Simulation of cohesive fracture method in concrete structures

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Abstract. The objective of fracture mechanics is to analyze the materials behavior and its failure modes applied to structures. Thereby, it is possible to identify the parameters that impact directly on crack evolution. Geometry, loading, and material properties are examples of crucial failure factors. There are some existing methods to analyze structural collapses, but the cohesive fracture is well known because of its efficiency, being used to calculate many different engineering materials. This paper uses the fundamental concepts of cohesive fracture to link experimental and numerical data. In other words, this paper aims to study a concrete structure in which was applied cohesive fracture method and then compare the theoretical results with experimental ones. Moreover, some parameters such as crack position, width, thickness, and fracture energy, were defined by finite element analyses. In general, the obtained results show conformity between both simulations.

Keywords: cohesive fracture, “L” shaped shell, numerical simulations

1 Introduction

Understanding structural behavior is crucial for the design stage. The description of structures by analytical equations is very limited, due to the high complexity of the differential equations that govern the problems. In order to overcome these problems, approximate methods emerged, which lead to approximate solutions to the problems. In particular for the numerical methods, the Finite Element Method (FEM) stands out. The non-linearity of the problems is another important aspect to be addressed. This behavior is intrinsic to materials, which do not present linear relationships in all situations. As consequence of linear elastic modeling, the structure might collapse under loads below its bearing capacity. Nonlinear theories have therefore emerged with the aim of evaluating these problems, in particular theory of plasticity, damage mechanics and fracture mechanics.

Theory of plasticity emerges aiming to analyze the nonlinear behavior of ductile materials, as permanent deformations. This theory leads to accurate results in plastic collapse problems, such as the one in reinforced concrete slabs, with the yield line theory [1]. However, the theory of plasticity is not able to modify the boundaries of the problem during the analysis. Continuum damage mechanics is other quite important nonlinear theory, which was formally presented by Lemaitre and Chaboche [2], introducing a new internal variable called damage. In such theory, these micro-cracks are not small enough to be neglected but not big enough to be considered as discrete cracks. However, some analysis through this theory may lead to problems in the formulation, due to the strain localization [3]. Fracture mechanics admits that all structures have initial discrete discontinuities, which allows to quantify the propagation of discrete cracks in continuum media. This theory emerges from the necessity to study the collapse of ships [4], being the initial researches purely analytical [5, 6]. Later, Griffith [7, 8] proposed that the cracking process based on an energy criterion.

The use of computational methods is also an important aspect in the fracture mechanics, once some problems present high complexity to be solved analytically. Cruse and Vanburen [9] were pioneers in this area, evaluating the stresses in the region near the crack tips of a three-dimensional structure. Later, Snyder and Cruse [10] evaluated the problem of fracture in an anisotropic media, with a solution based on Green's functions.

In the light of the foregoing, it is quite important to use theories that can adequately model the structures, taking into account the nonlinear effects, as for analyzing wooden structures [11], simple concrete structures [12-14], for bidimensional non-homogeneous and reinforced structures [15] or by proposing new computational framework for crack nucleation and propagation [16].

Therefore, this paper aims to evaluate a parametric study on the cohesive fracture method. Therewith, it was selected a structure from the literature, which were experimentally tested, and some of the parameters of the cohesive fracture model were changed, such as the width and position of the cohesive zone, as well as the stiffnesses of the cohesive elements.

2 Cohesive Fracture

The fracture mechanics have been developed, with the proposal of different nonlinear approaches, such as the theory of fictitious crack models. These models assume the presence of a fictitious crack in front of the real crack. The initial concepts were developed for brittle materials, such as glass, which were named as Linear Elastic Fracture Mechanics. This theory assumes the presence of a Zone of Inelastic Processes or Process Zone, in front of the actual crack, which for brittle materials has a negligible length [11].

Later it was found that for ductile and quasi-fragile materials the Process Zone have a considerably length. Hillerborg et al. [17] proposed the development of cohesive models for quasi-brittle materials, as shown in Figure 1, based on numerical simulations and experimental validation of concrete specimens.

