FRACTURE ANALYSIS OF CROSS LAMINATED TIMBER SHEAR-WALLS WITH OPENINGS

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ABSTRACT:

Strength capacity and deformation contributions of Cross Laminated Timber shearwalls with no openings are primarily governed by the behaviour of the connections. However, a considerably different behaviour and failure mechanism can be expected when openings are cut out of the shearwall panels – i.e. Monolithic Shear Walls. This paper aims to investigate the contribution of lintels and parapets on the mechanical behaviour of monolithic CLT shearwall assemblies with openings. The Abaqus software package was used to numerically investigate the racking resistance by using the extended finite element method (XFEM). A parametric study was performed on different configurations of two-storey CLT shearwalls with openings. The failure conditions related to either the CLT panels or mechanical anchors were taken into account in the analyses. The results showed that the strength and stiffness of shearwalls where openings are cut off the panel are significantly greater than those obtained for shearwalls assembled with separated elements – i.e. Segmented Shear Walls. The increase in strength and stiffness is particularly pronounced in the case of window openings.

KEYWORDS: Walls with Openings, Monolithic Shear Wall, Lintels, XFEM

1 INTRODUCTION

Connections strongly influence the strength capacity and strains of Cross Laminated Timber (CLT) shear-walls without openings but their behaviour and failure mechanism drastically change when openings are cut-out of Monolithic Shear Wall (MSW) panels (Figure 1a).

The opening could cause a significant increase in the shear deformation contribution of the CLT panel. This condition could led to high stress concentration around the corners of the opening, with a consequent possible premature and undesired brittle failure mode.

Openings can alternatively be realized by joining lintel and parapet elements to wall segments, denoted as Segmented Shear Walls (SSW) (Figure 1b). Following this construction method, no moment continuity is ensured between the timber members, so the wall segments could be assumed to behave as cantilevered beams.

Research on the mechanical behaviour of CLT shear-walls with openings has been quite limited, with some studies focussing on the determination of reduction factors on the stiffness of the CLT [1-2] or simplified modelling strategies [3-4]. Available literature on experimental tests indicates potential for brittle failure modes in the CLT panels [5-6], emphasizing the need to better quantify the conditions in which such failure mechanisms occur.

Investigating brittle failures in CLT shear-walls is quite challenging due to three main different aspects: the first one concerns the large scale and the complexity of the problem. In fact, shear-walls are characterized by the presence of both mechanical anchors (variable in number, type and position) and different geometrical properties of timber lintels and parapets

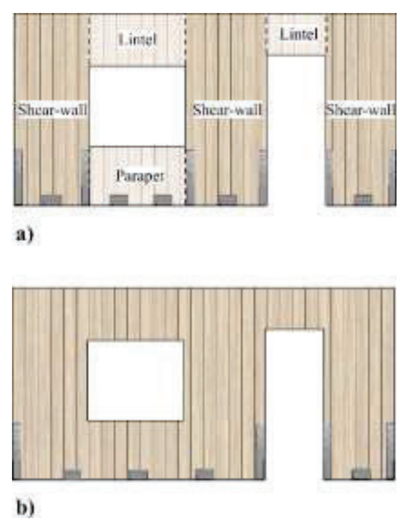

***Figure 1**. a) Monolithic (MSW) shear wall, b) Segmented (SSW) shear wall Fracture modes*

Up to now, instead, most studies involving the crack formation in timber were mainly performed at beam scale (such as LVL beams [7] and notched beams [8-9]), and to resolve detail issues (i.e joint bonding [10-11] and connection [12]).

The second aspect concerns the choice of either 2D or 3D analysis. Most of the FE timber fracture analyses have been carried out via 3D modelling; this latter is a powerful

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strategy to perform accurate fracture analyses on small scale components but, on the other way, makes the analysis time-consuming for large scale problems.

Finally, the modelling of structural elements with an existing sharp crack/notch allowed, in fracture analysis, the application of the classic finite element (FE) as well as the linear elastic fracture mechanics (LEFM) methods such as the Virtual Crack-Closure Technique (VCCT) or the Cohesive Zone Models (CZM).

