INNOVATIVE CONNECTIONS FOR TIMBER PANEL BUILDINGS

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SUMMARY- *Cross-laminated timber panel buildings are gaining a growing interest of the scientific community due to significant technical advantages, such as the material sustainability, the high fire resistance and quick constructability. Nevertheless, it is well known that timber panels themselves are not able to dissipate a significant amount of energy during an earthquake. In fact, the design of a Cross-Lam building is carried out in order to dissipate the energy in the steel connections (hold-downs or angle brackets) which govern the seismic performance. The paper here presented proposes to substitute the classical hold-downs, which usually exhibit a limited dissipation capacity, with an innovative type of dissipative angle. The new connection, called XL-stubs, apply the concept usually adopted for designing the hysteretic metallic dampers ADAS (Added Damping and Stiffness). In particular, the hourglass shape allows a better spread of plasticization resulting in a high dissipation capacity. In order to characterize the force-displacement response under cyclic loads of XL-stubs an experimental campaign is carried out comparing the hysteretic behavior of the classical hold-down with that of the proposed dissipative angle.*

Keywords: Cross-Lam, Joints, Dampers, Dissipation, Seismic Design, Experimental Analysis

1. Introduction

Traditionally, most of timber houses worldwide have been realized with the so-called framing system, in which the bearing walls are constituted by the assemblage of columns and girders on which is fixed a plywood panel connected by means of nails or screws. In more recent times, as an alternative to the classical framing, several modern timber construction systems have been developed and applied throughout Europe. Among these, the cross-laminated timber panel building system, despite the recent introduction, is gaining a great popularity in the residential market and it has already been applied to mid and low rise buildings. From the seismic standpoint, a timber panel building is conceptually similar to a box structure in which walls and floors are rigid in their plane. The structure is constituted by the assemblage of precast flat cross laminated panels used for realizing both the vertical resistant system and slabs. As far as the panels behave as rigid elements, the dissipation capacity of the whole structure under a seismic event is usually lumped in the connections. The typical details of the connections in cross-laminated timber panel buildings are three: there is a panel-panel connection realized by overlapping on two subsequent pre-cast panels a nailed or screwed strip of wood, a connection realized with a short angle bracket that is used to prevent the panel horizontal slip and a connection with a long angle used to prevent the rocking of the panel.

Recently a great experimental effort has been dedicated to this structural system in many countries but particularly in Italy, Slovenia and Canada. In Italy, an extensive research project supported by the Trento Province, the so-called SOFIE project, coordinated by the IVALSA-CNR institute has been carried out. The research work has been planned in order to validate

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the structural system and to investigate topics such as the seismic capacity and the fire resistance of buildings made of cross-lam panels. In fact, the SOFIE project has included several tests on the typical connections (i.e. angles, hold-downs and panel-panel joint), on walls with different layouts of connections and openings, the pseudo-dynamic test of a full-scale one-storey building, the full scale shaking table tests on a 3-storey and 7-storey residential building and the fire-test of the same 3-storey building tested on the shaking table (Ceccotti , et al., 2007; Ceccotti A, et al., 2006; Ceccotti, et al., 2000). The other most important experimental programs dealing with the characterization of the behaviour of cross-lam massive panels have been carried out at the University of Ljubliana in Slovenia (Dujic, 2001; Dujic & Zarnic, 2002) and at the FPInnovation Forintek in Vancouver, Canada (Popovski, et al., 2010). In the two works a number of experimental tests on single walls and system of walls with different combinations of openings, boundary conditions and connections have been carried out. In order to provide some indications on the behaviour factor of CTP buildings, (Ceccotti , et al., 2007) have carried out a set of Incremental Dynamic Analysis by carrying out a numerical model of the 3-storey building tested within the SOFIE project by means of the software DRAIN-3D. On the base of these analyses, the value of the q-factor proposed by the authors for the house employing classical fastening details is equal to 3. Even though the value found in (Ceccotti , et al., 2007) is referred to a single case study, it demonstrates the limited dissipative capacity of timber panel buildings compared to other traditional structural systems for which typical values of the behaviour factor are much higher. The reasons of such a result can be found in the response under cyclic loads of the elements mainly devoted to the energy dissipation, namely the Hold-downs. In fact, as already demonstrated in technical literature (Ceccotti A, et al., 2006; Gavric, et al., 2011; Dujic, 2001), Hold-downs subjected to cyclic reversals even though possess a good ductility, typically exhibit a response characterized by significant pinching phenomena and, therefore, by a low capacity of dissipating energy.

Within this framework, in this paper, in order to overcome the limitations provided by the adoption of the classical Hold-down, the authors propose the application of an innovative angle, called “XLStub”, to be applied in substitution of the classical Hold-downs. In the following paragraphs, the concept of the new type of connector will be introduced and the results of an experimental campaign carried out at the laboratory of materials and structures of the University of Salerno will be presented. In particular, the experimental analysis deals with the monotonic and cyclic testing of the innovative type of damper, which has been designed in order to have the same stiffness and resistance of the Hold-down tested in the SOFIE project. The design process has been carried out with the support of a Finite Element Model carried out in ABAQUS 6.11 software (Simulia, 2012). The obtained results show potentialities of the proposed system, which could be used to improve the behaviour factor of cross-laminated timber panel buildings.

2. Cyclic Behavior of Typical Connections

It is well known that wooden cross-lam panels exhibit a brittle behavior which is characterized by a low capacity of energy dissipation. It is for this reason that the design philosophy of timber panel buildings provides to concentrate the plasticization in the connections rather than in wood according to a hierarchy criterion of strong wall-weak joint. Under this design assumption it is easy to understand that the knowledge of the behavior of connections is of paramount importance for determining the response of the whole building under seismic loads. In fact, under severe earthquakes, the only sources of energy dissipation of a CTP building are the steel parts, i.e. the angles, the nails and the screws.

