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3D MODELLING OF THE ELASTO-PLASTIC BEHAVIOUR OF ADHESIVELY BONDED JOINTS SUITED FOR A WIDE RANGE OF TENSILE-SHEAR LOADS

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Abstract.

Airframe developments use composite components extensively; bonding, as a rivetless assembly solution, is thus gaining in importance, leading to the need for accurate characterization of adhesive behaviour and the development of adapted models.

Structural adhesives often show large inelastic behaviour before failure [1]; however the modelling of the 3D elasto-plastic behaviour of adhesives is not straightforward. Indeed, advanced models taking into account the hydrostatic pressure dependency and defined under a non-associated formalism ([1- 4]) are needed for an accurate description of adhesive materials under a wide range of loads covering tension, shear, mixed tension/compression-shear loads.

This study presents the assessment of two non-associated elasto-plastic models: the Exponent Drucker-Prager model, and the Mahnken-Schlimmer model [3], using a large experimental database obtained with a modified Arcan apparatus [5] on a structural adhesive. The aim is to develop a reliable numerical model in order to obtain good numerical predictions of the real behaviour of complex industrial type bonded assemblies.

1 INTRODUCTION

In a context of the growing importance of composite in modern commercial aircrafts, bonding has kept gaining in importance in the design of airframe components over the last 40 years, and is now to be used extensively [6].

In order to model the local behaviour of a bonded assembly and to achieve a good prediction of crack onset within the adhesive, it is necessary to develop non-linear constitutive laws well-suited for adhesive materials.

It is well known that the yielding and the plastic flow behaviour of epoxy adhesives depend on the hydrostatic stress component ([1-4], [7-12]). Besides, recent studies tend to prove that non-associated formalism ([3,4,11,12]) is also needed for a good description of the high ratio between the normal and the tangential non-linear deformations of adhesives subjected to mixed tensile/compression-shear loads. This makes the characterization and the 3D modelling of such behaviour under a wide range of loads all but straightforward, since several parameters have to be identified, which involves using several load test configurations.

The aim of this paper is to present the identification and the validation of two elasto-plastic models using experimental results obtained by means of a modified Arcan test [5]. This test presents the advantages of requiring a unique apparatus mounted on a tension machine and only one type of bonded specimen design, while offering a wide range of proportional loads from tension, shear, mixed tension-shear and compression-shear with different ratios.
Using these characterization results, a simplified inverse identification approach using FEA is proposed for two models: the Exponent Drucker-Prager model and the Mahnken-Schlimmer model [3]. Both of these models have been shown recently to be well suited for the modelling of adhesive materials ([3,11,12]) in a tension-shear domain.

The particularity of this study lies in the fact that a whole wide range of proportional loads, including mixed compression-shear, are covered and that only experimental results obtained using a modified Arcan apparatus test results are used for the identification of the models and a first validation.

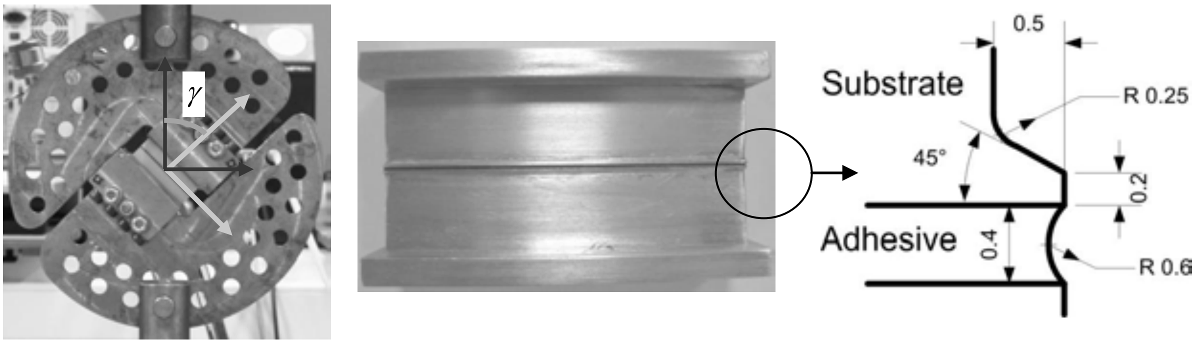
2. EXPERIMENTAL RESULTS

2.1 Presentation of the modified Arcan test used

The adhesive considered for this study is the Redux 420 A/B of Huntsman [13], a bi-component epoxy-based paste.