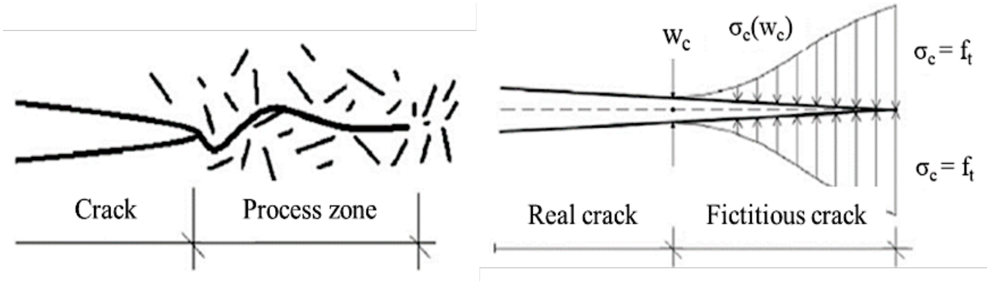


Figure 1. Cohesive stress distribution [11].

The development of models for evaluating ductile and quasi-brittle materials gave rise to what is known as Nonlinear Fracture Mechanics. This model assumes that the residual resistance within the Process Zone is a function dependent on the actual crack opening, known as cohesive stress. This stress represents the residual resistance in the process zone and acts to close the crack faces. As the evaluated point comes closer to the actual crack boundary, these cohesive stresses tend to zero. See e.g. Elices et al. [18] and Cordeiro and Leonel [11] and the references therein for a brief review.

The software Abaqus allows the nonlinear modeling of structures using the cohesive fracture model. It is possible to use different damage initiation and evolution criteria. The damage initiation methods include maximum stress, maximum specific strain, nominal quadratic stress and nominal quadratic strain. For the damage evolution, there are two available options: the maximum displacement or the fracture energy. In the first case, when the displacement value is reached, failure is complete and the simulation ends [19].

Fracture energy is a well-known variable, which corresponds to the work needed to a complete rupture of a cross section and may be defined as the area below the traction-separation graph or, experimentally, can be determined from the loads versus displacement curve measured from a three-point bending [20]. For this second damage evolution criterion Abaqus ensures that the area under this curve is equal to the fracture energy entered by the user as a material property. In addition, it is possible to choose between different post-peak softening behaviors, such as linear or exponential [19].

3 Numerical simulation procedures

This paper presents a parametric study on the cohesive fracture model, using the software Abaqus. Some parameters were varied, as the crack position, thickness and width of the cohesive zone, and the stiffnesses of the cohesive elements.

The study was applied to the experimental test developed by Winkler et al. [21]. The example consists in a "L" shaped shell, with dimensions 500 mm x 250 mm, 100 mm thick, with displacement of 1 mm, applied at 30 mm from the edge of the element, and a clamped support at the base, as shown in Figure 2(a). The cracked condition is shown in Figure 2(b). The elasticity modulus, Poisson's ratio, tensile strength, and fracture energy are equal to 25.85 GPa, 0.18, 2.7 MPa and 0.065 N/mm, respectively, which were fixed for all analyses.

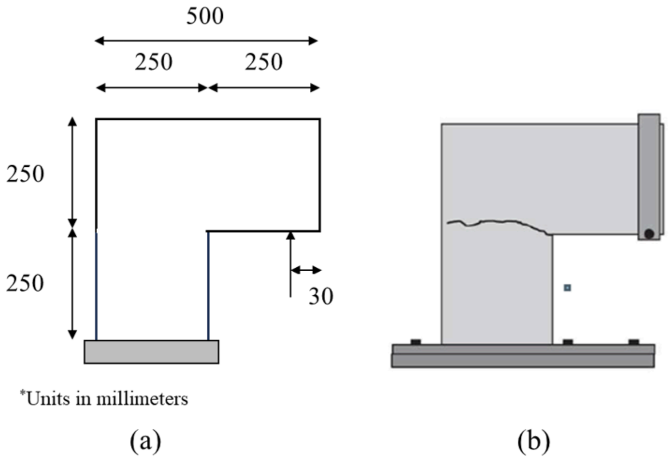


Figure 2. Test set-up [21].

For the numerical analyses developed in this paper, it was considered two different cracked conditions: a horizontal (Figure 3(a)) and other with position similar to the experimental cracking (Figure 3(b)). Moreover, the example was sketched on Abaqus, considering a 2D shell, and all meshes have approximately 25 mm global size.

