# A damage interface model for adhesive bonded joints

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***Abstract.*** *The need for increasing structural performance, with low weight and high strength, has demanded the use of more effective joining methodologies. Mainly due to their low weight, low cost and ease of assembly, the adhesive bonds have emerged as a promising technology. This paper proposes a damage interface model to simulate the behaviour of adhesive bonded joints. This model was used before to represent the interlaminar degradation in composite materials and is based on damage mechanics. Considering the mechanical tests of aluminium/epoxy specimens, comparisons between experimental and numerical results are presented.*
***Keywords:*** *damage interface, bonded joints, mechanical tests*

## 1. Introduction

The widespread use of adhesive joints is indicative of the advantages of the adhesive bondind over techniques such as welding and riveting. Contrary to holes, rivets, clamps and screws which have a tendency to cause stress points in concentrated areas, adhesives tend to distribute the load over the entire bonded area. However, the use of adhesive bonding in aircraft structures and other safety critical applications has been limited due to the lack of adequate tools of design and control.The development of numerical tools of design is necessary to increase the utilization of bonded joints in the industry. Interface damage models have been extensively used for the non-linear incremental analysis of debonding in the last years (Allix and Corigliano, 1996; Allix *et al.* , 1998; Mi *et al.* , 1998; Alfano and Crisfield, 2001). This damage models used some parametres that can be identified from mechanicals tests.
This paper proposes a damage interface model to simulate the behaviour of adhesive bonded joints. Comparisons between experimental results in aluminium/epoxy specimens and numerical simulation are presented.

## 2. Interface model

In the cohesive-zone approach the description of a state of damage along an interface relies upon the definition of a traction-separation law incorporating the dependence of the surface tractions on the corresponding displacement discontinuities $[u] = u^+ - u^-$ and the damage criterion to be met for the cohesive process zone to grow and the crack advance. In the simplest one-dimensional case the damage onset and decohesion propagation conditions only involve the single-mode displacement or energy release rate component; on the contrary, when considering the mixed-mode case these conditions have to properly account for the interaction of the pure-mode contributions.
In this last case the work of separation per unit fracture area does actually results from the interplay of the I and II pure-mode contributions, that are not independent in that they evolve together as a consequence of the interaction of the traction-displacement jump relationships in two directions.
In what follows we shall briefly discuss the cohesive-zone model used in this work. A more exhaustive presentation of this model can be found in Champaney and Valoroso (2004).

### 2.1 Pure-mode model

The adhesive joint here considered consists of two elastic bodies (adherends) joined by a plane adhesive layer the thickness of which is assumed to be negligible compared to both that of the joined bodies and to its in-plane dimensions. These features enable the adhesive layer to be conveniently schematized as an interface, i.e. as a zero-thickness surface entity which ensures displacement and stress transfer between the adherends, see fig. 1.
Assuming that the displacement jump $[u] = u^+ - u^-$ at the interface in one direction is small in the usual sense, the elastic damage model for the interface can be derived based on a stored energy function defined as:

$$\psi([u], D) = (1 - D)\frac{1}{2}K[u]^2 \tag{1}$$

where $D$ is a scalar variable measuring the damage of the interface as a loss of stiffness $K$. The associated interface traction in the direction of the jump is then the following:

$$t = \frac{\partial \psi}{\partial [u]} = (1 - D)K[u] \tag{2}$$

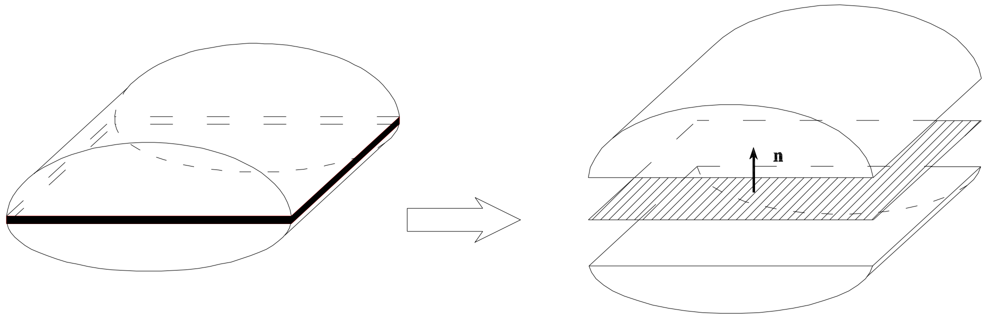


Figure 1. Interface model

The damage driving force is classicaly defined by:

$$Y = -\frac{\partial \psi}{\partial D} = \frac{1}{2} K [u]^2 \tag{3}$$

The damage evolution is subjected to the classical loading/unloading conditions:

$$f(Y) \leq 0 \qquad \dot{D} \geq 0 \qquad f(Y)\dot{D} = 0 \tag{4}$$

$$f(Y) = Y - Y^{\star} \qquad D \in [0,1] \tag{5}$$

where the damage threshold $Y^{\star}$ is defined by:

$$\begin{cases} Y^{\star} = G_0 & if D = 0 \\ Y^{\star} = G_0 + (Y^f - G_0)\left[-\log(1-D)\right]^N & if D \in ]0,1[ \\ Y^{\star} = \max\limits_{\tau \in [0,T]} Y(\tau) & if D = 1 \end{cases} \tag{6}$$

The energy dissipated in the decohesion process is:

$$\int_0^1 Y^{\star}(D) dD = G_o + \left(Y^f - G_o\right) \Gamma(N+1) = G_c \tag{7}$$

where $\Gamma$ is the Gamma function (Andrews et al., 1999), defined by:

$$\Gamma(N+1) = \int_0^{+\infty} x^N e^{-x} dx = N \cdot \Gamma(N) \tag{8}$$

The traction-separation relationship for this model is depicted in Figure 2.

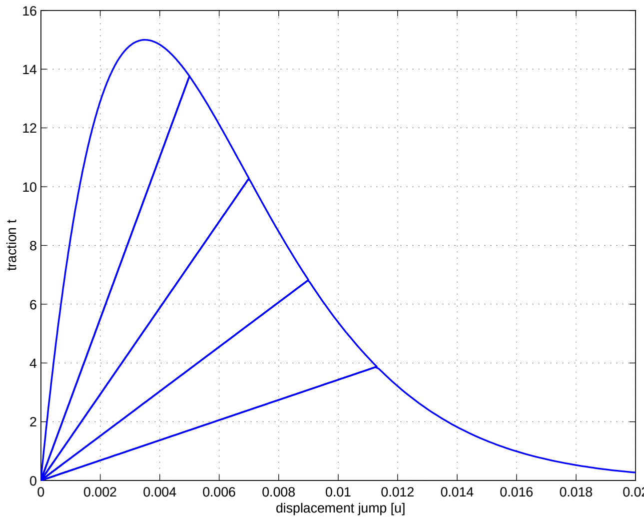


Figure 2. Pure-mode model

### 2.2 Mixed-mode model

As opposite to the single-mode case, where the criteria used for determining damage onset and propagation up to complete failure only involve one single component of the energy release rate, when considering mixed-mode conditions the total energy released during decohesion ($G_T$) results from the interplay of the $I$ and $II$ pure-mode contributions that evolve together as a consequence of the interactions between the traction-displacement jump in the normal and tangencial directions.

$$G_T = G_I + G_{II} \tag{9}$$

The stored energy function takes the following form:

$$\psi([\mathbf{u}], D) = (1-D)\left[\frac{1}{2}K_L < [u_L] >_+^2 + \frac{1}{2}K_T[u_T]^2\right] + \frac{1}{2}K_L < [u_L] >_-^2 \tag{10}$$

where $K_L$ is the longitudinal stiffness and $K_T$ is the transversal stiffness, the symbols $< . >_+$ and $< . >_-$ stand for the positive and negative part of $< . >$, defined as $< x >_\pm = 1/2(x \pm |x|)$.

