DESIGN OF A BONDED ANCHORAGE FOR COMPOSITE PLATES: INFLUENCE OF THE ADHESIVE PLASTICITY

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ABSTRACT

While designing specific anchorage devices for a pedestrian bridge made with composite material [1], an interest was given to the use of adhesives exhibiting elasto-plastic behaviour. The use of the adhesive bonding technology for the anchorage of composite elements is indeed particularly well-suited when properly designed and realized as it reduces stress concentrations which occur when bolting is used for instance. The way an elastic adhesive joint transfers stresses is nowadays rather well-known, and has been studied by numerous authors who highlighted more particularly the concept of characteristic anchorage length [2].

Here, the use of an elasto-plastic adhesive was studied. Both experimental and theoretical analyses were conducted to investigate the influence of the non-linear behaviour of the polymeric adhesive. In the first part, the different tests will be presented including tensile tests on the adhesive, and tests on symetric double-lap joints using both elastic and elasto-plastic adhesives. Then, a finite element analysis will be described and its results compared to the obtained experimental ones. First comparisons made in the experimental part will focus on joint maximum capacities, and following comparisons on a parameter called slip which characterizes the way the joint is deformed in shear.

1. INTRODUCTION

The bonding technology, though known since centuries, has only started recently to be used in civil engineering structural realizations. Main reasons invoked against the use of such a technique was the importance of the realization step for the joint efficiency and its durability, and the lack of experience of such assembly. Yet, regarding the structural advantages and new concerns, more particularly in the field of bridge restoration or capacity increase, it is nowadays commonly used for FRP reinforcement [3]. More data being available about the durability of such a technique, this gives now good ideas of new structures relying entirely on bonding assembly [4].

Besides the realization of new structures, the adhesive bonding technology appears as a good alternative for anchorage devices provided the design is well-adapted and take into account the typical characteristics of bonded joints. The aim of this study is to observe the influence of the use of an elastoplastic adhesive in commonly lap joints. It is a part of a more general study focused on the design of an anchorage for composite plates. The surface preparation step which is momentous was adressed in order to obtain a cohesive failure occurring in the studied case in the adherends. It is not the main focus of this part of the research. Similarly, several authors have studied the influence of design details on the stress transfer such as the geometry of adhesive fillets [5,6], or the geometry of the adherends [7,8]. These interesting points will not be raised here. Yet, they will be taken into account when realizing the final anchorage geometry. Finally, other authors deepened the importance of the material's mechanical properties on the stress transfer and underlined for instance the advantages of the use of graded modulus adhesives [9] or adherends [10]. Here, a non-linear adhesive was used to

investigate its influence on the shear stress transfer of lap joints. The non-linearities change drastically the stress profiles along the bonded lap length, and the interest was here to check its consequences in term of maximum capacity, and the adequacy of commonly used modeling techniques with experimental results.
The lead experimental testing is presented in the first part including bulk material characterization, and lap joint testing using both elastic and elasto-plastic adhesives. The second part is dedicated to the describing of the used finite element model and the interesting points regarding stress transfer. Finally, the last part provides a comparison between experimental and theoretical results in terms of slip profiles along the lap length. The slip parameter is commonly used to characterize global shear deformation of the adhesive. It is measured in our study thanks to microscopic observations.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Materials in stake

The used adherends were uni-directional composite carbon plates commonly used for concrete structural reinforcement. Its orthotropic behaviour was defined realizing two tensile tests and the mechanical theoretical "Rule of mixture". The tensile Young modulus in the fiber direction was shown to be 162 Gpa and 10,6 Gpa in the transverse direction, and the Poisson's ratio 0,325. The out-of-plane shear modulus was found to be 4077 MPa. The used pultruded plate thickness was 1,2 mm.
Two different two-component epoxy adhesives were used, and both were characterized using typical bulk tensile tests. The first one, commonly used for concrete FRP reinforcement operations, exhibited an elastic behaviour and its tensile modulus was found to be 4940 MPa. The second one is used in the industry, and its tensile behaviour was elasto-plastic. It was decomposed in two parts: an elastic one with a Young modulus of 2500 MPa, and a plastic plateau reached for a yielding stress value of 37 MPa. For both adhesives, Poisson's ratio is considered to be 0.3.