In general, ductility and hysteresis of the steel joints are mainly governed by the dissipative characteristics of the element which first undergoes plastic deformation. In case of an angle such an element could be the fastener (nail, screw, etc.) or the steel angle. As demonstrated by the past experimental works, the typical behavior of traditional joints employed in cross-laminated timber panel buildings is characterized by a strong plate-weak connector behavior and, therefore, the dissipative response is governed by the bearing of nails or screws into the wood. In order to show the main features of typical hysteresis loops of classical joints, in the following, reference is made to the tension and shear tests of the connections employed in the 3-storey building of the SOFIE project. The tests considered in this paper have been carried out by (Gavric, et al., 2011) after the first phase of the SOFIE project. In (Gavric, et al., 2011) work, several quasi-static monotonic and cyclic tests have been carried out on the Hold-down WHT540 with 12 annular ringed nails 4x60 mm, whose geometry and thickness is very similar to that of the Hold-down HTT22 originally used in SOFIE project. Furthermore, also some tests both in tension and shear on the angle bracket BMF 90x116x48x3 mm with 11 annular ringed nails 4x60 mm have been carried out.

The Cyclic tests demonstrate that all connections, both loaded in shear and tension, are affected by significant pinching phenomena (Fig.1). In particular, the Hold-down in tension exhibits a good ductility (about 25.4 mm), but a quite limited energy dissipation capacity. This is mainly due to the dissipative mechanism. In fact, the Hold-down, which is designed according to a weak connector-strong angle philosophy, dissipates through the bearing mechanism of the nails that, at any load reversal, have to slide into the hole before restoring the force. Therefore, this failure mechanism results in significant stiffness degradation which gives rise to very narrow hysteresis loops. A similar behavior is exhibited also by the angle bracket in tension, which mainly dissipates due to the punching of bolt into the steel around the hole. A better behavior is shown by the Hold-down and by the angles in shear but, as well as in the other cases, the hysteresis loops are characterized by significant pinching, limited dissipation capacity and good ductility supply (about 30 mm). In these cases, the failure mode of the Hold-down in shear is typically characterized by the plasticization of the steel in the region close to the first row of nails. Conversely the angle brackets in shear usually fail due to the contemporary yielding of the nails and failure of the wood. What is important to observe is that since plasticization under cyclic reversals is concentrated in connections, the hysteresis cycles of a wall subjected to cyclic loads is also characterized by a behavior with good ductility but affected by pinching, stiffness degradation and limited capacity of energy dissipation. This result is clearly shown in all the past experimental experiences made by different researchers (Ceccotti, et al., 2000; Dujic, 2001).

The scope of the work herein presented is to propose an innovative approach to improve the dissipative capacities of cross-laminated timber panel buildings by enhancing the behavior of the structural fuses, i.e. the connections. As aforesaid, the typical angles employed in cross-laminated timber panel buildings appear to possess a limited capacity of energy dissipation due to the dissipative mechanism that is imposed in the design philosophy of the angle, i.e. the failure of the fasteners. In this paper, the main idea of the authors is to overturn the classical philosophy by switching the joint design from the weak fastener-strong angle to the strong fastener-weak angle philosophy. Therefore, in the following, the concept of the proposed angle is first shown and after the results of an experimental analysis devoted to compare the monotonic and cyclic behavior of the classical and of the innovative joint will be described. Finally, the results of the experimental analysis will be used to calibrate a numerical model of the cross-lam wall tested by (Gavric, et al., 2011) with the aim of comparing the cyclic behavior of the same wall alternatively equipped with the classical Hold-down and with the proposed XL-Stub.

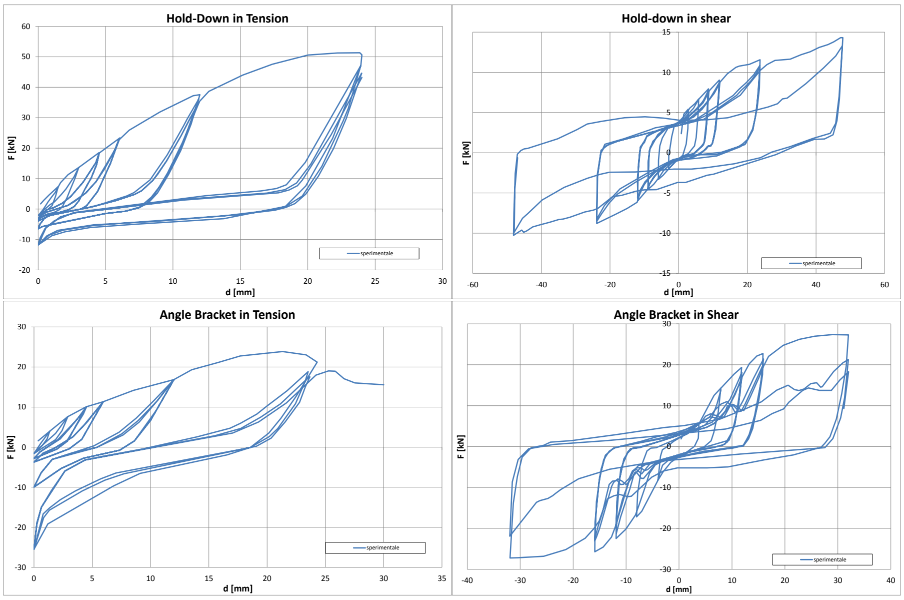


Fig. 1. Hysteresis loops of an hold-down loaded in tension and of an angle bracket loaded in shear