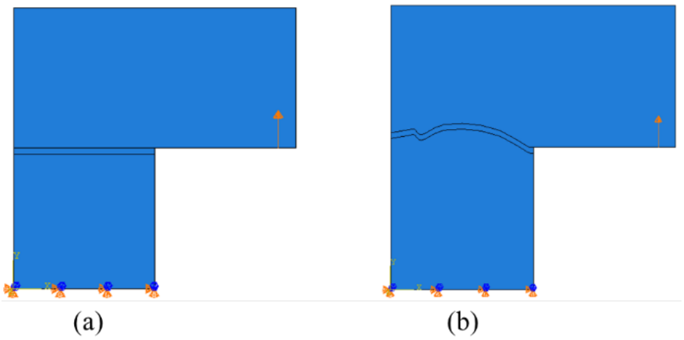


Figure 3. Cohesive fracture zones: (a) horizontal and (b) similar.

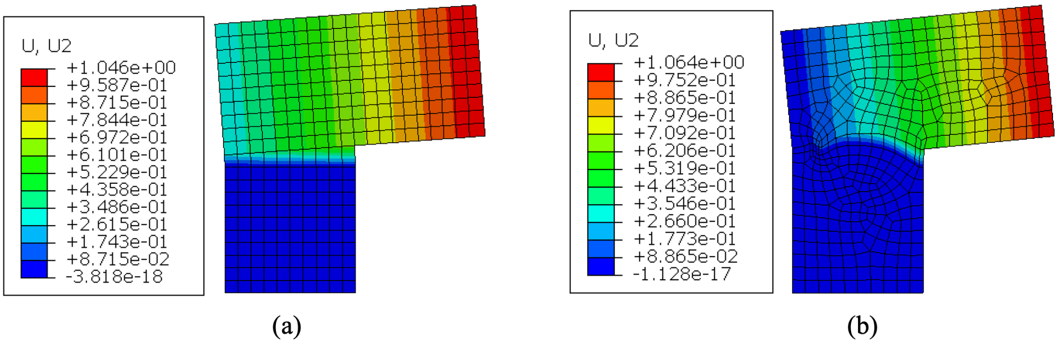
The element COH2D4 of the Abaqus library was chosen for the cohesive zone. This is a 4-node two-dimentional cohesive element, with 2 degrees of freedom per node. For the remaining area of the example, the CPS4 finite elements was set. It is a 4-node bilinear plane stress quadrilateral finite element, without reduced integration, also from the Abaqus library, with 2 degrees of freedom per node [19].

Regarding the constitutive model, for the cohesive zone (COH2D4 finite elements), for the elastic stage, the analysis type was defined as traction, which stiffnesses where varied in the parametric analyses. For the damage initiation, it was selected the Quadratic nominal stress criterion (Quads damage), which assumes the interaction among the stresses in the section, which maximum values were set equal to the tensile strength. The damage evolution was selected based on a energy criteria, with linear softening behavior. For this condition, the experimentaly reported fracture energy was set. The remaining regions of the example (CPS4 finite elements) were defined to have only elastic behavior, the analysis type was defined as isotropic, and the elasticity modulus and Poisson's ratio were defined according to the experimental report.

4 Results

4.1 Cracks shape of the cohesive zone

The first analysis is related to the position of the cohesive zone (Figure 3). The thickness of the cohesive zone, for both conditions, was equal to 10 mm, the stiffnesses of cohesive elements were set equal to 10 times elasticity modulus and the cohesive zone was defined from the front surface until the back surface of the structure, as presented in Figure 3. The deformed condition for the horizontal and similar cracked position are shown in Figure 4 (a) and Figure 4 (b), respectively.



(a) (b)

Figure 4. Deformed condition for the cracks: (a) horizontal and (b) similar.

The experimental Load vs. Displacement curves from Winkler et al. [21] were compared to the ones obtained through the numerical simulations, which are shown in Figure 5. Note that, both numerical results are quite close, which the case with the horizontal crack tends to zero faster. It indicates that defining the crack with similar shape to the experimental one, leads to more accurate results.

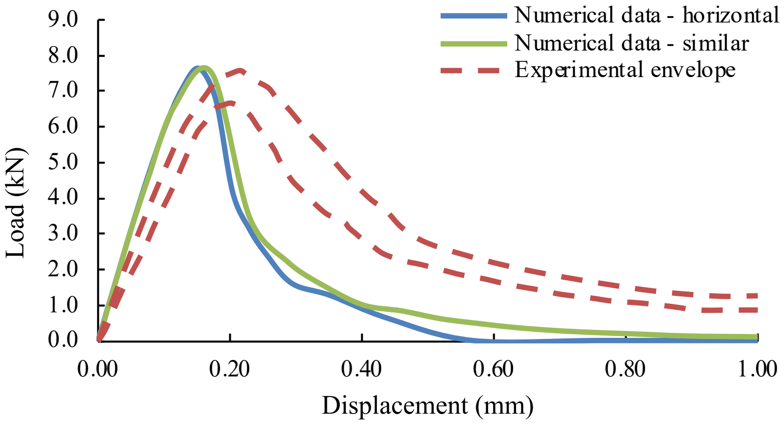


Figure 5. Load vs. Displacement: Horizontal and similar cracks shape analysis.