2.2 Bonded joints

The studied bonded joints are common symmetric double lap bonded joints (Figure 1). This geometry was chosen to minimize peel stresses and obtain shear stresses in the adhesive layer. Fulfilling technical data sheets recommandations, the adhesive thickness was 0,6 mm in the case of the elastic adhesive, and 0,25 mm in the case of the elasto-plastic adhesive. First series of tests were dedicated to the surface preparation. Their aim was to obtain cohesive failure of the joints occuring in the studied case in the composite adherend. The results are not presented here, but the obtained surface preparation procedure was adopted for the following experimental investigations.

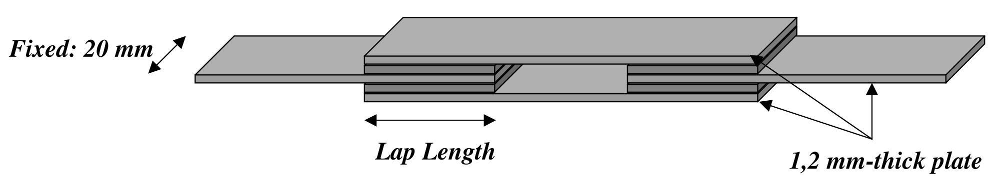

Figure 1: Scheme of the studied symetric double lap joints

The next step was to conduct failure tests on bonded joints having different bonded lap lengths with both adhesives. The results in terms of axial stress at failures against the lap length are reported on Figure 2. In addition to the experimental failure loads, qualitative expectations according to the well-known elastic theory of O. Volkersen [2] are plotted. This theory considers all the materials as isotropic and elastic. The two different obtained curves take into account the differences in terms of adhesive thickness and adhesive shear modulus and have been suited to experimental data using different maximum shear stress values (1: 145 MPa and 2: 40 MPa). Yet, these quantitative values do not affect qualitative expectations in terms of anchorage length. This one is expected to be around 10 mm with the studied geometry and materials. From Figure 2, it is clear that the elastic theory suits well the experimental results with the elastic adhesive. As far as the elasto-plastic adhesive is concerned, the obtained failure loads can not be fitted with Volkersen theory: the anchorage length seems to be much higher (around 40 mm at least). Having noted that the elastic theory was not adequate to describe adhesive joints when the adhesive exhibited elasto-plasticity, it is important to highlight the differences in terms of maximum capacity. The use of an elasto-plastic adhesive allows in that case to triple the maximum capacity of the joint. It is certainly to be linked to the increase of the anchorage length. The anchorage length value when using elasto-plastic has been adressed by several authors and is not the issue of this article. The first who introduced elasto-plasticity in the adhesively bonded lap joint was Hart-Smith in [11], and it was also adressed more recently in [12].

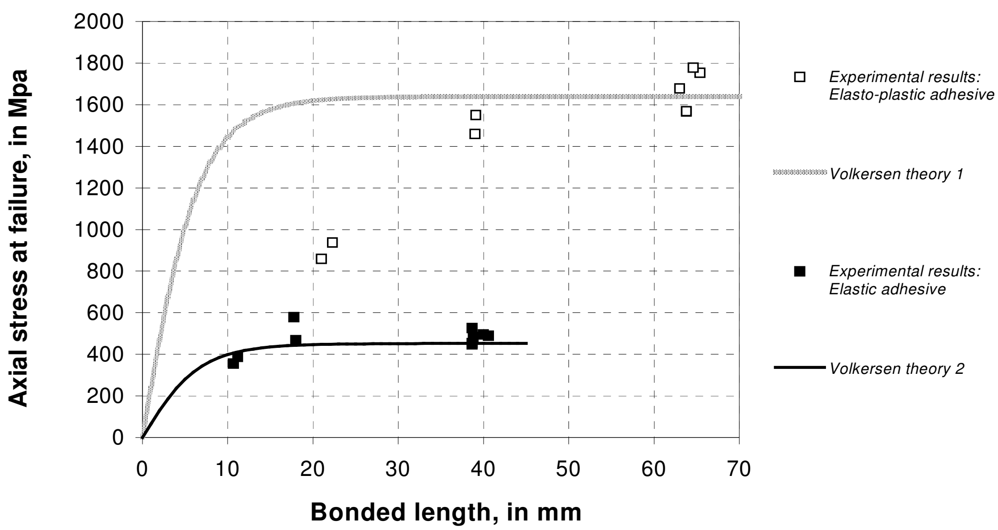

Figure 2: Experimental axial stress at failure for both adhesives and expectations according to the elastic Volkersen theory.

