An innovative connector system for fast and safe erection with CLT

Ein innovatives Verbindungssystem für eine schnelle und sichere Montage der CLT-Konstruktionen

Présentation d’un système innovant pour le montage rapide et sûr d’éléments en CLT

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1. Introduction

The versatile nature of Cross Laminated Timber (CLT) as a structural product has certainly helped the diffusion of CLT buildings. CLT panels in fact, guarantee to the timber structures a high strength in both loading directions, in-plane or out-of-plane (wall/diaphragm configuration). In addition, when loaded edgewise, they also offer an extremely stiff response. Another aspect that has fuelled the use of CLT, is its "environmental friendliness", being a renewable and recyclable material with excellent insulating qualities. The CLT technology is characterized by a high level of prefabrication: the panels are manufactured in modern factories equipped with computer numerical control (CNC) systems. The critical point of the whole CLT construction method can be identified in the mechanical connections. In the traditional CLT assembling system, single panels are connected to the foundation and to the panels of the upper floor through hold-down elements and angle brackets which are nailed to the panels as shown in Figure 1. These connectors which have originally been designed for other technologies (like platform frame) have been adopted for CLT structures with little or no modifications. As a result, the building capacity is limited by the strength of the connectors, which also show ultimate deformations not compatible with the CLT panel stiffness. Hence, in order to comply with the most recent and most advanced standards (especially with regards to seismic hazard) and also satisfy the needs of an international market that is getting more and more interested in the CLT technology, it is fundamental to develop new and more efficient connection systems.

The innovative solution herein proposed, named X-RAD, consists of a point-to-point mechanical connection system, fixed to the corners of the CLT panels. This connection, designed to be prefabricated, is comprised of a metal wrapping and an inner hard wood element which are fastened to the panel by means of all-threaded self-tapping screws. Such system permits to reduce significantly the number of bolts/fasteners required to assemble two or more panels together or to connect the panels to the foundation.

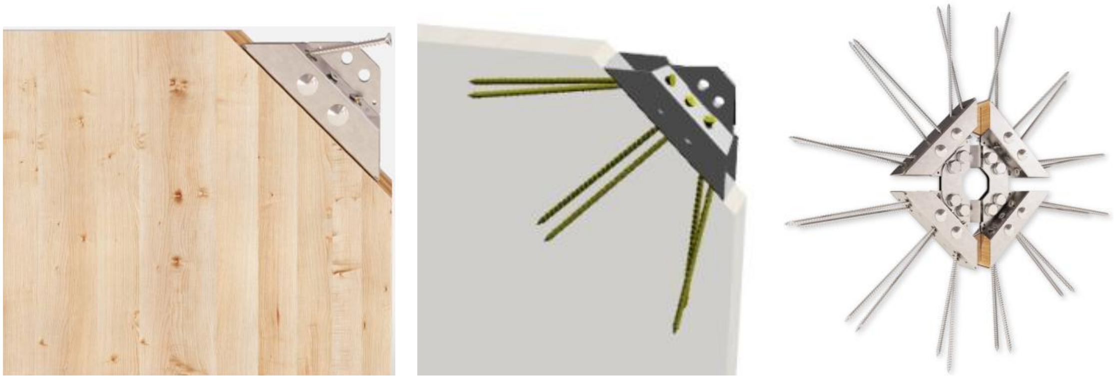

Figure 1: Schematic view of the new connection fixed at a CLT panel and a joint between 4 connectors

The main purpose of X-RAD is to enhance the production, the handling and the onsite assembly of CLT panels. This enhancement is achieved through the increased level of prefabrication which means an improved safety, a better precision and a higher speed of assembly as well as an advantage in terms of costs and time planning. Among the varied reasons that fostered the development of the X-RAD system, there is the desire of offering a solution to those issues (e.g. to satisfy ductility and energetic dissipation requirements) that are commonly related to the seismic safety of timber structures. In other words there was the will of defining a system able to guarantee an adequate level of ductility and energetic dissipation.

2. Description of the innovative connector

The X-RAD solution, consists of a point-to-point mechanical connection system, placed at the corners of the CLT panels. In particular, three components are the basic constituting elements of the new system: an outer metallic envelope, an inner core made of hard wood and all-threaded self-tapping screws (Figure 2).

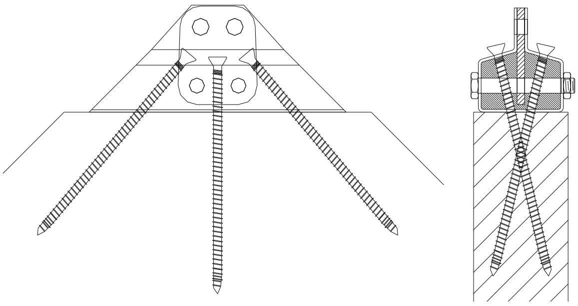

Figure 2: Schematic view of the X-RAD connection fixed at a corner of a CLT panel, lateral view (left), front view (right)

The all-threaded screws can be installed at two different angles of inclination, so as to maximize the withdrawal strength. Because the screws are subjected to a tension force, the resulting joints are stronger and stiffer than the traditional ones where shear is the predominant action. The proposed system exploits the high performance (capacity and stiffness) provided by the usage of all-threaded screws inserted in a crossed disposition. Because of such peculiar disposition of the fasteners, the X-RAD system (which is positioned symmetrically to the main stress-plane), is capable of developing the full capacity of both the CLT panels and the all-threaded screws. Once the CLT panels have arrived at the construction site, the assembly phase is facilitated by apposite metal plates that require just few steel bolts in order to join together the elements placed at the corners of adjacent panels (Figure 3).