The constitutive equations for the interface traction vector **t** and the damage driving force are obtained in the usual way as:

$$\mathbf{t} = \frac{\partial \psi}{\partial [\mathbf{u}]} \tag{11}$$

$$Y = -\frac{\partial \psi}{\partial D} = \frac{1}{2}K_L \delta^2 \tag{12}$$

where $\delta$ represent an equivalent displacement defined as:

$$\delta = \left(< [u_L] >_+^2 + \frac{K_T}{K_L}[u_T]^2\right)^{\frac{1}{2}} \tag{13}$$

The energy release rate for the two modes are:

$$\begin{cases} Y_I = \dfrac{1}{2}K_L < [u_L] >_+^2 & = \dfrac{1}{1+\overline{\beta}^2} Y_m \quad (modeIparticipation) \\ Y_{II} = \dfrac{1}{2}K_T[u_T]^2 & = \dfrac{\overline{\beta}^2}{1+\overline{\beta}^2} Y_m \quad (modeIIparticipation) \end{cases} \tag{14}$$

where $\overline{\beta}$ account for the mode mixity:

$$\overline{\beta} = \sqrt{\frac{K_T}{K_L}}\beta \qquad and \qquad \beta = \frac{[u_T]}{< [u_L] >_+} \in [0, +\infty] \tag{15}$$

$\beta$ is the mixed mode ratio.

The damage evolution is subjected to the classical loading/unloading conditions:

$$f(Y_m) \le 0 \qquad \dot{D} \ge 0 \qquad f(Y_m)\dot{D} = 0 \tag{16}$$

$$f(Y_m) = Y - Y_m^\star \qquad D \in [0,1] \tag{17}$$

where the damage threshold $Y_m^\star$ is defined by:

$$\begin{cases} Y_m^\star = Y_m^0 & if D = 0 \\ Y_m^\star = Y_m^0 + (Y_m^f - Y_m^0)\left[-\log(1-D)\right]^N & if D \in ]0,1[ \\ Y_m^\star = \max\limits_{\tau \in [0,T]} Y(\tau) & if D = 1 \end{cases} \tag{18}$$

The damage onset is obtained according to the following criteria:

$$\left(\frac{Y_I}{G_{0I}}\right)^\alpha + \left(\frac{Y_{II}}{G_{0II}}\right)^\alpha = 1 \tag{19}$$

which gives:

$$Y_m^0 = \frac{(1+\overline{\beta}^2)G_{0I}G_{0II}}{\left[G_{0II}^\alpha + (\overline{\beta}^2 G_{0I})^\alpha\right]^{\frac{1}{\alpha}}} \tag{20}$$

For the delamination propagation, the well-known ellyspe criterion is assumed:

$$\left(\frac{G_I}{G_{cI}}\right)^\alpha + \left(\frac{G_{II}}{G_{cII}}\right)^\alpha = 1 \tag{21}$$

where the released energies are defined as:

$$\begin{cases} G_I = \int_0^{+\infty} Y_I \dot{D} dt \\ G_{II} = \int_0^{+\infty} Y_{II} \dot{D} dt = \overline{\beta}^2 G_I \end{cases} \tag{22}$$

The propagation of decohesion takes place for:

$$G_{Tc} = \frac{\left(1+\overline{\beta}^2\right) G_{cI} G_{cII}}{\left[\left(G_{cII}\right)^\alpha + \left(\overline{\beta}^2 G_{cI}\right)^\alpha\right]^{1/\alpha}} \tag{23}$$

where $G_{Tc}$ is computed as the total work of separation: :

$$G_{Tc} = \int_0^{+\infty} Y_m^\star \dot{D} dt \tag{24}$$

According to the damage evolution law, one has the expression of the parameter $Y_m^f$ as:

$$Y_m^f = Y_m^0 + \frac{1}{\Gamma\left(N+1\right)}\left[G_{Tc} - Y_m^0\right] \tag{25}$$

One can see that the interface model takes into account the modification of the mixed mode ratio during the loading path. Figure 3 presents the behaviour of the model for mixed mode.