2.2 Slip measurement

Though in the previous part, the elastic theory was proved to be unsufficient in the case of the elasto-plastic adhesive, the presence of plasticity was not demonstrated. The bulk tensile tests revealed its occurrence, but several authors highlighted that the polymeric nature of the used adhesives could lead to anisotropic behaviour particularly when disposed in thin layers. It was thus decided to conduct slip measurement along the lap length while testing to observe shear strain evolution when doing load/unload cycles. The method developped in [13] was used. It consisted in measuring the relative displacement called slip between both adherends thanks to pencil marks made on finely polished joint edges. The measurement was made using microscopic magnification lens and is possible only for relatively high shear strains. It was thus well adapted for the case of the elasto-plastic adhesive. An exemple of two images obtained using this method is given in Figure 3. The bolt lines along the pencil mark on the photo on the left allows to measure the slip on the photo on the right (To get a good idea of the images scale, one can remember that the adhesive's thickness is 0,25 mm.).

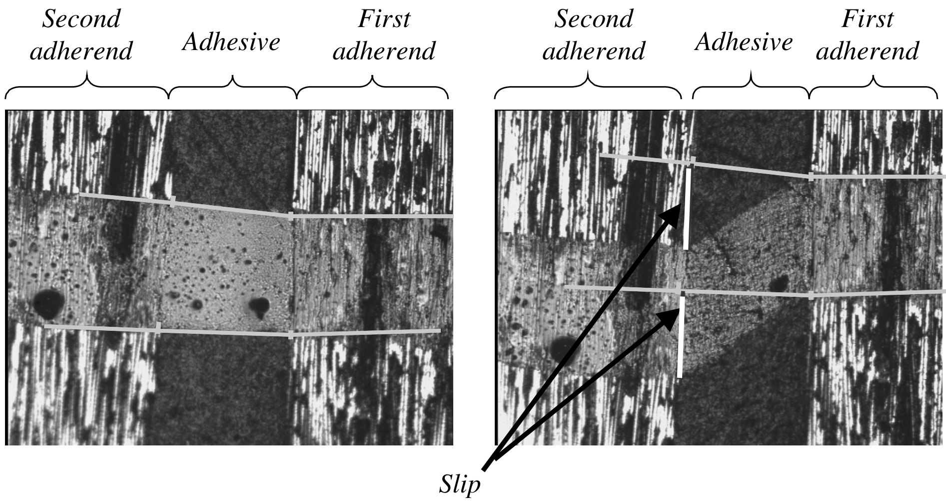

Figure 3: Measurement of the shear slip along the joint (Before loading on the left, and after loading on the right).

Having checked the ability of the used test setting, an experimental investigation was conducted applying one load/unload cycle untill 26 kN to a bonded joint, and measuring slip at 5 kN at first loading and after unloading. Results in terms of slip profiles along the lap length are shown on Figure 4. Firstly, it is interesting to note that these are qualitatively close to the ones of the elastic theory of O. Volkersen indicating stress concentrations on the edges. Secondly, the non-linear effect is clearly highlighted. The slip values are indeed much higher for a same load after one load/unload cycle. The additional slip or strain may certainly be associated within shear plasticity of the adhesive layer, and this is the hypothesis which was considered in the modeling part.