3. Concept of the proposed Angle and Setup of the experimental program

In order to better understand the principle on which is based the shape of the developed innovative angle it is preliminarily necessary to consider the actions arising and the possible failure mechanisms occurring in a generic steel angle fixed to a wooden panel under tension loadings. It is well known that, if the flange plate is less resistant than the fasteners and less resistant than the wooden part, the possible failure mechanisms are the same coming from the T-stub theory (Faella, et al., 2000). Within such a theory, it is well known that the bending moment arising in the flange plate of an angle in the region between the stem and the anchor bolt is governed by the ratio between the axial resistance of the bolt and the bending resistance of the plate. Depending on this ratio three are the possible failure mechanisms. In case of strong bolt and weak plate, namely mechanism type-1, the bolt is able to fully constrain the plate and the bending moment diagram is linear along the flange with point of contra-flexure in the middle of the plate. In case of strong plate and weak bolt, namely mechanism type-3, the plate completely detaches and the bolt behaves as a hinge, giving rise to a bending moment diagram with zero-value at the bolt line and maximum in correspondence of the stem. In all the other cases the behavior is intermediate between the two aforesaid extreme situations and the bolt is only able to partially restrain the bending moment. Among the three mentioned failure mechanisms, the most dissipative is the type-1, which is characterized by the formation of two plastic hinges in the most stressed zones of the plate, one in correspondence of the stem-plate attach and the other one in correspondence of the bolt-line. Nevertheless, past experimental researches have demonstrated that also when the failure is due to mechanism type-1, even though the angle is able to dissipate a significant amount of energy, the hysteresis cycles are characterized by significant pinching phenomena, strength and stiffness degradation. This is due to the mechanism of plasticization of the rectangular angle which concentrates the strain demand in two finite regions, requiring a very high ductility supply in small zones (Iannone, et al., 2011; Latour, et al., 2011).

A possible approach to overcome the issues related to the limited energy dissipation capacity of rectangular angles is the one proposed in (Latour & Rizzano, 2012; Latour, et al., 2011a) dealing with the application of dissipative T-stubs to beam-to-column joints of steel structures. Such approach provides to taper the plate in the zone in between the stem and the bolt accordingly with the diagram of the bending moment. In fact, it is intuitive to understand that if the plate is cut providing a law of the width which varies accordingly with the diagram of the bending moment it is ideally possible to obtain the contemporary plasticization of all plate sections leading to a ductility demand distributed along the whole plate. Starting from the diagram of the bending moment arising in a plate, under the assumption of strong bolt and weak plate, it is easy to verify that the shape which provides the contemporary plasticization of all the plate sections is an ideal X-shape (Fig. 2).

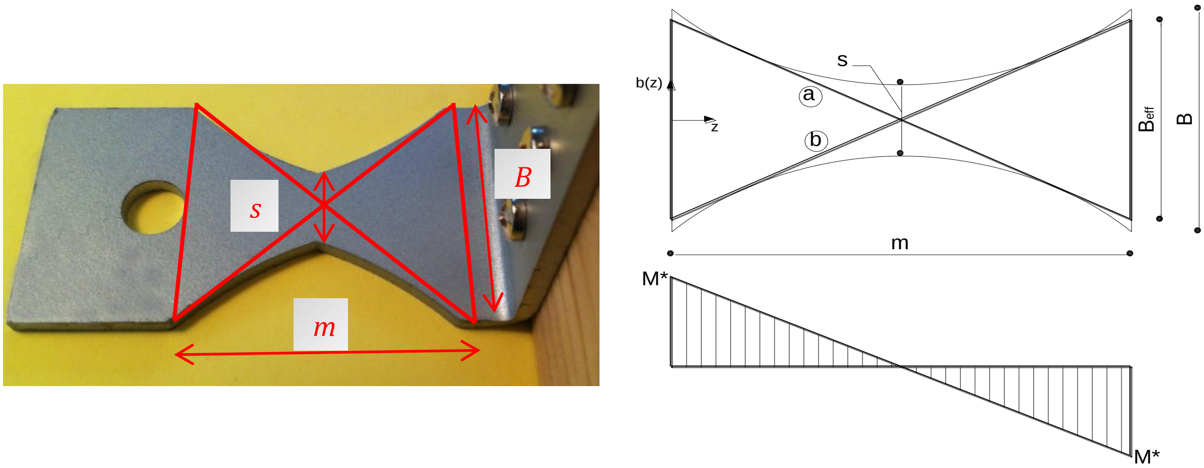


Fig. 2. Bending Moment Diagram arising on the tapered flange

The approach proposed by (Latour & Rizzano, 2012) follows the same principle which is applied in the design of metallic hysteretic dampers working in double curvature such as ADAS devices (Added Stiffness And Damping) (Whittaker, et al., 1989), which are elements usually adopted in combination with chevron bracing systems. The main idea of the device is to shift the dissipative zone of the Hold-down from the stem zone to the flange plate. To this scope, from the design standpoint, the stem zone has to be overstrengthened by adopting a proper number of nails and by checking the resistance of stem and wood with respect to force needed to yield the flange plate. In addition, in order to overcome the usual problems concerning the cyclic behavior of rectangular steel plates subjected to bending moment and to maximize the plate energy dissipation, the proposal is to provide to the flange plate of the angle an hourglass shape very similar to that usually adopted in ADAS devices. In (Latour & Rizzano, 2012) a direct comparison between the dissipation capacity of dissipative T-stubs and rectangular T-stubs characterized by equal stiffness and resistance has been carried out, evidencing a significant improvement of the performance under cyclic loads both in terms of ductility and energy dissipation capacity.
In the following the design process of the proposed angle is shown and an experimental program aimed at evaluating the cyclic characteristics of the XL-stub is presented. The main results of the experimental activity are reported and also compared to that of the classical Hold-down system.

