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EUROPEAN SEISMIC DESIGN OF SHEAR WALLS: EXPERIMENTAL AND NUMERICAL TESTS AND OBSERVATIONS

Clément Boudaud[1], Stéphane Hameury[1], Carole Faye[2], Laurent Daudeville[3].

ABSTRACT: This paper presents series of monotonic and cyclic tests on wood shear walls and on single nail connections used to connect wood based panels to studs of shear walls. Tests results underline difficulties in interpreting the European seismic-code, Eurocode 8 (EC8). Moreover, a finite element model of shear walls has been built using all the tests results as input data. The aim of the work is to gather enough data to propose an update of the EC8, taking into account missing material (OSB panels) and new criteria for the ductility classification of the tested elements.

KEYWORDS: Wood shear wall, cyclic tests, Eurocode 8, finite element modelling.

1 INTRODUCTION

It is generally accepted that timber frame houses display a good behaviour and resistance when facing a seismic event. Nevertheless, the need of codes dealing with earthquake resistance cannot be disregarded. Europe is about to deal with a modern design code, Eurocode 8 [1], which brings up harmonized methods to justify earthquake resistance of structure for limitation of damages and against collapse [2]. According to the future French regulations, the necessity of justify the earthquake resistance of a building depends on the building importance classification and the seismic area. Buildings are classified in 4 importance classes, depending on the consequences of collapse. Seismic areas define a classification of seismic hazards and provide for each region a reference Peak Ground Acceleration a_{gr}.

Different design approaches are given in EC8. Depending on the regularity of the building, the structural model and analysis can be either simplified (plain) or global (spatial). The method mostly used to design timber frame houses is based on lateral forces analysis. It consists on performing an elastic analysis of the structure and introducing a behaviour factor q to take into account the ductility and the energy dissipation of a structure. Eventually, the base shear force equivalent to earthquake (F_b) is divided by the behaviour factor. The more the structure can dissipate strain energy and develop plastic strain through identified dissipative zones, the greater is the behaviour factor value. This value goes from 1.5 for low dissipative structures (Low Ductility Level) to 5 for dissipative structures (classified in Medium Ductility Level for q=2 and q=2.5 and High Ductility Level for higher q values). We can note that French authorities enforced q=3 as a maximum. The obtained F_b value is compared to the design capacity of the structure calculated according Eurocode 5 [3]. One of the critical point of this method is the determination of the behaviour factor. Two approaches are available in EC8 when designing wood structures. The first proposes prescriptions in order to classify a few standard structures in ductility levels with corresponding q value. The second method requires monotonic and cyclic tests, according to EN standards protocols. The results of tests can be used to classify the ductility of the structure according to criteria defined in EC8. As experimental tests on shear walls are long and expensive, tests were also performed on single nail connections. Others reasons are that behaviour of shear walls is mostly dependant of its connections [4, 5] and that EC8 states that tests on dissipative zones shall be performed on connections, structures or parts of the structure. The non linear analysis of timber structures under seismic loading was based on this assumption in previous papers of the authors [5 - 7].

This paper provides:

- a comparison between these two approaches,

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- a comparison of shear walls and single nails connections behaviour which led to discuss the criteria used in the EC8 to classify the ductility level,
- a finite element model of the cyclic behaviour of shear walls using experimental results on connections as input data.

For the first point, tests were performed on particleboards sheathed walls, in order to confront tests results to EC8 prescriptions (these walls are High Ductility Level according to EC8). Moreover, tests on OSB sheathed walls have been performed because prescriptions of EC8 did not deal with them. Shear walls tested were standard configurations commonly used in France. The idea was to realize tests according to the second method of EC8 in order to find adequate prescriptions for OSB panels. Tests on single nail connections were conducted in order to compare behaviour between a shear wall and its constitutive connections.