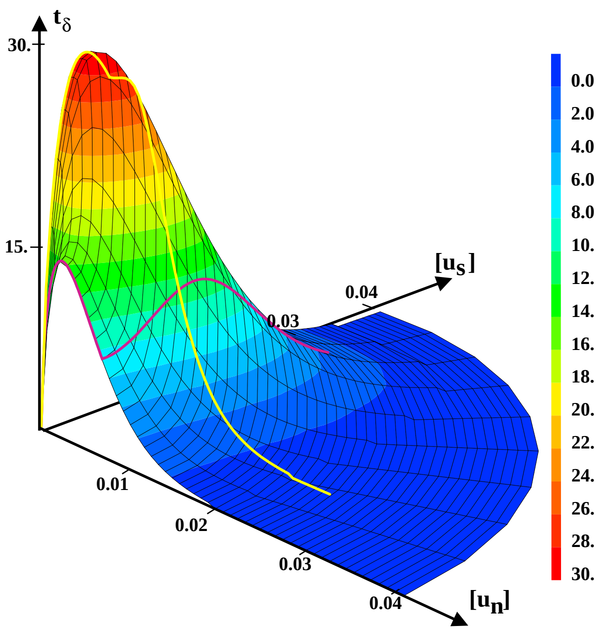


Figure 3. Mixed-mode model

This model has been implemented in the Finite Element Code CAST3M, where it can be used for simulation of damage evolution in adhesively bonded joints.

## 3. Mechanical tests

The parameters of the interface model are the undamaged stiffnesses ($K_L$ and $K_T$), the activation energies for each pure mode ($G_{0I}$ and $G_{0II}$), the critical energies ($G_{cI}$ and $G_{cII}$) and the exponent of the ellipse criterion for activation and propagation ($\alpha$). The exponent $\alpha$ is classicaly set to 2.

The stiffnesses of a thin layer of adhesive can not be easily derived from the elastic properties of the adhesive itself. They can not be identified from mechanical tests on adhesively bonded assemblies as they have a small influence on the global response of the assemby. $K_l$ and $K_T$ could be indentified from acoustical tests not presented in this paper (Vlasie and Rousseau, 2003).

The activation energies $G_{0i}$ and the critical energies $G_{ci}$ can be indentified straight from classical crack propagation test results. The tests depend on the solicitation mode used to propagate the crack. The double-cantilever bean (DCB) and the end-notched flexure (ENF) are pure mode I and pure mode II tests, respectively. We can also have mixed-mode tests like the mixed-mode flexure (MMF). These test are presented schematically in Figure 4.

