MECHANICAL CHARACTERIZATION OF TRADITIONAL TIMBER CONNECTIONS: EXPERIMENTAL RESULTS

CARACTERIZAÇÃO MECÂNICA DE LIGAÇÕES TRADICIONAIS EM MADEIRA: RESULTADOS EXPERIMENTAIS

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ABSTRACT

Timber connections are an important part of a timber structure and a great variability exists in terms of types of connections and mechanisms. Taking as case study the traditional timber frame structures, the half-lap joint was selected. Connections play a major role in the overall behaviour of a structure, particularly when assessing their seismic response, since damage is concentrated at the connections. Therefore, an experimental campaign was carried out on traditional half-lap joints to assess their in-plane response, carrying out pull-out and in-plane cyclic tests. Subsequently, the connections were retrofitted using self-tapping screws, steel plates and GFRP sheets. In this paper, the experimental results are presented taking into account factors such as dissipated energy, damping and influence on the wall behaviour.

RESUMO

As ligações em madeira constituem uma parte importante das estruturas em madeira e existe uma grande variabilidade em termos de tipologia de ligações e mecânismos. Considerando como caso de estudo os edifícios com paredes de madeira tradicionais (paredes de frontal), foi adotada a ligação madeira-madeira. As ligações tem uma função fundamental no comportamento global da estrutura, em particular na analise sismica, uma vez que o dano é concentrado nas ligações. Portanto, foi executada uma campanha experimental sobre ligações tradicionais madeira-madeira para avaliar o comportamento no plano, realizando ensaios cíclicos e de pull-out. A seguir, as ligações foram reforçadas com parafusos auto-perforantes, chapas metalicas e folhas de fibra de vidro. Neste artigo são apresentados os resultados experimentais considerando factores tal como a dissipação de energia, o amortecimento viscoso e a influência no comportamento global das paredes de frontal.

1. INTRODUCTION

Timber connections are used in a great variety of timber structures and structural elements, varying from floors to walls to roofs. In literature, it is possible to find numerous experimental results on traditional timber connections. Various studies are available on bird’s mouth connections, typically used for roofs (Branco, 2008; Parisi and Piazza, 2002) and on mortise and tenon connections regarding pull-out, bending and shear tests (Descamps et al. 2006; Koch et al. 2013), as well as on dowel-type joints (Xu et al. 2009). Moreover, studies exist on the characterization of specific traditional joints, e.g. on the rotational performance of traditional Nuki joints in Taiwan (Chang et al. 2006), rotational and pull-out tests on historic Dou–Gon joints in Taiwan (D'Ayala and Tsai 2008), tensile tests of Japanese Kama Tsugi and Okkake DaisenTsugi joints, which are traditional notched joints (Ukyo et al. 2008).

Due to the very great variability that exists as far as connections type is concerned, usually specific tests have to be carried out for each type of connection, due to the different mechanism developed.

1.1. Use of timber connections in timber frame walls

As a case study, the joints used in traditional timber frame walls will be taken into account here. Timber frame structures are common all over the world and a great variability exists in terms of geometries and connections type (Poletti 2013; Branco 2008). They are essential to the seismic efficiency of such structures as they dissipate the energy accumulated in a seismic event. Little information is available on joints specifically tested for the response of timber frame walls. Vieux-Champagne et al. (2014) performed pull-out tests on steel-wood nail connections used in timber structures in Haiti.

For the purpose of this study, the half-lap joint, typical of traditional Portuguese timber frame walls, was selected and studied.

2. EXPERIMENTAL CAMPAIGN

An experimental campaign on traditional connections used in Portuguese timber frame walls was carried out in order to better study their behaviour, since they are the key elements of the walls. Prior to these tests, real scale timber frame walls were tested and retrofitted, revealing a prevalent rocking mechanism and a failure mode dominated by their connections (Poletti 2013). Therefore, a significant connection of the wall tested was selected. The lateral bottom half-lap joint was adopted, since it was seen that, for unreinforced walls, it was governing the walls, behaviour, as it was preponderant for its rocking movement. The evaluation of the deformation patterns and damage progress assists in the further understanding of the mechanical behaviour and in the selection of the most appropriate retrofitting solutions for traditional timber frame walls.

2.1. Specimens adopted

The specimen selected has the same geometry of the bottom joint in the wall (Fig. 1). The specimens were built in the same period of the timber frame walls with the same type of wood, *Pinus Pinaster*. A nail was inserted in the centre of the joint.

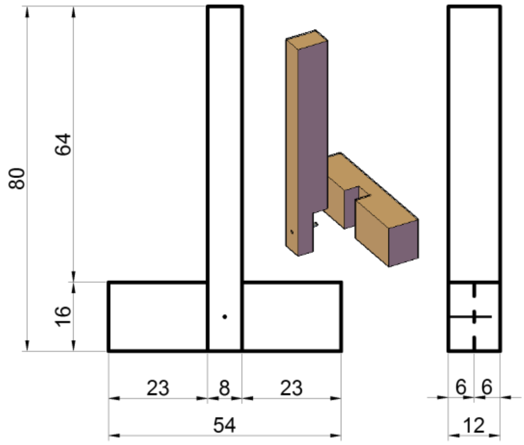


Fig. 1 – Half-lap joint adopted.

