CILAMCE 2017

Florianópolis - Santa Catarina - Brazil

COHESIVE MODELS FOR DAMAGE EVOLUTION IN ADHESIVE JOINTS USING FINITE ELEMENT.

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Abstract. *In the last years, adhesive joints have been widely used for structural applications such as aeronautical, automotive and others, in which high structural performance is necessary. However, joining components may not be trivial. Considering their nature, bonding appears to be the natural choice for joining. The use of structural bonded joints has consequently increased due to the benefits this type of joint can offer with respect to the mechanical fastening efficiency. More uniform stress distributions, lower maintenance costs and improved fatigue resistance are some advantages, among others. However, to improve accuracy of numerical failure predictions for adhesively bonded joints design, inclusion of different damage modes and damage growth cohesive zone models (CZM) are necessary. Both static (material strength) and dynamic (fracture mechanics) based criteria are important in the design. Different damage modes can occur, such as intraply open (mode I) or shear (mode II) cracks, and interply delamination. The use of cohesive elements within the Finite Element Method (FEM) in conjunction to adequate failure criteria is desirable to accurately describe failure of bonded joints. In this work, the commercial FEM platform Abaqus® will be used to studies parameters like adherent thickness, initial crack length and joint strength for the assessment of static debonding of Double Cantilever Beam (DCB) configuration using cohesive elements. Numerical predictions will be compared to analytical results.*

Keywords*: FEM; delamination; adhesive bonded joints; cohesive elements, double cantilever beam.*

1 INTRODUCTION

Adhesive joints presents several advantages over other conventional bonding methods like mechanically fastened joints. To benefit from these advantages it is crucial to design bonded joints properly. Two classical methods of failure prediction was current used: strength of materials and fracture mechanics. However, these methods presents some disadvantages. As mentioned by Da Silva (2000), the stress calculated by strength of materials methods present mesh dependency during numerical analysis due to stress singularities. Already, the fracture mechanics approach relies on the definition of crack length but in many structural applications, the damage initiation locus is not obvious. Therefore, some methods like cohesive zone methods (CZM) emerge as suitable options.

This model have a large advantage because combine methodologies of strength of materials and fracture mechanics to predict the behavior of adhesive joints. Because of that, CZMs are included in several commercial finite element codes like *FEM platform Abaqus®* and are widely used for various applications, in particular to study of the resistance of adhesive joints. So cohesive elements enable the modeling of fracture initiation and propagation in FEM analyses.

The cohesive zone methods (CZM) are models used in a numerical progressive damage analysis that accounts for damage development and degradation of the properties of adherents and adhesive. As mentioned by Barbero (2013), physically, these methods assumption that the stress transfer capacity between two separating faces of a debonding is governed by progressive stiffness reduction.

The cohesive behavior is described in terms of traction-separation (P-δ) through of relation of damage evolution, damage initiation and elastic stiffness. However, as seen in Diehl (2005) for accurate overall simulation of fracture initiation and propagation, the most important property is damage evolution followed by the damage initiation and finally the elastic stiffness. Fracture toughness defines damage evolution and interface strength defines damage initiation of cohesive elements. The fracture toughness is a critical energy released rate measure experimentally.

The accurate evaluation of cohesive parameters is a fundamental task in order to obtain good strength predictions. This can be achieved using as specimen a Double Cantilever Beam (DCB) fracture characterization. This article provides an application of cohesive zone models using the DCB standard test (ASTM D3433) to measure materials fracture properties under pure mode I loading. Therefore, some parameters like adherent thickness, initial crack length and joint strength was studies to modeling debonding growth.

2 COHESIVE ZONE METHOD

Cohesive Zone Method assume that ahead of the crack tip, there is a very thin layer separating two solids where the damage mechanisms leading to fracture are localized. Therefore, after damage onset, the interface material starts losing its stiffness.

In a recent work (Barbero et al, 2013), suggested that there are three condition of damage variable. The first one occur when $D = 0$ and in that stage, the interface material is undamaged, thus retaining its initial stiffness. In a second condition, $0 < D < 1$, the material

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is gradually losing its stiffness. Finally, for $D = 1$, there is no remaining stiffness for the interface joint., in other words, occurs total separation of the cohesive connection between the two faces. The Fig 1 illustrate these conditions of damage variable in cohesive method.

