Introduction of a Numerical Technique for the Estimation of Force of Welded Joints

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ABSTRACT: An experimental and numerical analysis on welded, adhesive, and hybrid (weld-bonded) T-peel joints under peeling loads is described in the present work. The called adhesives included the brittle Araldite ® AV138, the moderately ductile Araldite ® 2015 and the ductile Sikaforce ® 7752. An analysis of the experimental values and a comparison of these values with the Finite Element Method (FEM) results was carried out in Abaqus ®, which included Cohesive Zone Models (CZM) strength prediction considering simulation of the adhesive layer as well as weld-nugget failures. The Sikaforce ® 7752 has been found to perform best in the bonded and hybrid configurations. The strong agreement between the experimental and numerical results made it possible to predict the power of the adhesive and hybrid T-peel joints through CZM validation. CZM is a computational technique focused on traction-separation laws integrating stress principles with fracture mechanics to predict structural strength, including bonded joints. In reality, the initiation of damage, i.e. the cancelation of the elastic behaviour and the depreciation of strength, is predicted by strength-based criteria, while failure of the CZM elements is predicted by energetic criteria, allowing the simulation of damage growth to failure.

KEYWORDS: Cohesive Zone Models, Finite Element Analysis, Hybrid Joints, Structural adhesives.

INTRODUCTION

The widespread use of adhesive bonding in structural components and devices presupposes that designers may use accurate analytical methods to implement the best solution for a given application. Traditionally, continuum mechanics or fracture mechanics may perform the strength prediction of bonded joints. The stress distributions in the adhesive layer in continuum mechanics are initially calculated by theoretical or computational methods such as the FEM. Studies of fracture mechanics applied to bonded joints are scarce in the literature, but the Virtual Crack Closure Technique (VCCT) can be used, although it is limited to the principles of Linear Elastic Fracture Mechanics (LEFM) and involves an initial crack. Xu et al. used a generalized stress intensity factor similar to the stress intensity factor used in classical fracture mechanics to predict fault initiation in bonded joints at the interface corners.

CZM is a computational technique focused on traction- laws integrating stress principles with fracture mechanics to predict structural strength, including bonded joints. In addition, the initiation of damage, i.e. the cancelation of the elastic behaviour and the depreciation of energy, is predicted by energy-based criteria, while failure of the CZM elements is predicted by energetic criteria, enabling the simulation of damage growth to failure. Regional or continuum techniques may conduct the CZM modelling of bonded joints [1], [2]. In local technique, the propagation of damage occurs in zero lines of thickness, while the plasticity of the adhesives is modelled with solid materials. In continuum modelling, a row of CZM components completely reflects the behaviour of the adhesive layer.

Kafkalidis and Thouless found CZM to evaluate symmetric and asymmetric single-lap joints in numerical terms. Taking into account a particular joint structure for the adhesive under study, the characteristic parameters of the CZM laws were calculated and used in several different configurations afterwards. The comparison with the experiments showed accurate estimates of the full load (Pm) and displacement respectively. Extended Finite Element Method (XFEM) simulations exceed CZM modelling by not allowing coherent elements to be positioned at the growth paths. The XFEM is based on the principle of unity partition and consists of enriching the displacements in the traditional formulation of FEM.

Throughout the literature, bonded joints exposed to peel loads are widely studied and recorded. Maybe the most commonly studied T-peel joints, for instance by Grant et al. T-peel joints have a geometry that makes them vulnerable to tensile (pull-out) loads, as stresses are usually concentrated in a small bonded region in the adhesive layer. Therefore, by combining the bonded joint with a rivet, bolt or spot-welding to call a hybrid T-peel joint, the peel strength can effectively increase. Hybrid welded joints are obtained by combining adhesive bonding with a welded joint, becoming the spot-welding method most commonly used in the manufacture of these joints. Throughout the literature, bonded joints exposed to peel loads are widely studied and recorded [3]–[5].