It was decided not to take into account the influence of the masonry infill in these tests. From what was observed during the tests on the walls (Poletti 2013), infill has an important confining effect on the timber frame and adds stiffness and strength to the frame. The non-consideration of the infill represents the most unfavourable condition, since the connection is weaker without infill. Moreover, for these tests the effect of the diagonal element on the connection was not taken into account.

2.2. Test setup and test procedure

Two types of tests have been performed on traditional timber joints: (1) pull-out cyclic tests and (2) in-plane static cyclic tests. This choice is justified by the fact that, during the tests performed on the walls, there was a tendency for the bottom connections to uplift, particularly in infill walls. Therefore, it was decided to test the uplifting capacity of the connections in the unreinforced and retrofitted condition as well as further investigate their in-plane cyclic performance.

The test setup configuration was similar for both tests. The beam of the connection was anchored to a steel profile which was linked to the reaction floor (Fig. 2). For pull-out tests, the post was pulled-out by means of a hydraulic actuator which was linked through a hinge at the top of the post. For in-plane tests, a constant vertical load was applied to the post by means of a hydraulic jack. The actuator was placed in a horizontal position and anchored to the rigid steel frame linked to the reaction floor. Two 2-dimensional hinges were placed in order to allow rotations during the test. Similarly to what the wall tests (Poletti 2013), the in-plane cyclic tests were performed considering two levels of vertical pre-compression (25 and 50 kN).

The procedures used for these tests were adapted from standard EN 12512 (2001). For both pull-out and in-plane cyclic tests, a preliminary monotonic test was carried out in order to obtain the yield and ultimate displacement (Poletti 2013).

2.3. Type of strengthening

The connections were retrofitted with some of the same strengthening solutions adopted for the tests performed on timber frame walls (Poletti et al. 2014), namely using steel plates and Near Surface Mounted (NSM) steel rods. Moreover, two additional retrofitting techniques were tested in order to evaluate the possibility for them to be used in walls, namely self-tapping screws and Glass Fibre Reinforced Polymers (GFRP) sheets.

Commercial steel plates (Rothoblaas 2012) were adopted on both sides of the connections and linked with bolts and screws (Fig. 3a). Two overlapping plates were used on each side. NSM rods were inserted in the connections adopting a cross shape (Fig. 4); where the rods met a half-lap joint was created and welded to guarantee the performance of the bar as a whole.

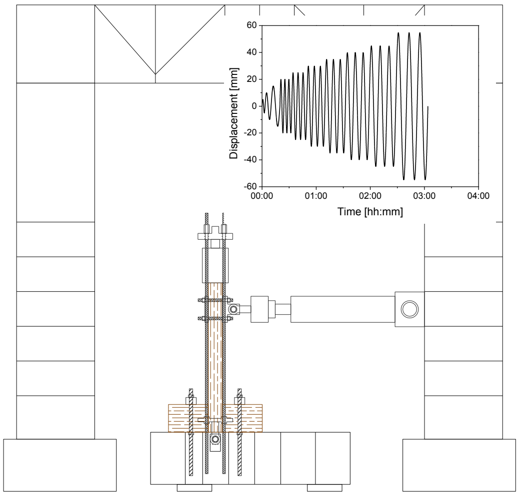
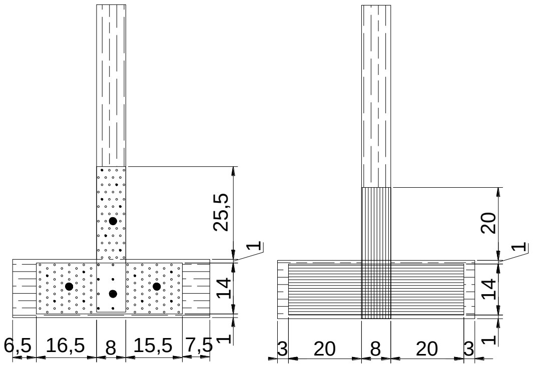


Fig. 2 – Typical pull-out cyclic test result on unreinforced connection.



(a) (b)

Fig. 3 – Retrofitting: (a) steel plates; (b) GFRP sheets

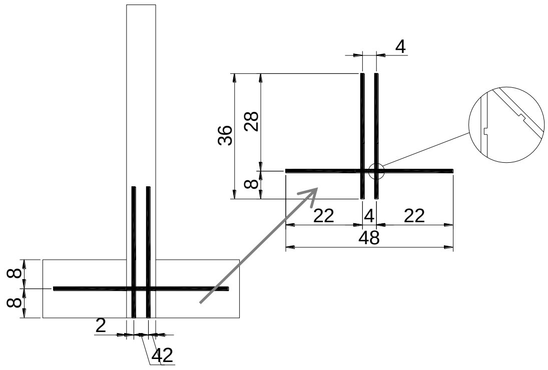


Fig. 4 – Retrofitting used: NSM steel rods.