3.1 Finite Element Modelling of the Device

The main goal of the experimental work herein presented is to provide a comparison between the cyclic behavior of the classical Hold-down and the proposed XL-Stub angle. In order to show the difference in terms of hysteresis loops and to carry out a meaningful comparison it is necessary to compare elements with same stiffness and resistance. To this scope the tested

XL-stub has been designed in order to have a monotonic behavior that is largely the same of that of the Hold-downs tested within the SOFIE project by (Gavric, et al., 2011).
The design of the tested specimens has been performed with the support of a Finite Element Model carried out by means of the ABAQUS 6.11 software. The model is solid and three-dimensional using the library element C3D8R, that is a 8-node linear brick, with reduced integration and instability mesh control. ABAQUS software has in its libraries several elements of first and second order. The element choice has been done in order to reduce the computational effort, that in problems which involve contacts and slip exponentially increases. In addition, in order to account for the catenary actions arising at large displacements a static non-linear analysis has been carried out. The geometric non linearity has been properly accounted for to grasp the full post elastic behavior of tested angles, which are characterized, at large displacements, by second order effects. Furthermore, in FE model, the interactions between the plates and between hole and bolt have been modeled by means of a frictionless formulation and the bolt pretension effect has been modeled by imposing, in a preliminary loading step, an appropriate thermal distortion.
As aforesaid, an experimental analysis has been planned to verify the possibility to increase the energy dissipation capacity under cyclic loads of XL-stubs with respect to the classical Hold-down. To this goal, the design process has been carried out by applying a trial and error procedure by imposing the following design conditions:

- the collapse of XL-stub arises according to Type-1 collapse mechanism avoiding a significant engagement of the bolts in plastic range;
- the initial stiffness of the XL-stub is equal to that of the corresponding T-stub with rectangular flange;
- the inelastic branch of the F-δ curve of the XL-stub fits that of the Hold-down tested within the SOFIE project by (Gavric, et al., 2011).

In order to achieve the design goals, within the design process, the following three geometrical parameters have been considered: the distance *m* between the bolt and the plastic hinge, the width of the plate *B*, and the thickness of the plate *t*. The three parameters have been chosen as main design parameters because they strongly affect angle overall behavior and, in particular, initial stiffness, resistance and the ductility. In fact, as already examined in (Faella, et al., 2000), the initial stiffness is related to the ratio (Bt^3/m^3), the plastic resistance corresponding to the knee of the force-displacement curve of the T-stub depends mainly on the parameter (Bt^2/m) and the ductility is governed by the parameter (m^2/t). It is clear that the reduction of the section width along the plate due to the hourglass shape leads mainly to a reduction of the angle stiffness which can be recovered by increasing width *B* and thickness *t* and reducing the distance *m*. The simultaneous respect of the previous design conditions provided the most appropriate combination of values of the three geometrical design parameters. As a result of the design process in Fig.3 is reported the comparison between the force-displacement response of the XL-stub predicted by the finite element model and that of the Hold-down tested in (Gavric, et al., 2011). It is possible to note the good agreement between the force-displacement curve of the dissipative angle and that of the Hold-down. Furthermore from the finite element model is possible to appreciate the distribution of the stresses within the plate and the distribution of the plasticization that involve the whole plate section, confirming the spread of plasticization within the whole flange plate (Fig.3).

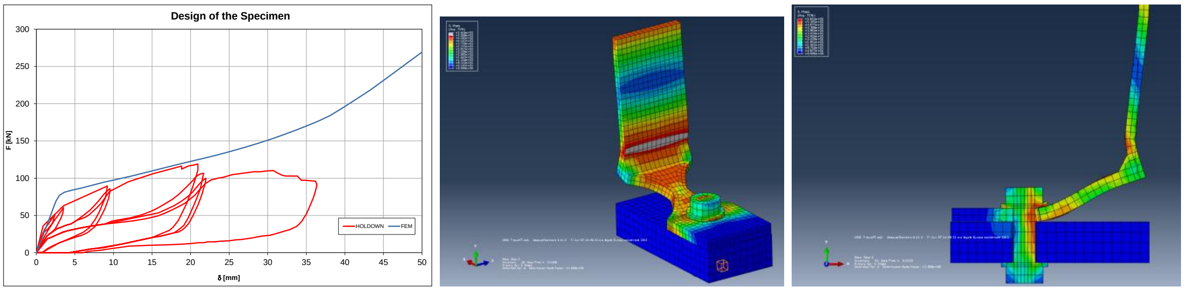


Fig. 3. Comparison between Hold-down and ABAQUS model of the XL-stub - Von mises Stresses in the XL-Stub (Perspective view and view cut)