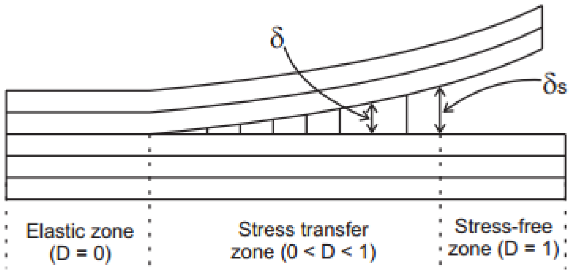

Figure 1. Cohesive zone method to simulate crack propagation - Barbero (2013)

Cohesive elements capture the initiation and propagation of debonding using the concept of CZM. As seen in Abrate (2015), constitutive law used a bilinear relation between the tractions and the displacement as presented in Fig. 2.

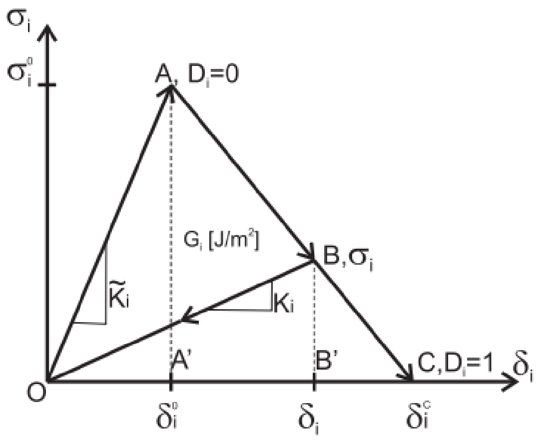

Figure 2. Stress transfer model for cohesive zone model - Barbero (2013)

Looking at Fig. 2, the line OA corresponding to a linear elastic undamaged material behavior ($D = 0$). Segment AC damage represents damage evolution ($0 < D < 1$) when the material is gradually losing its stiffness. The CZM element uses the classical assumption of elastic damage typical of continuum damage mechanics. Therefore, unloading from any point such as B on the line AF will return to the origin without permanent deformation.

In the numerical formulation, the corresponding separations between the opposite faces of the CZM element are denoted as function of displacement (δ_i) and surface traction (σ_i) through the interface stiffness (k_i). The index i represents mode I, II, or III illustrated by Fig.3.

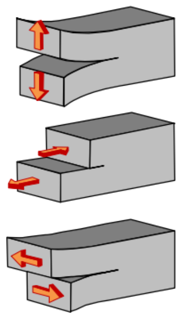

Figure 3. The three fracture modes: (a) Mode I; (b) Mode II; (c) Mode III - Abrate (2015)

The traction-separation is described by:

$$\sigma_i = k_i \delta_i \tag{1}$$

$$k_i = (1 - D_i)\widetilde{k_i} \tag{2}$$

Where D_i are the damage variables, and $\widetilde{k_i}$ are the stiffness values of the undamaged materials at the interface.

Numerically the process start when the damage onset at point A (see Fig. 2). In this point, the stress σ_i and displacement δ_i achieve a critical level. Damage initiation criteria to stress and separation (displacement) are calculate by:

$$\sigma_i = \sigma_i^0 \tag{3}$$

$$\delta_i^0 = \sigma_i^0 / \widetilde{k_i} \tag{4}$$

After damage onset, the interface material starts losing its stiffness. This stage involve the damage evolution parameter, which, as said before, is important to accurate overall simulation of fracture initiation and propagation. The correlation is made considering that the area under the (σ−δ) curve in Fig. 2 is equal to the critical energy released rate (G_{ic}). Separation at fracture displacement (δ_i^c) can be calculate as:

$$\delta_i^c = 2G_{ic} / \sigma_i^0 \tag{5}$$

Thereby, substituting Eq. (1) into Eq. (2) and rearranging using Eq. (4), damage parameter of Cohesive Zone Method is calculate by:

$$D_i = 1 - \frac{\sigma_i \delta_i^0}{\sigma_i^0 \delta_i} \tag{6}$$

By similarity of triangles BB'F and AA'F (see Fig. 2),

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$$\frac{\sigma_i}{\sigma_0} = \frac{\delta_i^c - \delta_i}{\delta_i^c - \delta_i^0} \quad (7)$$

Substituted Eq. (7) into Eq. (6),

$$D_i = \frac{\delta_i^c(\delta_i - \delta_i^0)}{\delta_i(\delta_i^c - \delta_i^0)} \quad (8)$$

In this way, solution damage variable D_i, in finite elements method, is calculated as a function of the relative separation between the faces of the laminate δ_i, evaluated in each interactive process, and δ_i^0, δ_i^c, calculates with Eq. (4) e Eq. (5) respectively.