However, the crack initiation and its propagation path is unknown a-priori in analysis of full scale walls due to the complex shear-walls mechanical behaviour.

The extended finite element method (XFEM) does not require to know a-priori the crack location and to re-mesh the crack surfaces (typical of the aforementioned classic FE, LEFM-based methods). The XFEM assesses the presence of discontinuities in a material by using special enriched functions in conjunction with additional degrees of freedom. It was first introduced by Belytschko and Black [13] and represents an extension of the conventional finite element method based on the concept of partition of unity introduced by Melenk et Babuska [14], which allows local enrichment functions to be easily incorporated into a finite element approximation.

The XFEM is a well-established method that does not require to know a priori crack path. This method, which is available with both 2D and 3D models, was used to model fracture mechanics problem on different structural materials such as steel [15], concrete [16] and composites [17], however just little was done in the field of timber and wood-based composites.

In this paper, the possibility to apply the XFEM procedure for the crack detection on CLT walls with opening is investigated. The aforementioned benefits of XFEM combined with a 2D analysis will be exploited to provide a novel CLT shear-walls modelling which furthermore allows the crack detection.

The two main aims of this paper are: *i)* to validate the proposed procedure for the cracks initiation and propagation in CLT shear-walls with openings and *ii)* to investigate the contribution of lintels and parapets on the mechanical behaviour of multi-storey CLT shear-wall assemblies.

2 STATE OF THE ART

2.1 FRACTURE MECHANICS

The solution to crack and defect problems can be achieved in the framework of the linear elastic fracture mechanics (LFEM), which is the basic theory of fracture that dealing with the initiation and propagation of cracks in elastic bodies. It was originally developed by Griffith [18] and completed in its essential form by Irwin [19] and Rice [20].

The fracture resistance is the ability of materials to withstand flaws that initiate failure, and usually these properties could be assessed by estimating the fracture toughness (based on Griffith's approach) or the critical value of energy release rate (based on Irwin's approach). These parameters measure the severity of the stress field around crack tips and determine the fracture criteria [21].

A material fracture resistance value varies depending on the loading mode. There are three fracture modes depending on the loading conditions for a crack, Mode I, II and III, representing fracture induced by pure tensile stress perpendicular to the crack plane and that induced by shear stresses, respectively. A mixed mode of Mode I and Mode II is the most common combination in structural applications [22].

The study of brittle failures in timber elements is challenging due to both to the nature of the material and the geometric complexity of some problems. In fact, being timber an orthotropic material, it is far more complicated than for isotropic materials due to the relevance of crack orientation, material stiffness and strength properties, which can all have an impact on the direction and load level at which cracks propagate [23].

However, the fast development of the finite element methods (FEM) allow the user to extended the LEFM concepts and crack criteria to problems with complex geometries and loading conditions [24].

For this purpose, the most common methods used are the Virtual Crack Closure Technique (VCCT) and the Cohesive Zone Model (CZM). VCCT theory assumes that when a crack is extended, the energy required to open the crack is the same required to close it. In the CZM, the equations needed to analyse the fracture process are simplified and focused only on the tip region of the crack, which considers the characteristics of this region with a traction-separation law. In the FEM, the traction-separation law is assigned to cohesive elements defined in the crack path [25].

Modelling stationary discontinuities, such as a crack, with the conventional finite element method requires that the mesh conforms to the geometric discontinuities. Therefore, considerable mesh refinement is needed in the neighbourhood of the crack tip to properly capture the singular asymptotic stress and the strain fields.

It is also required to establish a priori the path crack.

The extended finite element method (XFEM) alleviates these shortcomings as it assess the presence of discontinuities in a material by introducing specially enriched functions in conjunction with additional degrees of freedom.

To simulate crack propagation in wood by FEM, a crack initiation and a crack propagation criterion needs to be specified.

The damage initiation refers to the beginning of degradation of the material response in a certain point. Several damage initiation criteria are available: maximum nominal stress/strain, quadratic nominal stress or maximum principal stress/strain. In each case, damage is assumed to initiate when the stress/strain satisfy the input damage criteria.