3.2 Experimental Setup

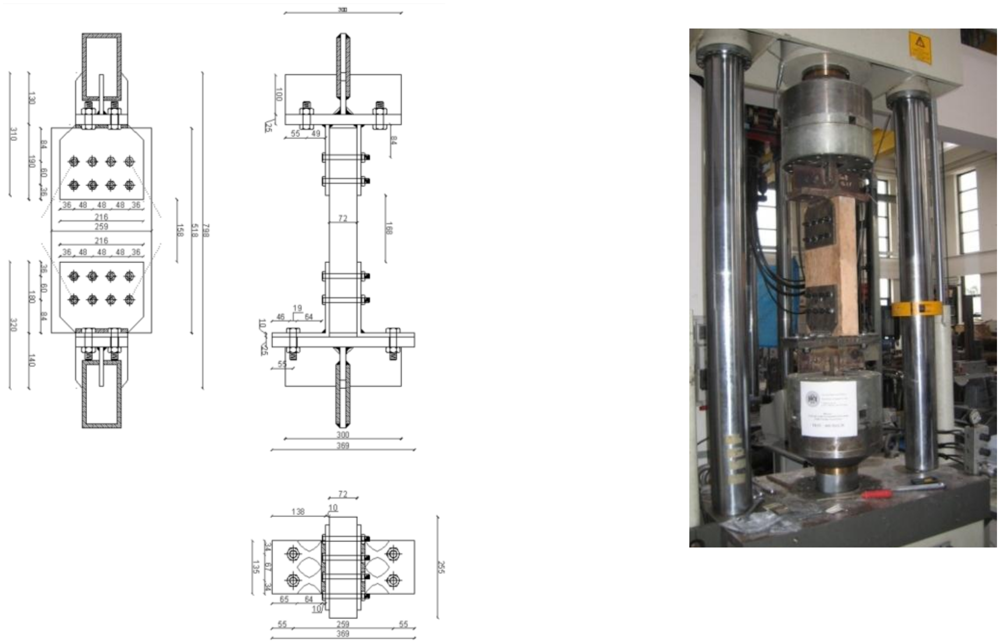


Fig. 4. Experimental Set up and Test arrangement

In order to compare the monotonic and cyclic behaviour of the classical Hold-down and of the proposed angle an experimental program has been set up. All the tests have been carried out at the laboratory of materials and structures of the University of Salerno by means of a universal testing machine Schenck Hydropuls S56 (maximum load 630 kN, piston stroke +/- 125 mm). The campaign has included one uniaxial monotonic test (A05-M), three cyclic tests at constant amplitude (A01-C15, A02-C25, A03-C30) and one cyclic test at variable amplitude (A04-CV). The scope of the constant amplitude cyclic tests is to define the fatigue life curve of the angle that is a fundamental tool for defining the damage and the collapse condition of the XL-stub in cyclic and dynamic analyses. The variable amplitude test has been carried out in order to verify the hypothesis of linear accumulation of damage as proposed by (Miner, 1945). Furthermore, the cyclic tests have been carried out aiming to compare the dissipative capacities of the Xl-stubs with respect to the Hold-downs.

The tested specimens consist of a panel of larch with dimension 518x255x72 mm on which is fixed on the top side a very stiff and strong T-stub and on the bottom side a couple of the designed XL-stubs (Fig.4). The elements are fastened through eight M12 bolts of 8.8 class. The steel grade of the angles is S275 (CEN, 2005). The connection of the angles to the wood has been designed by following the rules provided by Eurocode 5 in order to have fasteners overstrength with respect to the load carried by the tapered flange plate. In this way, the bearing failure is avoided and the failure of the dissipative zone is promoted. All the tests are quasi-static and in particular they have been conducted under displacement control, with a variable speed from 0.3 mm/s to 0.6 mm/s for the cyclic tests with constant amplitude (0.01 Hz), from 0.5 mm/s to 0.9 mm/s for the cyclic test at variable amplitude and with a constant speed of 0,025 mm/s for the monotonic test. In addition, coupon tensile tests have been performed in order to establish the mechanical properties of the base material constituting the plates.

4 Experimental Analysis of Dissipative Devices

All the tests have been executed by using the same specimen. At the end of each test the only part that has been substituted are the couple of angles that are the elements which undergo damage after the test. In the following, the results obtained from the cyclic and monotonic tests are reported, showing the significant improvement of the behaviour of the traditional detail.

4.1 Monotonic Test Results

The monotonic test (A05-M) has been carried out under displacement control at the constant speed of 0,025 mm/s. The test has been stopped because the piston stroke of the universal machine has been reached. Nevertheless, the ultimate displacement obtained during the test has been very high and no damage or cracks have been evidenced. As predicted by the FE modelling the experimental results of the monotonic tests have been very close to the one provided by Hold-down tested by *(Gavric, et al., 2011)*. In fact, the monotonic force-displacement curve has a behaviour which is very similar in terms of force and stiffness to the cyclic envelope of the test on the hold-down of the SOFIE project but, has a higher ductility that is almost two times greater (Fig.5).
As desired in the design phase, all the deformation capacity of the specimen has been concentrated in the flange plate of the XL-stub. No wooden or steel part has evidenced damages, but significant second order effects have been shown. This can be clearly noted also from the force-displacement curve of the angle. In fact, in plastic range, after a first phase of strain-hardening which follows the complete yielding of the plate, there is a slight increase of the stiffness which is due to the catenary effects that arise in the plate. These second-order effects are demonstrated by the plasticization of the stem of the angle in the zone in between the attachment with the flange plate and the first row of bolts.

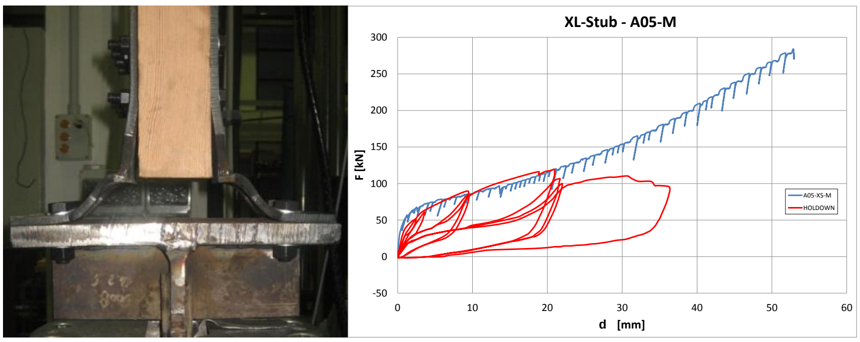


Fig. 5. Monotonic Test and results

The experimental test evidences a displacement capacity of the XL-stub greater than 50 mm which is consistent with the uplift demand under seismic loadings condition. In fact, if we refer, as failure condition, to the interstorey drift ratio at the ULS, as an example, in the US International Building Code (IBC) such limit value, for shearwall assembly is fixed as equal to the 2.8%. Starting from this limit it is possible to define the ductility demand at the hold-down level for typical width of the walls. Considering a width equal to 2.0 m, the corresponding displacement demand at the ULS on the hold-down can be estimated as equal to 56 mm.

4.2 Cyclic Test Results

- *Constant Amplitude Tests (A01-C15, A02-C25, A03-C30)*

As already underlined, the experimental analysis has been planned in order to verify the possibility to increase the energy dissipation capacity under cyclic loads of classical hold-downs by overturning the classical design philosophy from the nail to the flange plate plasticization. The purpose of the study is comparative. In fact, basic idea is to show that a dissipative hold-down can be properly designed in order to have a monotonic behaviour very close to that of a classical hold-down but a more dissipative behaviour under cyclic loads.