To calculate D_i and k_i is necessary fracture mechanics concepts. The strength of materials concepts is related to value of effective elastic modulus value (E_{eff}) of the cohesive material, which is calculate as:

$$E_{eff} = k_i h_{eff} \quad (9)$$

Where h_{eff} is initial effective thickness of cohesive element.

3 FINITE ELEMENT MODEL DEVELOPMENT

The double cantilever beam (DCB) test, as defined in ASTM 3433, is generally used to determine the mode I fracture toughness. As mentioned before, DCB was used in this work to modeling fracture and failure of adhesive joint using cohesive element. The Fig 4 present DCB model simulate *FEM platform Abaqus®.*

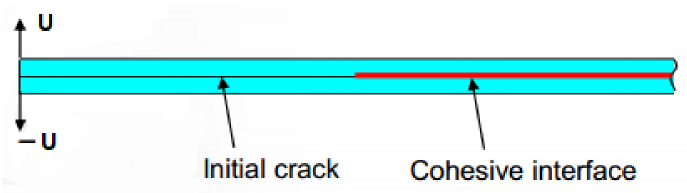

Figure 4. Double cantilever beam (DCB) model (Surface-based Cohesive Behavior Lecture 6 – Abaqus Course)

As was proposed by Barbero (2013), there are two types of cohesive elements in *Abaqus:* CZM elements with finite thickness and CZM elements with zero thickness. The first is used to modeling fracture behavior of adhesive bonds where the thickness of the interface is considerable. Already, the second element is used when the thickness of the interface is negligible. In this work, DCB was modelling with elements with zero thickness because in our models the adherent layer is much thicker than adhesive layer.

To execute debonding analysis using surface based in cohesive behavior you must define:

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- Contact pairs and initially bonded crack surfaces;
- Traction-separation behavior;
- Damage initiation criterion;
- Damage evolution.

The Fig. 4 illustrated contact pairs and initially bonded crack surfaces in DCB. The bond region connect top to the bottom surface with cohesive element. Nodes, as seen in Fig. 5 accomplish this contact between surfaces in FEM. The initially bonded crack represents the length of bond onset before the damage evolution start.

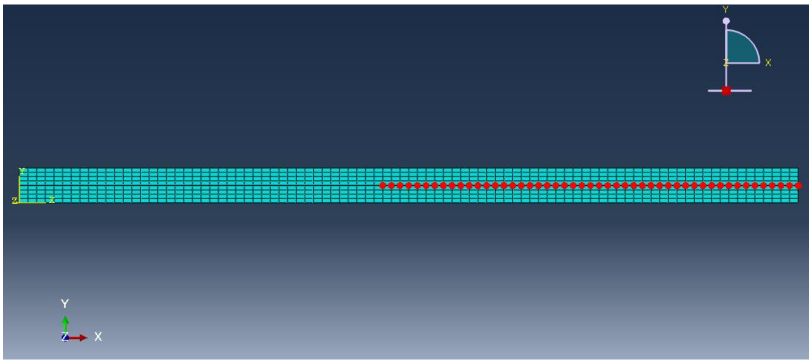

Figure 5. FEM model to contact pairs and initially bonded crack surfaces

The traction-separation behavior is defined by stiffness values ($\widetilde{k_i}$) to open (mode I), shear (mode II) and tearing (mode III) cracks. Thus, in FEM analysis there are four criterions damage initiation: maximum stress, maximum separation, quadratic stress and quadratic separation. Inside table 1, Eq. (10), (11), (12) and (13) present each criterion cited above. The maximum value of stress (σ_i^{max}) and separation (δ_i^{max}) are calculate by stiffness($\widetilde{k_i}$) values