An alternative solution was to strengthen the connections with GFRP sheets. A uni-directional fibre glass fabric (MapeWrap G UNI-AX (MAPEI 2012)) was used together with an appropriate epoxy resin (MapeWrap 31 (MAPEI 2013)) for fibre impregnation with a dry system. Notice that two sheets were applied, one horizontally and one vertically in order to completely cover the joint (Fig. 3b). The idea is that the GFRP sheets should be able to prevent both the uplift of the post and the out-of-plane opening of the connection.

Another alternative solution was the adoption of self-tapping screws (Fig. 5). This solution was only adopted for pull-out tests, to evaluate its effect on the connection against uplifting forces, but not against a cyclic lateral action. Four screws were inserted in the connection, two with an angle of 60° inserted from the post and intersecting the beam and two with an angle of 45° screwed from the beam and intercepting the notched part of the post. Type VGZ9200 screws were used (Rothoblaas 2012), with a length of 19 cm and a diameter of 8 mm.

3. RESULTS ON UNREINFOCED SPECIMENS

3.1. Pull-out tests

From the results of the pull-out tests it was observed that all connections behaved similarly, being the response characterized by out-of-plane opening when the post was pulled out and deformation of the nail. The connection failed when the nail was not effective, as it pulled out completely from the beam.

Fig. 6 presents a typical force-displacement diagram characterizing the pull out response of the connection. The diagram is characterized by a high initial stiffness and an early non-linear behaviour. In the unloading branch, the connection has an immediate loss of strength and then acquires compression forces. This is associated to the reaction to the re-entering of the post to its original position in the beam, due to the plastic deformation developed in the nail.

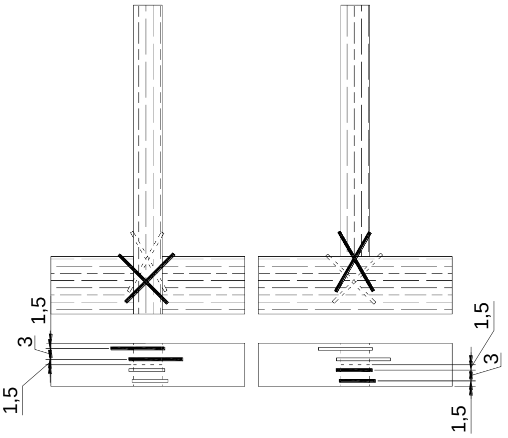


Fig. 5 – Retrofitting adopted: self-tapping screws.

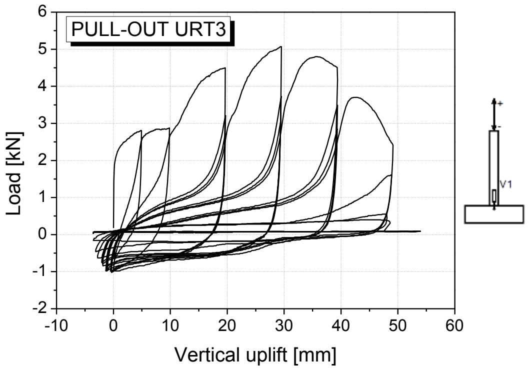


Fig. 6 – Typical pull-out cyclic test result on unreinforced connection.

On the other hand, the reloading branches present a high amount of pinching, caused by the crushing of the wood surrounding the nail and consequent increasing clearances. Important strength degradation is observed during the tests. This phenomenon is not only observed between two successive steps, but also in the stabilization cycles. These two characteristics (pinching and strength degradation) were observed in the cyclic behaviour of timber frame walls without infill, as the behaviour of the connections affects the response of the wall.

Even though the general behaviour of the specimens was similar, it was noticed that the maximum load and stiffness of the joint depends greatly on its level of interlocking. For high clearances present in the joint, its load capacity decreased and the out-of-plane opening of the post progressed more rapidly. Comparing the envelope curves of the specimens (Fig. 7), specimen URT3 reached a maximum load of 5.07 kN, whereas URT2 only reached 2.79 kN, meaning that the resistance decreased by 45%. Moreover, the two specimens with the higher clearances (URT2 and URT4) failed earlier, since the nail pulled out of the beam completely.

3.2.In-plane tests

For in-plane cyclic tests, the specimens behaved in a similar way for both vertical load levels. Vertical cracks were observed in the notched part of the post, associated to shear

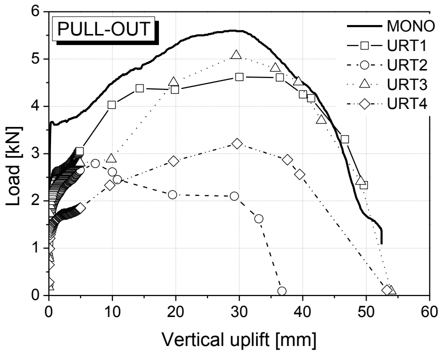


Fig. 7 – Envelope curves for all specimens.

stresses developed during the cyclic test. Moreover, cracks perpendicular to the grain developed at the interface between the post and the beam, as the beam cuts the post during its cyclic movement. The level and shape of cracking depended greatly on the grain alignment and the presence of knots.