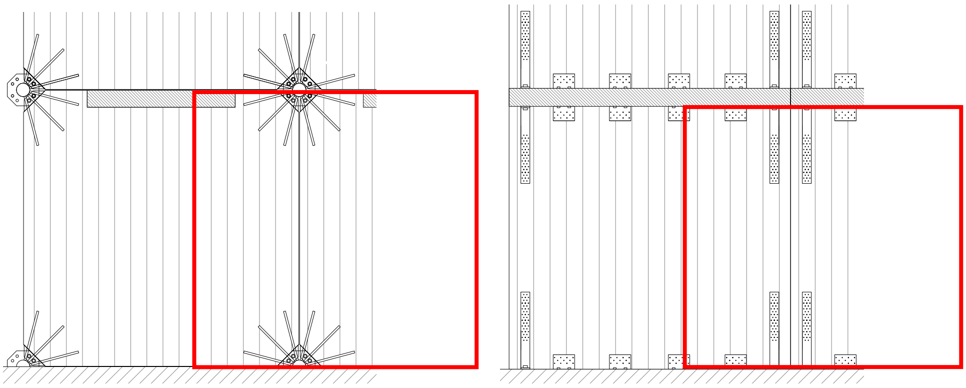

Figure 3: Schematic representation of X-RAD system (left) compared with the traditional system (right)

3. Description of the innovative construction system

The X-RAD system has generated a new approach to CLT constructions, characterized by precision and effectiveness. Thanks to the possibility of assembling the X-RAD connectors directly within the factory, the CLT panels can be lifted during the production phases, transported to the construction site and assembled by the use of a sole element represented by the steel elements placed at the corners of the different panels. The X-RAD components in fact are meant to be pre-assembled in the factory by using all-threaded self-tapping screws, so that the system could act as a lifting point for the positioning operations. In addition, as previously mentioned, the panel installation requires just the tightening of few bolts in order to secure a timber wall to the next or to the foundation.

3.1. In factory production phases

The innovative solution herein proposed, consists of a point-to-point mechanical connection system that is fixed to the corners of the panels directly at the CLT production site. During the panel "sizing phase", the corners edge have to be cut using CNC system in order to create sufficient space for the X-RAD connection to be installed. Nowadays this kind of timber manufacturing (where high precision is required due to acceptable errors of less than two millimetres), do not represent an obstacle as similar cuts are usually performed on every CLT panel that may need to be shaped in accordance with a particular structure design. Once the panel has been properly shaped, the all-threaded self-tapping screws are inserted into the pre-drilled hard-wood element and the X-RAD connection is definitively joined to the panel (Figure 4). When all the connectors are installed, the panel is ready to be lifted and transported to the building site.

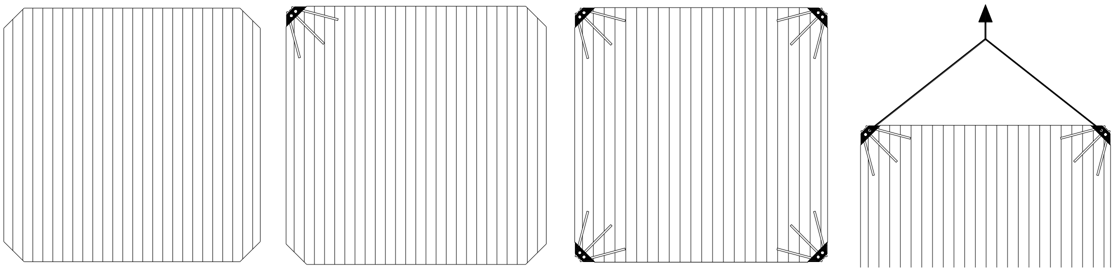

Figure 4: Production phases: shaped CLT panel in the factory with the first connector screwed at one corner and the panel ready to be lifted with 4 connectors

3.2. On site assembling phases

Once at the building site the CLT panels, already preassembled with the X-RAD connections placed at the corners, can be lifted directly from the truck and positioned on steel plates anchored to the foundation. Such plates are fixed to the foundation according to the design of the building, allowing the correct positioning of the CLT panels. To fix the panels into their final position, just few standard steel bolts have to be inserted in order to connect the plates to X-RAD connection. As shown in the next figures, it is possible to connect different panels to create the structural walls of the building, by means of different types of special elements that will be presented in the next paragraph. In particular it is possible to connect two adjacent panels collocated in the same plane, two edge panels or orthogonal panels creating a 3 or 4 way intersection.

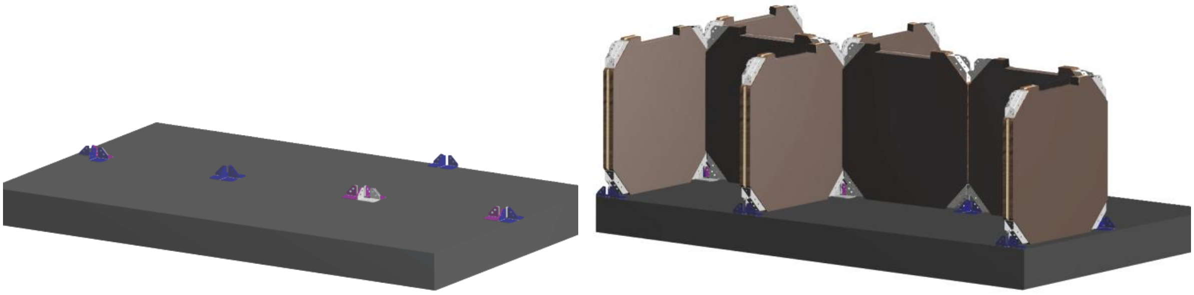

Figure 5: Assembling phase: foundation plates (left) and walls connected to the foundation (right), it is possible to see the slots for the floors

The proposed construction system, thanks to the fact that the connection elements are located only at the panel corners allows to accommodate the CLT floor panels by simply cutting a slot at the top of the wall panel as displayed in Figure 6. Therefore by laying the floor panels in the aforementioned groves, it is possible to avoid the direct contact between the horizontal panels and the upper walls with a consequent reduction of those issues related to loading orthogonal to the fibres.

