

Numerical Modelling of Adhesive Connections Including Cohesive Damage

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Adhesive connections offer a number of benefits in structural applications, especially in the case of brittle adherends such as glass. There, a multitude of materials can be used to provide structural bonding between glass and/or metal components, giving evidence of different mechanical behaviours as well as structural performances. This paper reports on a Finite Element numerical investigation carried out on small-scale adhesive joint specimens. Taking advantage of a past experimental study performed at CTU in Prague - focused on both material tests and small-scale adhesive connections subjected to shear loading - the numerical modelling approach is validated by taking into account a selection of shear tests on glass-to-steel adhesive joints. The typical specimen is composed of two glass plates bonded to two steel plates with a gap between them and four adhesive joints per one specimens. Finite Element numerical analyses are presented, as obtained from full 3D solid models representative of the specimens components. While careful consideration is spent for the mechanical description of materials, a key role is indeed assigned to cohesive surface interactions, being representative of any possible damage occurring at the interface between the adhesive layers and the bonded substrates. The sensitivity of FE results to input parameters responsible of damage initiation and propagation is discussed, based on past experimental observations.

Keywords: Structural Glass, Adhesive Connections, Numerical Modelling, Cohesive Zone Modelling (CZM) and Damage, Inverse Calibration, Parametric Analyses

1. Introduction

Brittle substrates, such as glass, are advantageously bonded by adhesives due to more uniform stress distribution along the joint than conventional fastening techniques. There, a multitude of materials can be used to provide structural bonding between glass and/or metal components, giving evidence of different mechanical behaviours as well as structural performances. The stress distribution along the contact depends on the mechanical properties of the adhesives and adherends, the geometry of the joint (the length of the overlap, the thickness of the bond-line, and the thicknesses of the adherends), see (Petrie, 2007; da Silva et al., 2005). Significant stress concentrations in adhesive joints can be avoided by applying glue with a low modulus of elasticity and with ductile behavior. Flexible adhesives generally have low strength, but their ability to distribute the stress more evenly along the overlap may result in higher joint strength than when rigid adhesives are used. This is because rigid adhesives are not able to redistribute the stress concentrations at the ends of the overlap (da Silva & Campilho, 2015). The use of adhesives that are relatively strong and - at the same time - flexible would therefore be ideal for structural applications. For this reason, SikaFast 5211 NT acrylate adhesive was selected in (Pravdová et al., 2016; Machalická et al., 2016) for an experimental and numerical study on bonded glass-metal connections.

This paper reports on a Finite Element numerical investigation carried out in ABAQUS (Simulia, 2017) on small-scale adhesive joint specimens. Taking advantage of a past experimental study (CTU in Prague) focused on both material tests and small-scale adhesive connections subjected to shear loading, the numerical modelling approach is validated and assessed by taking into account a set of available shear tests on glass-to-metal adhesive joints. The reference specimen, as shown, is composed of two glass components bonded to two disconnected steel plates - i.e. with a gap between them - and four adhesive joints per one specimen. Since the past experimental study included two series of geometrical arrangements with different bonding areas, both the experimental set of shear stress-strain curves and failure mechanisms are taken into account for comparative purposes and discussion of selected FE estimations.

In the typical FE model - consisting of full 3D solid element representative of the nominal specimens components - a key role is in fact given to the mechanical description of materials (especially the adhesive and glass, so to account for possible cracking phenomena during the shear loading phase), as well as to cohesive surface interactions, being representative - within the Cohesive Zone Modelling (CZM) technique - of any kind of damage occurring and propagating at the interface between the adhesive layer and the bonded substrates. There, special attention should be paid for the definition of major input cohesive parameters, being responsible of huge effects on the corresponding FE

estimations, as well as being sensitive to material and surface conditions. A parametric FE analysis is hence proposed for selected adhesive joints, giving evidence of FE results sensitivity.

2. Summary of past research on steel-glass shear connections

2.1. Shear experiments on acrylate glass-steel connections

As a reference configuration for the FE numerical study reported in this paper, the experimental tests carried out on glass-steel acrylate shear connections reported in (Pravdová et al., 2016) are taken into account, see Figure 1. The typical specimen was prepared as a sequential double lap shear connection, see Figure 1(a), where each joint contained four SikaFast 5211 NT adhesive layers (3mm the nominal thickness). The nominal bonded area was 50×50mm and 50×38mm respectively (50mm and 38mm their overlap length). Adhesives layers were then used to bond together two small annealed glass plates (110×50×19mm) and two middle steel plates (75×50×25mm).