The damage propagation specifies how the response (cohesive stiffness) of the material changes (degrade) once the initiation criterion is reached. The overall damage could be accounted by a scalar parameter D which ranges from 0 (no damage) to 1 (complete failure).

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The stress that would be measured without damage is multiplied by (1-D) to calculate the stress after damage has occurred. Without damage (D=0), this leads to the undamaged response; with complete failure (D=1), the stress is 0; and in between a fraction of the stress will remain (Figure 3).

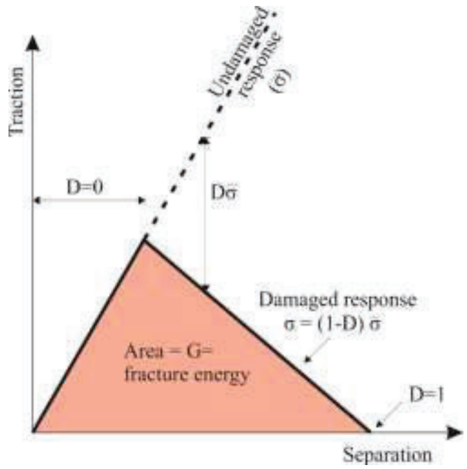

***Figure 3**. Damage initiation and evolution*

3 NUMERICAL ANALYSES

At first, the proposed XFEM procedure was validated for the crack detection on CLT walls with opening. The numerical results from FEM analyses were compared with the experimental ones obtained from a full-scale test performed by Casagrande et al [26] on a single-storey CLT shearwalls with single opening.

3.1 MODELLING STRATEGY

Abaqus software package [25] was used to carry out the numerical analysis.

In this work, 2D planar element were used to model the CLT panel and non-linear link elements were adopted to represent the behaviour of mechanical anchors (Figure 4). By using partitions, the shear-walls lintels and parapets were properly identified in the model. This procedure was particularly useful for our purposes since it allows the user to attribute different material features and enrichments (damage) to portions of mesh which can either experience damage (lintels and parapets) or not.

The elastic orthotropic material behaviour is accounted by considering the effective modulus of elasticity along the vertical, $E_{eff,v}$ (Eq. 1) and horizontal, $E_{eff,h}$ (Eq. 2) directions, as and the shear modulus, G_{eff} (Eq. 3) in accordance with Bogensperger et al. [27] and Brandner et al. [28].

$$E_{eff,v} = \frac{E \cdot t_v}{t_{tot}} \quad (1)$$

$$E_{eff,h} = \frac{E \cdot t_h}{t_{tot}} \quad (2)$$

$$G_{eff} = \frac{G}{1 + 6 \cdot \alpha_T \cdot \left(\frac{t_{mean}}{w_b}\right)^2} \quad (3)$$

being E the elastic modulus parallel to the grain, t_{tot} the total thickness of the CLT panel, t_v and t_h are the sum of thethicknesses of the vertical and horizontal layers, respectively, G is the board'sshear modulus, t_{mean} is the average thickness of boards, w_b is the width of boards and α_T is reported in Eq.4.

$$\alpha_T = p_B \cdot \left(\frac{t_{mean}}{w_b}\right)^{q_B} \quad (4)$$

where q_B is equal to -0.79 and p_B and is equal to 0.53 and 0.43 for 3 and 5 layers CLT panel, respectively, as reported in Brandner et al. [28].

For members not involved in the damage detection (i.e. wall segments), timber was defined as an elasto-plastic orthotropic material to take into account the local plasticization of wood in compression (Figure 4).