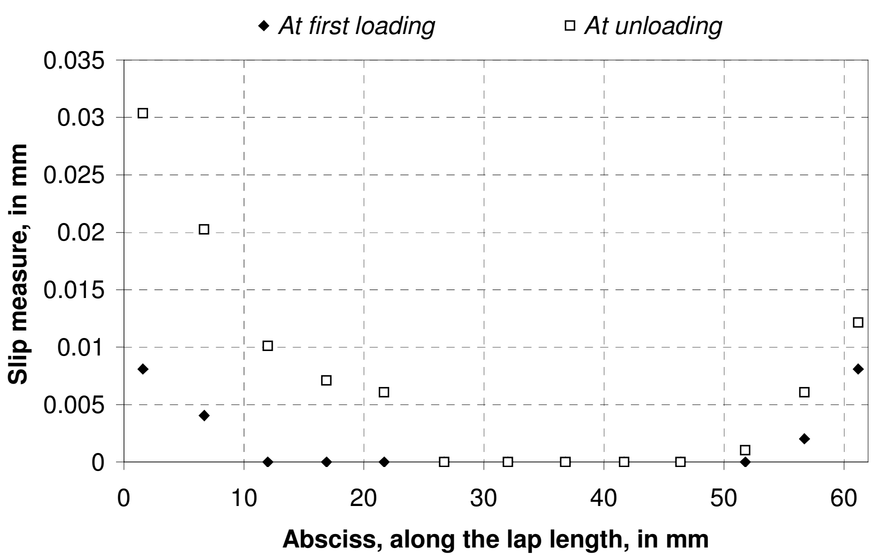

Figure 4: Experimentally measure slip along the lap length at 5 kN at first loading and after one load/unload cycle.

3. FINITE ELEMENT MODELING

Bonded joints stress transfer may be analyzed using different kind of tools. It was decided here to lead a finite element analysis as done in [14] to be able to take easily into account the non-linear effects described before.

3.1 The chosen mesh configuration and material properties

A finite element modeling was conducted using the commercial software Abaqus. A 2D plane strain model was used and a quadrilateral interpolation considered. Consequently, the influence of the width of the samples is not taken into account in the following study. Quadrilateral interpolation was used to obtain sufficiently precise results with a rather small number of elements in the adhesive's thickness. The mesh density was chosen so that 4 reduced quadrilateral square elements were used in the adhesive's thickness. The adhesive fillet was not modelled and only a quarter of the joints was modeled using symetry considerations. The choice of the elements is momentous to avoid shear locking, and hourglass modes which could strongly affect the obtained results, more particularly as the number of elements in the adhesive thickness is limited. As far as the adhesive's plasticity is concerned, it was chosen to use a classic Von Mises yielding criteria, and to suppose its behaviour as isotropic. Consequently, the modeling of the adhesive was made using only the tensile results described above. Two main questions remain and are being currently adressed concerning the choice of the yielding criteria (a pressure-sensitive criteria has been shown to be more consistent for polymeric materials [15]), and the isotropic hypothesis. Yet, this first study allows to make interesting conclusions about the influence of plasticity on the behaviour of a bonded joint. Additional studies will adress these issues later on.

3.2 Shear strain and slip results

The experimental method consisted in measuring the relative displacement between both adherends called slip. This parameter allows to obtain an averaged shear strain value of the adhesive along the lap length. Yet, observing closely shear strain profiles along the lap length in the adhesive thickness reveals unhomogeneous profiles. Similarly to the existence of strain concentration on the edges, there are strain concentrations in the adhesive's thickness. In Figure 5, the strain concentration in a part of the adhesive layer is represented by the dark color. It indicates that strain is not uniform in the adhesive's thickness, and that the position of the maximum strain value evolves along the lap length. When using slip data, one has consequently to be conscious that it softens the shear strain and deletes the non-uniformities in the thickness. Besides, when using finite element analysis, it is necessary to calculate slip data from the adherends displacement values in order to compare it to the experimental measured ones. The shear strain results can not be used as it vary drastically in the adhesive's thickness.

Figure 5: Shear plastic strain concentration in the adhesive.

The non-uniformity of the strain in the thickness was also detected when looking more closely at the obtained images. In Figure 6, the experimental measure reveals an elliptic shape of the deformed adhesive layer. Keeping this particularity in mind, the comparison is though lead in terms of slip and consequently of averaged shear strain.