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EXPERIMENTAL WORK

Adherents and adhesives:

In this study, adherents of C45E carbon steel (EN 10083-2: 2006) is considered for the joints, defined by the ASTM-E8M-04 norm in tension in a previous test. The related mechanical properties are: 204.32±2.40 GPa, yield stress (y) of 279.11±0.82 MPa, failure strength (f) of 347.51±0.93 MPa, and failure stress (f) of 36.36±2.45 percent, respectively. The bonded and composite joints tested three structural adhesives: the brittle Araldite ® AV138 epoxy, the relatively ductile Araldite ® 2015 epoxy and the ductile Sikaforce ® 7752 polyurethane. In previous works, mechanical and fracture characterisation of the adhesives was performed. Tensile tests were conducted on bulk specimens to determine the values of the adhesives E, uppermost, uppermost and uppermost. The Double-Cantilever Beam (DCB) test was considered to assess the toughness of the tensile fracture (GIc), and the End-Notched Flexure (ENF) test for toughness of the shear fracture (GIIc or GIIc for shear and GIIIc for tearing in three dimensions).

Joint geometry, fabrication and testing:

Figure. 1 The geometry and corresponding dimensions of the T-peel joints used in this work. The dimensions are as follows (in mm): bonded length L=90, width w=25, free length c=22, adhering radius R=1, adhering thickness tP=2, a and b=12,5 (spot-welded position) and adhesive thickness tA=0 for the welded joints and tA=0,2 for the bonded and welded joints. During the curing phase the aforementioned tA value was obtained by using Ø0.2 mm calibrated wire at the overlap edges. The welds for the spot-welded and hybrid joints were performed with conical electrode tips truncated to Ø6 mm in a CEA ® NKLT-28 welder. Both bonding and testing for the bonded and welded joints a one week duration was guaranteed. In an electro-mechanical tester Shimadzu AG-X 100 (Shimadzu, Kyoto, Japan) fitted with a 100 kN load cell, the joints were measured at room temperature, with a speed of 1 mm / min. Each joint configuration was tested on five specimens.

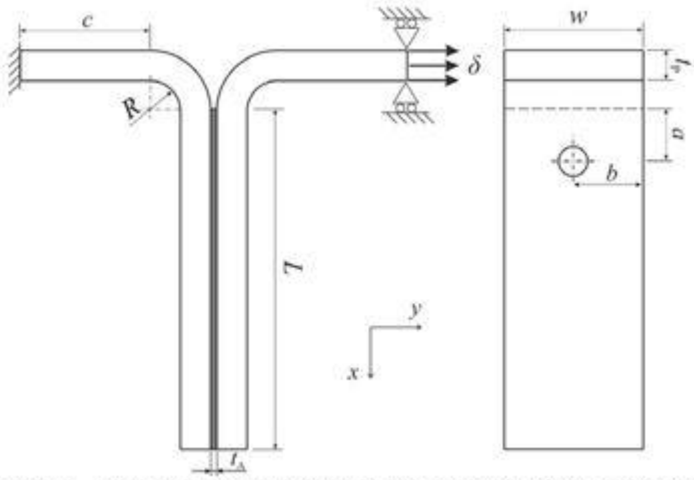


Figure 1. Geometry and dimensions of the T-peel joints.

NUMERICAL WORK

Modelling conditions:

The computational analysis was conducted in the geometrical nonlinearities accounting for Abaqus ®. Due to the presence of the spot-weld, it was appropriate to allow a three-dimensional analysis, though longitudinal symmetry may be included. The models were designed with continuum elements (Abaqus ® C3D8R) with a damage model for the adherents, while spot-welded and adhesive layer damage growth was made possible by modelling these media with triangular CZM elements (COH3D8 8-node cohesive elements). Figure. 2 An example of this is the mesh for the hybrid joint, the construction of which was similar to the spot-welded and bonded joint versions.

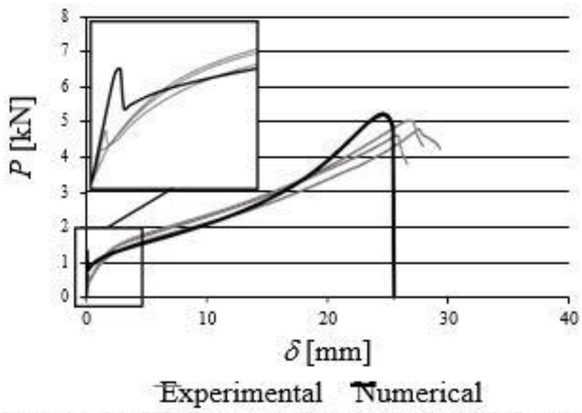


Fig. 5. Experimental and numerical P-δ curves for the hybrid joints with the Araldite® 2015.