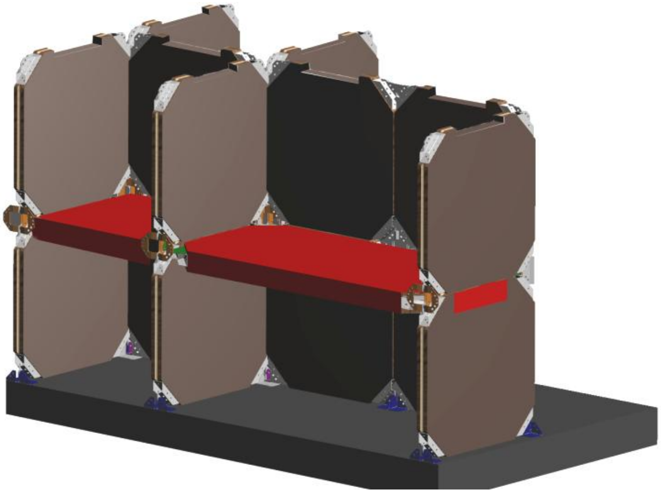

Figure 6: Assembling phase two levels of walls connected each other, it is possible to note the different plates designed to connect the different configurations of walls intersections

3.3. Steel components to create the different structural joint

Different special hexagonal plates were designed to join the different CLT wall panels intersecting into one node (Figure 6). In particular Figure gives the steel elements required for a 4 ways node. In such way, it is possible to obtain all the connections between the orthogonal walls by simply bolting the external hexagonal plates to the X-RAD elements that are fixed to the different panels converging into one node.

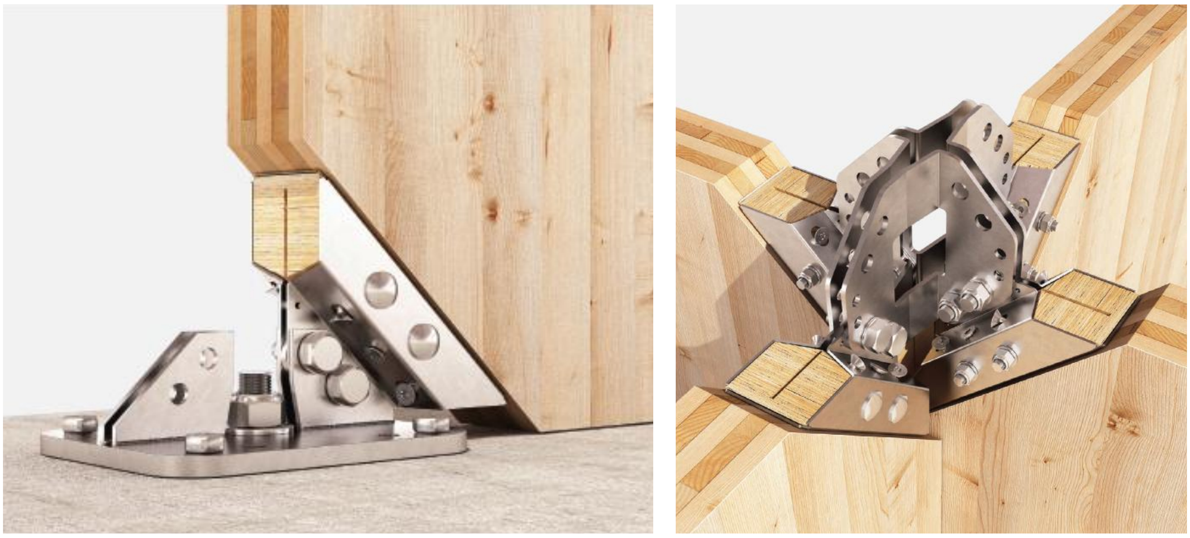

Figure 7: Examples of special plates design to connect the walls: wall-foundation joint (left) and 4-way joint (right).

4. Mechanical behaviour of the system

In the traditional CLT assembling system the CLT walls are connected to the foundation by the use of hold-downs and angular brackets. The same type of connectors are used to link a wall to the CLT floor and again to the wall of the upper storey, as shown in Figure 8 where a single horizontal CLT panel is connected to the lower wall and to the upper wall by a couple of hold-downs. The floor panel is supported by the lower wall panel while is supporting the upper wall: for this reason the horizontal panel is subjected to compression perpendicular to the grain. Another consequence of an interposed floor panel (that is interrupting the continuity of the vertical walls), is that the uplifting forces and the horizontal forces have to be transmitted at each level from the upper wall to the intermediate floor and again to the lower wall by means of a great number of connectors.