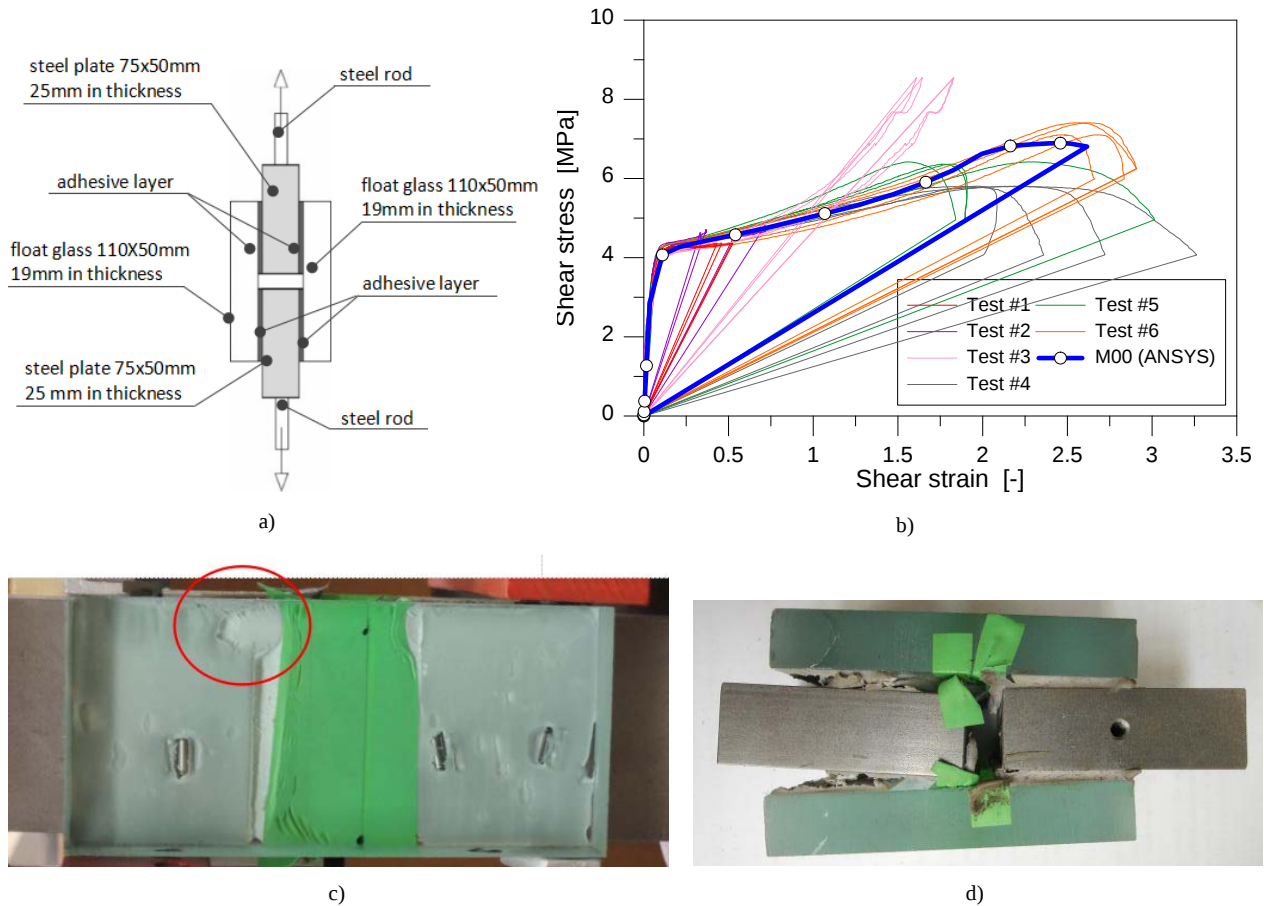


Fig. 1 Shear glass-steel connection tests: a) experimental setup; b) stress-strain experimental results, compared to the M00 model; c) beginning of delamination in the corner of the bonded area (specimen #5); d) adhesive/cohesive failure in the adhesive layer (specimen #6).

The full experimental program reported in (Pravdová et al., 2016) included 6 specimens (three for each overlap length), and gave evidence of various failure modes, see Figures 1(c)-(d) and Table 1 (with F denoting the total specimens resistance). In Table 1, in particular, the failure mode type “A” denotes a major glass rupture, while the failure mode type “B” (being reported for the specimen #6 only) corresponds to combined adhesive / cohesive failure mechanisms in the adhesive layers. The test specimens were loaded by a compressive or tensile force, see Table 1, with a constant displacement rate of 1 mm/min. The so obtained stress-strain results are shown in Figure 1(b) for all tested specimens.

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Table 1: Summary of past experimental test results on glass-steel acrylate shear connections (Pravdová et al., 2016).

Key: A= glass rupture, B= adhesive/cohesive failure				
Specimen #	Bonded area [mm]	Failure load F [kN]	Failure mode	Loading protocol
1	50 x 50	21.8	A	Tensile load
2		33.2	A	Compressive load
3		42.7	A	Compressive load
4	50 x 38	21.4	A	Compressive load
5		24.7	A	Compressive load
6		27.6	B	Compressive load

2.2. Preliminary Finite Element numerical modelling

Following the testing program summarized in Section 2.1, preliminary FE numerical modelling was also developed in ANSYS and discussed in (Machalická et al., 2016), so to derive from numerical fitting the stress-strain input properties able to best capture the experimental observations. The so calibrated reference FE model, to this aim, consisted of full 3D solid elements representative of glass, steel and adhesive components. Ideal linear elastic constitutive laws were used for glass and steel components, while a Von Mises mechanical relationship was experimentally calibrated for the acrylate layers. A fully rigid connection was finally used for all the glass-to-adhesive and steel-to-adhesive interfaces, hence neglecting possible debonding and interface failure mechanisms. Comparative results are shown in Figure 1(b), and denoted as ‘M00’ results.

