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Numerical Investigation of the Failure Phenomena in Adhesively Bonded Joints by Means of a Multi-Linear Equivalent Plastic Stress/Strain Approach

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Abstract

In this work, a multi-linear material model for elastic-plastic response of ductile adhesives is proposed. Indeed, the proposed formulation allows to evaluate equivalent stress and strains to be used as material model input in FE commercial codes instead of the classical true stress and true strains. The presented model, which is capable to simulate the plasticity related phenomena and the failure event, has been implemented in the FEM code ABAQUS and used to numerically simulate the mechanical behaviour of adhesively bonded joints in traction. Several joints configurations have been considered with ductile, fragile and mix adhesives' behaviour to test the effectiveness and the range of applicability of the proposed model. Encouraging comparisons with literature experimental data demonstrates the added value of the suggested material model in predicting the failure of adhesively bonded joints.

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Keywords: Bonded joints; Ductile adhesives; Multi-linear material model; Composite repair; Finite element model

1. Introduction

Composite materials are widely used in commercial and military aerospace applications because of their high specific elastic modulus and strength. Fast growth in employment of composite structures has consequently led to deep interest in composite repair technologies [1]. Design of composite joints reveals itself to be as a very important

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task for the structural efficiency of repaired composite structures. Usually, the joining methods for composite structures are classified into two main categories, i.e. mechanical and adhesive. Generally, mechanical bolted joints involve weight increase, stress concentration around the drilled holes and variations in the structure shape and thickness. On the other hand, bonded joints does not hardly affect the stress distribution and the load distribution; however, they may be sensitive to surface treatments and environmental conditions, such as temperature and humidity [2-3]. The benefits of adhesively repaired composite structures, makes their use spreading as much as the need of a continuous improvement of design techniques. To this end, the Finite Elements Method proves to be a valuable and effective tool. It gives the possibility to evaluate the stress distribution in the adhesive layer with good accuracy [4-9] providing the chance to minimize stress and strain peaks in order to guarantee adequate joint performances in terms of strength and reliability [10-12]. The real difficulty within the FE modelling is the definition of a valid material model capable of simulating the adhesive mechanical behaviour. The adhesives may present a non-negligible degree of ductility resulting in more or less extended non-linear response before failure onset and propagation. While a number of works analyse the elastic-plastic phase of the joints to compute the stress distribution within the bonded area [13-19], others have focused their efforts into defining the joints' strength mostly making use of the Cohesive Zone Model [20-22]. However, it looks useful to take simultaneously into account non-linear response, failure initiation and damage growth in order to have a comprehensive outlook of the phenomenon.

The aim of this work is the formulation of an effective method to simulate the elastic-plastic and failure behaviour of adhesives. The implemented model proposes the computation of equivalent stresses and strains as input to the FE code material model rather than the usual true stresses and true strains. The methodology, meant to be applied to bonded joints such as single laps and scarfs undergoing mainly shear stress, has been tested thanks to comparisons with the experimental data provided in [23] for adhesives holding different degrees of ductility (frail, extensive plasticity and mid-plasticity). Thanks to a parametric study, performed by means of the Finite Element code ABAQUS, the influence of several numerical model aspects has been assessed.

In Section 2 the formulation of the developed method is introduced. In section 3, a simple shear case is analysed in order to validate the model together with a comparison with alternative input data. Finally, with the purpose to assess the effectiveness of the proposed method, section 4 presents a numerical-experimental correlation activity performed on a series of single lap joint tests by adopting different numerical approaches.

2. A Multi-linear Input Curve Approach: Theoretical Background And FEM Implementation

In order to model the plastic behaviour of a material, ABAQUS requires, as an input, the uniaxial true stress and the equivalent plastic strain data without the chance to input, at the same time, the tensile and shear plastic stress-strain curves. In literature, it is possible to find a variety of approaches, adopting as input data Shear True Stress vs. Plastic Strain, Tensile True Stress vs. Plastic Strain or curves specifically calculated for the investigation of specific phenomena. However, the most of these alternative methods was found not able to represent the category of phenomena investigated in this work.