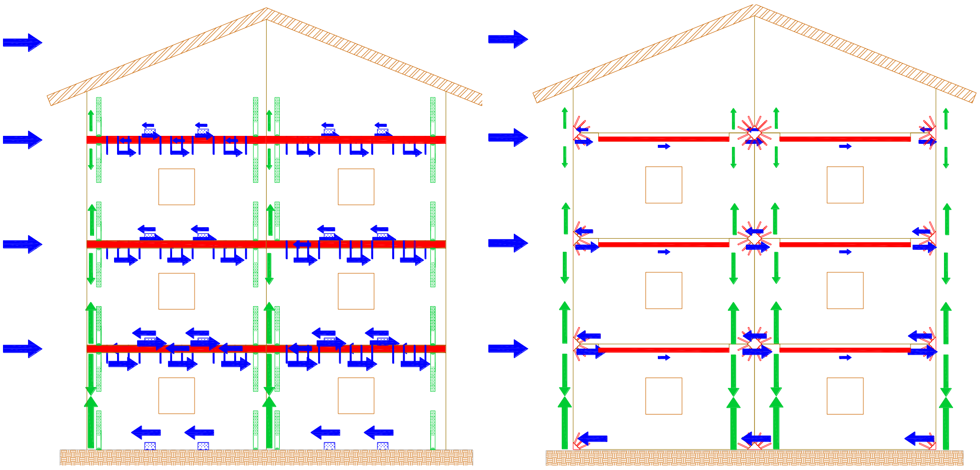

Figure 8: Comparison between the load path into a CLT structure built according to the traditional connection system (left) and according to the X-RAD system (right)

Considering that the X-RAD connecting system is located at the corners of the panels it is possible to create slots where to insert the panels constituting the floor diaphragms (Figure 8). By doing this, the vertical loads can be transferred to the foundations by direct contact between the vertical walls. The floor panels can be connected to the vertical skeleton by fixing them, directly with screws, to the aforementioned slots created into the CLT wall. In case of particularly high horizontal design loads, vertical steel rods may be used to link each connection to the next one (placed on the upper/lower level) so as to transfer directly to the foundation the forces generated by the external horizontal loads (Figure 9).

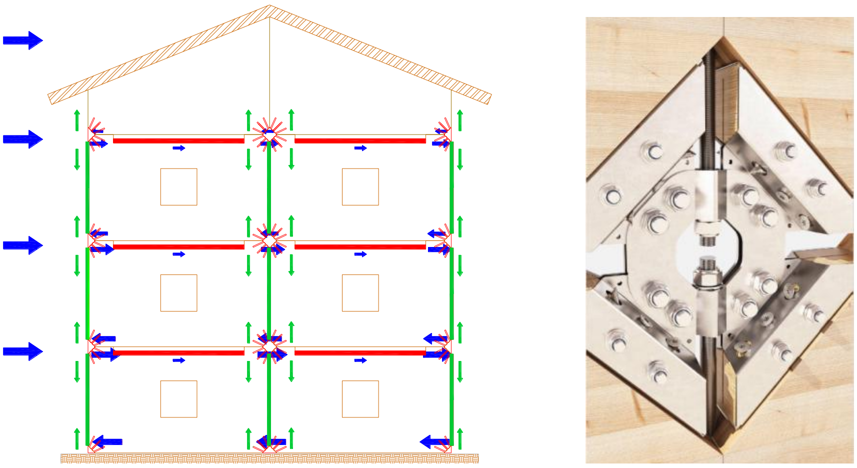

Figure 9: Load path into a CLT structure built by the use of X-RAD system with vertical steel rope (left) and detail of the wall-wall joint (right)

5. Experimental analysis

5.1. Preliminary Test

An extended experimental campaign was performed in 2013 at the Mechanical Testing Laboratory of CNR-IVALSA, in San Michele all'Adige (Trento) in order to develop and optimize the X-RAD prototype. The first phase had the particular purpose of determining the maximum withdrawal capacity of different types of full threaded self-tapping screws driven into different typologies of wood elements which are inserted into a steel tube profile. Once the proper typology of screws and wood insert had been chosen it was possible to design the first version of the connectors. Consequently, by studying the results of the test campaign and the results of the numerical models that will be reported in Paragraph 6, it was possible to design the actual connector. Several tests were performed on the screw fasteners taking into account different hard-wood species (like oak and beech) as both solid wood and veneered specimens (LVL). The LVL inserts consisted of special Laminated Veneer Lumber elements made of beech veneers (LVL) and other

LVL product "Panzerholz" (LVL*). Three different diameter sizes were selected for the full-threaded self-tapping screws that were to be inserted into the specimens: 9mm and 11mm Rothoblaas VGS screws and 13mm SFS WR-T screws. The specimens were tested according to the procedure given in EN 1382:2002. For the X-RAD test prototypes (Ver.1) LVL inserts were adopted due to the smaller variability in density of LVL when compared to massive wood. According to the results summarized in Table 1 it appeared that when a LVL* insert with very high density (approximately equal to 1400 kg/m3) is used the withdrawal capacity of the screw is sufficient to absorb the entire force exchanged by the screws and the wood elements. In such condition all the specimens showed steel tensile failure of the screws. For the actual prototype, because of production issues, beech LVL characterized by a mean density equal to 750 kg/m3 was used.

Table 1: Tests to analyze the withdrawal capacity of fasteners

Spec. N.	Type	H	ρ_{mean}	d	F_u	Failure mode
		[mm]	kg/m^3	[mm]	[kN]	
001-003	Oak	34	354	9	12.32	Withdrawal
004-006	Oak	34	382	11	15.18	Withdrawal
007-009	Beech	34	370	9	16.51	Withdrawal
010-012	Beech	34	369	11	19.72	Withdrawal
013-015	Oak	54	544	9	18.92	Withdrawal
016-018	Oak	54	529	11	22.01	Withdrawal
019-020	Beech	54	438	9	17.52	Withdrawal
021-022	Beech	54	434	11	18.5	Withdrawal
035-036	LVL	54	746	11	24.75	Withdrawal
037-039	LVL*	40	1393	11	36.29	Steel Tensile
040-042	LVL*	30	1411	11	37.12	Steel Tensile
043-045	LVL	34	762	11	17.71	Withdrawal
046-048	LVL*	40	1379	13	60.05	Steel Tensile
049-051	LVL	54	756	13	32.38	Withdrawal

Fourteen tests were conducted on a complete X-RAD connection system constituted by a steel element (box) and a wood internal insert. The connection system was connected to a CLT panel by means of 6 full-threaded self-tapping screws. The connection system was tested in two different loading configurations (Figure 11), from here on referred to as "tension configuration" and "shear configuration". The adopted CLT panel was a typical 5-layer panel with a thickness equal to 100 mm. To connect the X-RAD system to the CLT panels, full-threaded self-tapping VGS screws (11mm diameter and 350mm length) were employed. The area of the CLT panels interested by the VGS screws was reinforced by using 4 full-threaded self-tapping VGZ screws (9mm diameter; 100mm length) inserted orthogonally to the panel edges.