Table 1.Criterions to damage initiation

Maximum stress criterion $MAX(\sigma_i/\sigma_i^{max}) = 1$ (10)	Maximum separation criterion $MAX(\delta_i/\delta_i^{max}) = 1$ (11)
Quadratic stress criterion $\left(\frac{\sigma_I}{\sigma_I^{max}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{II}^{max}}\right)^2 + \left(\frac{\sigma_{III}}{\sigma_{III}^{max}}\right)^2 = 1$ (12)	Quadratic separation criterion $\left(\frac{\delta_I}{\delta_I^{max}}\right)^2 + \left(\frac{\delta_{II}}{\delta_{II}^{max}}\right)^2 + \left(\frac{\delta_{III}}{\delta_{III}^{max}}\right)^2 = 1$ (13)

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Fracture toughness G_{ic} is a critical energy released rate measure experimentally and its define damage evolution. Power Law and Benzeggagh-Kenane (BK) are criterions to calculate damage evolution in FEM analysis. Equations (14) and (15) presents in a reference Surface-Based Cohesive Behavior, power law and BK are calculate, respectively, as function of mode mix.

$$\left(\frac{G_I}{G_{IC}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIC}}\right)^{\alpha} + \left(\frac{G_{III}}{G_{IIIC}}\right)^{\alpha} = 1 \quad (14)$$

$$G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{shear}}{G_T}\right)^{\eta} = G_{TC} \quad (15)$$

Where

$$G_{shear} = G_{II} + G_{III} \quad (16)$$

$$G_T = G_I + G_{shear} \quad (17)$$

Finally, to complete double cantilever beam analysis is necessary set boundary condition. Figure 6 illustrated axial and transversal displacements, u_x and u_y, fixed in one edge, and opposite displacement opening the joint. This FEM model represent exactly DCB model seen in Fig. 4.

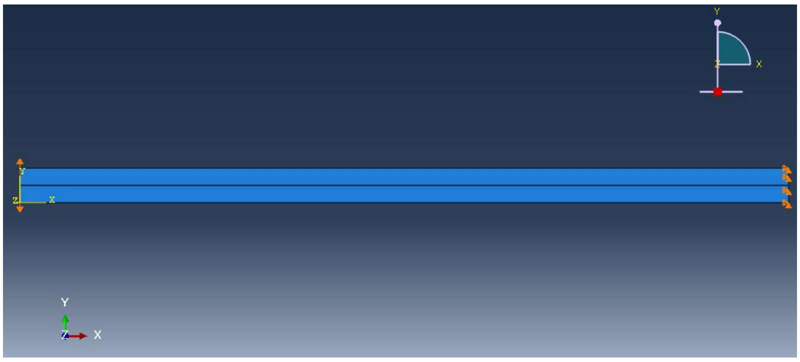

Figure 6. DCB boundary Conditions.

4 FINITE ELEMENT MODEL VALIDATION

The numerical model was validated by DCB standard test with known of analytical solution proposed by Hermes (2010) and ASTM D3433. Figure 7 shows main dimensions of specimen where the adherents have linear elastic isotropic material with a modulus of 55 GPa and Poisson's ratio 0.3. The fracture energy of the interface in mode I (assumed given, based on suitable experiments) is 0.350 kJ/m2 and the interface was modeled via zero-thickness cohesive elements. The initial debond length (a0) was considered 90 mm.

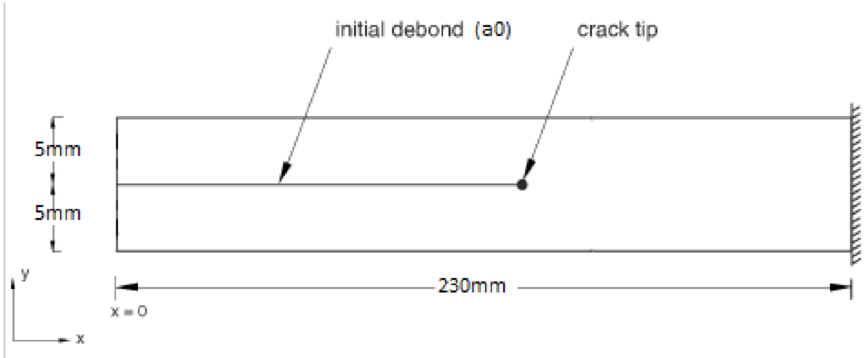

Figure 7. Main dimensions setted in FEM analysis.