2 EXPERIMENTAL INVESTIGATIONS

According to EN 12512 [8], cyclic test is a sequence of 3 cycles with the same amplitude of displacement. Failure of the component is defined as the loss of 20% of the shear resistance of the wall between the first and the third cycle at a given amplitude. If the component resists three cycles of amplitude 4×Vy (where V_y is the yield slip) the component is classified in Medium Ductilty Level (MDL). For the High Ductility Level (HDL), the component has to endure three cycles of amplitude $6\times V_y$ without failure. Every failure occurring before or at the amplitude 4×Vy classifies the shear wall in Low Ductility Level (LDL).

2.1 TESTS METHOD ON SHEAR WALLS

2.1.1 Tests plan

Experimental tests consist on applying a horizontal load F at the top of the shear wall, as shown in Figure 1.

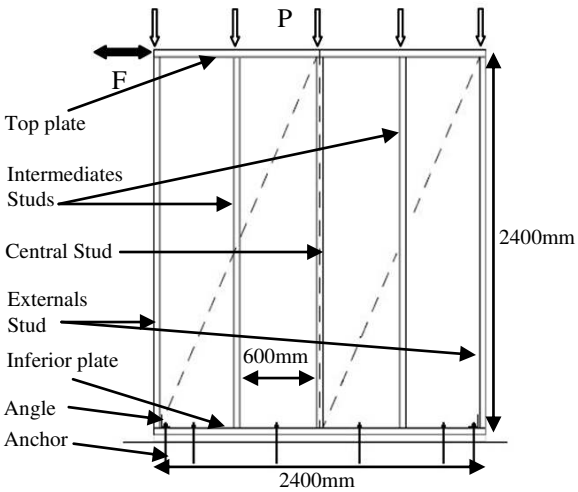

Figure 1: *Test shear wall dimensions and loading*

The load is in the plane of the shear wall and can be applied in both directions (left and right). Roof and upper storey masses can be simulate by a vertical dead load P. When used, P is between 5.5 and 6kN on each vertical stud of the shear wall, this corresponds to the load applied on the ground floor of a two storeys building. For each configuration of shear wall, one test was carried out according to EN 594 [9]. This method describes the setting of shear walls on the test machine and the loading protocol for a monotonic test. It has to be noted that EN 594 considers that a vertical dead load does not influence the result of the test. Monotonic tests provide the reference value needed to setup the loading protocol of cyclic test. For each panel configuration, two cyclic tests were performed according to EN 12512 [8], the reference value used to determine the loading protocol is the yield slip (V_y). Few cyclic tests were performed the ISO 21581 [10], this test method uses ultimate slip (V_u) as reference value to define the loading protocol.

2.1.2 Shear Walls description

Figure 1 shows dimensions of the shear wall and all configurations tested are shown in Table 1, where panels type is given according to EN 12369 [11] and mechanical class of studs according to EN 338 [12]. Moreover, the space between nails - which all have a ring shank - around the perimeter of the panel is set to 150mm. This space is set to 300mm along intermediates studs. At the connections between external studs and inferior plate, angles were settled with nails at the stud and bolts were screwed on anchors to maintain the plate. Angles aim at preventing a premature failure of the stud/plate connection, which would result in stopping the test in early cycles. In addition, one anchor was settled in every space between studs.

Panel	Thickness	Nail	Stud section	Stud Mechanical class
OSB 3	9	2.1x45	35x120	C24
OSB 3	12	2.1x45	35x120	C24
P5	10	2.5x55	45x120	C24
P5	16	2.5x50	45x115	C24

Dimensions are given in mm
OSB 3: waterproof OSB panel glue for construction outdoor
P5: waterproof particleboard for construction outdoor