Table 2: Test on prototype: setup configurations and maximum capacity

Spec. N.	Prototype	Load conf.	Load history	Fu [kN]	Failure mode
023	Ver.0	Tension	Monotonic	181.71	External support
024	Ver.0	Tension	Monotonic	196.84	VGS tensile failure
025	Ver.0	Tension	Cyclic	174.18	No failure
026	Ver.1	Tension	Cyclic	164.04	Block shear
027	Ver.1	Tension	Monotonic	157.39	Block shear
028	Ver.0	Shear	Monotonic	81.35	External support
029	Ver.0	Shear	Monotonic	91.36	No failure
030	Ver.0	Shear	Cyclic	88.12	No failure
031	Ver.1	Shear	Monotonic	89.51	No failure
032	Ver.1	Shear	Cyclic	94.84	No failure
001B	Ver.1	Tension	Monotonic	175.92	External support
002B	Ver.1	Tension	Monotonic	181.22	Block shear
003B	Ver.1	Tension	Monotonic	178.27	Block shear
004B	Ver.1	Tension	Monotonic	173.16	Block shear

Two different prototype versions were tested. The first one “Ver.0” was comprised of two separate elements, each one composed by two 3 mm thick curved steel plates welded at the bottom face; these two mirrored elements were linked by means of two M16 bolts (Figure 10). The second tested prototype “Ver.1” consisted in a single external element obtained by a 2.5 mm thick curved steel plate. The whole X-RAD Ver.1 included an external steel plate, a 6mm thick internal plate (Figure 10) and 12mm diameter transversal-bolts. Both prototypes presented an internal predrilled insert made of hard wood: starting from the predrilled 6,5 mm holes, 6 VGS screws (diameter 11mm) were screwed both in the hardwood insert and into the CLT panel.

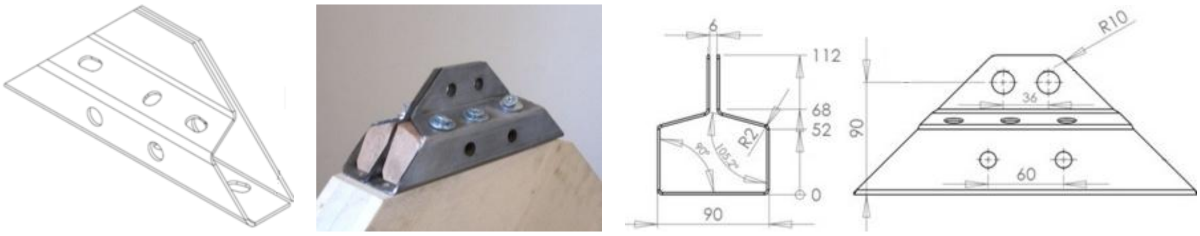

Figure 10: Prototype Version 0 (left) and Version 1 (right)

Both prototypes were tested in tension and shear configuration according to the procedure suggested by EN 26891:1991 for monotonic tests and according to EN 12512:2006 for cyclic test, Table 2.

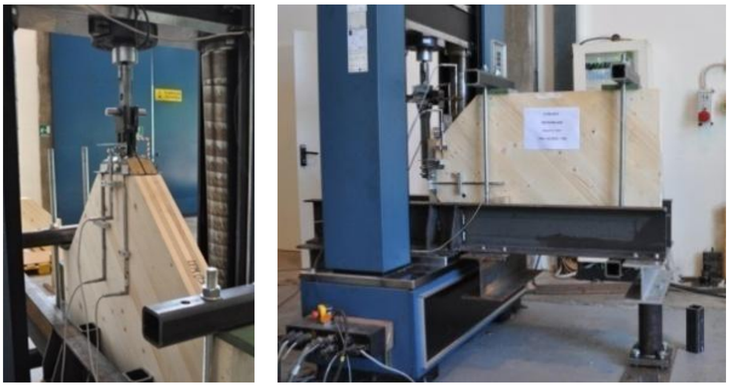

Figure 11: Setup adopted for tension configuration and shear configuration

Considering the results of the first tests, the Ver. 0 prototype was modified in order to avoid the brittle failure of the self-tapping screws. The aim was to change the failure mode by shifting the weak point from the screws to the steel box element. It was possible, starting from the characteristic tensile capacity of the VGS screws, to calculate the characteristic capacity of the whole connection in the tensile configuration, that in case of screw failure, is equal to 197kN. As far as the failure of the external steel box is concerned (e.g. as happened for prototype Ver.1), the maximum capacity of the external steel box can be determined in accordance with EN 1993:2009 if the failure is due to block shear failure, then the maximum characteristic capacity is equal to 162 kN.

5.2. Mechanical characterization of the connector

The actual version of the X-RAD connection is geometrically similar to prototype Ver.1. To avoid local deformation at the head of the screws, two upper thin holed steel plates have been added Figure 13. In 2014 have been concluded a large number of tests on the actual connector in particular 15 monotonic tests at TU Graz and 30 cyclic tests at CNR-IVALSA. The adopted tests setup configuration has been reported in Figure 12, unlike the tests on prototype performed in 2013, the CLT panels were 3 layer panels and were not reinforced by transversal screws.