The Hill anisotropic yield criterion was adopted and based on the panel orientation, the reference resistance value was assumed equal to the CLT compressive strength parallel to grain: $f_{c,0}$. The corresponding anisotropic stress ratios (R_{ii} with i=1..3; j=1..3) for the other principal directions of interest were properly calculated (Equations 5 and 6).

$$R_{ii} = \frac{\bar{\sigma}_{ii}}{\sigma^0} \quad (5)$$

$$R_{ij} = \frac{\bar{\tau}_{ij}}{\sigma^0/\sqrt{3}} \quad (6)$$

where $\bar{\sigma}_{11} = f_{c,0}$, $\bar{\sigma}_{22} = \bar{\sigma}_{33} = f_{c,90}$ and $\bar{\tau}_{12} = \bar{\tau}_{13} = \bar{\tau}_{23} = f_v$ are the measured yield stress value and $\sigma_0 = f_{c,0}$ is the reference yield stress specified for the plasticity definition;

The failure conditions related to either the CLT lintels and parapets or mechanical anchors were taken into account in the model analyses.

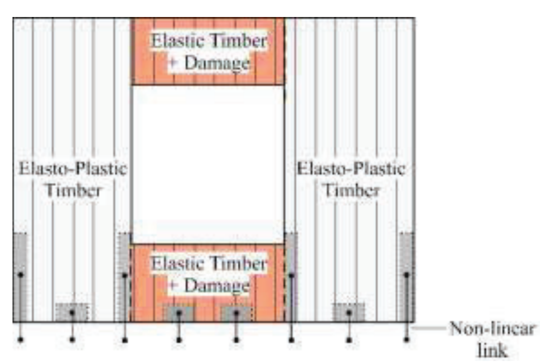

***Figure 4:** Schematic partitions, materials and mechanical anchors definition in Abaqus models*

Damage initiation is defined in the material properties by using a traction-separation law with the maximum nominal stress criterion – (MAXS). With this option, damage will initiate when the maximum stress ratio exceeds the unit (Eq. 7).

$$\max\left\{\frac{\sigma_n}{\sigma_n^0},\frac{\sigma_s}{\sigma_s^0}\right\}=1 \quad (7)$$

Being the CLT shear-walls lintels subjected primarily to bending and shear, the peak values of the nominal stresses, σ_n^0 and σ_s^0, are set equal to the effective bending strength in the horizontal direction $f_{m,h,eff}=\frac{f_m \cdot t_h}{t_{tot}}$ and the effective shear strength $f_{v,eff}=\frac{f_v \cdot min(t_h;t_v)}{t_{tot}}$, respectively.

The Wu crack propagation criterion was defined to compute the equivalent fracture energy release rate. It can be expressed in terms of energy release rate as in the following:

$$\left(\frac{G_I}{G_{IC}}\right)^{a_m}+\left(\frac{G_{II}}{G_{IIC}}\right)^{a_n}\geq 1 \quad (8)$$

where G_{IC} and G_{IIC} are the critical fracture energies required to cause failure in the normal and the shear directions, respectively, and G_I and G_{II} are the strain energy release rates which refer to the work done by the traction and its conjugate relative displacement in the normal and shear directions, respectively.

3.2 VALIDATION

A validation of the proposed FE model was carried out by comparing the model results with those obtained from experimental tests conducted by Casagrande et al [26] on single-storey CLT shear-walls with single opening (i.e. Wall 1).

The wall was made with a 3-layered 90 mm thick (30v-30h-30v) CLT panel .

The mechanical properties of the CLT panels are assumed from [26] and are E_0=13411 MPa, G=690 MPa, f_m=48.5 MPa, and f_v= 9.1 MPa. The wall height was equal to 2380 mm and the length was equal to 3300 mm. The geometrical dimensions of the door opening were (b x h / 600 mm x 2040 mm), while the lintel height was equal to 340 mm.

The test was carried out by using a commercially available hold-down anchors (WHT620) to connect the wall to the foundation. Each hold-down was connected to the wall panel using fifty-five 4x60 mm ring shanked nails, while the connection to the steel base beam was achieved using an M20 bolt. Additional blocking systems were adopted [26]. The mechanical anchor was modelled as a non-linear link accounting for its load-displacement curves obtained from Casagrande et al [26]. The blocking systems were modelled by applying a displacement boundary conditions with the component u_1=0 (Figure 5).

The critical values of the energy release needed for describing the fracture criterion were selected to be equal to $G_{IC}=176\ N/m$ and $G_{IIC}=734\ N/m$, according to the experimental evidences presented by Haller and Putzger [28], achieved by performing double cantilever beam (DBC) fracture tests and assumed by Kováčiková et al. [29] to study studies related to C24-graded elements fracture.