The device used is the modified Arcan test presented in figure 1. It aims to load with different ratios of shear and tension or compression (given by γ the angle of load defined in figure 1-a) a single configuration of bonded assemblies loaded with a standard tensile testing machine. The bonded specimens (figure 1-b) are made of substrates in 2017 aluminium designed with beaks all around the surfaces to be bonded according to the geometry presented in figure 1-c. A rounded shape is also applied to the adhesive layer at the edges by "cleaning" immediately after the application of the adhesive. This specific design enables us to significantly limit the influence of edge effects (i.e. stress concentrations) that can lead to premature crack onset and thus misunderstanding of the results. More details on the design and advantages of the system can be found in [4] and [5].

The measurements were made using 3D video correlation [14]. This enables the displacement field to be recorded against the applied load at the centre of the bonded joint. Relative displacements between the two substrates in the two directions, called DT for the tangential one and DN for the normal one, at a given length from the adhesive layer are then post-processed respectively against the tangential (FT) and normal (FN) transmitted load components.



(a) (b) (c)

Figure 1: Modified Arcan apparatus with the definition of the angle of load ratio: γ Bonded assembly (a) and specific design of the beaks (b) to limit edge effects within the adhesive layer (c) geometry of the beaks.

2.2 Experimental results

The adhesive layer for all the specimens considered in this study was 0.4 mm thick and the load was imposed by a constant velocity of the crosshead of the tensile testing machine of 0.5 mm/min.

The results obtained are presented by the dotted lines in figure 4 for $\gamma = 0°$ (tension load) and 90° (shear) and in figures 5-a, 5-b and 5-c for $\gamma = 30°$, 45° (mixed tension-shear) and 135° (compression-shear) respectively. In figure 5, N and T represent respectively the results obtained in the normal and the tangential directions.

For mixed loads (30°, 45°, 135°) an important ratio between DN and DT can be noted. Indeed, when failure is reached, $|DT/DN|$ is equal to 3.2 at 30° and 7 at 45°.
The response of the bonded assembly also exhibits large inelastic behaviour and the relative tangential displacements at failure are in the order of the adhesive thickness. Because the substrates remain in their elastic domain, and assuming a constant strain rate between the

different load ratios, the behaviour can be first approximated as elasto-plastic for the adhesive considered here (under such conditions viscous effects can be neglected).
The aim is thus to propose a 3D elasto-plastic model that enables the most accurate description of the adhesive material over the whole range of load ratios considered.

3. INVERSE IDENTIFICATION OF THE EDP AND THE MS MODELS

Two models were considered: the Exponent Drucker-Prager (EDP) model, as implemented in Abaqus FE code [15] and the Mahnken-Schlimmer (MS) model that has been implemented as a user subroutine in Abaqus as proposed by [3]. Both of them take into account the dependence of the yield surface and the flow rule on the hydrostatic stress component. They have been proved to be well-suited for the modelling of structural adhesive behaviour [1-3, 11, 12] under tension-shear loads.

3.1 Description of the constitutive laws

The Yield functions of the EDP and the MS models are respectively given by $F_0^{EDP} = 0$ and $F_0^{MS} = 0$ with:

$$F_0^{EDP} = a\sigma_{VM}^{b} + p - p_{t0} \tag{1}$$

$$F_0^{MS} = \sqrt{\sigma_{VM}^2 + a_1 Y_0 p + a_2 p^2} - Y_0 \tag{2}$$

where: p is the hydrostatic stress component, σ_{VM} is the von Mises stress, and (a,b, p_{t0}) and (a_1, a_2, Y_0) are material parameters to be identified.