Table 1: *Configurations of shear walls tested*

2.2 TESTS METHOD ON CONNECTIONS

2.2.1 Tests plan

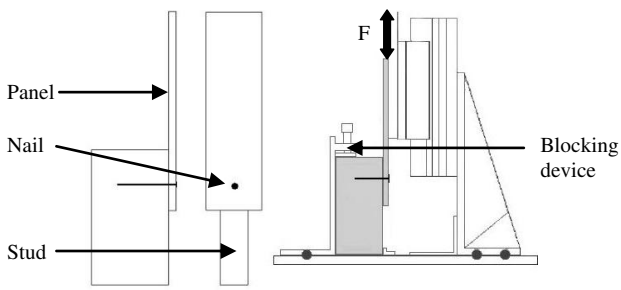

Figure 2: *Connection and testing machine*

Tests consist on applying a shear force F on a nail connection. This connection is made of a stud, a panel

and a nail. The load-displacement curve is obtained by using a universal testing machine, see Figure 2. In order to evaluate the effect of the variability of materials and connections properties, three monotonic and five cyclic tests were performed for each configuration.

2.2.2 Configurations tested

Tests were conducted on the same configurations as the shear walls previously tested, as well as 29 others configurations in order to observe the effect of panel thickness and type and nail size, shape and material. These configurations were chosen after an industrialists survey and a look at the provisions of the French code for timber frame houses [13]. Both showed a wide variety of solutions. Table 2 summarizes all tested configurations tested in order to cover this variety.

Nail Size	Shape	Material	Panel type	Panel thick. (mm)
2.1x38	RS	SS	OSB 3	9, 12, 15
2.5x60	RS	SS	OSB 3	9, 12, 15
3.1x85	RS	SS	OSB 3	9, 12, 15
2.1x45	RS	ZP	OSB 3	9, 12
2.5x50	RS	ZP	P 5	10, 16
2.1x55	RS	ZP	OSB 3	9, 15
2.8x80	RS	ZP	OSB 3	9, 15
2.3x60	RS	Ga	OSB 3	9, 15
3.1x90	RS	Ga	OSB 3	9, 15
2.3x60	X	SS	OSB 3	9, 15
3.1x85	X	SS	OSB 3	9, 15
2.3x60	X	Ga	OSB 3	9, 15
3.1x75	X	Ga	OSB 3	9, 15
2.3x60	RS	Ga	P 5	10, 16
3.1x90	RS	Ga	P 5	10, 16

RS: Ring-shank nail, X: "X" shaped cross section nail, SS: Stainless Steel (X5 CrNiMo 18-10), ZP: Zinc-plated c3+ (15µ), Ga: hot-dip galvanisation (50µ)

Table 2: *Configurations of connections tested*

Sections and shank shape of nails tested are shown in Figure 3.

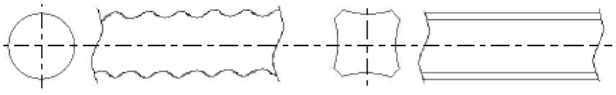

Figure 3: *Ring-shank nail (left) and "X" shaped nail (right)*

2.3 RESULTS FOR SHEAR WALLS

Figure 4 shows the force-displacement curve for a 16mm particleboard sheathed wall and Table 3 shows the resistance weakening in percentage for each amplitude and the viscous damping coefficient υ_{eq}.

For the amplitude corresponding to $4\times V_y$, the resistance weakening is more than 20% - see encircled area - which is the failure criteria used by EC8. A failure at $4\times V_y$ means that the shear wall is classified in LDL.

Results show that OSB shear walls with OSB are classified in LDL whatever the thickness tested. Walls sheathed with particleboards and made in accordance with prescriptions of EC8 for HDL class showed the same result.

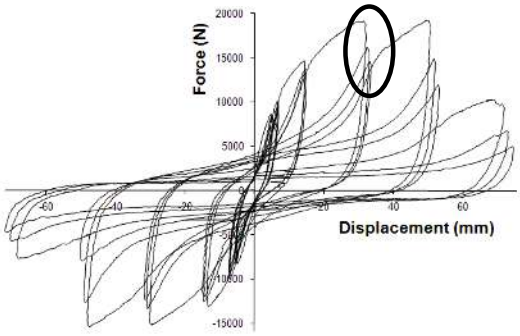

Figure 4: *Force-displacement hysteretic evolution of a16mm particleboard sheathed wall undergoing the load F*

	Amplitude			
	0,75xVy	Vy	2xVy	4xVy
w% pos	4,6	5,9	14,2	40,5
w% neg	18,8	10,7	8,9	29,0
υ_{eq} pos	14,3	12,6	15,5	24,1
υ_{eq} neg	12,3	12,8	13,3	14,7

w%: resistance weakening in %, υ_{eq} viscous damping coefficient
pos: positive displacement, neg: negative displacement.