Fig. 8 presents a typical hysteretic curve for the lower pre-compression level. The connection has a linear initial response and non-linearity appears nearer to the maximum load capacity. Strength and stiffness degradation was observed. From the comparison of the envelope curves of all tests performed (Fig. 9), differences in the response regarding mainly the maximum load capacity were attributed to the quality of the joint and of the material, as the presence of knots or of grain misalignment led to lower values of load.

For the lower vertical load level, the average maximum load is 5.53 kN while the minimum -6.61 kN, with variations of 19%. For the higher vertical load, the variation was lower, with an average maximum load of 6.48 kN and a minimum of -5.98 kN and a variation of 10% and 14% respectively.

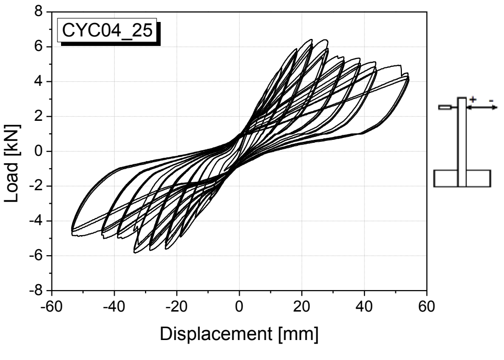


Fig. 8 – Typical pull-out cyclic test result on unreinforced connection.

The out-of-plane opening of the connection varied among the tests depending on the level of interlocking. However, the rate of opening was similar. In Fig. 10, where the progressive opening of the connection versus the top horizontal displacement is shown, it is seen that the increase in the connection opening is almost linear and the opening becomes significant only for displacement levels higher than the yield displacement (19.9 mm).

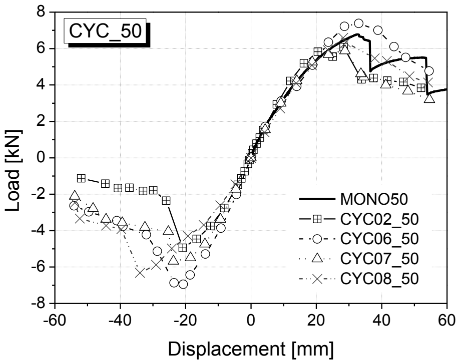


Fig. 9 – Envelope curves for all specimens.

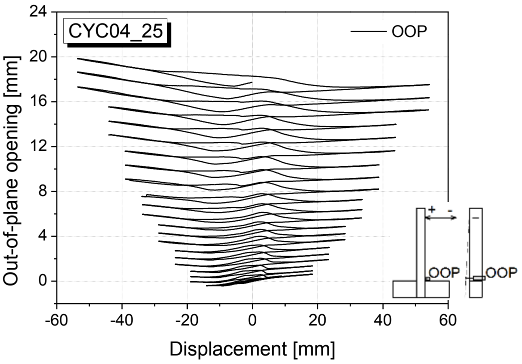


Fig. 10 – Progressive opening of joint.

4. RESULTS ON RETROFITTED SPECIMENS

After the unreinforced tests, the specimens were repaired and retrofitted in order to (1) understand the influence of the retrofitting solution on the behaviour of the connection and (2) to compare different retrofitting solutions understanding their strong points and shortcomings.

For the in-plane cyclic tests, various cracks were present in the notched part of the posts and, in two occasions, total failure of that part occurred. Since applying the strengthening on such damaged part could alter the efficiency of the strengthening, it was decided to cut out the damaged part of the post and replace it with a prosthesis. It was decided not to substitute the entire post, as in an existing structure this is not always possible. The adopted solution consisted of a glued prosthesis, taking out a bigger part of the damaged post and creating an S shape contact connection by gluing the two pieces. To improve the adherence, two screws were used to better link the two elements of the post (Poletti 2013). The idea was to re-establish the continuity of the post. In this way, it was possible to apply all retrofitting techniques.

Results on retrofitted pull-out tests demonstrated that even the simplest retrofitting technique can help in decreasing the level of uplifting of the joint. Depending on the type of strengthening, the connections showed a great increase of initial stiffness and maximum load capacity, and failure modes changed completely, sometimes being extremely brittle.

4.1. Pull-out tests

Retrofitting performed with GFRP sheets had a very high initial stiffness and reached its maximum capacity for a low value of vertical uplift (Fig. 11). The diagram presents two peak values, corresponding to the failure of the GFRP sheet first on one side of the connection and then on the opposite side. The strength achieved was 15 times greater than that of the unreinforced specimen. After failure, the strength of the connection was lower than the one obtained for the unreinforced specimen, indicating that this solution is viable only if the maximum strength of the connection is not reached, since its post-peak behaviour is not performing.