They both have a quadratic form in the Mises stress- hydrostatic stress plane. However, the MS model is an ellipse-like surface whereas the EDP is an open parabola in the direction of negative hydrostatic stress component: hence, the yielding limit is never reached under a pure compressive hydrostatic load for the latter criteria.

For the MS model, the hardening is given by the three parameters q, b and H, with:

$$Y = Y_0 + q(1 - e^{-be_v}) + He_v \quad \text{where } \dot{e}_v Y_0 = \underline{\underline{\sigma}} : \underline{\underline{\dot{\varepsilon}}}^{pl} \tag{3}$$

For the EDP model, it is given by:

$$p_t = a\,(\sigma_t)^{b} + \frac{\sigma_t}{3} \quad \text{where : } \sigma_t = \tilde{\sigma}\big|_0 + Ke_p \tag{4}$$

There are thus only two parameters, K and $\tilde{\sigma}\big|_0$, to be identified.

Considering the flow rule, the formalism proposed by the two models differs. For the EDP, the flow rule is always non-associated with the yield function.

$$G^{EDP} = \sqrt{(e\tilde{\sigma}|_0 \tan\psi)^2 + \sigma_{VM}^2} + p\tan\psi \qquad (5)$$

The only parameter to identify is ψ, called the dilatation angle; e has a default value of 0.1 that will be kept unchanged in the following.

For the MS model, both associated and non-associated formalisms are possible. However as demonstrated in [3], it is more convenient for thermodynamic consistency to choose the non-associated one, reducing to a_2^* the only parameter to be defined:

$$G^{MS} = \sqrt{\sigma_{VM}^2 + a_2^* p^2} \qquad (6)$$

Because the stress and strain states are multi-axial within the bonded layer, inverse identification of the models using 3D finite element analysis (FEA) is more appropriate. It consists of an optimization loop that enables the best parameter set to be found for a given model considering the experimental results obtained.

The bonded specimens were modelled with appropriate geometry, loads and symmetry as presented in figure 2. A relatively coarse mesh was used within the adhesive layer since refining the mesh near the edges has no effect on the global response considered for the identification (relative displacement vs. applied load). Substrates were modelled assuming an elastic behaviour with a Young's modulus of 70 GPa and a Poisson's coefficient of 0.3.