Among the studied literature approaches, Ban et al. [24] propose the calculation of a multi-linear curve to use as input to the numerical model to predict the failure load of single lap joints. In [24] the need to use the shear stress-strain curve of the adhesive is pointed out because the adhesive joints mainly undergo shear stress. The multi-linear curve is calculated by means of the Von Mises criterion as:

$$\begin{aligned} \sigma_y &= \sqrt{3}\tau_y \\ \varepsilon_y &= \frac{\sqrt{3}\tau_y}{2G(1+\nu)} \end{aligned} \qquad (1)$$

where σ_y is the tensile yielding stress, τ_y is the shear yielding stress, ε_y is the tensile yielding strain, ν is the Poisson's ratio and G the shear modulus. The obtained curve is similar to the tensile stress-strain curve of the adhesive, but its ultimate strain is larger than that of the tensile curve.

In order to obtain an improvement of the method proposed by Ban et al., a further step has been made in the evaluation of the multi-linear curve. Indeed, the equivalent strain has been evaluated by averaging successive points in the stress-strain curve.

The input data are evaluated starting from the shear stress-strain curve. The nominal stress-strain data are preliminary converted into true stress and logarithmic strain making use of Eqs. (2):

$$\begin{aligned}\tau_{true} &= \tau_{nom}\left(1+\varepsilon_{nom}\right)\\ \varepsilon_{\log} &= \log\left(1+\varepsilon_{nom}\right)\end{aligned} \tag{2}$$

The calculated Stress and strain values have been used for the evaluation of shear modulus (Eq. 3), and elastic modulus (Eq. 4).

$$G_i = \frac{\tau_{true_i} - \tau_{true_{i-1}}}{\varepsilon_{\log_i} - \varepsilon_{\log_{i-1}}} \tag{3}$$

$$E_i = 2G_i\left(1+\upsilon\right) \tag{4}$$

Finally, by means of the equivalent stress estimated according to Eq. 5, the averaged strain is given in Eq. 6.

$$\sigma_{eqv_i} = \sqrt{3}\tau_{true_i} \tag{5}$$

$$\varepsilon_{avg_i} = \left(\frac{\sigma_{eqv_i} - \sigma_{eqv_{i-1}}}{E_i}\right) + \varepsilon_{avg_{i-1}} \tag{6}$$

As a matter of fact, the plastic tabular input data only requires the plastic part of the strain, so the elastic part of the strain, here denoted as ε_{avg0}, should be eliminated in the expression of the equivalent strains:

$$\varepsilon_{eqv_i} = \varepsilon_{avg_i} - \varepsilon_{avg_0} \tag{7}$$

A schematic depiction of the described procedure providing equivalent stress (Eq. 5) and equivalent strain (Eq. 7) is schematically shown in Figure 1 pointing out the new developments introduced with respect to the state of the art technique.

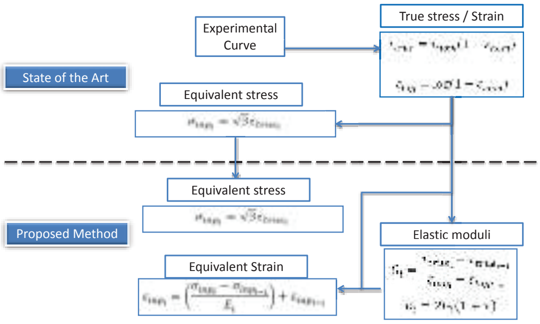

Figure 1: Flowchart of the developed input method

3. Numerical Application: pure shear test

In order to assess the efficiency of the technique presented in section 2, with respect to other literature methodologies, a numerical comparison has been performed. To this aim, the characterized adhesives in [23] have been utilized and various material models have been taken into account.

A simple case of pure shear has been simulated with the purpose of comparing various methodologies of plasticity material modelling. In particular, the shear stress in output has been evaluated and compared to the experimental shear stress-strain curves of the three adhesives under investigation in this phase (Hysol EA9359.3, Supreme 10HT and Redux 326) holding different degrees of ductility (frail, extensive plasticity and mid-plasticity).

The compared approaches are characterized by different curves defining the plastic material model:

- Tensile curve (true stress vs. plastic strain);
- Shear curve (true stress vs. plastic strain);
- Ban et al. [24];
- Developed Input Method.

Moreover, two different analyses for each material model and adhesive have been carried out: a first one that does not consider active any failure option of the adhesive and a second one in which the failure is taken into account. Figures 2 to 4 give an overview of the obtained results.