Table 3: *Materials properties*

2.4 RESULTS FOR CONNECTIONS

Figure 5 shows a force-displacement hysteretic evolution of a nail connection.

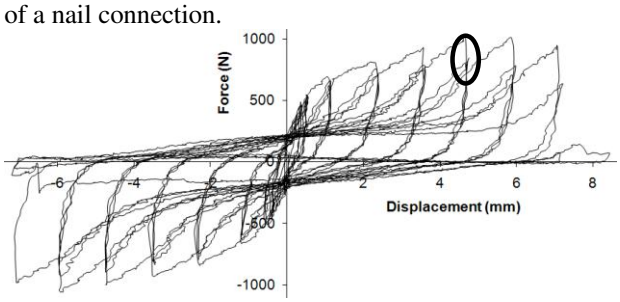

Figure 5: *Force-displacement hysteretic evolution of the single nail connection used in the shear wall of Figure 4*

	Shear Wall		Single Connection	
Panel	X × Vy	Class	X × Vy	Level
OSB 9	1	LDL	2	LDL
OSB 12	2	LDL	4	MDL
P5 10	2	LDL	2	LDL
P5 16	2	LDL	8	HDL

Table 4: *Comparison of ductility levels between shear walls and nail connections using the same connectors*

Table 4 contains results of the single nail connections corresponding to shear walls tested. Ductility level according to EC8 can be compared and numbers indicate the amplitude of the last cycle before the failure happens – e. g. the number 2 in the X×Vy column means that cycles of amplitude 2×Vy were completed and the rupture happened at amplitude 4×Vy.

For each cyclic test, the force-displacement response has been characterized according to the behaviour law described later in §3. Curves plotted in Figure 6 are average responses of five tests for each diameter. For each configuration, it shows the envelop curve of the first loading at every amplitude, the envelop curve of the

third loading at every amplitude and the hysteresis curves at the six millimetres amplitude. As tests were symmetrical, only the positive range of amplitudes has been represented.

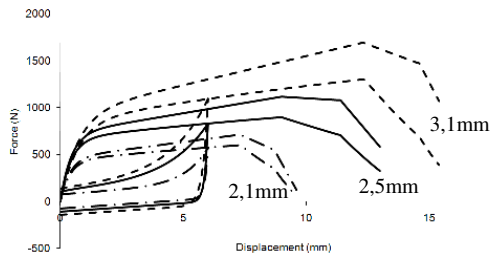

Figure 6: *Influence of the fastener diameter on the force-displacement evolution*

Influence of thickness, see Figure 7, and type of panel was very small. Shape and material coating for nails were not much influential either. Moreover, these tests showed that rupture was often a combination of the phenomenon described in §3.2, e.g. a rupture consecutive to the pull-out from the stud along with a plastically deformed shank in the stud and a slightly pull-through of the connector head in the panel.

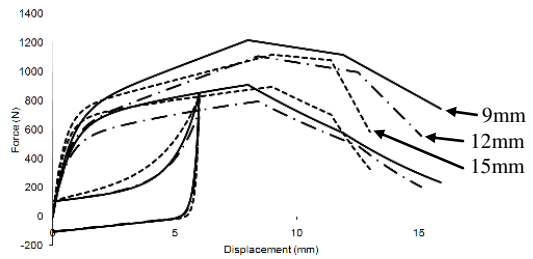

Figure 7: *Influence of the panel thickness on the force-displacement evolution*

3 NUMERICAL APPROACH

Finite elements method is used to model the mechanical behaviour of shear walls. Force-displacement curves of panels to studs connections are modelled using the behaviour law developed by N. Richard [5], which has been adjusted to fit better to tests data.

