Comparative modelling of seismic performance of L-shaped reinforced concrete shear walls

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Abstract. This paper proposes an improved model for the reinforced concrete shear walls. The main contribution of this work is to provide a comparison between the proposed numerical model and an existed experimental test. It indicates the necessity of performing more complex numerical simulations, in order to describe the behaviour of L-shaped walls. To validate the accuracy of the proposed model, an investigation has been carried out in two parts. In the first part, the numerical model is developed by ANSYS to predict the cyclic behaviour of the L-shaped reinforced concrete walls, which has been designed according to the Algerian seismic design codes. The second part reports a numerical investigation that evaluates the behaviour of L-shaped walls by comparing the proposed model with the experimental tests. The results of this study demonstrate that the deformation by inflection at the base of the L-shaped reinforced concrete shear walls is dominant and occupies nearly eighty percent of the total deflection. The established model constitutes a practical tool for developing and reviewing the conditions of the reinforcement stipulated in the design codes.

Key words: numerical analyses, behaviour, L-shaped reinforced concrete shear wall, static and cyclic analysis, cracks.

1. Introduction
Currently, there are many reinforced concrete buildings located in seismic zones that are insufficient to resist earthquakes, whether moderate or severe (Holden et al., 2003; Restrepo and
Rahman, 2007). Therefore, the necessity to improve the resistance of these buildings is more pressing (Alarcon et al., 2014). In order to guarantee the compliance with the safety provisions imposed by the different applicable regulations, including the requirements of deformability and resistance, L-shaped reinforced concrete shear walls are utilized in multi-story buildings, because they possess a high capacity of resisting lateral loads and can expend a great quantity of seismic energy if they are properly detailed and reinforced (Inada et al., 2008; Aaleti et al., 2013). The idea of creating reinforced concrete walls at the four corners of the building with L shape was proposed by certain civil engineers. Nowadays, this new configuration is often used in civil construction practice (Hube et al., 2014). Reinforced concrete structures with L-shaped walls offer several advantages for architects, which allows them to design constructions with larger open spaces and more flexible architectures. However, more experimental tests and numerical models must be done (Taleb et al., 2012; Riva and Franchi, 2001; Popa and Mușat, 2018; Toader and Kiss, 2013).

Significant researches have been devoted to L-shaped reinforced concrete shear walls and numerous models have been proposed. A brief review of these works is given below.

- Karamlou and Kabir (2012) simulated the behaviour of L-shaped slender R-ICF shear walls under cyclic lateral loading, where it presented four slender shear walls with L-shaped cross sections tested under the combined action of constant axial and cyclic lateral loads.
- Su and Wong (2007) verified the seismic behaviour of slender reinforced concrete shear walls under high axial load ratio.
- Pugh et al. (2015) developed a model for simulating the nonlinear cyclic response of flexure controlled concrete walls, which meets the dual objectives of accuracy and computational efficiency.
- Inada et al. (2008) verified the seismic performance of reinforced concrete L-shaped core structural walls to study the effect of loading direction and the section configuration on the seismic behaviour of the core-wall.
- Zhang and Wang (2000) presented the results of an experimental study that investigated the failure mechanism and ductility of rectangular reinforced concrete shear walls subjected to high axial loading.
- Rosso et al. (2016) verified the stability of thin reinforced concrete walls under cyclic loads.

The previous studies were undertaken at the full scale of the L-shaped reinforced concrete shear walls. There are few studies which attempted to model the finer scale of the structural elements in order to take into account the parameters that influence the structural behaviour at coarse scale (Panagiotou et al., 2012). In this paper, numerical simulations of L-shaped reinforced concrete shear walls are presented. Firstly, numerical models are developed to predict the behaviour of experimental L-shaped reinforced concrete shear walls and steel bars under cyclic lateral loading, which has been
designated according to the Algerian seismic design codes (Chaouch et al., 2015). Secondly, a numerical investigation that evaluates the comparative behaviour of L-shaped reinforced concrete shear walls subjected to cyclic lateral loading, in which a parametric study related to the L-shaped reinforced concrete shear walls was done. This numerical modelling was done using finite element software ANSYS. The results obtained are discussed and compared to other results from experimental tests done by other researchers and published in the literature (Inada et al., 2008).