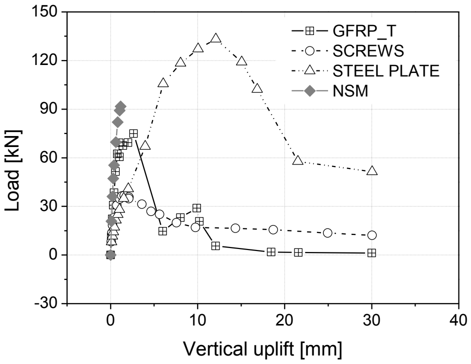


Fig. 11 – Envelope curves for retrofitted specimens.

Considering the test performed with steel plates, the maximum load capacity exceeded the maximum load recorded in the unreinforced tests by over 46 times. Moreover, the stiffness of the connection increased greatly and a good post-peak behaviour was observed, since the steel plates were able to ensure a good residual strength even after peak load. For this case pinching plays an important role, particularly after peak load is attained. Similarly to what happened with GFRP strengthening, the plate failed first on one side of the joint with a clearly horizontal rupture in correspondence with a line of holes, given that they represent the weakest point of the plate. The plates on the other side were able to withstand the maximum uplift imposed. At the end of the test, most of the screws on the post failed in shear, whereas the bolts deformed plastically.

Strengthening executed with self-tapping screws was the less invasive on the connection, being able to greatly improve its strength (6 times over) and stiffness without showing a brittle failure, but actually being able to ensure a post-peak softening behaviour and therefore a great capacity to dissipate energy. For this retrofitting solution, failure was mild, since the damage was progressing throughout the test, with pulling out of the screws, causing slight damages to the beam (Fig. 12). After the peak load the screws were responsible of grain disorganization, which eventually became wood dust. Moreover, at the end of the test, plastic deformations of the screws were observed. Notice that this test is characterized by severe pinching, typical of dowel-type connections.

Fig. 12 – Failures observed for specimen retrofitted with self-tapping screws.

The connection retrofitted with NSM steel rods had a very high initial stiffness and no deformations were observed on the steel rods. Unfortunately, it was not possible to finish the test, as a problem occurred with the control LVDT and it was decided to cancel the test on the connection in order to preserve the equipment. Nonetheless, the solution showed a good potential for it to be used in walls without failing due to insufficient anchorage length (Poletti 2013).

4.2. In-plane tests

The analysis of the results obtained in the in-plane cyclic tests on the connections shows that their mechanical behaviour is greatly influenced by the condition of the prosthesis.

For strengthening performed with GFRP, the failure of the sheets occurs in the direction perpendicular to the fibres at the height where the post meets the beam. It has to be pointed out that, due to limited availability, the glass fibre sheets used were uni-directional. It is possible that, by applying multi-directional GFRP sheets, failure could have been prevented or at least postponed. The same type of failure was observed for both vertical pre-compression levels. In average, the strengthening applied to specimens with prosthesis was able to increase both initial stiffness and maximum load capacity for both vertical pre-compression levels by 43% and 52% respectively. However, this behaviour was observed only up to a certain value of drift, after which the prosthesis failed, the lower part of the post remained vertical, whereas the upper part was rocking around the screws. This occurred for both load levels and pointed out the weakness of the prosthesis adopted. In fact, it presented a lower stiffness than that of the retrofitting solution applied and was not able to promote the continuity of the post.

In case of retrofitting with steel plates submitted to lowest pre-compression an increase of 40% was observed for the maximum load (Fig. 13). When the prosthesis failed the upper part of the post was simply rocking. However, for the higher level of pre-compression, this trend was not observed. In this case the post bended and deformations related to buckling were also observed in the steel plate. Moreover, cracks opened laterally on the post, similarly to what happened in the unreinforced tests, but the steel plate was still able to promote a higher dissipative capacity. There was an increase in lateral load of 21% and even stiffness increased, though in a lower degree.

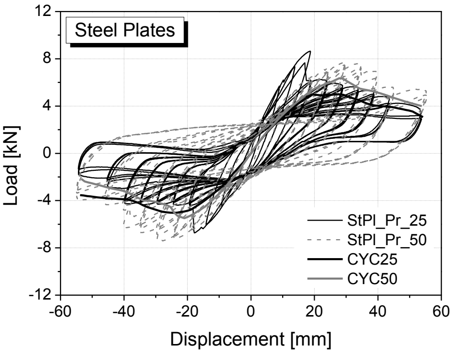


Fig. 13 – Hysteretic diagrams of specimens retrofitted with steel plates.

Given this behaviour, it was decided to test the specimens retrofitted with NSM steel rods directly with the higher vertical load. Nevertheless for this kind of strengthening the prosthesis failed even for the higher pre-compression level (Fig. 14). After experiencing an increase in load of 34%, the lower part of the post once again stopped contributing to the resisting mechanism (Fig. 15). This was probably due to the fact that NSM retrofitting stiffens the post more and the high difference in stiffness between the two parts of the post caused the prosthesis to fail even for the higher vertical load.