(a) Test A01-C15 *(b) Test A02-C25* *(c) Test A03-C30*

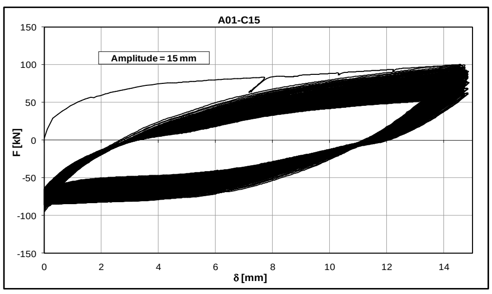
Fig. 6. Failure modes exhibited by the tested specimens

To this scope, a series of cyclic tests on the XL-stubs specifically designed for dissipating energy has been planned. In particular, as aforesaid, three constant amplitude tests have been performed with the scope of defining the cyclic behaviour and the fatigue life curve of the element. Fatigue life curve is a powerful tool for carrying out incremental dynamic analysis in order to define the damage and the collapse condition of an element.
The displacement amplitudes of the tests, equal to 15, 25 and 30 mm, have been chosen aiming to cover a range of displacements that is compatible with the typical structural applications to timber panel buildings (Ceccotti, et al., 2000). In fact, considering the results of the SOFIE project, under the most severe seismic events considered, the uplift of the hold-down is equal to 25 mm. All the cyclic tests have shown the same collapse mechanism for all the XL-stubs. In particular, after a number of cycles the formation of a crack in correspondence of the flange plate-stem connection has been evidenced. It is clear that the failure of the XL-stub occurs in that zone, even though the angle is ideally designed to have the same resistance in all the plate sections, because it is the less resistant region of the plate due to the welding process. This is the reason why the cracking of the flange plate first developed at welds and progressively propagated through the plate leading to the complete fracture after a high number of cycles (Fig.6). Under cyclic loads, such behaviour gave rise to a progressive deterioration up to failure of stiffness, resistance and energy dissipation capacity. In terms of hysteretic behaviour, the design goal of the angle appears achieved. In fact, the cyclic behaviour in all the three constant amplitude tests is characterized by a very stable response with a low rate of stiffness, strength and energy dissipation capacity

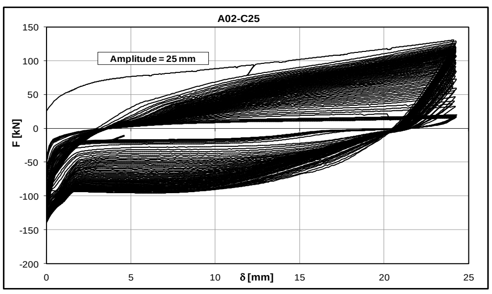
degradation before the quick failure due to the development of the crack in the plate (Fig.7). A moderate loss of energy-dissipation at the reverse of the loading direction is shown in Fig. 7. It is mainly due to the recovering in compression of the axial plastic deformation of the flange plate and to the different effect of the bolts in restraining the angle when it is in tension or compression. In particular, a full constraint can be properly assumed when the angle is in tension, while, due to the moderate bolt head deformation, a lower degree of restraint may be adopted in compression. Moreover, the different restraining action of the bolts in tension and in compression is negligible as confirmed by the contemporary failure at the plate-to-web connection and at the bolt line observed in some tests, demonstrating the significant bending actions arising in the plate also at the bolt line (Test A03-C30).
It is evident that the hysteretic response of the developed XL-stub is almost unaffected by pinching phenomena which usually characterizes the behaviour of the classical hold-downs failing in the nails due to bearing. This result is due to the particular shape provided to the flange which leads to a very high dissipative capacity under cyclic loadings. The results here reported are represented in the following also in terms of fatigue life curve.

Variable Amplitude Test (A04-CV)

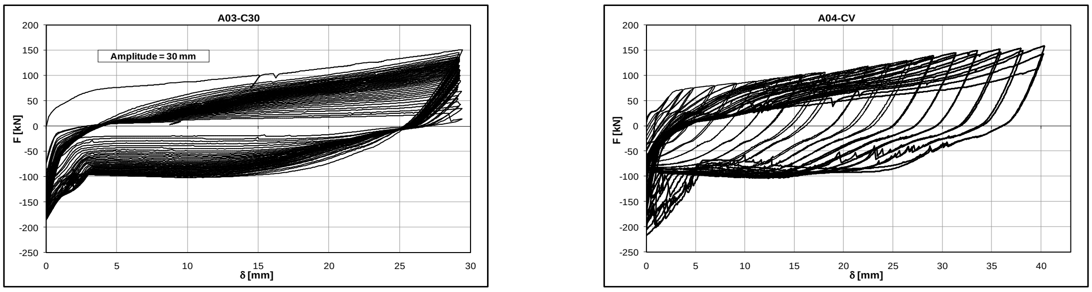
The test at variable amplitude has been carried out in order to verify the validity of the linear accumulation of damage rule proposed by Miner. The loading protocol followed is inspired to that developed in (AISC, 2005) for tests on steel connection details. Within this protocol the amplitude of the cycles progressively increases up to collapse.
The test results have evidenced also in this case a satisfactory hysteretic response of the angle under cyclic loads with a large amount of dissipated energy. In fact, the response has been characterized by wide and stable cycles with almost no degradation phenomena up to failure as in cases of tests at constant amplitude. The failure arose after the 42nd cycle at the amplitude of 41.5 mm. In particular, the collapse of the specimen occurred due to the contemporary fracture of the plate in correspondence of the welding and of the bolt line. This result testifies again the efficiency of the design criteria of the element which is able to dissipate the external energy by means of the plastic engagement of the whole plate.
From the analysis of the response under variable amplitude cycles it is evident that the angle is able to dissipate an amount of energy that is much greater compared to that of the classical hold-down. In fact, in comparison to the hold-down tested in (Gavric, et al., 2011), it is possible to observe that, even though the XL-stub has been subjected to a displacement history much more demanding compared to the loading history adopted in the SOFIE project, the cyclic response has been much more stable, dissipative and also with a higher ductility. All these results are better pointed out in the following paragraph dealing with the characterization of the fatigue life and with the comparison of the behaviour of the classical detail with respect to the innovative one.