This research has been examined according to the parameters and characteristics of the Algerian seismic design codes. It is clearly shown by this study that the proposed model is able to regenerate the behaviour of the experimental L-shaped walls including: the yield strength, the panel peak strength, the deformation remaining at load reversals, energy dissipation capacity and the subsequent hardening behaviour.

The numerical results are in good accordance with the experimental ones, this demonstrates that the proposed numerical model with ANSYS is robust and efficient in terms of regenerating the cyclic behaviour of L-shaped reinforced concrete shear walls. The main contribution of this study and the results of the research are interpreted and discussed in the following sections.

2. Research significance
All reinforced concrete shear walls are affected by some parameters. The impact of these parameters was examined in the past. However, a lot of research has focused on the rectangular reinforced concrete shear walls, because the latter are frequently used in buildings (Palermo and Vecchio, 2002; Ghobarah and Youssef, 1999; Ugalde and Lopez-Garcia, 2017; Xu and Lu, 2006; Henriques et al., 2013; Park and Yun, 2005; Moroz et al., 2014).

There are other researchers interested in studying different forms of reinforced concrete shear walls, including U-shaped, H-shaped and T-shaped cross sections (Adebar and Ibrahim, 2002; Andor et al., 2016; Tibea et al., 2012; Krolicki et al., 2011; Carrillo and Alcocer, 2013). More researchers have studied the behaviour of the symmetric cross section walls and focused on it compared to the asymmetric cross section walls, such as L-shaped reinforced concrete shear walls which did not acquire big interest (Sritharan et al., 2014; Greifenhagen and Lestuzzi, 2005; Hidalgo et al., 2002; Ile and Reynouard, 2000; Jalali and Dasheti, 2010; Kezmane et al., 2016; Saari et al., 2004; Shedid et al., 2008; Luna et al., 2015). This paper contributes to the understanding of the cyclic behaviour of L-shaped reinforced concrete shear walls and steel bars using the finite element modelling.

3. Experimental program description
According to the experimental tests performed in the Department of Architecture and Architectural Engineering, Kyoto University, China, Fig. 1 shows the configuration and the reinforcement arrangement of two specimens (L00A, L45A). They were L-shaped core-walls with 1/4.5 scale, and represented the lower three stories in a 40-story reinforced concrete core wall. All wall panels had the same thickness of 200 mm and height of 2480 mm. L45A and L00A are equilateral L-shaped walls (Inada et al., 2008). The details of the
geometry and reinforcement of the L-shaped reinforced concrete shear walls are shown in Fig. 2. In order to generate the loading system, a hydraulic pump was used in experimental tests as illustrated in Fig. 3.

The steps of preparing the L-shaped reinforced concrete shear walls are presented in Fig. 4.

4. Finite element modelling
The purpose of the numerical analysis is to describe the behaviour of the L-shaped reinforced concrete shear walls as if they were done experimentally.

Different methods have been used to analyse the behaviour of typical failures of the reinforced concrete structures, such as flexural, shear, torsion, etc. Finite Element Analysis (FEA) represents a numerical approach, which provides solutions to difficult problems. The numerical analysis of the proposed model in this paper was performed using ANSYS Mechanical APDL.

The results of this study have shown that ANSYS can accurately simulate the behaviour of the concrete. These precise results are almost identical to the experimental tests (Inada et al., 2008).
The geometry and position of the nodes are shown in Fig. 5. The linear isotropic and multilinear properties of the concrete are given by the modulus of elasticity (Ec), Poisson’s ratio (ν), shear transfer coefficient (βt) and the stress-strain relationship in uniaxial compressions. The modulus of elasticity Ec is taken as 25 N/mm² and the Poisson’s ratio ν is considered as 0,3. The shear transfer coefficient βt varies between 0,05 and 0,25. In this study, the taken value of βt is 0,2. The ANSYS program uses the stress-strain relationship for the concrete in uniaxial compressions. The concrete properties used are those obtained by the formulation in the experimental study. Table 1 represents the material properties defined in the model.