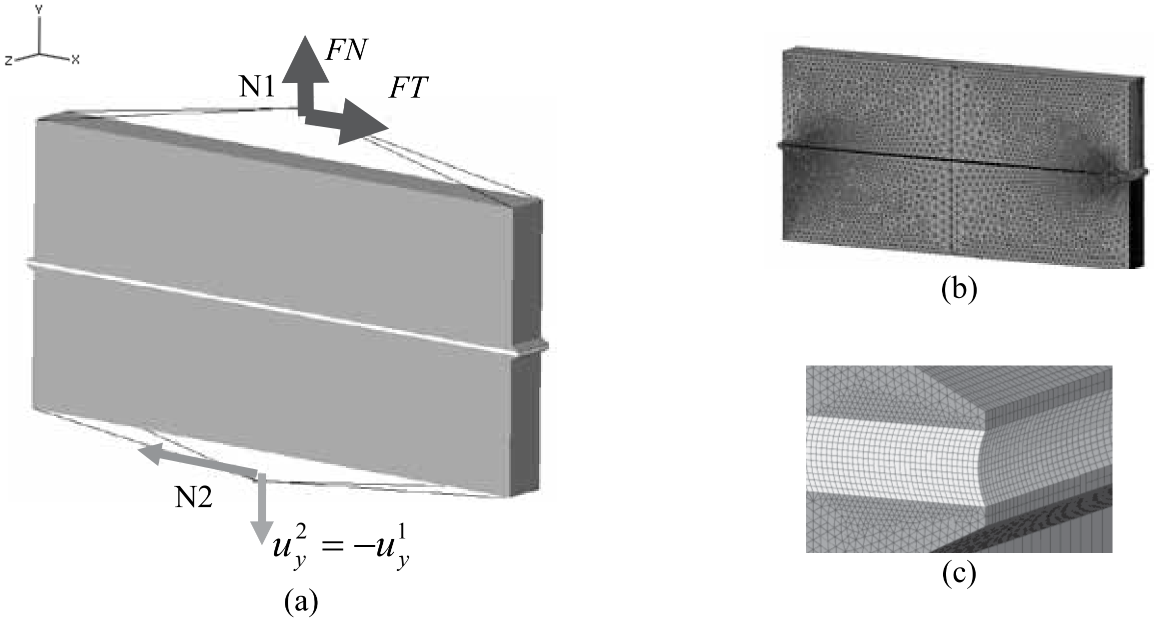


Figure 2 : Mesh of the Arcan bonded assembly : (a) Loads and boundary conditions (b) Global mesh (c) Beak's mesh

3.2 Identification of the models

Due to the large number of parameters to be identified, 7 for the MS and 5 for the EDP plus the elastic constants, and considering that only inverse identification based on FEA is appropriate, a sequential and simplified approach, summmarized as follows, has been chosen:

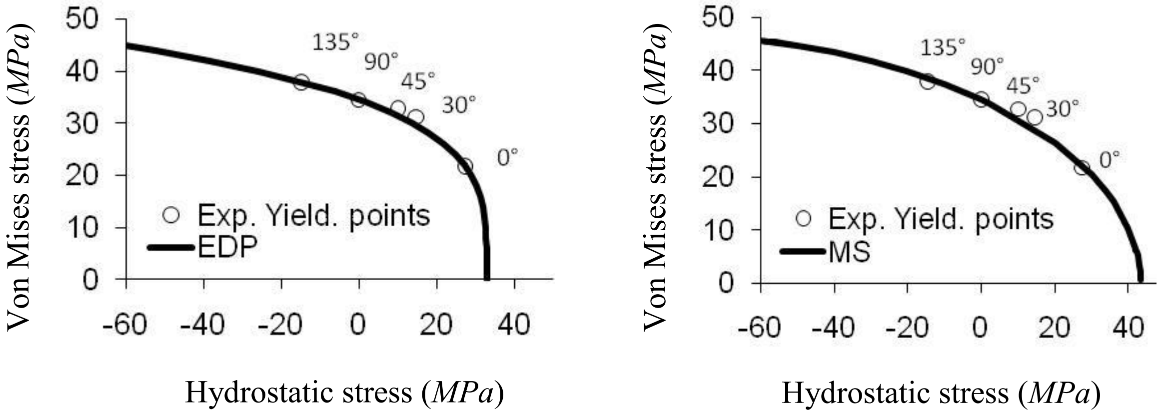
- Step 1: Identification of the elastic parameters of the adhesive: E (Young's modulus) and ν (Poisson's coefficient) using modified Arcan test results at 0° and 90°.
- Step 2: Identification of the yield surfaces based on experimental yield points obtained at 0°, 90° and 135°.
- Step 3: Identification of the hardening functions and the flow rule parameters using 0° and 90°.

Since only 90° (shear) and 0° (tension) results were completely used for the identification of the two parameters sets, a validation could be performed using experimental results at 45°, 135° and 30°.

- Identification of the Elastic parameters and the Yield surface (Steps 1 and 2)

Young's modulus and Poisson's coefficient of the adhesive have been identified using a parametric study on the domain respectively covering: 1700 to 2200 MPa with increments of 100 MPa and 0.3 to 0.45 with increments of 0.05. By comparing FE and experimental results at 0° and 90°, the set minimising a least-square type error has been found to be: E = 2100 MPa and Nu= 0.35.