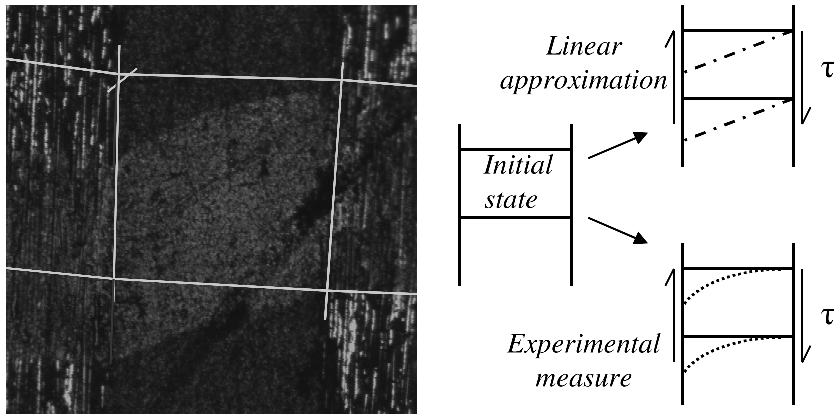

Figure 6: The measured shear deformation and its non-uniformity.

3.3 The obtained slip and stress profiles

The previous test including one load/unload cycle was modeled using the finite element code. Five points listed in chronological order are considered. Point A corresponds to an applied load of 5kN, and it is checked that none of the adhesive is plasticized. Point B corresponds to the reaching of the load of 26 kN. Then, the joint is unloaded until reaching 5kN again corresponding to Point C. The joint is then loaded again reaching Point D at 15 kN, and Point E at 26 kN. In Figure 7, the five obtained horizontal slip profiles are plotted along the lap length. As experimentally observed in Figure 4, the profiles of Point A and Point C are highly different indicating the importance of plasticity in the studied case.

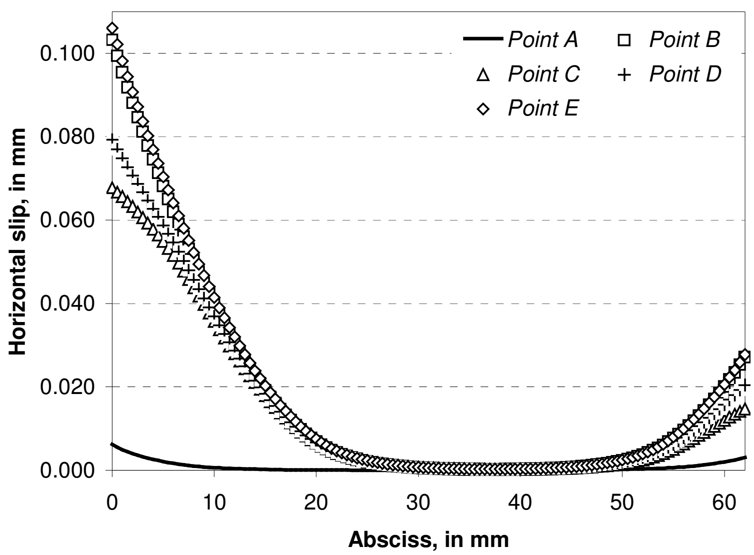

Figure 7: Obtained horizontal slip profiles for the five different points along the lap length.

In Figure 8 are plotted the resulting shear stress profiles along the lap length for the five points. For point A, the classical O.Volkersen [2] shape is recognized indicating no plasticity has occured. For point B, a shape similar to the one described by Hart-Smith [11] is obtained. Two distinct parts can be distinguished: on both edges a plasticized part, and in the middle a part working according to elastic expectations. What is interesting, is what occurs for points C, and D. The plastic strain induces a prestressing of the adhesive joint and consequently inverse shear stresses which equilibrate the prestressing force. This means that in the case of bonded joints using an elasto-plastic adhesive, a load/unload cycle can induce a prestressing of the adherends and the adhesive joint. Though the joint may be unloaded, materials could thus be stressed in service. This implies that when using elastoplastic bonded joints, the fatigue characteristics are momentous and should be taken into account. Additionaly, several durability studies on adhesively bonded joints shown that polymers tend to plasticize with time when exposed to severe conditions. Consequently, the remarks made above may be also consistent for initially elastic adhesives.

