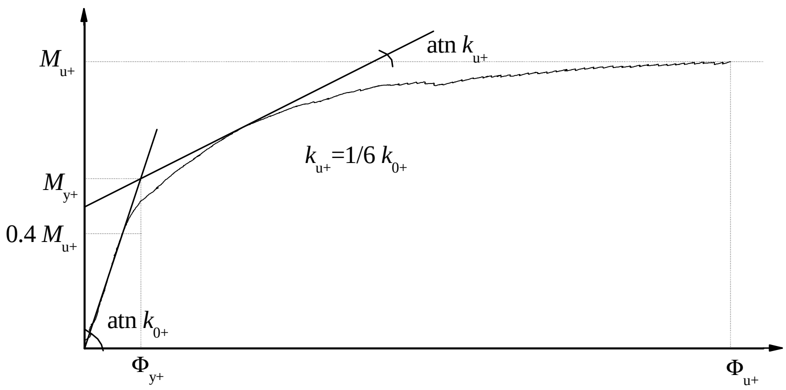


Figure 7 : Example of an experimental M-Φ diagram without a bilinear behaviour.

Although it is advisable that the reduction of the order curve used in the mathematical description, this bilinear law was considered not adequate to represent the structural response of the studied timber connections. In order to achieve a more accurate model, the adoption of the trilinear approximation is proposed, as shown in Fig. 8.

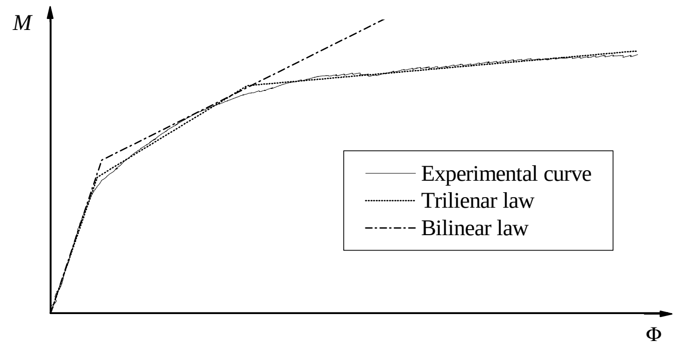


Figure 8 : M-Φ diagrams (experimental results and adjusted curves).

With the trilinear law, the introduction of the new branch (stiffness k_3) allows a better approximation to the experimental results, particularly, in terms of energy dissipation.

Table 3 : Comparison between the stiffness parameters using bilinear and trilinear laws, for the connections strengthened with bolts (average values).

Force direction	Law order	K_0 [kNm/rad]	k_u [kNm/rad]	k_3 [kNm/rad]
Positive	Bilinear	714	119	—
	Trilinear	692	139	16
Negative	Bilinear	689	115	—
	Trilinear	683	179	103

4.2 The cyclic behaviour

The first remark pointed out by the tests on full-scale connections was the highly non-symmetric cycles that characterize the rotational behaviour of these joints. This asymmetry affects stiffness, as well as the bending moments at the yielding and ultimate conditions, in both unsetrengthened and strengthened connections. Significant nonlinear behaviour was observed, beyond the initial loading stages, for positive and negative imposed rotations (opening and closing the skew angle, respectively), see Fig. 6.

From the final complete cycle for each tested connection, according to Dolan (1994) recommendation, it were estimated the mechanical parameters that better describe the rotational behaviour (M-Φ) of the connection, as shown in Fig. 9.

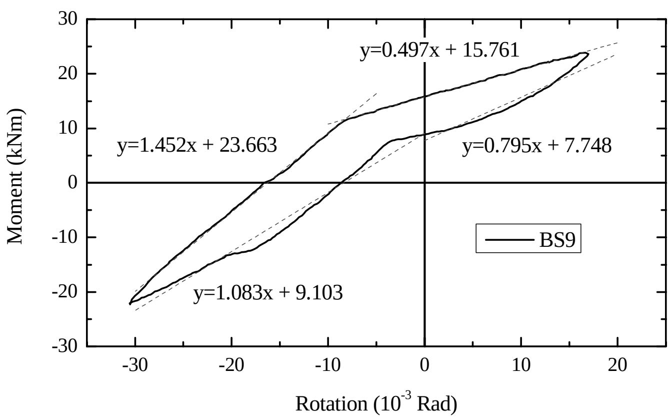


Figure 9 : Final complete cycle for the specimen BS9 (strengthened connection with binding strip).