(a) Test A01-C15



(b) Test A02-C25



(c) Test A03-C30 *(d) A04-CV*

Fig. 7. Force-Displacement response of the cyclic tests

4.3 Fatigue Life

Aiming to provide a synthetic representation of the cyclic behaviour of the XL-stub, starting from the results of the cyclic tests, the fatigue life curve has been defined. To this scope, it is preliminary necessary to define the conventional collapse criteria. According to (Castiglioni & Calado, 1996) the collapse of a specimen can be defined when the maximum degradation of the energy dissipation capacity achieves a value equal to the 50% of the energy dissipated in the first loading cycle. In fact, usually after a degradation of about the 50% a sudden reduction of the energy dissipation capacity occurs, leading to the quick failure of the considered element.

According to this criterion the individuation of the number of cycles at failure for the constant amplitude tests has been carried out. In particular, in Fig.8 the number of cycles at collapse for the tests before reported is depicted. In particular, the maximum value of the degradation of the energy dissipation capacity has been achieved for the three tests at the amplitudes of 15, 25 and 30 mm after 107, 43 and 29 cycles respectively.

Therefore, starting from the knowledge of the number of cycles at collapse it is possible to obtain easily the fatigue life curve that defines the relationship between the number of cycles needed to attain the collapse condition and the displacement amplitude. It is well known that in the low-cycle range the fatigue curves can be represented by means of straight lines in bi-logarithmic scales. In particular, the number of plastic reversals at failure n_c can be related to the total displacement amplitude δ by means of the following relationship:

$$\delta = a n_c^b \tag{1}$$

where a and b are two regression parameters to be found experimentally. Starting from the results of the cyclic tests the fatigue life curve depicted in Fig.8 has been defined, obtaining a value of the slope b equal to -0.53 and an intercept with the vertical axis a equal to 177.8. It is useful to note that the value of the slope found in this work is in agreement with what found in past experimental works carried out by several authors (Faella, et al., 1998; Castiglioni & Calado, 1996; Latour & Rizzano, 2012).

As already stated, the fatigue life curve is one of the most powerful tools to describe the damage state of an element. In fact, through the fatigue life curve, under the assumption of linear accumulation of damage, it is possible to define the accumulated deterioration of an element under a generic loading history, starting from the knowledge of the degradation expected at each amplitude value. It has to be underlined that in case of random cyclic loads characterized by small amplitude the use of counting methods to convert the arbitrary individual excursions from a seismic response history into a sequence of closed cycles of constant amplitude could underestimate the damage provided by small-amplitude cycles.

Such disadvantage could be overcome by adopting other methods taking into account that the response of a structure up to the ultimate limit state is path independent (Wang & Brown, 1993). Nevertheless, it has to be noted that in case of seismic loading condition, the damage of a structure is usually mainly due to few cycles of high amplitude. Therefore, even though other methods could be more accurate, in case of seismic loading conditions, the adopted methodology can be accepted.

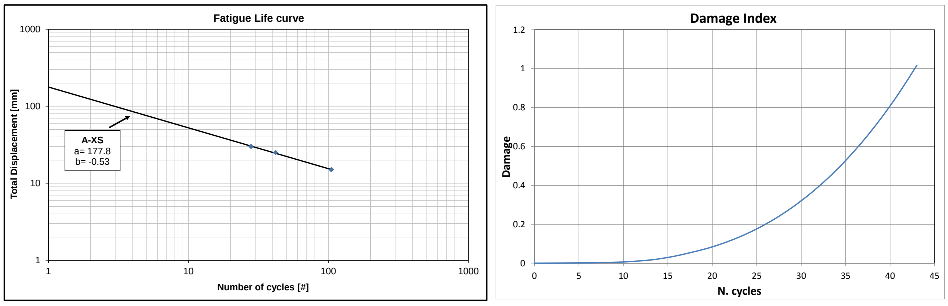


Fig. 8. Fatigue Life Curve of the XL-Stub and Damage Index for test A04-CV

According to the Miner's rule the total damage can be expressed as:

$$D = \sum_{i=1}^{n_c} \frac{n_i}{n_c} \tag{2}$$

where n_i is the number of cycles at a certain value of the displacement amplitude and n_c is the number of cycles at failure that the element can withstand at that amplitude value.
In order to evaluate the accuracy of the obtained fatigue life curve in predicting the collapse of the XL-stub, the Miner's rule has been applied to test A04-CV in order to predict the failure cycle. To this scope, the accumulated damage at the i-th cycle has been evaluated by means of Eq.3, leading to the result depicted in Fig.9. The reported result leads to a prediction of the failure after 43 loading cycles, which is almost the same value found in the experimental test. In fact, as said in the previous paragraph, the failure of the XL-stub tested under variable cyclic amplitude has occurred at the 42nd cycle. This result confirms the accuracy of the hypothesis of linear accumulation of the damage and confirms that the obtained fatigue life curve is able to predict the failure of the XL-stub.