Aiming at preventing this undesirable behaviour, commercial steel plates were screwed laterally to the post, linking the two parts in order to guarantee continuity. With this procedure, a better continuity was obtained, even if the post was still not monolithic. Comparing the hysteretic diagram with the previous one (Fig. 14), the maximum load increased by 45% in the positive direction and by 24% in the negative one, whereas the initial stiffness remained approximately the same, since the addition of the steel plates influenced only the continuity of the post (Fig. 15), but not the stiffness of the connection. Some vertical cracks were observed between the rods, but the opening did not occur at the glue interface, but in timber.

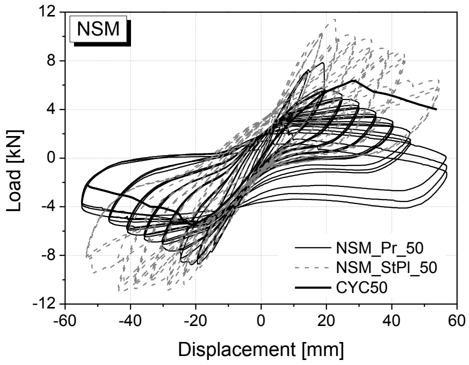


Fig. 14 – Hysteretic diagrams of specimens retrofitted with NSM rods.

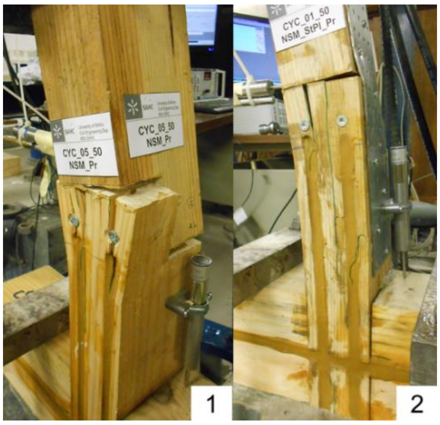


Fig. 15 – Damages for retrofitted specimens: (1) NSM retrofitting; (2) NSM+steel plates.

Comparing the different retrofitting solutions adopted, on healthy connections steel plates and GFRP sheets could improve significantly the performance of the connection, even if the prosthesis influenced and reduced the efficiency of the strengthening. For the higher vertical pre-compression level, results are clearer and it appears that GFRP and NSM are able to guarantee the highest stiffness while the connection with steel plates experienced the less degradation in terms of strength.

4.3. Initial and cyclic stiffness

For the pull-out specimens, all unreinforced connections presented low values of initial stiffness. Additionally, it is observed some variation among the results, being the average value of stiffness of 3.94 kN/mm with a coefficient of variation (c.o.v.) of 24%. This is due to the level of interlocking in the connection, since some specimens presented important clearances, which depends greatly on the workmanship of the carpenter.

All retrofitted specimens presented very high values of initial stiffness, over four times that of unreinforced specimens. With this respect, it should be noticed that the specimen strengthened with the NSM technique did not give final results, since the maximum load was not reached. Steel plates presented the lowest value of initial stiffness (14.96 kN/mm) followed by self-tapping screws (67.96 kN/mm). Self-tapping screws are driven into the timber elements and they tighten the connection, since they create their own precisely fitted hole, therefore possible clearances between the post and the beam, which influence the vertical uplift, are eliminated and the contact of the horizontal interface is improved, as well as the friction of the vertical interfaces. In the case of strengthening with steel plates holes have to be drilled to accommodate the bolt, therefore small clearances could be created decreasing the initial stiffness of the connection. This is one of the advantages of self-tapping screws, since they allow a direct entrance of the element ensuring a perfect adherence to the material. The strengthening with FRP sheets led to a high initial stiffness (128.53 kN/mm), but its failure was quite brittle.

As far as stiffness degradation is concerned, all unreinforced connections presented a similar trend (Poletti, 2013), with initial values of about 0.60 kN/mm and reaching an almost complete degradation. Specimens with higher clearances exhibited the highest degradation in stiffness, pointing out the importance of a good interlocking in the connection. Apart for the specimen retrofitted with steel plates, all the other retrofitted connections had a similar trend in terms of stiffness degradation. Even though the specimen retrofitted with steel plates presented the lower initial stiffness, its degradation was the slowest and at the end of the test its residual stiffness was almost the double of the solution adopting self-tapping screws (Poletti, 2013).

Joints subjected to in-plane cyclic tests presented lower variations in terms of cyclic stiffness for the unreinforced specimens (0.33 kN/mm, c.o.v. 13% for the lower vertical load level and 0.34 kN/mm, c.o.v.

19% for the higher level). Similar values of stiffness were obtained for both vertical load levels, contrarily to what observed in timber frame walls, for which a higher vertical pre-compression resulted into a higher initial stiffness. All types of strengthening increased the values of initial stiffness. GFRP strengthening increased the initial stiffness by 45% and 44% for the lower and higher vertical load, while steel plates increased the initial stiffness by 103% and 58% for the lower and higher vertical load respectively. NSM retrofitting increased the value of initial stiffness by 75%.