5 MAIN CONCLUSIONS AND FINAL CONSIDERATIONS

The typical birdsmouth joints, even without any strengthening device, usually have a significant moment-resisting capacity. Therefore, they cannot be represented by common constraint models, like perfect hinges, but should be considered semi-rigid and friction based. The test results show that this capacity is function of the rafter compression stress level. Moreover, it is clear that the width of the rafter, the friction angle, and the skew angle in the connection are also important. The experimental analysis has been of fundamental importance in order to understand the real behaviour, by pointing out some important aspects like force transmission mechanisms, failure modes and guidance for appropriate strengthening solutions.

Strengthening, usually performed by insertion of metal devices, is indispensable for ensuring adequate joint response, in particular, for seismic loading, or in other adverse and unpredictable loading conditions. The strengthening of the joints results in a significant increase of the hysteretic equivalent viscous damping ratio (*Veq*). The energy dissipation became significant. In conclusion, the strengthening solutions studied improve the seismic behaviour of the birdsmouth joints typically presented in traditional timber roofs.

The possibility of modelling these connections numerically, by means of nonlinear moment-rotation laws, intends to represent the seismic behaviour of historical constructions with a comparable level of detail for all the components.

Modelling these connections by means of nonlinear moment-rotation laws is shown in this paper. Next step of the research shall be the implementation and verification of those models in numerical analysis of traditional timber trusses.

ACKNOWLEDGMENTS

The first author gratefully acknowledges the Portuguese Foundation for Science and Technology, for his PhD grant, with the reference SFRH/BD/18515/2004. The research described in this paper was conducted with financial support of the Portuguese Foundation for Science and Technology (contract reference POCI/ECM/56552/2004). This work has been carried out with a partial financial contribution of the Italian Earthquake Engineering Laboratory Network (RELUIS).

REFERENCES

Branco J., Cruz P., Varum H. 2005a. *Experimental Analysis of Birdsmouth Joints*. Report E-11/05. DECivil, University of Minho, 49 pp.

Branco J., Cruz P., Varum H., Piazza M. 2005b. *Portuguese traditional timber trusses: static and dynamic behaviour*. Report E-19/05. DECivil, University of Minho, 50 pp.

Bulleit W. M., Sandberg B. L., Drewek M. W., O'Bryant T. L. 1999. Behaviour and modelling of wood-pegged timber frames. *J.Struct. Engrg.*, ASCE, 125(1), 3–9.

CEN 2000. T*imber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*. prEN 408, CEN, Brussels, Belgium.

CEN 2001. *Timber structures - Test methods – Cyclic testing of joints made with mechanical fasteners*. EN 12512, CEN, Brussels, Belgium.

CEN 2003. *Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*. prEN 1998-1, CEN, Brussels, Belgium.

Dolan J. D. 1994. RILEM Technical Committee 109 TSA, Timber Structures in Seismic Regions, *Materials and Structures*, Vol. 27, 167, pp. 157-184.

IPQ 1995. *Structural maritime pine swan timber – Visual grading*. NP 4305, IPQ, Lisbon, Portugal.

Parisi M. A, Piazza M. 2000. Mechanics of plain and retrofitted traditional timber connections. *J Struct Engrg.*, ASCE; 126(12): 1395–403.

Seo J.-M., Choi I.-K., Lee J.-R. 1999. Static and cyclic behaviour of wooden frames with tenon joints under lateral load. *J. Struct. Engrg.*, ASCE, 125(3), 344–349.