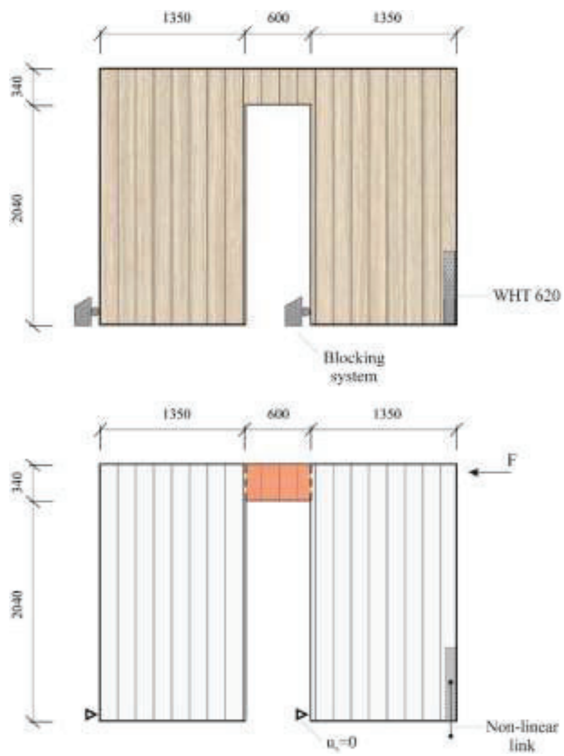

Figure 5: *Wall 1: Test setup (top) and schematic plan of partitions and mechanical anchors definition in Abaqus models (bottom) (measures in mm)*

The empirical parameters a_n and a_m are assumed as 0,5 and 1 respectively, according to [30].

A push-over analysis was carried out by increasing the lateral load applied at the top of the shear-wall.

In Figure 6 the comparison between the experimental and the FEM model curves proved a reasanable match, while in Figure 6 the position and the path of the crack reveal the same propagation observed in the test.

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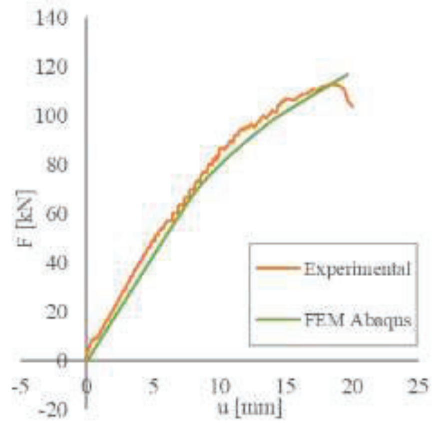

Figure 6. *Model validation with crack opening*

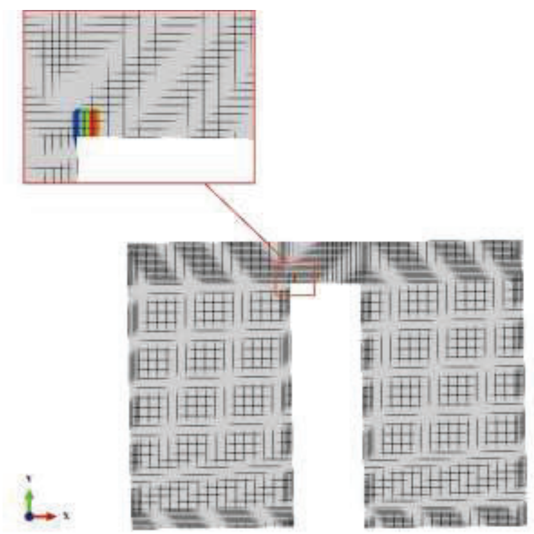

Figure 7. *Model validation with crack opening*

4 MULTI-STORY SHEAR-WALL CONFIGURATIONS

The validated model strategy was applied to two configurations of two-storey and multi-openings shear-walls.

Push-over analyses are carried out by applying a triangular distribution of horizontal forces on the top of the shear-wall.