Taking into consideration the cyclic stiffness degradation, the unreinforced specimens presented a similar trend in stiffness degradation: (1) for the lower vertical load, the specimens with the highest strength and initial stiffness had the lower degradation, stabilizing at values of cyclic stiffness of approximately 0.1 kN/mm, while the other specimens had a higher level of degradation and stabilized at a value of approximately 0.03 kN/mm; (2) for the unreinforced specimens tested with the higher vertical load level, the same trend was observed, even if in this case the final values of cyclic stiffness were nearer, between 0.5 and 0.8 kN/mm.

The stiffness degradation of retrofitted connections was heavily influenced by the prosthesis. For the lower vertical load level, only the steel plates retrofitting was able to increase the values of cyclic stiffness, even if once the prosthesis failed, the stiffness became similar to the one recorded in the unreinforced specimen. The GFRP strengthening applied on a specimen with prosthesis increased the values of cyclic stiffness only slightly prior to the failure of the prosthesis. For the higher vertical load level (Fig. 16), all retrofitting solutions had an increase of cyclic stiffness, even if it quickly degraded as the prosthesis became ineffective. The specimen retrofitted with NSM rods and additional steel plates to make the prosthesis effective showed higher values of cyclic stiffness and a higher residual stiffness indicating that, with an appropriate prosthesis or even in an undamaged connection, the retrofitting solution should behave appropriately. The other connection where the prosthesis partially worked (steel plates) showed a similar slope of degradation. For all connections, the degradation trend was approximately linear.

4.4. Dissipated energy and viscous damping

The dissipated energy during pull-out tests carried out on unreinforced specimens was minimal (between 150 and 550 kNmm), especially for connections with an inadequate interlocking, meaning that friction does not play a role in the dissipation of energy. It increases considerably once strengthening against uplifting is applied (Fig. 17). The stiffer solutions highly increased the dissipative capacity of the connections. The more dissipative strengthening technique was the steel plates solution, which increases the energy dissipation by over 8 times. NSM retrofitting gave inconclusive results. Retrofitting with screws was able to promote a good dissipative capacity of the connection, with an increase of 175% in relation to unreinforced specimen. The strengthening with GFRP leads to a good dissipative capacity for low values of uplift, but after failure the energy dissipation is lower than the value found for the equivalent unreinforced connection. Therefore, it is evident that brittle failures should be avoided, since the strengthening becomes inefficient.

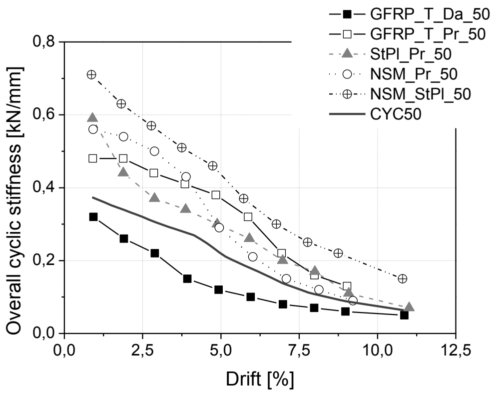


Fig. 16 – Stiffness degradation for retrofitted pull-out tests.

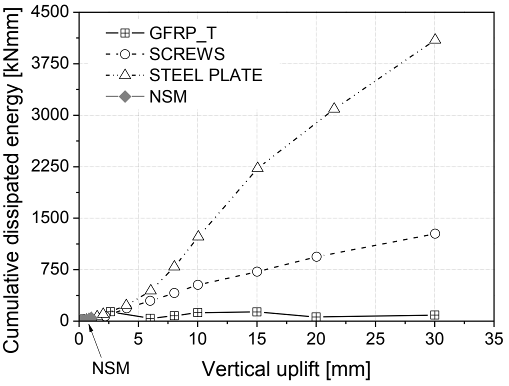


Fig. 17 – Cumulative dissipated energy evolution for retrofitted pull-out tests.

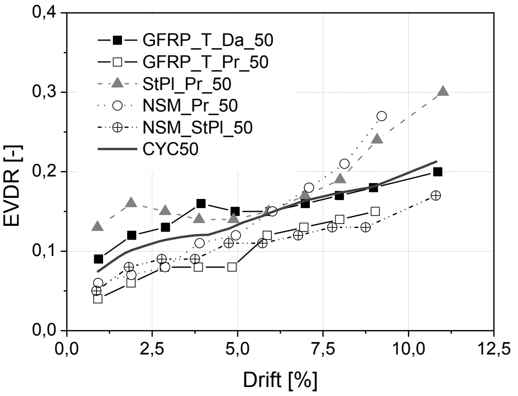


Fig. 18 – EVDR values for retrofitted specimens, in-plane tests.