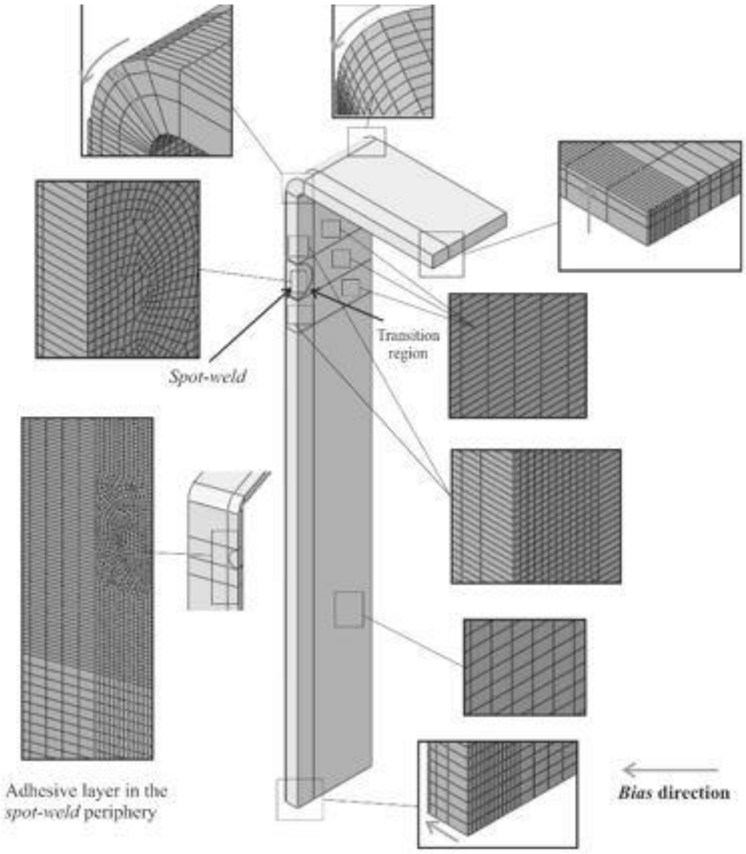


Figure 2. Mesh details at the most relevant joint regions (hybrid joint).

The boundary conditions consisted of fixing one of the edges of the adherents, while the other edge was subjected to a displacement prescribed by a tensile and was transversely confined. The plane with the symmetry was set in its usual position. CZM elements have modelled the adhesive layer and weld-nugget to facilitate harm growth taking into account the spectrum CZM method, i.e. use CZM elements to reflect the complete adhesive layer actions between the adherents.

Triangular CZM and cohesive parameters:

CZM elements model the linear behavior of materials up to the cohesive strength (t ^{0} in stress and t ^{0} in shear; n s in tri-dimensions ts10 in shear or ts20 in tearing) and subsequent material degradation up to failure. The areas in stress, shear or tearing (GI, GII or GIII, respectively) under the traction-separation laws are identical to GIc, GIIc or GIIIc, by their respective order. A triangular law was used in this work which initially considers an elastic behaviour and linear degradation takes place after damage. Under pure loading, as stresses are released in the respective harm rule, harm develops at a particular point of integration.

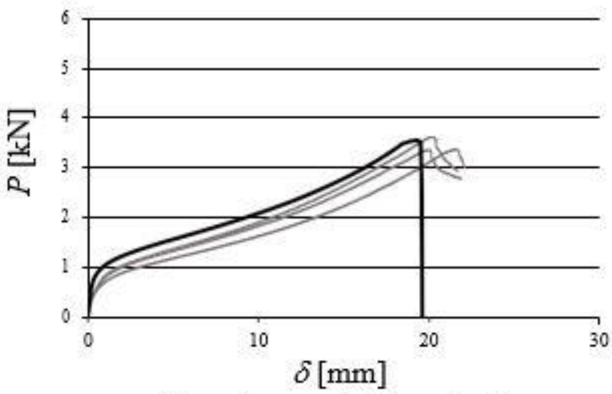
Table 1. Cohesive parameters of the adhesives and weld-nugget for CZM modelling.