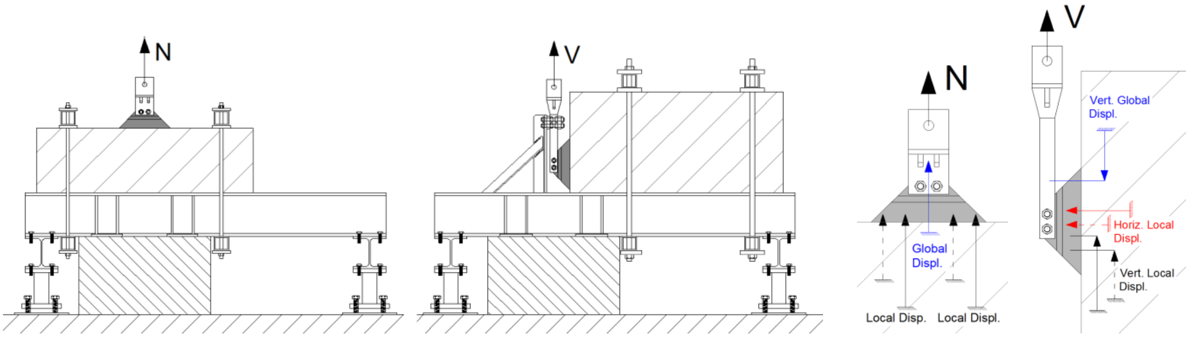

Figure 12: Setup adopted for tension and shear configuration (left) and instrumentation (right)

In the following, the maximum capacity reached by the different specimens during the cyclic tests has been reported.

Table 3: Cyclic tests on actual version of the connector: reached maximum capacity

Tension Configuration		Shear Configuration		
Spec. N	F_{max}	Spec. N	F_{max} (+)	F_{max} (-)
	[kN]		[kN]	[kN]
LPM-35/2014-009	174.34	LPM-35/2014-008	91.45	-101.94
LPM-35/2014-010	172.63	LPM-35/2014-022	94.43	-106.15
LPM-35/2014-011	177.68	LPM-35/2014-023	137.91	-126.14
LPM-35/2014-012	171.54	LPM-35/2014-024	110.86	-112.03
LPM-35/2014-013	180.03	LPM-35/2014-025	108.01	-107.35
LPM-35/2014-014	174.98	LPM-35/2014-026	113.05	-114.00
LPM-35/2014-015	173.59	LPM-35/2014-027	109.67	-111.29
LPM-35/2014-016	173.10	LPM-35/2014-028	113.32	-107.65
LPM-35/2014-017	172.16	LPM-35/2014-029	95.06	-103.23
LPM-35/2014-018	167.26	LPM-35/2014-030	102.46	-103.18
LPM-35/2014-019	167.70	LPM-35/2014-031	89.00	-106.35
LPM-35/2014-034	162.48	LPM-35/2014-032	102.32	-108.48
LPM-35/2014-035	166.93	LPM-35/2014-033	116.03	-104.76
LPM-35/2014-036	162.91	LPM-35/2014-038	111.91	-113.05
LPM-35/2014-037	170.01	LPM-35/2014-039	118.74	-108.71

The specimens tested in the tension configuration reached the failure because of X-RAD steel plates block-shear failure. In particular, the failure occurred firstly around the 13 mm diameter holes at the bottom of the internal plate and consequently in the upper part of the steel connection both in the internal and the external steel plates, Figure 13. The specimens that were tested in the shear configuration reached the failure due to progressive tensile failure of the screws loaded in tension. At the end of the tests the internal wood insert showed large cracks and splitting phenomena near to the screws.

Figure 13: Failure mode in tension configuration (left) and shear configuration (right)

When observing the load-displacement curve that regards the tension configuration (Figure 14), an evident bilinear response is noticeable. This was mainly due to the tensioned screws remaining in the elastic field during the whole test and it was also influenced by the response of the steel box that behaved elastically during the first phase. After the point a global yielding was observed, plastic deformations both in the steel box and in the transversal bolts were registered. For this reason, it was possible to apply the “a Method” suggested by EN 12512. On the other hand, as far as shear configuration tests are concerned, it was not possible to identify clearly a yielding point: hence the “b Method” contained in EN 12512 was adopted.

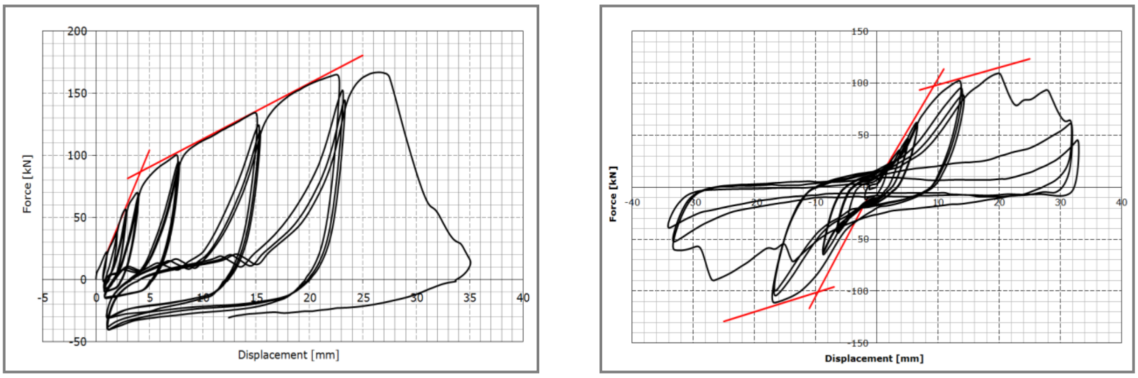

Figure 14: F-v curve and EN 12512 approximation, specimen LPM-35 (left) and LPM-27 (right)

Following, the mechanical parameters obtained from the elaboration of hysteresis cycles (2 tests) are reported as example. Two specimens were selected: the first one is LPM-035 (tension configuration) and the second one is LPM-027 (shear configuration).