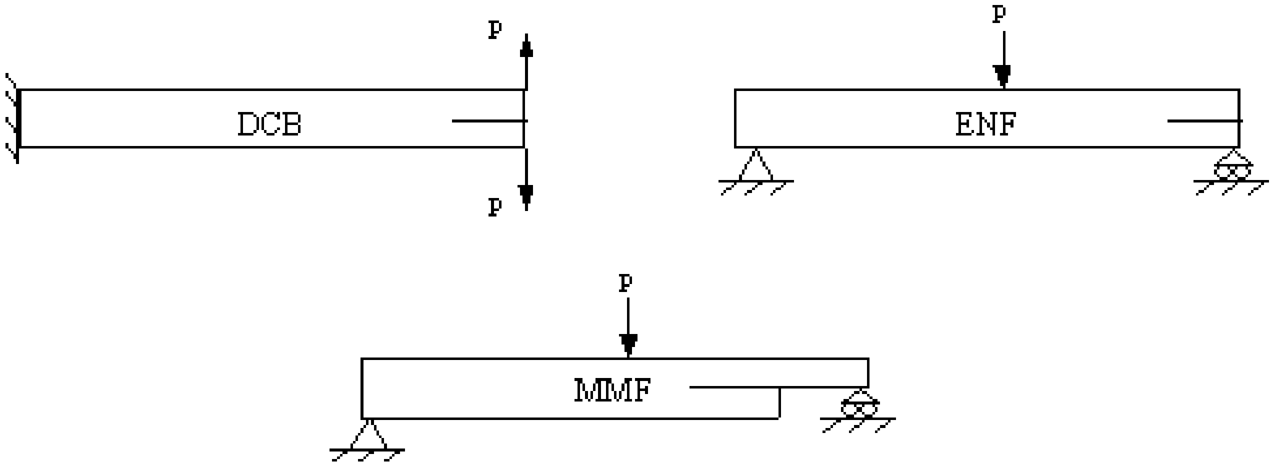


Figure 4. Classical crack propagation tests

Due to their boundary conditions simpler than mode I tests, ENF and MMF tests were performed first. DCB tests will be developed in a next work.

The samples tested consist of two $3mm$ thick and $20mm$ wide aluminum arms bonded with a layer of $0.5mm$ of epoxy. They were tested using a traction/compression machine MTS 816 with $7500kgf$ load capacity. The tests had been perfomed via displacement control with a three-point bending fixture with span $L = 120mm$. The elastic properties of the aluminum are $E = 75000MPa$ and $\nu = 0.3$. Figure 5 shows two results of ENF tests.

Figure 6 shows some results of this mixed-mode tests. On the different curves, inclinations at the beginning of each curve correspond to different initial crack lengths $a$. The structure is more or less stiff depending on the length of the initial crack.

**4. Numerical results**

Numerical simulations and tests results must be compared to evaluate the parameters of the mechanical interface model.

The finite-element (FE) mesh used to simulate an ENF test showed in Figure 7 is composed by 528 quadratic elements with eight nodes (3 elements in the thickness of each plate) and 74 quadratic elements of interface.

Figure 8 gives the comparison between an experimental curve and the result of the numerical model after identification of the damage parameters in mode II ($G_{0II}$ and $G_{cII}$. Just after the start of the crack, effects of dynamic propagation not represented in this quasi-static model do not allow the correct representation of the structure answer.

To simulate a MMF test, the FE mesh showed in Figure 9 is used. It's composed by 504 quadratic elements with eight nodes (3 elements in the thickness of each plate) and 77 quadratic elements of interface.

Figure 10 gives the comparison between a experimental curve and the result of the numerical model after identification of the rest of the damage parameters ($G_{OI}$ and $G_{cI}$). Just after the start of the crack, effects of great displacements of the lower plate not represented in this model do not allow the correct representation of the structure answer.

At least, the elastic characteristics of the bonded interface that were identified in the acoustic tests and its damage characteristics that were identified in mechanical tests in mode II (ENF) and mixed-mode (MMF) are: $\alpha = 2; K_T = 760N/mm^3; K_L = 810N/mm^3; G_{cI} = 0.02; G_{0I} = 0.4 \times G_{cI}; G_{cII} = 0.09; G_{0I} = 0.4 \times G_{cII}$