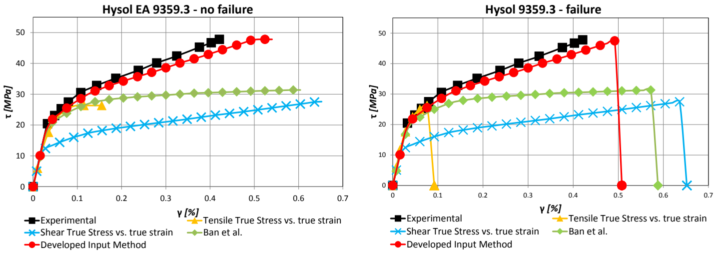

Figure 2: Shear stress vs. shear strain (τ-γ) curves' comparison for high ductility adhesive

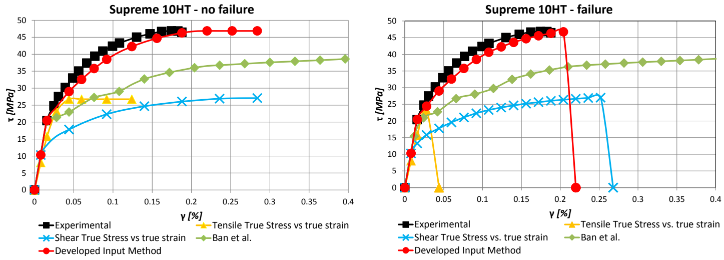

Figure 3: Shear stress vs. shear strain (τ-γ) curves' comparison for medium ductility adhesive

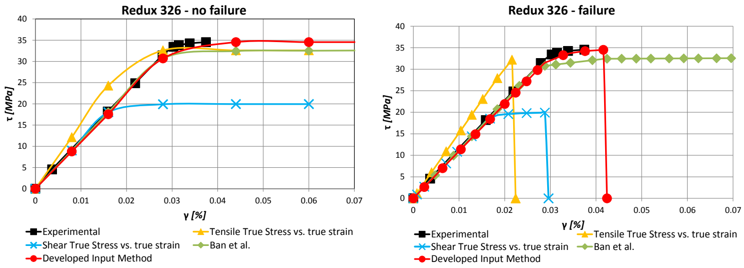

Figure 4: Shear stress vs. shear strain (τ-γ) curves' comparison for low ductility adhesive

The charts show how the results obtained thanks to the proposed new input methodology are in very excellent agreement with experimental data. This agreement is not reached by the other methodologies, at least in relation to the more ductile adhesives (Hysol EA9359.3 and Supreme 10HT). Figure 4, where the results regarding the frailer adhesive are displayed, shows a smaller performance gap among the compared outputs.

4. Numerical application: Single Lap Joint test

A series of single lap joints tests, reported in [25]. has been taken into account, in the present paper, to assess the performance of the proposed new method. The adhesives introduced in the previous sections: Hysol EA9359.3, Supreme 10HT and Redux 326 have been considered. For the adherents, hard steel was adopted. The geometry of the specimens used in the SLJ tests is shown in Figure 5.

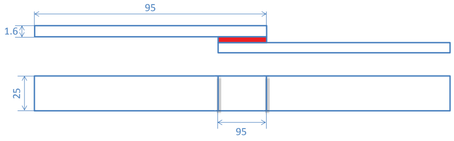

Figure 5: Sketch geometry of the specimens (dimensions in millimetres)

The bondline thickness of the adhesive (red zone in Figure 5) is 0.12 mm.

The reference results of the tests performed in [23] according to the ASTM standard D1002 [25] are shown in Figure 6.

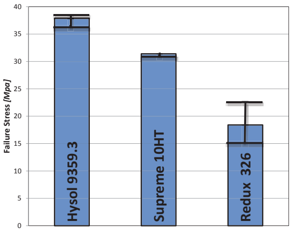

Figure 6: Single Lap Joints: Failure stresses from experimental tests [23]

4.1. FE Model and analysis' settings

2D FE models have been realized, thanks to the symmetry of the test, in order to reduce the associated computational cost. Four different element mesh have been considered with substantial differences in the adhesive layer (i.e. the elements number throughout the thickness). For the adherents a coarser mesh has been used. In Figure 7 a representation of the single lap joint model with boundary conditions is reported.