Table 4: An example of test results elaboration according to EN 12512: specimen LPM-35 and LPM-27

	$F_{y(+)}$	$v_{y(+)}$	$F_{y(-)}$	$v_{y(-)}$	$F_{u(+)}$	$v_{u(+)}$	$F_{u(-)}$	$v_{u(-)}$	$D_{(+)}$	$D_{(-)}$	$F_{max(+)}$	$F_{max(-)}$
	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]			[kN]	[kN]
LPM-035	97.6	9.4	-100.4	-9.5	87.7	20.0	-89.0	-26.2	2.1	2.7	109.6	-111.2
LPM-027	86.7	4.1			133.5	28.6			6.8		166.9	

Table 5: An example of test results elaboration according to EN 12512: specimen LPM-35 and LPM-27

LPM-035	Cycle 1			Cycle 2			Cycle 3			Impair. strength
	F_1	V_1	$v_{eq,1}$	F_2	V_2	$v_{eq,2}$	F_3	V_3	$v_{eq,3}$	$\Delta F_{,F1-F3}$
	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]
$0.75v_y$	56.79	2.81	4.27	54.70	2.85	2.31	53.91	2.88	2.22	2.87
v_y	70.27	3.93	4.56	67.73	3.98	2.45	66.87	4.01	2.31	3.40
$2\ v_y$	100.50	7.64	7.41	94.96	7.76	3.19	92.61	7.81	3.08	7.90
$4\ v_y$	134.49	15.04	8.90	124.53	15.30	2.67	119.88	15.41	5.69	14.60
6 vy	165.05	22.62	7.57	152.46	23.16	4.38	143.91	23.32	4.13	21.14
8 vy	166.45	26.12								

LPM-027	Cycle 1			Cycle 2			Cycle 3			Impair. strength
	F_1	V_1	$v_{eq,1}$	F_2	V_2	$v_{eq,2}$	F_3	V_3	$v_{eq,3}$	$\Delta F_{,F1-F3}$
	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]
$0.75\ v_y$	41.11	4.97	14.10	38.18	4.82	15.21	38.99	4.81	15.78	2.12
v_y	54.83	6.48	14.93	54.11	6.48	14.90	53.71	6.48	15.02	1.12
$2\ v_y$	95.59	13.79	18.38	83.77	13.86	16.57	80.75	14.19	14.96	14.84
$4\ v_y$	64.50	31.77	37.90	61.01	31.98	18.12	45.24	33.03	13.08	19.25

LPM-027	Cycle 1			Cycle 2			Cycle 3			Impair. strength
	F_1	V_1	$v_{eq,1}$	F_2	V_2	$v_{eq,2}$	F_3	V_3	$v_{eq,3}$	$\Delta F_{,F1-F3}$
	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]	[mm]	[%]	[kN]
$-\ 0.75\ v_y$	-35.21	-6.01	20.71	-30.80	-5.89	22.54	-32.35	-6.02	21.71	2.86
$-\ v_y$	-52.40	-8.28	17.37	-51.51	-8.29	16.44	-51.09	-8.29	16.82	1.31
$-\ 2\ v_y$	-96.45	-16.71	20.91	-88.45	-16.34	16.27	-81.99	-16.13	16.09	14.46
$-\ 4\ v_y$	-59.97	-33.13	31.09	-52.54	-33.27	13.13	-36.87	-33.99	10.51	23.10

5.3. Tests on walls

The last series of tests, was performed at the Mechanical Laboratory of the University of Trento. Three tests were conducted. The first one on a CLT wall (100mm ‘w’; 2500mm ‘h’; 2500mm ‘l’) connected to the steel foundation element by the use of two X-RAD connectors following both monotonic and cyclic protocols. For the last test, the original CLT panel was firstly cut into four parts and then re-assembled to form a single element by using 10 X-RAD connectors and 4 of the steel plates described in Paragraph 4. and connected to the ground by the use of 4 connectors.