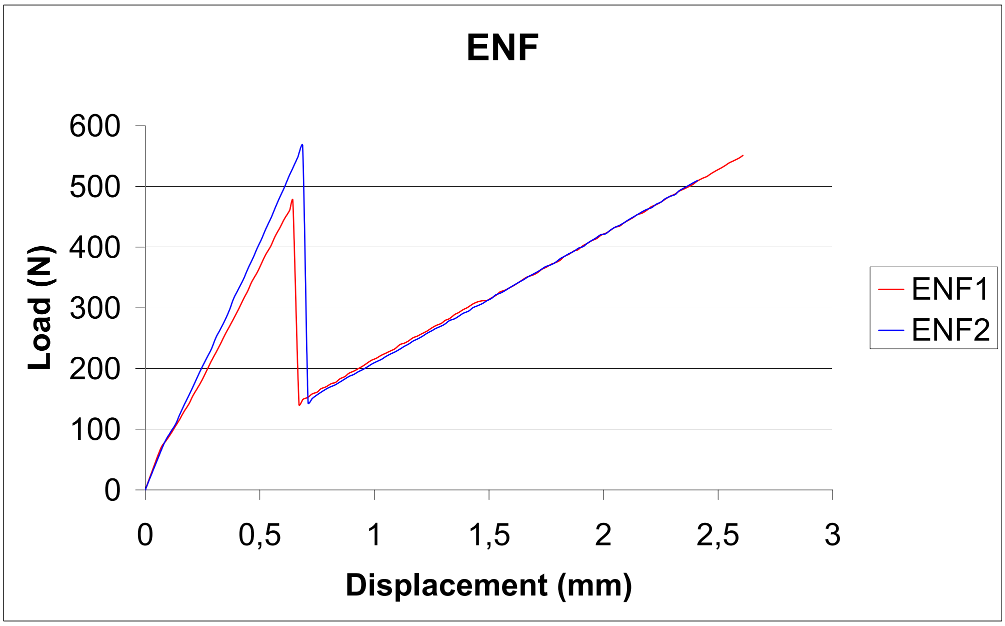


Figure 5. ENF results

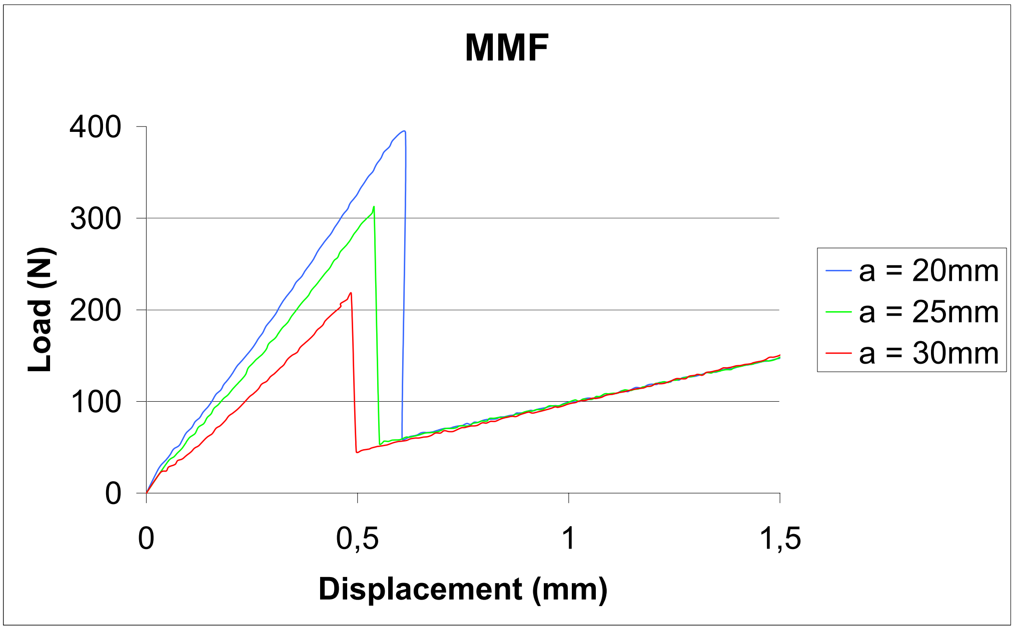


Figure 6. MMF results

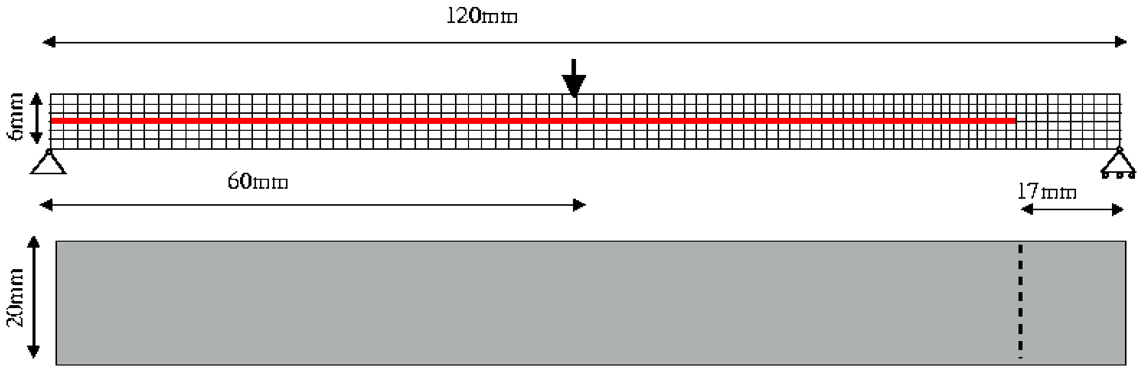


Figure 7. ENF test

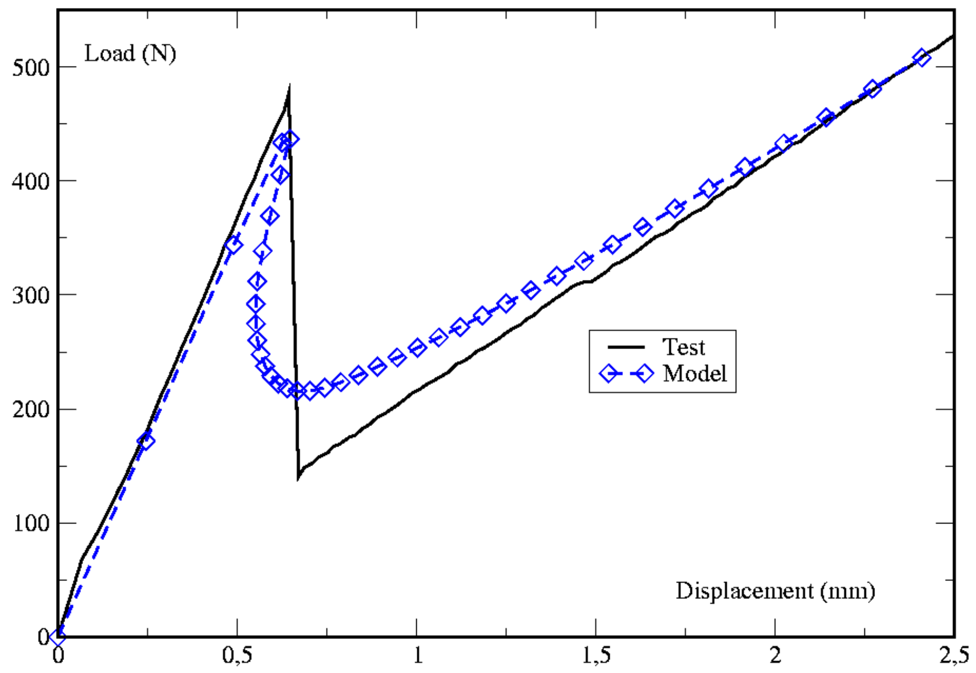


Figure 8. ENF numerical and test results