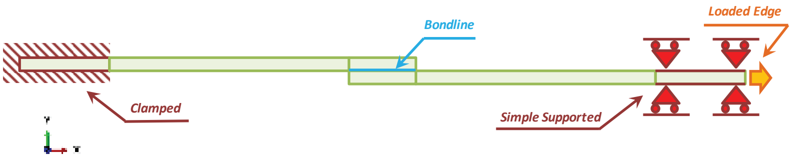

Figure 7: FE model sketch

A series of analyses has been carried out to test the effectiveness of the proposed method and to obtain a picture as complete as possible of the behaviour of the adhesives in the single lap joint tests. Specifically, three groups of analysis have been performed, one for each adhesive, by varying:

- the number of elements throughout the adhesive thickness;
- numerical parameter: *damping factor*;
- numerical parameter: *element viscosity*.

The bondline thickness has been modelled with 2, 4, 6 and 8 elements. Three values of the element viscosity (0.1, 0.01, and 0.001) and two values of the damping factor ($2{\cdot}10^{-3}$ and $2{\cdot}10^{-5}$) have been considered.

Tables 1 report for each test the results of the three groups of analyses performed for each adhesive. It can be noted how the damping factor has a negligible influence on the models outcomes differently from the viscosity which value has a far more sensible consequence on the numerical test. An increase in the viscosity's value will rise the failure stress at which the modelled adhesive will collapse. On the other hand, the increase of element modelling the bondline thickness will result in a reduction of the failure stress. This reduction is remarkable for the frailer adhesive (Redux 326) and much more gradual for the ductile ones (Supreme 10HT and Hysol EA9359.3).

However, the variations in results related to elements number in adhesive thickness, related to the singularity in stress in the numerical model at material interfaces, tend to stabilize for a value of 6 elements which is actually the number of elements to be considered as the best compromise between accuracy and computational cost.

4.2. Methodologies comparisons

To further point out the effectiveness of the proposed methodology, three more groups of analysis have been carried out, using the multi-linear curve proposed in [24]. In Figure 8, such results are compared with the ones previously achieved with40 the developed methodology (in the graph, the results obtained with the proposed model are represented by white bars while the experimental bar is the dithered one). For the more ductile adhesive (Hysol EA9359.3) the added value of the new proposed methodology is extremely noticeable. A less remarkable improvement can be noticed also for the average ductility adhesive (Supreme 10HT). Finally, for the Redux 326, the frailer adhesive, the two approaches show almost the same results.

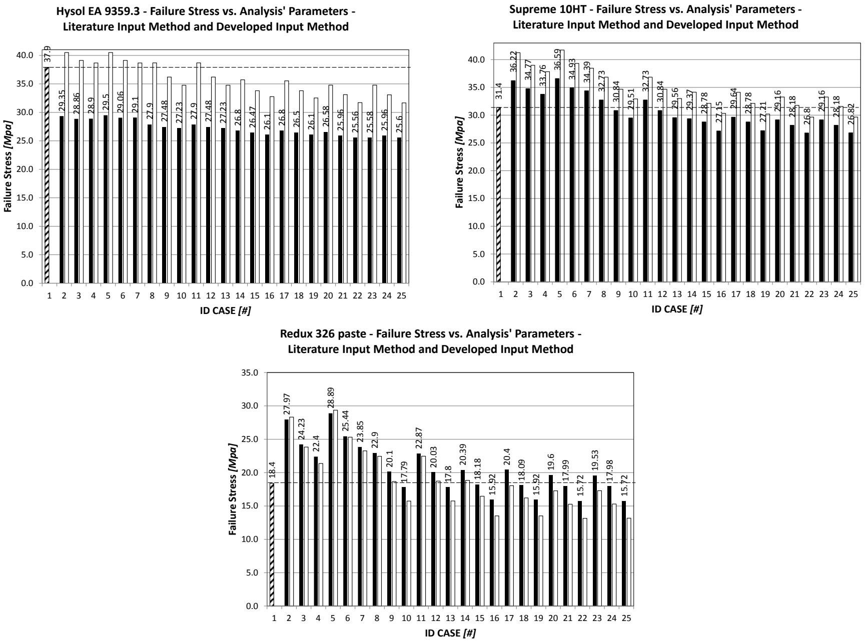

Figure 8: Methods' comparison for Hysol EA 9359.3, Supreme 10HT and Redux 326 (the input method developed in this work is represented by