4.2 Thickness of the cohesive zone

The second analysis realized was the comparison of the thickness of the cohesive zone. For these numerical simulations, it was considered the cohesive zone with horizontal shape (Figure 3(a)), using different thickness between 5 mm and 10 mm. Similar to the first analysis, the stiffnesses of cohesive elements were set equal to 10 times the elasticity modulus and the cohesive zone was defined from the front surface until the back surface of the structure. Different thicknesses were tested, resulting similar curves, which two of them are displayed in Figure 6. Regardless of the thickness, the deformation is similar to the observed in Figure 4.

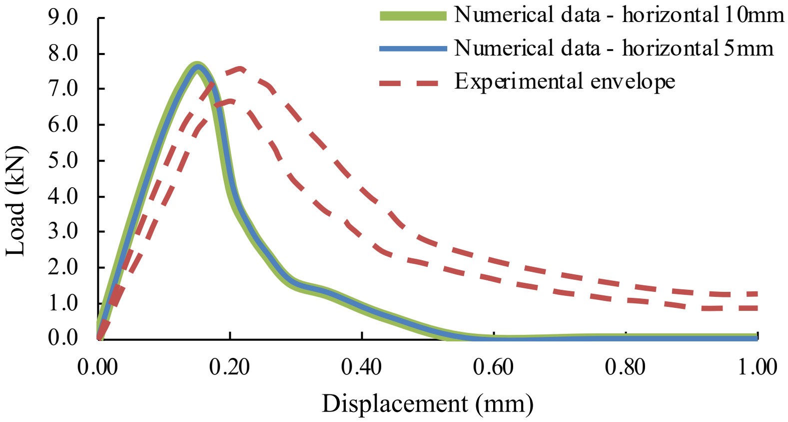
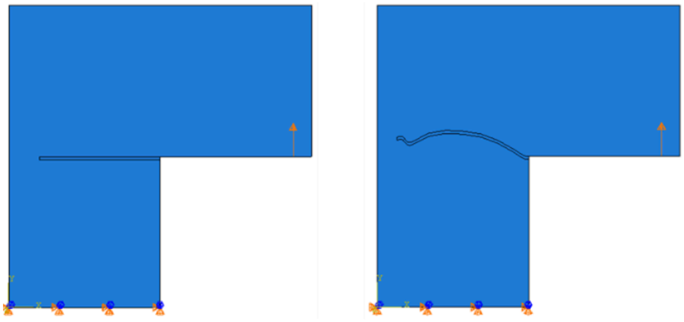


Figure 6. Load vs Displacement: Horizontal thickness of the cohesive zone analysis.

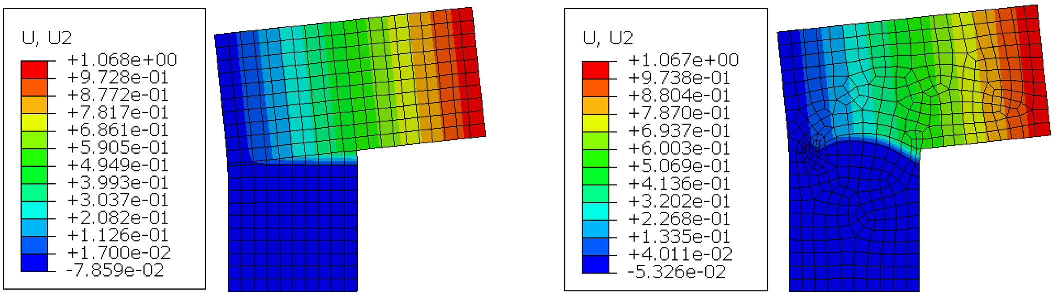
4.3 Width of the cohesive zone

The width of the cohesive zone was also analyzed. It was defined a cohesive zone from the front surface until 50 millimeters before the back surface of the "L" shaped shell, as shown in Figure 7. The stiffnesses of cohesive elements were defined equal to 10 times the elasticity modulus. The deformed condition for the example with the horizontal crack and the crack similar to that experimentally observed are presented in Figure 8 (a) and Figure 8 (b), respectively.



(a) (b)

Figure 7. Cohesive zones width: (a) horizontal and (b) similar.