It has been demonstrated that, once the elastic parameters are known, the Modified Arcan test results enable the experimental yield surface to be determined in the Mises stress- hydrostatic stress plane [11]. Using this result, the yield functions were fitted using the ratio loads of 0°, 90° and 135°. Figure 3 presents the comparison of this identification for the two models in the Mises stress- hydrostatic stress plane.



(a) (b)

Figure 3: Comparison of the identification of the yield surfaces using Arcan test results at angles loads of 0°, 45° and 135° and the experimental yield surface: (a) EDP model, (b) MS model

Both of the criteria provide a good correlation over the wide range of loads considered: the yield points at 30° and 45°, which were not used for the identification, are slightly underestimated.

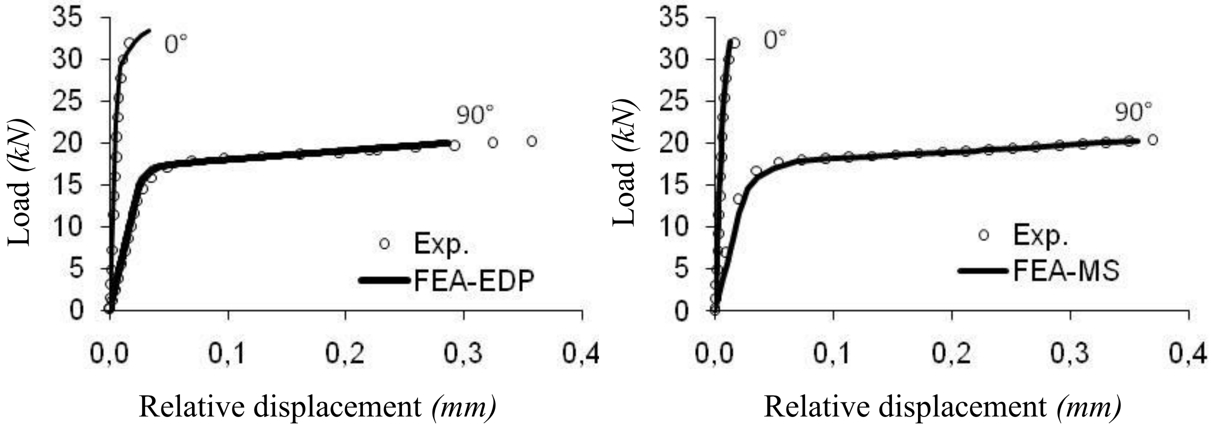
The main difference is in the predicted yield point under pure hydrostatic tension (for such tests we have no experimental results). For the EDP model yielding occurs at 33 MPa compared with 42 MPa for the MS model. The identified EDP yield criterion has a higher sensitivity to peel loads than the MS yield criterion; this sensitivity being emphasized for von Mises stresses below 20 MPa for which the slope is almost vertical.

- Identification of the hardening function and the flow rule (step 3)

The third step consists of the identification of the complete response at 0° and 90° by optimizing the hardening and flow function parameters.

Results are presented in figure 4-a and 4-b respectively for the EDP and the MS models.

Both of the models enabled the experimental results to be fitted correctly. The rounded shape at 90° and the linear asymptotic part are described well, and the fact that the non-linear response is reduced to a small part of the curve at 0° whereas it is predominant in shear is well represented.



(a) (b)

Figure 4: Comparison of FE and experimental results at 0° and 90°: (a) EDP model; (b) MS model

Table I: Parameter sets with the simplified identification approach for the Mahnken-Schlimmer and the EDP models