Table 1: Test Matrix

Id case	**Number of elements in the bondline thickness**	**Viscosity**	**Damping factor**	***Hysol EA9359.3***		***Supreme 10HT***		***Redux 326***	
				Failure stress [MPa]	**Error [%]**	**Failure stress [MPa]**	**Error [%]**	**Failure stress [MPa]**	**Error [%]**
1	Experimental value	//	//	37.9	*0.00*	31.4	*0.00*	18.4	*0.00*
2	2	0.1	2.00E-05	40.52	*6.91*	41.24	*31.34*	28.32	*53.91*
3		0.01		39.13	*3.25*	38.98	*24.14*	23.83	*29.51*
4		0.001		38.67	*2.03*	37.83	*20.48*	21.37	*16.14*
5		0.1	2.00E-03	40.52	*6.91*	41.73	*32.90*	29.36	*59.57*
6		0.01		39.13	*3.25*	39.31	*25.19*	25.32	*37.61*
7		0.001		38.67	*2.03*	38.46	*22.48*	23.26	*26.41*
8	4	0.1	2.00E-05	38.69	*2.08*	36.85	*17.36*	22.45	*22.01*
9		0.01		36.21	*-4.46*	34.68	*10.45*	18.66	*1.41*
10		0.001		34.78	*-8.23*	32.92	*4.84*	15.74	*-14.46*
11		0.1	2.00E-03	38.7	*2.11*	36.85	*17.36*	22.46	*22.07*
12		0.01		36.21	*-4.46*	34.68	*10.45*	18.73	*1.79*
13		0.001		34.78	*-8.23*	32.99	*5.06*	15.75	*-14.40*
14	6	0.1	2.00E-05	35.72	*-5.75*	34.15	*8.76*	18.84	*2.39*
15		0.01		33.8	*-10.82*	32.13	*2.32*	16.46	*-10.54*
16		0.001		32.77	*-13.54*	30.32	*-3.44*	13.52	*-26.52*
17		0.1	2.00E-03	35.54	*-6.23*	34.13	*8.69*	18.04	*-1.96*
18		0.01		33.8	*-10.82*	32.13	*2.32*	16.21	*-11.90*
19		0.001		32.53	*-14.17*	30.2	*-3.82*	13.52	*-26.52*
20	8	0.1	2.00E-05	34.79	*-8.21*	33.27	*5.96*	17.28	*-6.09*
21		0.01		33.12	*-12.61*	31.77	*1.18*	15.27	*-17.01*
22		0.001		31.72	*-16.31*	29.66	*-5.54*	13.15	*-28.53*
23		0.1	2.00E-03	34.79	*-8.21*	33.27	*5.96*	17.29	*-6.03*
24		0.01		33.09	*-12.69*	31.58	*0.57*	15.29	*-16.90*
25		0.001		31.67	*-16.44*	29.66	*-5.54*	13.17	*-28.42*

5. Conclusions

This work presents a methodology to study the elastic-plastic behaviour in bonded joints undergoing mainly shear stress. The new method has been developed in order to by-pass the classical user-defined material models for the commercial FE codes not able to fully reproduce the experimental characterization tests. Its effectiveness has been tested thanks to literature experimental data.

A multi-linear material model capable to replicate ductile adhesives elastic-plastic response has been implemented and used to evaluate the strength of Single Lap Joints under tensile loading. Comparisons between models with different input parameters, as well adhesives presenting different ductility degrees, have been perform in order to evaluate the effectiveness and the range of applicability of the newly proposed model.

The performed parametric study, where input numerical parameters and mesh discretization variables have been considered, offered exhaustive results for a proper evaluation of the method and resulted in a good correlation with the experimental data, above all for the more ductile adhesives. A multi-linear material model available in literature was tested as well, and its results were used as basis of comparison. This last comparison showed once again the very effective behaviour of the proposed approach, capable to predict the experimental failure load with much more accuracy with respect to the literature multi-linear approach especially for the high ductile adhesives. Finally, the introduced method can be surely considered a relevant step forward the development of numerical models able to improve the design of bonded composite joints and repaired composite structures.

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