3.1 MODEL

Studs and shear panels geometry and dimensions correspond to the shear walls tested, see §2.1. The model is bi-dimensional (plan XZ). Movements in Y direction are blocked. Panels are represented by four nodes meshes plate elements and studs by two nodes meshes Euler beams. Connections between studs are spherical articulations on which we can set different values of rotational rigidity. Beams and panels have a linear elastic behaviour. We suppose that all non-linearities are concentrated in connectors. Boundary conditions impose a null displacement in the three directions on inferior plate. The imposed displacement of loading is applied on the node on the left of the top plate. A vertical dead load is also applied along the top plate, this load is equivalent to 6kN on each stud to fit with experimental tests.

3.2 BEHAVIOUR LAW FOR CONNECTORS

Pre observations

Failure mode and design calculation of the resistance of a single nail connection is given by the theory of Johansen [14]. This theory supposes six failure modes (a, b, c, d, e and f). The most dissipative one is the mode f, which consists in a double plastic hinges. Yet, when calculating the resistance of connections in a shear wall, the dominant mode is d, which is a single plastic deformation in the stud. Behaviour description of connectors is a complex matter due to the important number of phenomenon taking place in such a connection when subjected to alternate loads. It is then almost impossible to get an analytical solution of the resistance under a seismic loading taking into account following failure modes:

- squashing of the stud, panel or both (mode a, b or c),
- plastic deformation of the connector in the stud, panel or both (mode d, e or f),
- pull-out of the connector from the stud,
- pull-through of the connector head in the panel.

Law description

Behaviour of connectors is represented by a set of rules describing the force-displacement evolution, this is given for a unique direction of loading. This law was developed by N. Richard [5].

3.3 MATERIALS PROPERTIES

Characteristics values[1] of the materials properties are resumed in Table 5.

Material	Property	Value	Unity
Timber frame	Young Modulus	11000	Mpa
	Poisson Coefficient	0.3	-
	Density	420	kg/m^3
OSB Panel	Young Modulus	3800	Mpa
	Poisson Coefficient	0.3	-
	Density	550	kg/m^3
Particleboard	Young Modulus	1800	Mpa
	Poisson Coefficient	0.3	-
	Density	650	kg/m^3

Table 5: *Materials properties*

3.4 CALCULATION

The procedure of calculation is the same as for tests. It first simulates a monotonic test and calculates the yield slip. This value is then used to elaborate the protocol of loading of a cyclic test and this test is simulated. At each amplitude, results are the force-displacement curve and the percentage of resistance weakening between the first and the third cycle and the viscous damping coefficient. The percentage of resistance weakening is directly linked to the ductility levels of EC8.

[1] Characteristic value: 5% fractile of the probability function of the random variable modelling the property value

3.5 NUMERICAL MODEL

Model is now robust, except in some cases that will need further improvements of the law. A satisfying adequacy between numerical and experimental results has been found for particleboards panels. Figure 9 displays the experimental and numerical curves for the same configuration as in Figures 4 and 5. Assessment with OSB panels has still to be conducted.

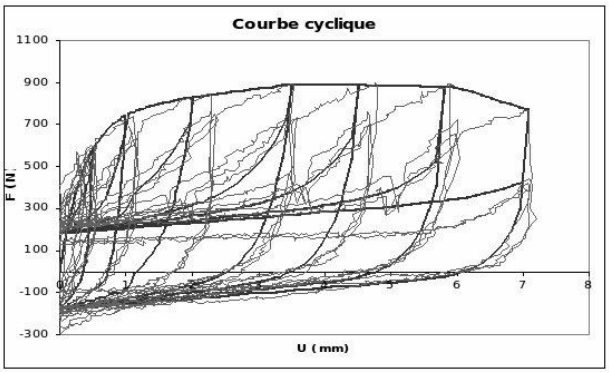

Figure 9: *Nail connection behaviour - test result versus N. Richard law (Title: Cyclic curve)*