Similar conclusions can be drawn on the equivalent viscous damping ratio measured for the connections (Poletti 2013). Values of damping of unreinforced connections are influenced by their level of interlocking, while for retrofitted connections pinching plays an important role. In fact, connections retrofitted with screws presented the higher values of damping (0.25), as the effect of pinching was less severe than what observed for example in case of retrofitting with steel plates, for which energy dissipation was diminished by pinching, decreasing its ratio with input energy.

In case of the connections tested under in-plane cyclic lateral loading the unreinforced specimens with higher strength were able to dissipate more energy. As was observed for the values of cyclic stiffness, this difference is more evident in the lower pre-compression level tests, also due to the higher variation in terms of results for this load level. In general, specimens tested with the higher pre-compression level were able to dissipate more energy, in average 29% more. Considering the retrofitted connections, energy dissipation was greater for the specimens where the prosthesis was more efficient (Poletti 2013).

EVDR values for unreinforced specimens were increasing, with final values between 0.14 and 0.25. For both load cases, values are higher for connections which after failure present a clear rocking behaviour, while connections with a marked softening behaviour have lower values of damping.

Even retrofitted connections presented peculiar results (Fig. 18), since the rocking behaviour of the upper part of the post led to high values of viscous damping. These values, though, are not really representative, since the failure obtained was not that of the connection per se, but of the prosthesis, which should be avoided.

5. COMPARISON BETWEEN WALL AND CONNECTION TESTS

It is difficult to correlate the results obtained on the connections to the global behaviour of a wall, since it is comprised of various joints interacting with each other. Notice that the tested connection is only representative of the bottom connections of the walls. The rest of the connections should also play an important role on the overall behaviour of the walls. However, some observations can be made.

One of the first things that can be pointed out is the similarity on the crack patterns of the bottom connection of the timber frame walls and the tested connection (Poletti et al. 2014). Some similarities are also observed between the damages found in the connection of the walls and the tested connection when steel plates are applied.

Pull-out tests can be compared to the cyclic tests on timber frame infill walls, where the post in tension is subjected to important uplifting. In this case, when the post is in tension, the diagonal does not influence the uplifting. There is however the lateral component of the movement of the post. In half-timbered walls, the out-of-plane opening of the post was observed, with plastic deformation of the nail and a final permanent deformation (Poletti et al. 2014). This uplifting caused by the rocking response of the walls needs an intervention to prevent it, keeping always in mind that the retrofitting has to be compatible with the lateral cyclic movement. The retrofitting with GFRP sheets can possibly improve the behaviour of the bottom connection of the walls under uplift movements. This technique exhibited good behaviour in terms of resistance, but it is considered that bi-axial sheets should be used in order to avoid brittle behaviour.

Comparing the strengthening with steel plates in walls and connections, it is seen in both cases that compressive stresses cause buckling of the plates. In tension, plastic deformation of the bolts and tensile failure of steel plates in correspondence to the holes was observed. From the results obtained in the connection it is seen that this solution is very good in terms of dissipative capacity. Considering the results on the NSM technique applied in the connections, it should be stressed that the configuration of the steel rods should be able to solve problems related to insufficient anchorage length (Poletti 2013). As a downside, the excessively high initial stiffness registered during pull-out tests could have a negative effect on the out-of-plane behaviour of the walls, particularly timber frame ones, but, as in the case of steel plates retrofitting, the free movement of the diagonals should limit this problem. The application of bi-axial GFRP sheets to timber frame connections linking the diagonals to the main frame could lead to similar problems.

6. CONCLUSIONS

Whichever intervention done on a structure has to be made keeping in mind that an interrelation exists on interventions at all levels, from the whole structure, to the structural elements, to the individual joints. In the present work, to better understand the behaviour of traditional timber frame walls, it is important to understand their correlation with the key factor influencing their structural response, i.e. the connections. To do this, pull-out and in-plane cyclic tests have been performed on unreinforced and retrofitted traditional connections to study the joint in more detail and try to correlate its behaviour with the behaviour of the walls. From the results obtained, the following conclusions can be made:

- Pull-out tests on unreinforced connections were mainly influenced by the quality of interlocking in the connection, which would increase the load carrying capacity of the nail;
- In-plane lateral behaviour of unreinforced connections was influenced by construction defects (clearances);
- Retrofitting applied to specimens for pull-out tests highly increased the initial stiffness of the connection presenting also a higher energy dissipation capacity. However, attention should be paid to the desired level of strength, since GFRP sheets strengthening led to brittle failure;
- The good response of self-tapping screws to uplifting forces should be complemented by a study of its response to in-plane cyclic actions, possibly with a different disposition of the screws, such as an application from the front of the connection;
- Uni-axial GFRP sheets are not appropriate for undergoing shear forces, due to their early rupture and debonding;
- The prosthesis solution adopted was inappropriate for the strengthening solutions used, since it created a weaker section in the post than some of the retrofitting techniques adopted in the actual connection;
- The NSM configuration adopted for the bottom connection appears to be able to guarantee sufficient anchorage length to the rods, without early failure of the welding;
- Additional information on the influence of the diagonal on the cyclic response of the connections is needed.

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