For these configurations, the lateral stiffness, strength capacity and failure modes were documented and compared for shear-walls with openings either cut of out of the panels (MSW) or constructed with separate elements (SSW) (Figure 8).

The geometrical dimensions as well as the layout of mechanical anchors are reported in Figure 9 for Configuration #1 and in Figure 10 for Configuration #2, respectively.

For Configuration #1, the CLT panels have the same geometrical and mechanical properties of those of the wall described in the previous section. A vertical load equal to 15 kN/m was applied at each storey. The shear walls are anchored using ABR105 angle brackets spaced at 300mm and WHT620 hold-downs at each end of wall segments. The angle brackets are connected to the CLT panel using ten 4,2x89mm spiral nails and the hold-down are attached to the panels using fifty-five 4x60mm ring shanked nails.

For Configuration #2, the CLT panel is a 5-layered 100mm thick boards (20v-20h-20v-20h-20v) CLT shear-wall made of Spruce boards of C24 grade.

The mechanical properties of the CLT panels are assumed from [28] and are E_0=13878 MPa, G=690 MPa, f_m=50,2 MPa, and f_v= 11.0MPa.

The WHT 620 hold-downs and the angle bracket BMF 90x116x48x3 with 11 nails [31] were accounted. No vertical load was applied on Configuration #2 shear-walls

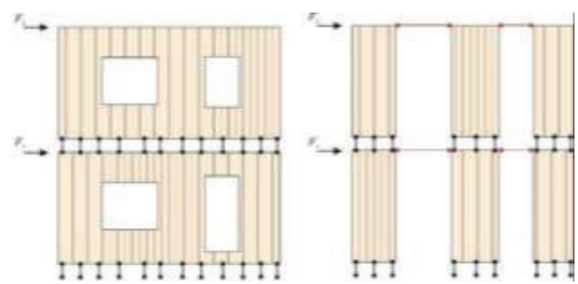

Figure 8: *left) MSW model; right) SSW model*

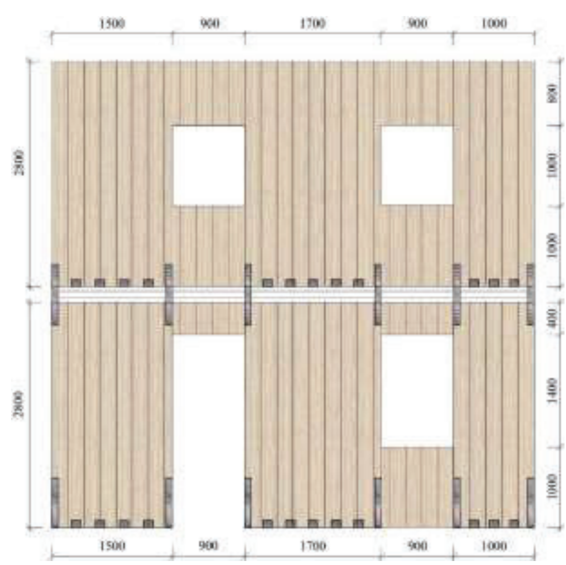

Figure 9: *Shear-wall Configuration #1 (measures in mm)*

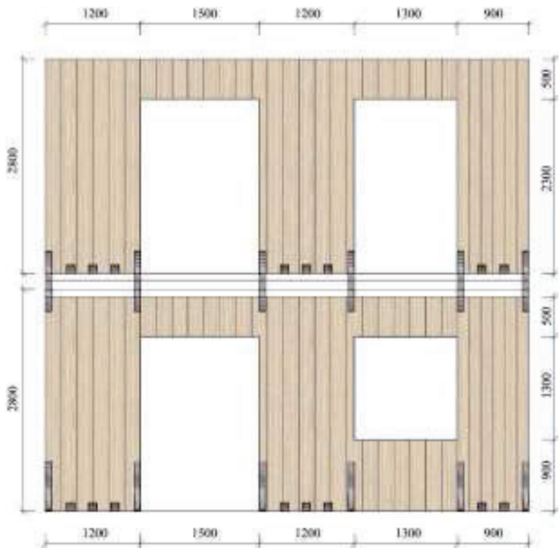

Figure 10: *Shear-wall Configuration #2 (measures in mm)*

The results from the two Configurations are significantly different both for in terms of strength and stiffness. In particular, the evidences from MSW are greater than those obtained for SSW, as displayed in Figure 11 and 12. The increase in strength and stiffness is particularly pronounced in the cases of window openings. The fracture analysis confirmed an high concentration of stress around opening leads to brittle failure modes in CLT lintels, which cannot be ignored in the design of such structural systems.