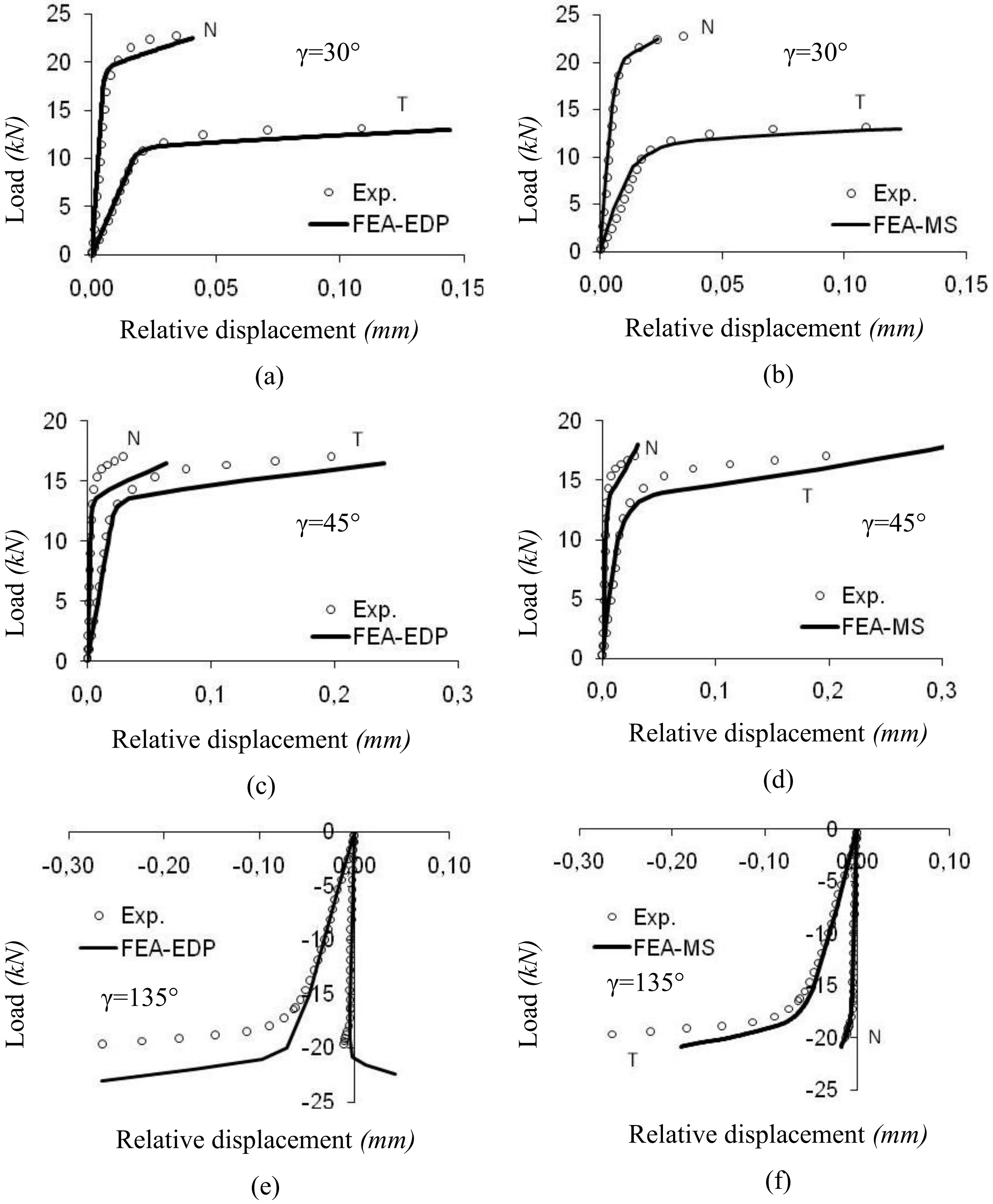
Mahnken-Schlimmer							Exponent Drucker-Prager					
a_1	a_2	Y_0	a_2^*	H	q	b	p_{t0}	a	b	K	$\tilde{\sigma}\|_0$	ψ
(-)	(-)	MPA	(-)	MPa	MPa	(-)	MPa	SI	SI	MPa	MPa	°
0.29	0.015	33.5	0.06	20	10	100	31.7	1.10^{-6}	4.87	29.3	37.2	25

4. VALIDATION AND DISCUSSION

Using the previous parameter sets identified using only 0° and 90° results (Table I.), a comparison, acting as a first validation of this previous identification, has been conducted.