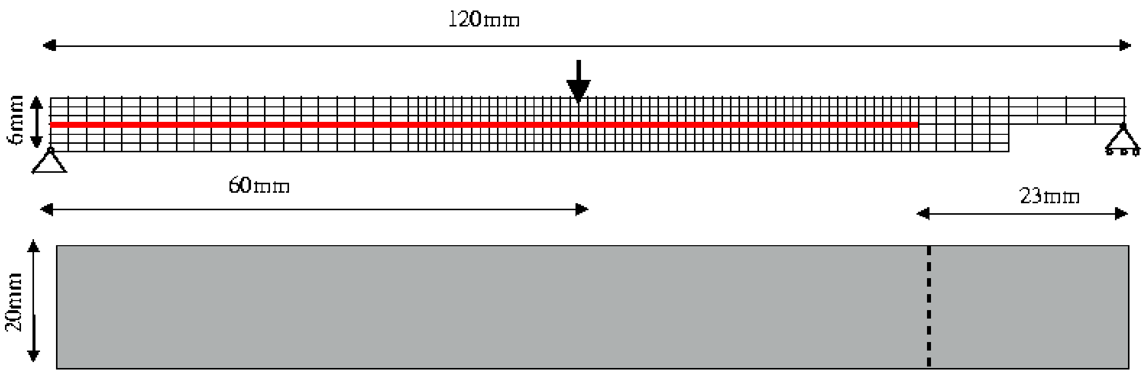


Figure 9. MMF test

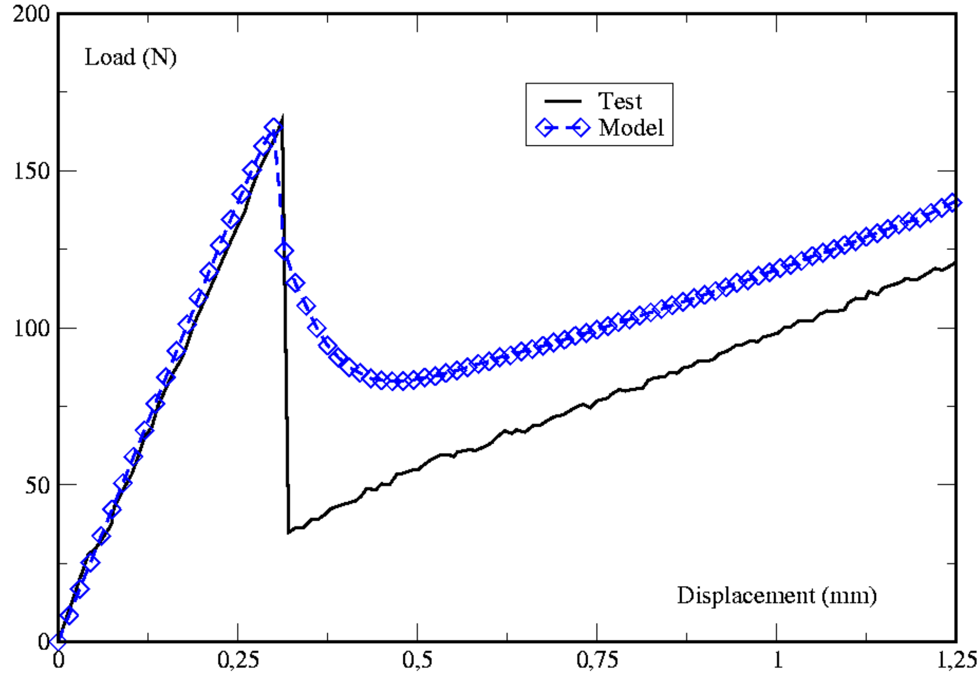


Figure 10. MMF numerical and test results

## 5. Conclusion

A damage interface model to simulate the behaviour of adhesive bonded joints was presented. The model has been implemented in a Finite Element Code and numerical simulations have been carried out for some examples referring to both single-mode and mixed mode solicitations.Comparasions with mechanical tests have shown a good agreement between the results.

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