4.1.2. Steel reinforcement
The element Link 180 is used for the modelling of steel, because this element has two nodes, each node contains three degrees of freedom and three moves in the X, Y, Z directions. This element is shown in Fig. 6. The material properties of Link 180 defined in the model are given in Table 2.

4.1.3. Steel plates and supports
Steel plate and supports for the L-shaped wall are modelled using an element called Solid185. This element has eight nodes, each node contains three degrees of freedom and three moves in the X, Y, Z directions. This element is shown in Fig. 7.

4.2. Finite element mesh
Finite element analysis requires a mesh of the model (discretization). In other words, the model is split into small elements,
delimited by nodes. The objective is to determine the stresses and deformations at the points of integration of these small elements, after applying the loads and identifying the conditions at the limits. The L-shaped element mesh is shown in Fig. 8.

4.3. Loads and conditions at the limits
The applied load and the conditions at the limits chosen for the wall are given in Fig. 9. The model is loaded with the same conditions as the experimental test.

Table 1. The evaluation scale of the swelling and compressibility factor.

<table>
<thead>
<tr>
<th>Linear Isotropic (C 20/25)</th>
<th>Multilinear Isotropic (C 20/25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ec</td>
<td>24020 [Mpa]</td>
</tr>
<tr>
<td>N</td>
<td>0.3</td>
</tr>
<tr>
<td>1</td>
<td>0.0003</td>
</tr>
<tr>
<td>2</td>
<td>0.0006</td>
</tr>
<tr>
<td>3</td>
<td>0.001</td>
</tr>
<tr>
<td>4</td>
<td>0.0013</td>
</tr>
<tr>
<td>5</td>
<td>0.0015</td>
</tr>
<tr>
<td>6</td>
<td>0.0018</td>
</tr>
<tr>
<td>7</td>
<td>0.0021</td>
</tr>
<tr>
<td>8</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

4.4. Cyclic loading
The analysis has been executed on the concrete model subjected to reversed cyclic loading. The top nodes of the steel plates are affected by 0,5 T of the axial load, at these nodes with the wall in the plane, the lateral cyclic load is applied. Fig. 10 shows the cyclic loading protocol adopted for the analysis.

5. Result, discussion and comparison with the experimental test
5.1. Starting the calculation of modelling
Based on the mechanical and geometric characteristics of each material, stresses, strains and displacements are calculated. The calculation is done in the post processor solution, where the calculation of the solution of the LS (load step) is done. There are two methods to view the results: graphically (stress-strains) or by lists (deflections, stresses and deformations). The results obtained are given in each node. The objective is to determine the most stressed and deformable nodes under this type of loading. At this point, the entire list of movements and deformations is drawn for each load step and for each node, and then the most unfavourable results are extracted.

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Fig. 6. Link 180 geometry (Reh et al., 2006).

Table 2. Material Properties for Link 8.

<table>
<thead>
<tr>
<th>Linear Isotropic (S 355)</th>
</tr>
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<tbody>
<tr>
<td>Elastic modulus Es</td>
</tr>
<tr>
<td>Poisson’s ratio ν</td>
</tr>
<tr>
<td>Bilinear Isotropic (S 355)</td>
</tr>
<tr>
<td>Yield stress fy</td>
</tr>
<tr>
<td>Tangent modulus E’s</td>
</tr>
</tbody>
</table>

Fig. 7. Solid 185 geometry (Reh et al., 2006).
The distribution of the stress in the L-shaped reinforced concrete shear wall is shown in Fig. 11. The stresses do not have axial symmetry, the two stresses observed in this figure are the compression stress that appears near the loading application, and a tensile stress on the stretched part of the wall. Its
maximum value is at the base of the L-shaped reinforced concrete shear wall. The deformations are represented in Fig. 12. The part of the base of the wall represented by the green colour is the most deformable part, which shows that the deformations of the L-shaped reinforced concrete shear wall are starting from the base; these deformations are due to the tensile of concrete and steel (Antoniades et al., 2003). The maximum displacement of the L-shaped reinforced concrete shear wall is indicated in Fig. 13, such as the distribution of displacement on the model of the concrete are represented in Fig. 13a. Likewise, the distribution on the transverse and longitudinal reinforcements of the wall are represented in Fig. 13b. The results of the stresses, deformations and displacements obtained from the finite element models will be interpreted in the following sections.