Comparisons of FE and experimental results obtained considering the force vs. relative displacements in the normal and tangential directions are presented in figure 5. At 30° and 45° the precision of the two models regarding the experimental results are similar. As noticed for the identification of the yield surface, the yield points are underestimated leading to a poor estimation of the rounded shape. This is particularly emphasized at 45° for both of the models.

Indeed, the stress-state is not uniform within the adhesive layer [5] and maximum stresses are encountered in the middle of the adhesive layer. Thus plasticity occurs progressively from the centre to the edges of the adhesive joint. An underestimation of the yielding thus leads to an underestimation of the transmitted load for a given relative displacement, since yielding spreads prematurely along the adhesive layer.



(a) (b) (c) (d) (e) (f)

Figure 5: Comparisons of the identifications at 30° (a) & (b) , 45° (c) & (d) and 135° (e) & (f) for the EDP (left) and the MS (right) models. Experimental (Exp.) vs. FE results (FEA-EDP or FEA-MS).

It could be interesting to perform an identification of the flow rule and hardening based on mixed tension-shear loads, using 0° and 90° results for validation. Indeed, because plasticity is not very developed at 0°, the identification domain remains limited and could be insufficient for an accurate identification.

The main difference in the predicted results concerns the normal behaviour for a compression-shear load (135°, Figure 5-e and 5-f). On the one hand, both models reach almost the same level of accuracy in the tangential behaviour: the EDP model gives a more over-estimated load compared to the MS model. But, on the other hand, only the MS model gives a good representation of the FN vs. DN behaviour whereas the EDP model predicts a plastic dilatation that starts with plasticity and that does not correspond to the experimental observations.

Such behaviour can be explained by the overall shape of the EDP flow rule given by ψ (the "dilatation angle"). Indeed, the EDP model only permits the flow direction to be towards positive hydrostatic stress whatever the position in the Mises stress - hydrostatic plane. On the contrary, the MS model, as identified in the previous section, gives flow directions that are symmetrical about the Mises axis for two points that are also symmetrical. This radically changes the behaviour in the normal direction when considering compression-shear loads which are load cases that are rarely taken into account for the characterization of structural adhesives since they are relatively difficult to obtain and are not considered as the most detrimental. However, as the stress-state in the adhesive spew fillet, which is often the location of crack onset, is multi-axial, a poor estimation of the behaviour over the whole domain of hydrostatic stresses can lead to inaccurate modelling of the stress state within this region, and misunderstanding when comparing different stress criteria for example.

5. CONCLUSIONS

This study aims to characterize and identify the 3D elasto-plastic behaviour of structural adhesive materials. Two models, taking into account the hydrostatic stress dependency and non-associated formalism, have been identified using experimental results obtained with a modified Arcan test and a simplified inverse identification approach. The main conclusions that can be drawn are the following:

- The modified Arcan test is very efficient to characterize the behaviour of adhesive materials since it enables several load configurations to be applied to a bonded assembly using a unique specimen design and single test apparatus. In particular it allows the hydrostatic stress dependency to be highlighted.
- Applied to the case of the Redux 420 A/B epoxy adhesive, it is very useful in the discrimination between different elasto-plastic models.
- When considering structural adhesive elasto-plastic behaviour, characterization and validation on both the tension-shear and compression-shear domain are needed and particular care has to be taken in the choice of the flow rule.

- Optimisation of the identification procedure and study of the robustness of the inverse identification could lead to a better fitting of the experimental results.

Application of a similar procedure for the case of adhesives films, that also show hydrostatic stress dependency [1] and are used in aircraft manufacturing, is in progress. Next, a validation on non-proportional cases will constitute a natural extension to this work in order to validate a Mahnken-Schlimmer type model. Finally, a damage and failure approach, based on the typical requirements of a design office will be implemented.

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