(a) (b)

Figure 8. Deformed for different widths: (a) horizontal and (b) similar.

Figure 9 depicts the Load vs. Displacement curves, comparing the numerical results to the experimental ones. Note that, for these analyses, the remain 50 mm width caused an increase in the resistance of the structures, which load increased after a displacement of approximately 35 mm (Figure 9), compared to the results, considering the cohesive zone along all specimen (Figure 5). This indicates that it is necessary to define the width of the cohesive zones in agreement with the cracked condition, for this example, along all "L" shaped shell.

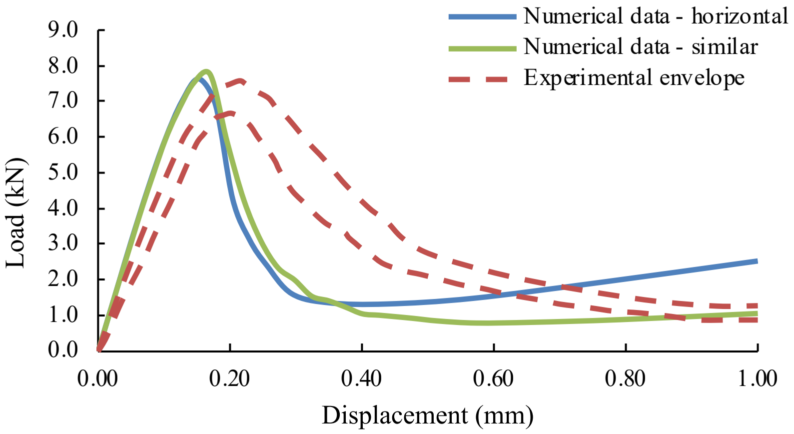


Figure 9. Load vs Displacement: Horizontal and similar width analysis.

4.4 Stiffnesses of the cohesive elements

Finally, it was analyzed the influence of the stiffnesses of the cohesive zone. All parameters of the width analysis were kept the same, except the stiffnesses of the cohesive elements. Instead of multiplying the stiffness by 10 times the elasticity modulus, it was tested different multiplier factors to find out a better relation. Therefore, it was found out that the best numerical coefficient is 20% of the elasticity modulus. The deformed condition is similar to one Figure 8 and the Load vs. Displacement curves are shown in Figure 10.

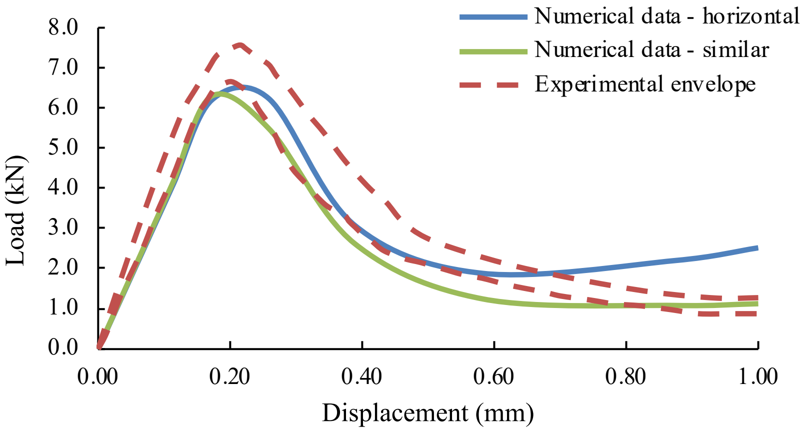


Figure 10. Load vs. Displacement: Stiffnesses analysis.

5 Conclusions

The accurate description of a structure is fundamental, in order to consider all parameters that causes influence in the response, specially aiming to take into account the inelastic effects. This paper evaluated a parametric study on the cohesive fracture method using the software Abaqus. Some parameters of the model were changed such as the cracking position, cohesive zone thickness and width, and the stiffnesses of the cohesive elements. It was noticed that the crack position (horizontal or similar to experimental) presents a low significance in the response, while the thickness of the cohesive zone does not present caused any influence in the results, analyzing the Load vs. Displacement curves. However, the width of the cohesive zone may significantly influence the structural response, which it is more appropriate to define widths similar to the experimental observations. The stiffnesses of the cohesive elements also presented a high influence in the response, which it was adopted equal to 20% of the elasticity modulus, and leaded the Load vs. Displacement closer to the experimental results. Finally, this paper contributes for a better understanding of the cohesive fracture model on Abaqus.

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