Figure 8 illustrated displacement of DCB specimen under pure mode I loading. Warm color represents traction-separation resistance around interface cohesive elements region. Figure 9, shows a comparison of traction-separation through of $P - \delta$ curve calculated by analytical solution and FEM numerical solution. Note that the numerical result is in a very good agreement with the analytical solution.

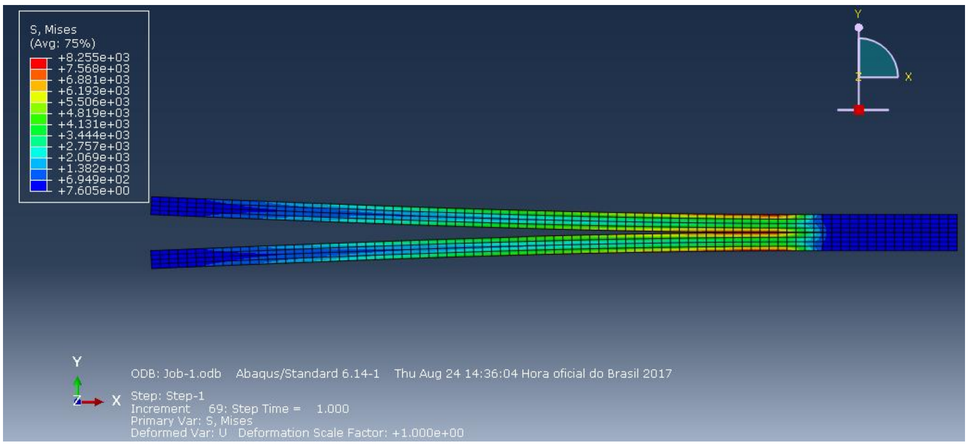

Figure 8. Stress-separation propagated by interface cohesive elements region.

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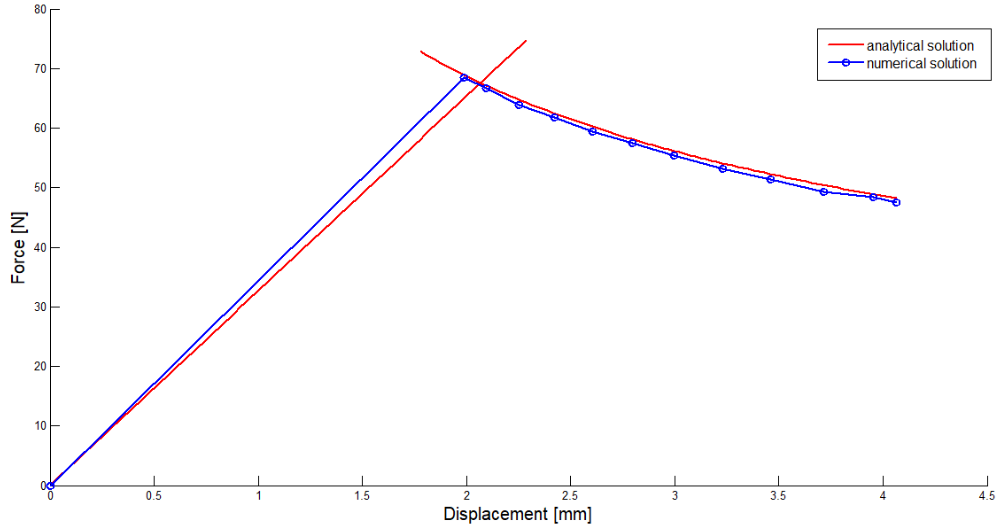

Figure 9. $P-\delta$ curve to numerical and analytical solution.

A mesh study was also performed. That is important to describe accurately failure of bonded joints. Figure 10 presents a $P-\delta$ response comparing a mesh with 180 and 360 elements.