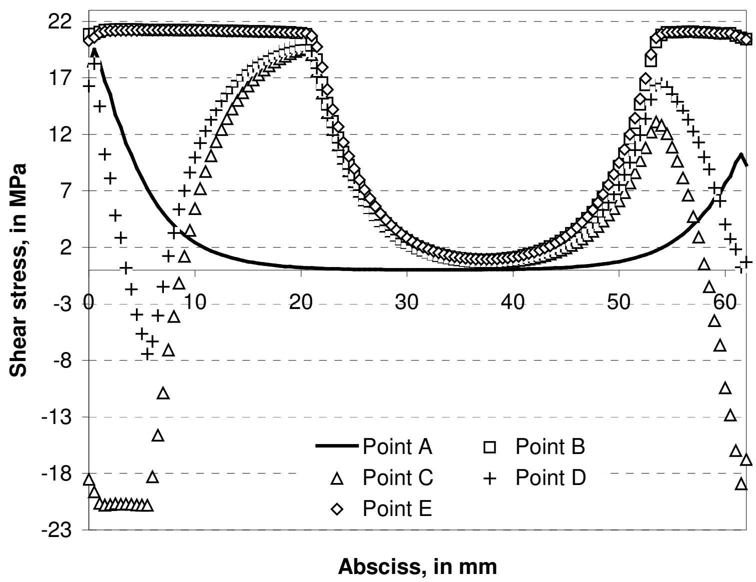

Figure 8: Obtained shear stress profiles for the five different points along the lap length.

4. COMPARISON OF EXPERIMENTAL MEASURES AND FINITE ELEMENT MODELING

The next step consisted obviously in comparing the finite element results with the measured slip data. Several tests have been carried out, and only two are presented here. The first is the one presented in the previous part which consisted in one load/unload path. Same steps are considered again: points A, B, C, D and E. In Figure 9, both slip profiles are compared for points A, C, D and E. One can remark that close results are obtained for points A and E. Point A corresponds to a fully-elastic state, and Point E corresponds to an highly-plasitcized state. The slip value seems to be over-assessed in the finite element analysis for intermediate steps. The chosen material model was perfectly elasto-plastic in the finite element analysis, and the differences may thus come from the non-taking into account of the real adhesive softening behaviour which is more complex. Besides, the chosen isotropic hypothesis over-assessed a little the shear modulus decreasing consequently the characteristic anchorage length. Yet, good correlation are found between the results and the used finite element model seems to have interesting perspectives provided finer material data are given for the adhesive's behaviour.