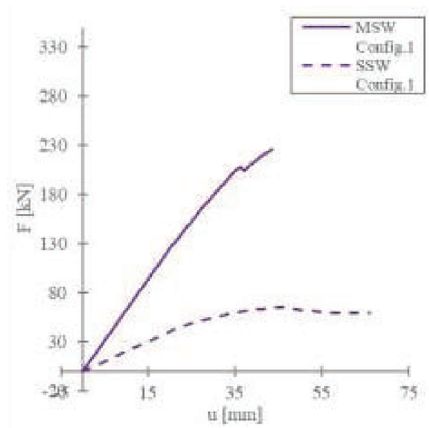

Figure 11: *MSW vs SSW models of cases shown in Figure 9 (Configuration #1)*

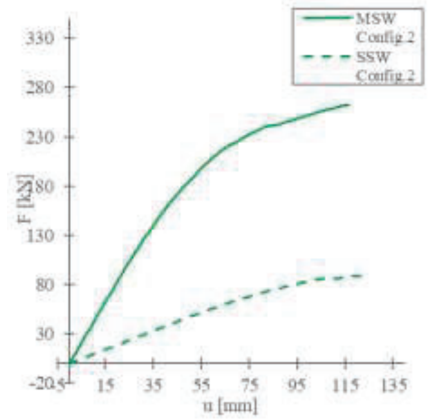

Figure 12: *MSW vs SSW models of cases shown in Figure 10 (Configuration #2)*

Moreover, the fracture mechanisms are also clearly highlighted for Configuration #2 (Figure 13).

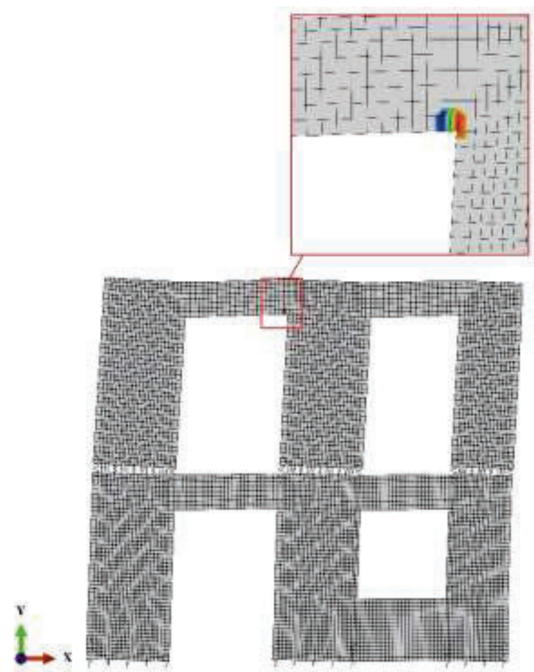

Figure 13: *Fracture mechanisms for Configuration #2.*

5 CONCLUSIONS

In this work a proposal for the crack detection in CLT shear-walls with openings is provided. The Abaqus software package was used to numerically investigate both the crack propagation by using the extended finite element method (XFEM) as well as the contribution of lintels and parapets on the mechanical behaviour of multi-storey CLT shear-wall assemblies.

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The proposal was validated on shear-walls experimental evidences and highlighted an excellent matching both in terms of load-displacement curve as for position and path of the crack. Later, two different configurations of two-storey and multi-openings shear-walls were carried on. In addition, in this case the proposal was effective for the crack detection; it was also highlighted the great influence of lintel and parapets in terms of shear-walls global mechanical behaviour.

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