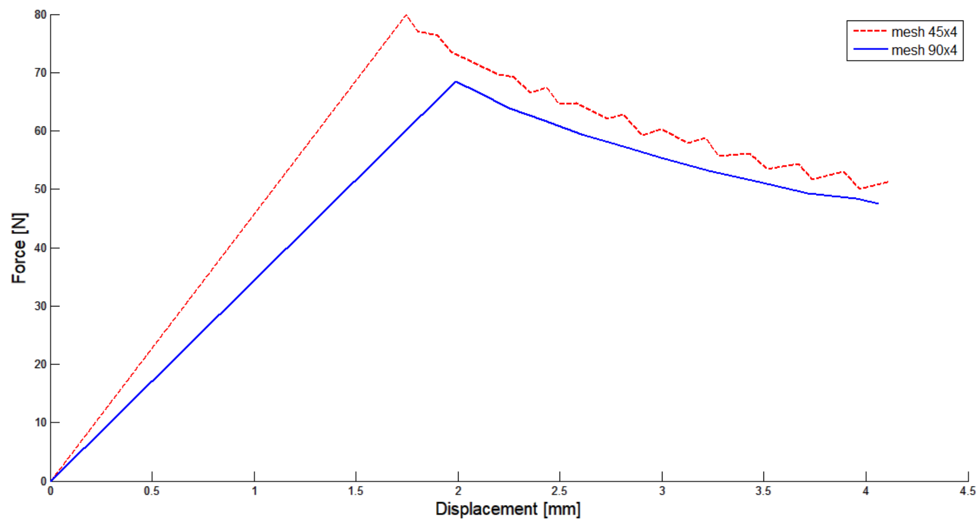

Figure 10. Influence of mesh on the $P-\delta$ curve

5 EFFECT OF THE ADHERENT THICKNESS AND INITIAL CRACK LENGTH ON DEBONDING GROWTH

In a DCB simulation, two parameters have great influence in joint strength: adherent thickness, h, and initial crack length, a0. These variables are important to define appropriate configuration of joint adhesive.

As expected, the Fig. 11, shows that a0 changed only damage initiation point. Therefore, is important to note that this parameter doesn´t influence on damage evolution. A smaller value of a0 means that the maximum load to start damage is higher while the critical separation displacement value is smaller. Comparing to Fig 3.19 showed in Hermes (2010), the numerical solution simulated in the present work calculated precisely this behavior.

The adherent thickness, h, alter damage initiation point and damage evolution curve. The $P-\delta$ curves (Fig. 12) obtained by FEM, shows that adhesive joint become more resistance using thicker adherents as expected. In other words, maximum load to achieve the damage initiation and load to achieve complete failure are higher. Again, the numerical simulation with CZM represented good agreement with joint strength behavior for debonding growth.

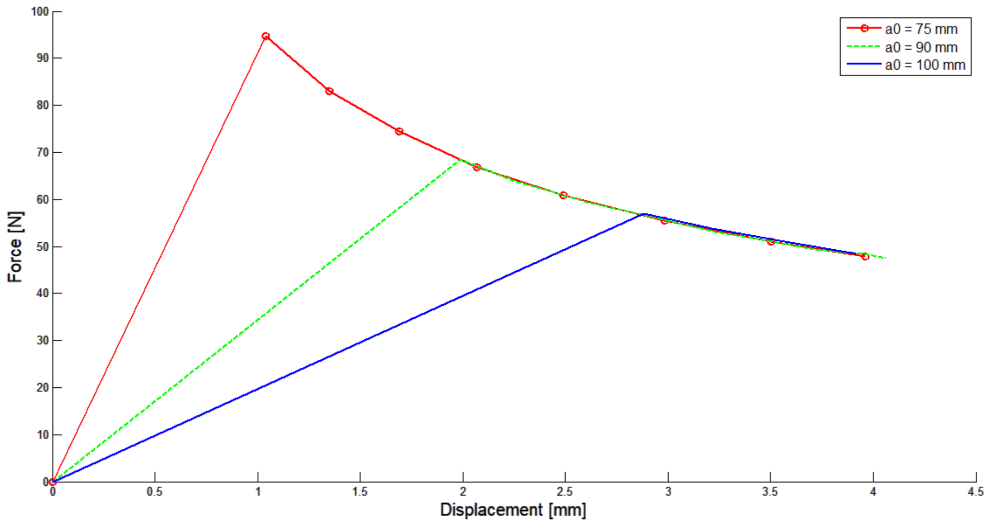

Figure 11. Initial crack influence in a $P-\delta$ curve.