5.2. Load-strain diagrams
The analysis is based on the load-displacement and load-deformation diagram prediction of the L-shaped reinforced concrete shear wall, first crack load; load at break and cracking at rupture. The deformations are measured at the base of the L-shaped reinforced concrete shear wall. Reading the results list allows to determine, for the most requested node, the deformation according to the applied load. Fig. 14 expresses the evolution curve of the L-shaped reinforced concrete shear wall deformation subjected to lateral reversible cyclic loading according to the load. A first linear part of the curve is observed, a variation of the load between (0-60) kN, giving a deformation between (0-400 μm/m). This phase corresponds to the phase of the un-cracked reinforced concrete. For the load from 60 kN on up to 150 kN, a deformation of up to (4200 μm/m) is observed, which is the phase of the reinforced concrete cracked plastic.

As can be seen in Table 3, at a load of 150 kN, the base of the L-shaped reinforced concrete shear wall subjected to reversed cyclic loading is crashing due to excessive cracking.

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>State of cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>First cracks start to appear at the base of the wall</td>
</tr>
<tr>
<td>70</td>
<td>First cracks start to appear in shear connections</td>
</tr>
<tr>
<td>150</td>
<td>Failure of the shear connections</td>
</tr>
</tbody>
</table>

5.3. Hysteretic behaviour of L-shaped reinforced concrete shear wall
The hysteretic behaviour of the L-shaped reinforced concrete shear wall is characterized by three different regimes (Fig. 15). The description and cracking patterns of each point on the hysteretic diagram are shown in Fig. 17.

- First point: the un-cracked reinforced concrete regime extends up to 58 kN with the appearance of the first cracks at the base of the wall due to the bending of the reinforced concrete (Fig. 15a).
- Second point: the cracked reinforced concrete regime is indicated by the appearance of the first inclined cracks in front of and behind the wall at 80 kN due to maximum load reached (Fig. 15b).
- Third point: the plastic cracked reinforced concrete regime is indicated by the crack that occurs on the wall after plasticizing the steel reinforcements due to a large concrete crushing formed at the base of the wall. When a force of 120 kN is applied, the yielding of steel reinforcement occurs. The rigidity of the L-shaped reinforced concrete wall decreases as the cracks on shear connections increase (Fig. 15c).
Considering the results of the tests and calculations, Fig. 15 and 16, respectively, illustrate the failures of the L-shaped reinforced concrete shear wall. The deformation by inflection at the base of the L-section reinforced concrete shear wall is dominant in “L”, and represents nearly 80% to the total deflection. At the base of the wall, the number and width of the crack increase when the load increases. A fracture at the base of the wall is noticed when an increase at the cyclic lateral loading occurs.

The numerical model allows to predict the ultimate displacement. It represents the behaviour of the experimentally studied L-shaped reinforced concrete shear wall, while the modelling of the material’s cyclical pattern was calibrated and refined in order to properly reflect the behaviour of the L-shaped reinforced concrete shear wall. It must be noted that such types of modelling are, in microscale, easily affected by material changes which could occur in real elements.
The lateral load vs. displacement hysteresis diagram for the experimental test is shown in Fig. 17. Comparing each hysteretic loop with the numerical diagram of ANSYS, we observe that the two diagrams are symmetrical during the reversible cyclic loading. Thus, according to these results, the cracking phases of these walls are the appearance of horizontal cracks due to inflection. The slope of these cracks increases at the approach of the intersection zone of the two wings and cracks due to shear, and after several cycles of loading and unloading, these cracks cause a crushing of the concrete at the base of the L-shaped reinforced concrete shear wall, which confirms that the numerical model is identical to the experimental data for the L-shaped reinforced concrete shear wall.