Property	AV138	2015	7752	weld-nugget
E [GPa]	4.89	1.85	0.49	204.32
G [GPa]	1.56	0.56	0.19	78.58
t_n^0 [MPa]	39.45	21.63	11.48	500
^{0} [MPa] $t_{s1}^0=t_{s2}$	30.2	17.9	10.17	395
G_{Ic} [N/mm]	0.20	0.43	2.36	110
$G_{IIc}=G_{IIIc}$ [N/mm]	0.38	4.70	5.41	230

RESULT AND DISCUSSION

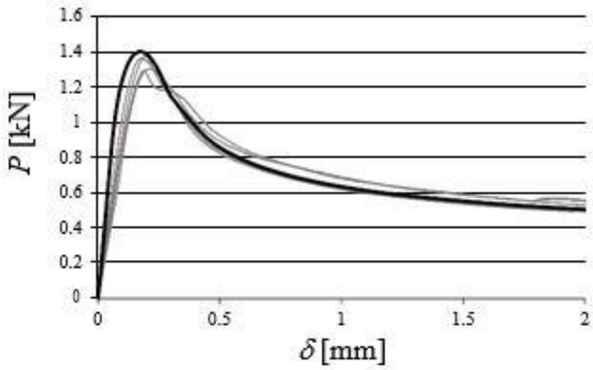
Failure modes and load-displacement curves:

Failure of the welded joints occurred through the welding line detaching the weld-nugget. Both bonded and hybrid joints in the adhesive layer experienced complete cohesive faults. Figure. 3 Displays the accurate experimental load displacement (P-) curves and the numerical approximation of the welded joints, with a rapid increase of P at the beginning of loading up to a limit of 1000 N. The high adherent deformations lead above this stage to a global stiffness reduction of the specimens. Pm is the initiation of weld-nugget failure at its edge. The simulation result managed to capture the behaviour of the curves and the Pm value very accurately.



Experimental Numerical

Figure 3. Experimental and numerical P-δ curves for the welded joints.



Experimental Numerical

Figure 4. Experimental and numerical P-δ curves for the bonded joints with the Sikaforce® 7752.

Figure. 4 Records P-shaped curves for bonded joints with Sikaforce ® 7752, the agreement of which is indicative of all joint configurations between experiments and simulations. Initially, the behaviour is usually linear to attain Pm, apart from mild softening close to this stage. It occurred because of the marked ductility of this particular adhesive, and was limited for the other two adhesives [10]–[12]. The load then slowly decreases as the crack propagates through the adhesive sheet. Figure. 5 Compares the experimental and numerical P-curves for hybrid joints with the Araldite ® 2015, the accuracy and curve features of which are similar to those of the Araldite ® AV138 joints.

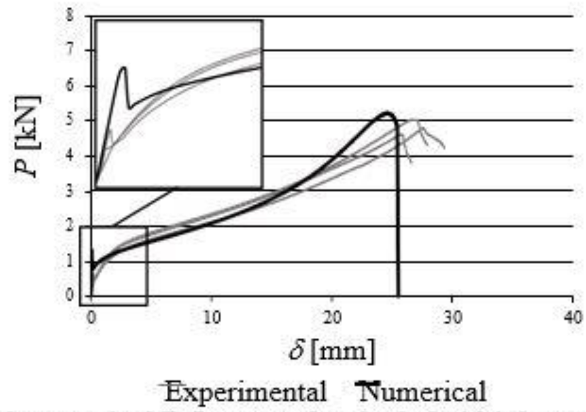


Fig. 5. Experimental and numerical P-δ curves for the hybrid joints with the Araldite® 2015.

Joint strength:

Fig. 6 shows a comparison between the average experimental values of Pm (solid columns) and the corresponding numerical predictions (with white background).