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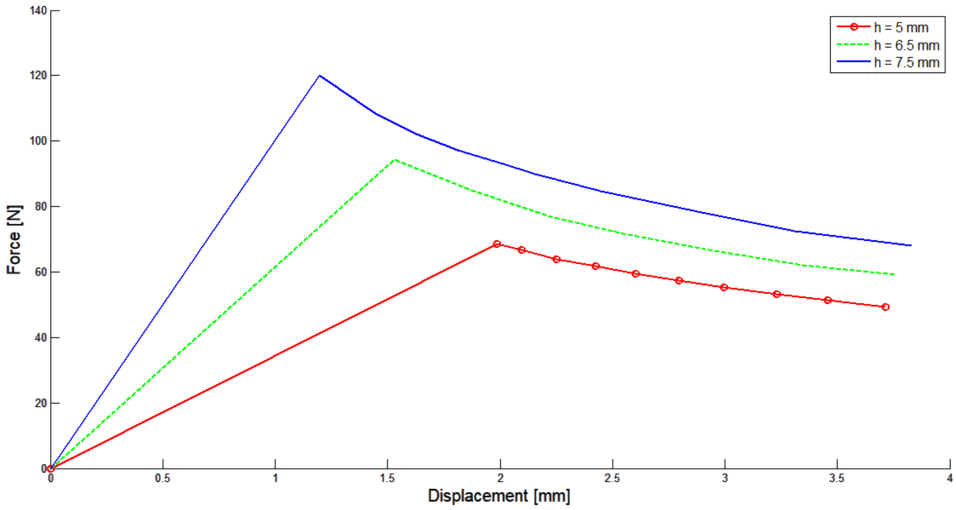

Figure 12. Adherent thickness,influence in a $P - \delta$ curve.

6 CONCLUSION

After a complete analysis on the parameters influencing the numerical results, a good correlation was obtained between the simulated and the analytical solution through load-displacement curves, as illustrated in Fig. 9. The study of adherent thickness and initial crack of length was important to check the efficiency of CZM to simulate correctly the behavior of fracture initiation and propagation.

This work presents fundamentals concepts and application of cohesive elements using Finite Element Method (FEM). In conjunction to adequate failure criteria, it is emerge as suitable option to accurately describe failure of bonded joints.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the important support of the Brazilian research agency FAPEMIG (in portuguese “Fundação de Amparo à Pesquisa do Estado de Minas Gerais”) and Department of Structural Engineering of UFMG (DEES).

REFERENCES

Abaqus Course, Lecture 6, *Modeling Fracture and Failure with Abaqus: Surface-based Cohesive Behavior.*

Abrate, S, Ferrero, J.F, Navarro, P, 2015 *Cohesive zone models and impact damage predictions for composite structures*, Advances in the mechanics of composite and sandwich structures, Springer.

Adrian, S.F, Mihai, C.D, 2012, I*nterface damage characterization through cohesive parameters,* Journal of Engineering Studies and Research – Volume 18 (2012) No. 3.

ASTM Standard D3433-99, 2012, *Standard test method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints*, ASTM Int., W. Conshohocken, PA.

Barbero, E. Jr, 2013 Finite Element Analysis of Composite Materials with Abaqus, CRC Press Taylor & Francis Group 2013, pp. 353-361.

Campilho, R.D.S.G., De Moura, M.F.S.F, Domingues J.J.M.S, 2008, *Using a cohesive damage model to predict the tensile behaviour of CFRP single-strap repairs,* International Journal of Solids and Structures 45 (2008) 1497–1512

Da Silva, L.F.M, 2008, *Modeling of Adhesively Bonded Joints,* eds. Springer Berlin Heidelberg 2008 pp. 155-162.

Hermes, F.H., 2010, *Process zone and cohesive e element size in numerical simulations of delamination in bi-layers.* Master Thesis, Eindhoven University of Technology Department of Mechanical Engineering.

Moslemi, M, Khoshravan, M, 2015, *Cohesive Zone Parameters Selection for Mode-I Prediction of Interfacial Delamination*, Journal of Mechanical Engineering 61(2015)9, 507-516.

Turon, A., Davila, C. G., Camanho, P. P., Costa, J., 2010, *Accurate simulation of delamination growth under mixed-mode loading using cohesive elements: Definition of interlaminar strengths and elastic stiffness*. Composite Structures 92 (2010).

Waseem, M.H.S, Kumar, N., 2014, *Finite Element Modeling for Delamination Analysis of Double Cantilever Beam Specimen,* SSRG international journal of mechanical engineering– volume1issue5, September 2014.