After having thoroughly examined these results, in the experimental test, a 1.40% difference is shown in the displacement, and another 13.33% relevant to the force over, comparing with the numerical modelling. As for the numerical behaviour, a slight difference is observed situated in the small areas encompassed by the hysteretic behaviour model. Such observations may be ascribed to the used numerical model, in which it was assumed that the bond between the concrete and reinforcement is perfect, and that is for the short-term cyclic loading. Nevertheless, the figure shows that the ductility of the L-shaped reinforced concrete shear wall is predicted to be close to the one that the test results had provided. In the numerical analysis, the initial shear stiffness was slightly lower than that of the experimental results.

The shear wall element is able to capture, with a considerable accuracy, the real behaviour of the reinforced concrete shear wall. The crack patterns that have been developed in the experimental tests
were thoroughly observed and were, thereafter, marked on the wall. Then they were compared with the cracking regions that were generated by the FEA.

(a). Distribution of the displacement on the concrete of the wall.

(b). Distribution of displacement on the transverse and longitudinal reinforcements of the wall.

Fig. 13. Maximum displacement of the L-shaped reinforced concrete shear wall.
Fig. 16, which presents the results, provides a good picture of the behaviour of the wall. It should be noted that the crack patterns that were generated using ANSYS are not necessarily the actual ones, but some possible cracking regions. The biggest differences in the structural response, which were detected by both the numerical analysis and the experimental results, depend mostly on the different refinement levels of the aspects of the crack model relevant to the shear failure, particularly the modelling of the aggregate interlock effect, the tension stiffening effect and the multi-axial stress-state effects. All the aforementioned effects were modelled using the ANSYS model in a more refined manner.

Fig. 14. Load vs. lateral displacement curves for the wall.

(a). At 58 kN (first cracks at the base of the wall).
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(b). At 70 kN (first cracks in the shear connections).

(c). At 150 kN (failure of the shear connections).

Fig. 15. Cracking and crushing of the L-shaped reinforced concrete wall.
(a). Distribution of cracks and failures obtained by the numerical model.

(b). Distribution of cracks and failures obtained by the experimental test (Inada et al., 2008).

Fig. 16. Comparison of the distribution of cracks and rupture obtained by the numerical model and the experimental test.
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6. Conclusions
Numerical investigations were performed on L-shaped reinforced concrete shear walls to simulate the actual seismic performance and the behaviour of these walls after cracking, steel yielding and concrete crashing during the reversible static and cyclic loading.

- These numerical investigations were presented by a comparative study between numerical modelling and experimental tests of L-shaped reinforced concrete shear walls.
- This helps engineers and researchers in using finite element modelling for evaluating the cyclic behaviour of L-shaped reinforced concrete shear walls.
- The numerical model concluded that the deformation by inflection at the base of the L-section reinforced concrete shear walls are dominant in “L”, and represents nearly 80% of the total deflection.
- The numerical and the experimental model of L-shaped shear walls present the same development of stresses, displacements, deformations, cracks distribution and failures. Furthermore, it has been shown that although the general hysteretic behaviour of the L-shaped reinforced concrete shear wall is similar in terms of load capacity and maximal displacement.

(a). Comparison of the lateral load vs. displacement hysteresis diagram for the specimen L00A.
The hysteretic behaviour of L-shaped reinforced concrete shear walls under cyclic loading obtained from the numerical model are identical to the experimental test.

The numerical results are in good accordance with the experimental ones, this demonstrates that the proposed numerical model with ANSYS is robust and efficient in terms of generating the cyclic behaviour of L-shaped reinforced concrete shear walls.

For this purpose, the present research obtained can be used:
- To develop design codes for L-shaped reinforced concrete shear walls.
- To review the conditions and provisions of the reinforcement stipulated in these codes.
- To propose other rules obtained from the experimental tests and this numerical study, especially those relevant to the cracking of the L-shaped walls.
For future work, the influence of some parameters (damage, stress, strain, cracks, etc.) at the finer scale on the behaviour of the macroscale model is ought to be determined.

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