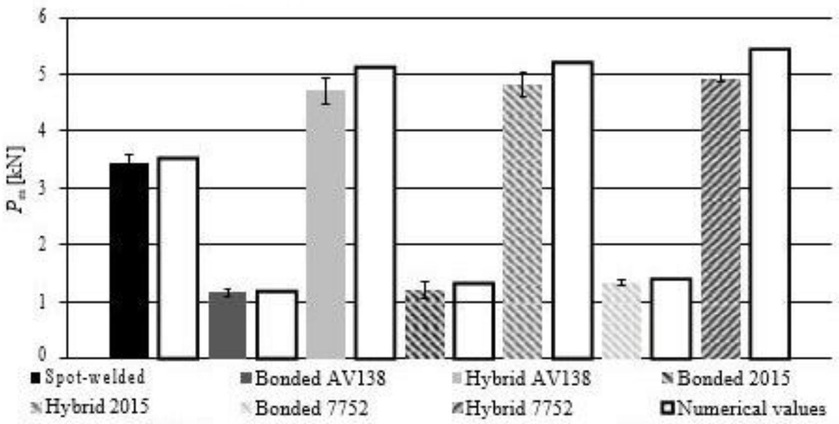


Figure 6. Experimental/CZM comparison between the spot-welded, bonded and hybrid joints (numerical values immediately to the right of the corresponding experiments).

There is a decrease in Pm for the bonded joints as opposed to the welded joints due to premature adhesive failure in comparison to the weld-nugget in the welded joints. The experimental reduction of Pm weighted against the welded joints was 66.1% (Araldite ® AV138), 64.7% (Araldite ® 2015), and 61.1% (Sikaforce ® 7752) respectively. This shows that the Sikaforce ® 7752 is the one which performs best in the T-peel bonded joint configuration, due to its smaller reduction in Pm. This behaviour is explained by its higher flexibility and ductility as opposed to the other two adhesives, as described before. Indeed, the Sikaforce ® 7752 is even more robust, as can be testified in Table 1, which translates into lower stress gradients near the edge of the adhesive layer. On the other hand, the ductility of the Sikaforce ® 7752, found in Table 1's GIc and GIIc values, also enables the layer adhesive to be greatly plasticised when the adhesive elastic limit is reached. This impact still exists for the Araldite ® 2015 adhesive, but to a lesser degree, and is almost non-existent with the Araldite ® AV138 adhesive, which excuses its worst results, while the stronger adhesive is. The hybrid joints demonstrate experimentally a percentile increase of 37.2 percent in Pm (Araldite ® AV138), 40.3 percent (Araldite ® 2015) and 43.8 percent (Sikaforce ® 7752) compared with the welded joints.

At the other hand, the percentile gain of Pm for the hybrid joints compared to the welded joint increases with the adhesive ductility, which can be clarified in an analogous manner to the one described for the bonded joints. Indeed, the Sikaforce ® 7752's improved versatility enables a more desirable distribution of stresses within the elastic range. The comparative study between the bonded and hybrid joints shows that the change in Pm from the bonded to the hybrid joints was substantial: 304.1% (Araldite ® AV138), 297.0% (Araldite ® 2015) and 269.4% (Sikaforce ® 7752) respectively. This discrepancy can be explained by the fact that when Pm (after failure of the adhesive layer between the loaded end of the joint and the proximity of the weld-nugget) is reached, the adhesive near the weld-nugget often plays an important role in the transmitted load between the adhesives, which helps to increase joint strength.

CONCLUSION

This work presented a CZM experimental and numerical study which allowed three joining techniques to be compared in T-peel joints: welded, bonded and welded when subjected to peeling loads. The CZM research included simulation of failure of both the adhesive and weld-nugget layers, with CZM parameters explicitly calculated for research. Experimentally it was found that the ductility of the adhesive increases Pm for the bonded joints. Bonded joints have a noticeable decrease in Pm relative to welded joints, albeit less important for the most ductile adhesive. The percentile Pm decreases were 66.1% (Araldite ® AV138), 64.7% (Araldite ® 2015), and 61.1% (Sikaforce ® 7752). The hybrid joints showed a percentile increase in Pm over welded joints of 37.2% (Araldite ® AV138), 40.3% (Araldite ® 2015) and 43.8% (Sikaforce ® 7752) respectively. Therefore, it is fair to assume that the increased strength of hybrid joints, along with other advantages in comparison to welded joints such as stiffness and peel resistance, will justify their usage in industrial applications requiring improved mechanical properties. For the welded joint, the CZM Pm projections showed a higher numerical Pm value of 2.73 per cent. The largest difference was 9.26 percent for the bonded joints (Araldite ® 2015), and 10.28 percent for the hybrid joints (Sikaforce ® 7752). Based on the results obtained, it follows that the CZM methodology has a reasonable accuracy and is ideal for modelling the actions of welded, bonded, and welded T-peel joints with precision.

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