4.4 Energetic Comparisons

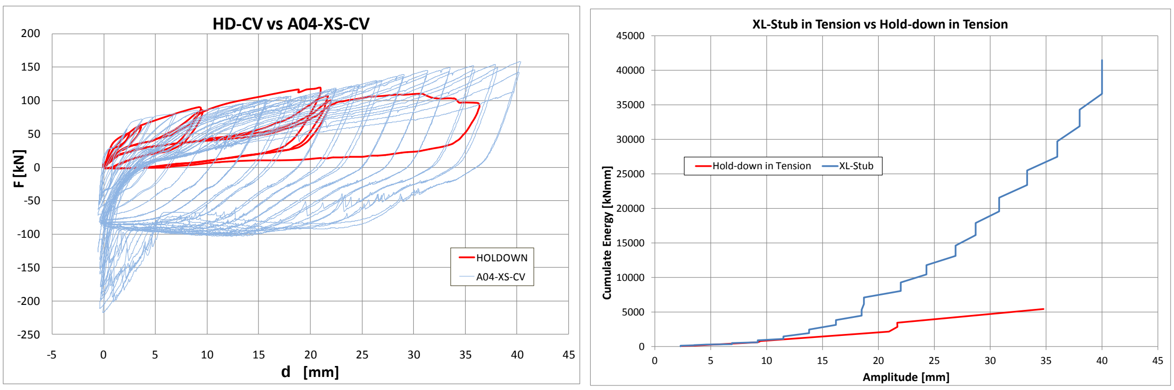
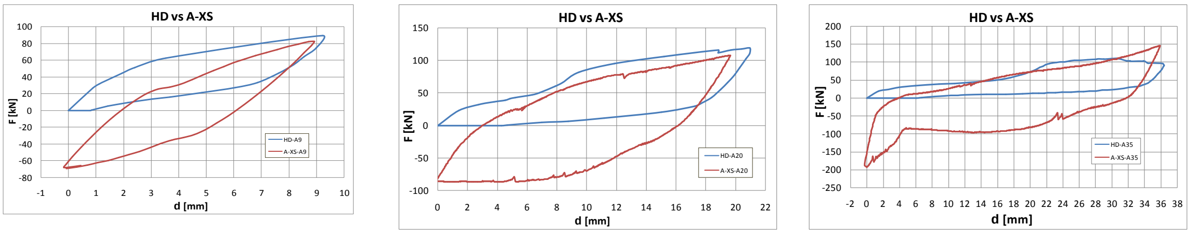


Fig. 9. XL-Stub *vs* Hold-down

In order to better point out the potentialities of the developed system a direct comparison with the hold-down tested within the SOFIE project has been carried out. In Fig.9 the hysteretic curves of the two details are overlapped in order to grasp the difference in terms of energy dissipation capacity of the XL-stub in comparison with the Hold-down. In particular, it is easy to note how the different types of hysteresis of the two elements affect the cyclic response. The Hold-down is characterized by significant pinching due to its dissipative mechanism that relies mainly on the plasticization of the nails due to bearing. In fact, as already said, at the reversals the nails have to slip into the deformed holes before restoring the force. It is for this reason that after unloading, at the re-loading the hysteretic curve is characterized by a first branch that is almost horizontal due to the nail slippage and a second branch with a significant increase of stiffness and energy dissipation (Fig.9). On the contrary, the XL-stub shows a behaviour that is much more dissipative due to the shift of the mechanism of plasticization from the stem to the plate. In addition, the particular hourglass shape of the plate provides a high dissipative capacity that is demonstrated by the comparison of the amount of energy dissipated at collapse.



Amplitude 9 mm. *Amplitude 20 mm* *Amplitude 35 mm*

Fig. 10. Comparison of single cycles at different values of the amplitude

Such a difference can be easily evidenced by comparing single cycles at different values of the amplitude. In Fig.10 the comparison of the hysteresis loops at displacements of 9, 20, 35 mm is reported. From this comparison results an improvement of the energy dissipation capacity that varies in the range from the 36% to the 128% depending on the displacement amplitude value. It is worth to note that the difference is more significant as far as the amplitude increase (Table 1). This result is again due to the failure mechanism of the classical hold-down. In fact as far as the amplitude of the cycle is greater, pinching phenomena become more significant due to the progressive ovalization of the wooden holes.

Table 1 Energy dissipation Improvement

Displacement Amplitude	Energy Dissipated Hold-Down [kNmm]	Energy Dissipated XL-Stub [kNmm]	Difference [%]
9 mm	338.4	462.7	+36.7 %
20 mm	1202.3	1879.6	+56.3%
35 mm	1908.7	4354.9	+128 %

Finally, in Fig.10 the comparison in terms of dissipated energy between the hold-down and the XL-stub is reported. The difference of energy dissipation of the two elements is significant. In fact, the XL-stub at collapse dissipates almost 30 times the energy dissipated by the Hold-down of the SOFIE project. This result appears very encouraging about the possibility of improving the dissipative behaviour of cross laminated timber panel buildings by enhancing the energy dissipation capacity of the structural fuses.

6 Conclusions

In this work, an approach to improve the behaviour of cross laminated timber panel buildings has been presented. In particular, aiming to improve the dissipative capacities of CTP buildings, the concept of a new type of angle to be used in substitution of the classical hold-down has been introduced. Afterwards, the possibility of enhancing the behaviour of CTP buildings by using the proposed connector has been demonstrated by directly comparing the cyclic behaviour of the classical hold-down with respect to the proposed XL-Stub. Within this experimental analysis one monotonic test, three cyclic constant amplitude tests and one cyclic test at variable amplitude have been carried out on the proposed dissipative angle that has been designed in order to have the same stiffness and resistance of the classical hold-down. The results of the experimental analysis have pointed out a significant improvement of the hysteretic behaviour of the classical hold-down mainly because the proposed angle has been designed to dissipate the energy in the flange plate rather than in the nails or the screws. In particular, in order to maximize the energy dissipation capacity of the angle, the flange plate was designed with a shape similar to that usually employed for ADAS devices.

The obtained results appear very encouraging about the possibility of improving the seismic behaviour of CTP buildings by enhancing the cyclic behaviour of the structural fuses adopting the proposed XL-Stubs.

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