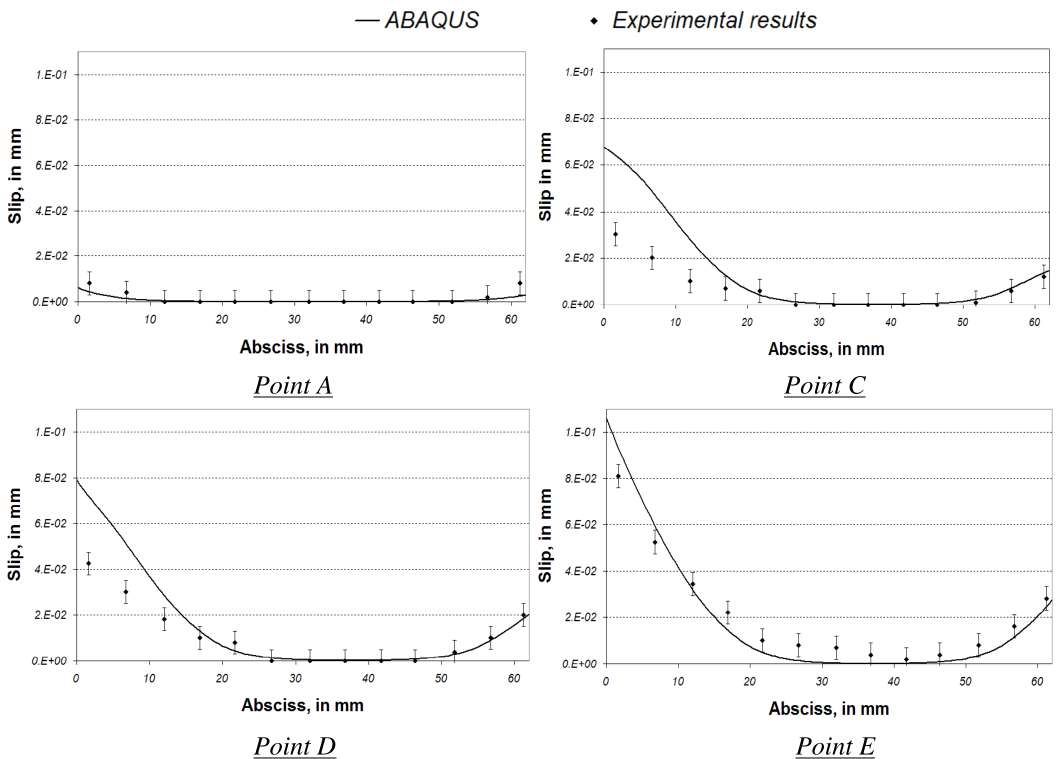

Figure 9: Comparison of experimental slip measures and finite element results for Points A, C, D and E.

Another test serie consisted in applying several load-unload cycles to a joint and in measuring slip at the same position during the whole test. The results are given in Figure 10 and superposed to finite element results. It is interesting to note that really close curves are obtained. Yet, unloading paths seem to be a little different between experiments and modeling. The area existing between load and unload paths is linked to the softening behaviour of the adhesive. Again, the lack of precise modeling of this particularity prevents the finite element results from perfectly fitting experimental measures.

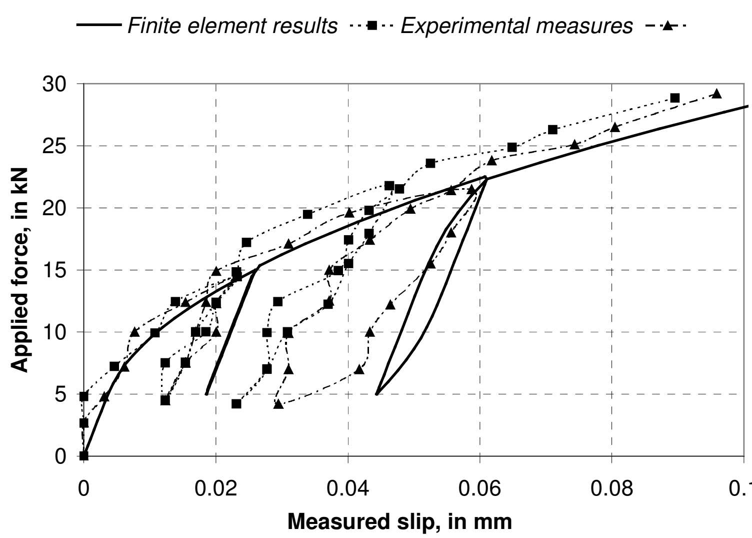

Figure 10: Comparison of experimental slip measures and finite element results for the applied force against the slip value at a given absciss along the lap length.

6. CONCLUSION

The presented work composed of both experimental and numerical investigations gave interesting results on the influence of an elasto-plastic behaviour of the adhesive for bonded lap joints. First of all, when comparing an elastic adhesive and an elasto-plastic one, it was shown that a great increase in terms of maximum capacity could be realized thanks to the increase of the typical anchorage length and consequently of the used bonded area. In addition to these remarks on the maximum capacities, the measurement of slip along the lap length allowed to conclude on the existence of remaining strain in the adhesive after a load/unload cycle, and consequenlty on non-linear effects. These non-linear effects have been supposed to come from the plasticity adhesive's behaviour observed on bulk tensile tests , and was implemented in the finite element code Abaqus. The obtained results were compared with the experimentally measured slips, and good correlation was found though more precise data needs to be used to model the adhesive's softening behaviour.

This work allowed to point out several interesting points linked to bonded joints, and raised several new interrogations. Firstly, the prestressing of the joint due to its plastic behaviour has been demonstrated numerically, and implies that even when unloaded, materials may be stressed in the case of lap joints bonded with an elasto-plastic adhesive. The issue of the fatigue under stress and consequently durability of such joints becomes then momentous. On another hand, this method could provide an interesting and easy way to maintain adhesive joints under stress and study creep, or fatigue of the realised joints. Secondly, the precise modeling of the adhesive's behaviour needs further investigations. Questions remain about the kind of yield criteria which must be used, and about the isotropy of its behaviour. This last topic could be deepened using a shear test such as the one described in [16] for instance. Good perspectives exist for this work, and some of these issues are being currently adressed.

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