4 DISCUSSION

4.1 SHEAR WALLS

Experimental results on shear walls for P5 and OSB were classified in LDL. These results were unexpected because prescriptions of EC8 for 16mm thick P5 classify the shear wall in HDL. Moreover, OSB and P5 mechanical properties are not that different. That leads us to think that prescriptions for HDL shear walls sheathed with OSB would not have been very different of prescriptions for P5 sheathed walls. We also have to note that all walls tested showed ductile behaviour and failure (plastic deformation of nails in timber frame and in shear panel), which is not consistent with the LDL classification.

4.2 SINGLE NAIL CONNECTIONS

The first aim of these experimental tests was to build a large data base describing single nail connections behaviour and to use it as input data for the finite elements model. The second aim was to classify connections in the ductility levels of EC8 in order to observe the effect of the scale of test (single nail connection or shear wall). Results showed that connections were as much or more ductile than a shear wall. Table 5 and figures 4 and 5 show it quite well.

The last aim was to observe the effects of different parameters. Results show that fastener dimensions have the most significant influence on the resistance. This can be explained by the failure mode commonly observed – plastic deformation of nails and pull out of the stud. Resistance to bending depends on the section of the shank (difference in material, stainless steel or coated steel, are not relevant compared to the section evolution for diameters from 2.1 to 3.1mm). Pull out depends on the penetration length of fasteners and the length of a fastener is linked to diameter. Then, the more the dimensions are important, the more nails will resist to dominant failure mode.

4.3 TEST PROCEDURE AND CRITERIA

This paragraph deals with the test procedure performed on both shear walls and single nail connections and the ductility classification criteria. A bibliographic study [15 - 22] concluded that the test procedure was a good compromise between results relevance and costs. However, some difficulties were pointed out, like the lack of a reliable method to determine the yield slip V_y from the load-displacement curve of a monotonic test. As previously said in §1, EC8 allows to perform tests on different scales (connection, part of the structure or structure). Yet, tests methods and even ductility classification criteria are the same whatever the test scale. Tests methods fit to test scale by using a reference value obtained after a first test to realize the second. There is no such thing for classification criteria, hypothesis according to which behaviour of a shear wall can be compared to behaviour of its constitutive connections is certainly right. However, ductility classification criteria still have to be suited to what is really tested, taking into account that additional loads (e.g. roof, upper stories), angles, anchorages and studs connections are also factors in the equation. This leads to consider that testing a single nail connection to determine the ductility level of a shear wall by using the current criteria of EC8 is not accurate.

4.4 FINITE ELEMENTS MODEL

When developing the finite elements model on Code_Aster [23], some modifications have been brought to the behaviour law previously described. The first observation was that for very small amplitudes, the law equations led to discontinuities around zero displacement. This is explained by the fact that these formulae are asymptotic to the point of maximal displacement, which seems too close of the zero displacement point in case of small amplitudes. This has been corrected by adding a α coefficient in the exponential term in order to accelerate the convergence.

Others modifications of the law may follow as the numerical model application is still ongoing work.

5 CONCLUSIONS

This paper focuses on an experimental approach according to the new European code on earthquake resistance design, EC8. Tests performed on timber frame shear walls and on single nail connections underlined that ductility classification criteria should not be the same whatever the scale of test. Moreover, to classify the ductility of a shear wall by only performing tests on single nail connections is not satisfactory. This first observation being made, a finite elements model has been built in order to complete the tests already carried out by a wide numerical tests study. The post-processing of this study is ongoing research. It should confirm - or not - our first observations and add to our understanding of shear walls behaviour. This research recognizes that

the scale of test has an influence on the tests results and therefore onto the classification of a shear wall to one of the ductility level according to EC8.

ACKNOWLEDGEMENT

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