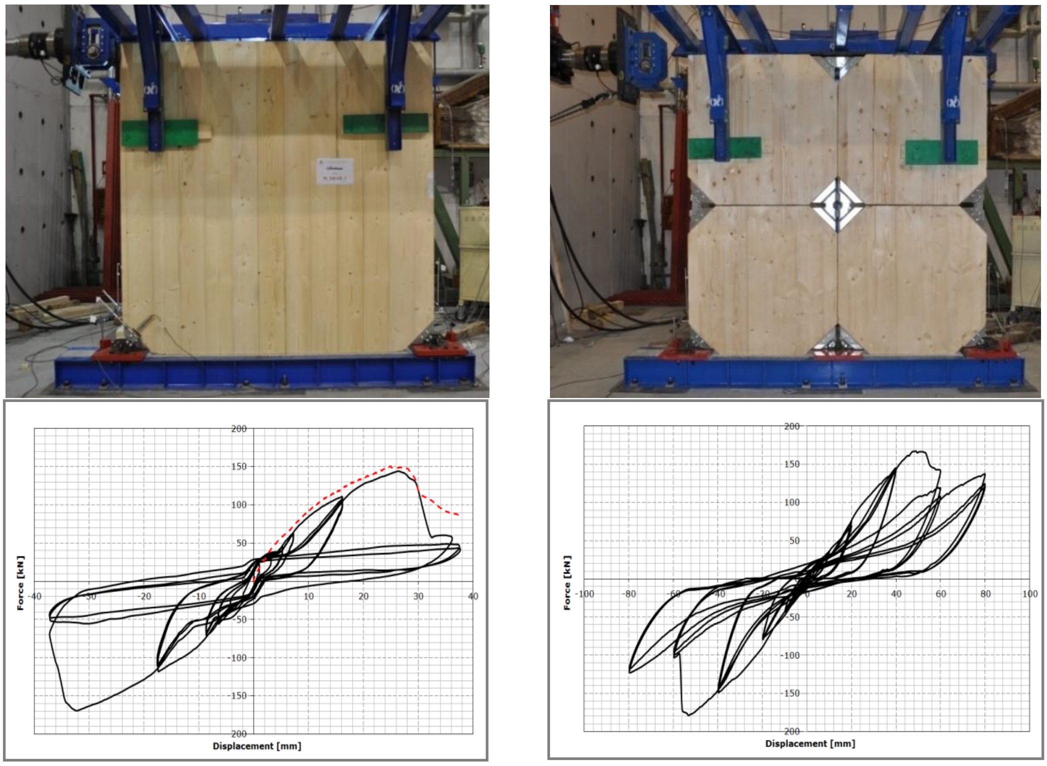

Figure 15: Pictures and F-v curves regarding tests on walls: at left cyclic – continuous line - and monotonic – dashed line- tests on single wall are reported and at right results on composite wall are reported

6. Numerical analysis

In order to have a term of comparison for the test results and to build a more in-depth comprehension of the mechanical behaviour of the different components of the system, a 3D FE (Finite Element) model was implemented at CNR-IVALSA. To achieve an exhaustive study of the system it was chosen to elaborate a solid model by the use of FE software Abaqus. The model, described herein, was aimed at studying the response of the different steel parts constituting the connection: screws, steel box, internal plate, transversal bolts and in a second phase also the external steel plates and the connection bolts. Solid elements were adopted for the mesh of all the parts. Constitutive laws were determined accordingly to the mechanical properties of the different materials used. The interaction between the inclined screws and the CLT part and also between the screws and the transversal bolts and the timber insert was schematized by "tie" constraints. In the presented model the external boundary conditions were accounted for by fixing the nodes at lateral and bottom faces of the CLT part by using the "encastre" option. The analysis was performed through a displacement controlled procedure: the imposed displacement was applied directly to the external bolts.

Figure 16: View of FEM Abaqus models (left) and comparison between the load – displacement curve obtained by experimental test -dashed line- and numerical mode -continuous line- (right)

By analysing the results of the model, it was possible to confirm some important aspects already evidenced by the experimental analysis such as the block shear failure, the role of the timber insert in redistributing the stresses among the screws and the external steel box, and the deformation of the transversal bolts. The numerical analysis demonstrated that the screws behaved elastically and that the global deformation was mainly due to the deformations of the steel transversal bolts and the steel box. A quite good matching was observed by comparing the load – displacement curves derived from the numerical model of the whole connection system, to those obtained from the experimental results (Figure 16).

7. Future developments

Two particular aspects should be developed by future studies: the fire protection of the connection and the acoustic insulation. Regarding the fire protection of the connection system, since the elements are located in a limited number of nodes, it is possible to cover the X-RAD elements and steel plates by the use of a layer of LVL or fireproof materials (e.g. gypsum boards). From an acoustic point of view the choice of having a non-continuous connection system helps limit to well defined points, the problem of noise propagation. For example it is possible to interpose a strip of noise insulation between the base X-RAD element and the face of CLT panel. Similarly it is possible to place an insulation strip between the CLT vertical panels in the wall-to-wall contact zone. The floors, resting in their apposite slots are not in direct contact with the upper walls and therefore should not represent a significant issue for the noise propagation problem.

Finally, the experimental testing and numerical analysis, will be followed by the definition of a capacity domain. In a real structure, in fact, the connection system is subjected to a composition of tensile and shear loads that depends on the external forces and on the geometric configuration of the walls. The purpose is to formulate a simple design method that permits to analyse the structure with the same ease as it is for a framed system. The design process of the X-RAD elements (forming the joints), will therefore start from the forces (module and direction) calculated at the nodes through the aforementioned simplified method and will end with the safety checks conducted in accordance with the capacity domain.

8. Conclusion

Starting from the analysis of the main problems that affect the "traditional" CLT construction system, an innovative connection system for CLT structures was developed. In particular, the proposed system is a point-to-point mechanical connection system, designed to be fixed to the corners of the panels and intended to substitute both the hold downs and the shear angular brackets. The innovative system will be factory-preassembled and is meant to be used as a lifting hook for a rapid and safe positioning. This will help improve the safety of the building process, its quality level and also its profitability. According to the proposed system, named X-RAD, the new connection-elements form the panel joints and are connected by means of metal plates, screw fasteners and steel bolts. The screws can be installed at two different angles of inclination, so as to maximize the withdrawal strength by crossing more board layers. In addition, the presence of the hardwood element guarantees the possibility of distributing the internal forces in all directions. Several experimental tests and FEM analyses were designed and performed: tests on screws, monotonic and cyclic tests on different prototype configurations and tests on the whole system. The test outcome lead to the definition of the actual prototype that is characterized by strong capacity and high stiffness. Once the experimental campaign on walls and on the whole system is completed and the data are deeply analysed, the response of the system in case of a seismic event will be investigated. The first data seem to confirm that the presence of a steel-to-steel link at the top/bottom of each wall provides to the CLT structure a sufficient ductility level and an adequate dissipating capability, thanks to the plastic deformation under cyclic loading of the steel elements.

9. Acknowledgement

The author wish to thank Rothoblaas company, CNR-IVALSA, University of Trento and TU Graz. The development of the presented connection system was conducted within the framework of a research project financed by the Autonomous Province of Bolzano.

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