Even under simplified FE assumptions, the preliminary FE study gave evidence of important outcomes for the overall structural performance of the examined acrylate joints. With respect to the experimentally observed failure mechanisms and damage propagation modes, for example, beginning of delamination (i.e. “adhesive failure”) was generally noticed for most of the experiments, at low levels of loading (see Figure 1(c)). Later on, with increasing the applied load, “glass rupture” or “cohesive failure” (i.e. specimen #6) followed, leading the specimens to collapse. The preliminary FE models reported in (Machalická et al., 2016), in this regard, proved to offer reliable predictions on the expected shear stress peaks location, giving evidence of critical regions in the adhesive layers where shear stress concentrations could be responsible of crack initiation (see Figure 2). Stress peaks, as expected, were noticed especially at the overlapping ends, as also in accordance with earlier research studies on similar joints (see for example (Overend et al., 2011; da Silva et al., 2015)).

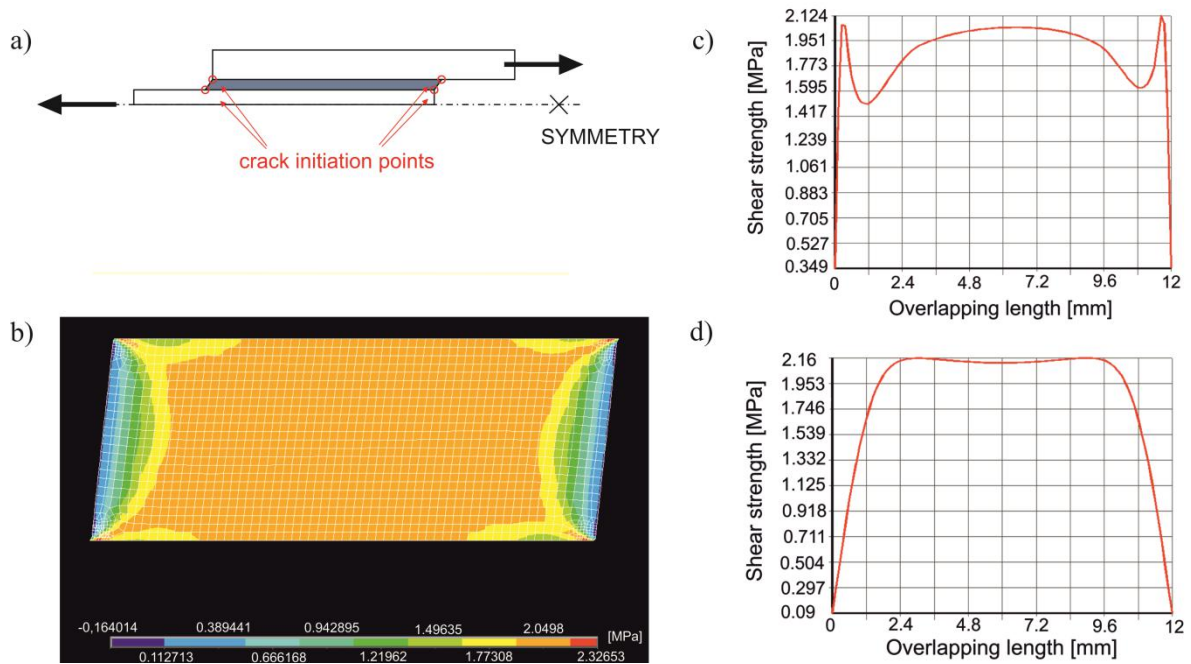


Fig. 2 Shear stress along the joint and crack initiation points: a) geometrical setup of loading; b) shear stress in adhesive layer; c) shear stress along the overlap length at substrate-adhesive interface; d) shear stress along the the overlap length at centre of adhesive layer (ANSYS).

3. Finite Element numerical study

Compared to earlier research efforts, the FE investigation summarized in this paper is carried out as a further extension of existing numerical studies. Careful consideration, in particular, is spent for materials calibration - to account for additional failure mechanisms during the loading stage - but especially for the possible initiation and propagation of interfacial damage between the bonded components.

3.1. Model assembly and solving method

The reference simulation is carried out in ABAQUS/Explicit (Simulia, 2017) and consists of a dynamic step with quasi-static imposed displacements and non-linear geometry effects, in which the shear test setup from experiments reported in (Pravdová et al., 2016) is properly reproduced.

Hexahedral continuum solid elements with 8 nodes and reduced integration (C3D8R type from ABAQUS library) are used to describe all the specimens components. In order to optimize the computational efficiency of the reference FE model, half the nominal geometry is numerically reproduced for each specimen. As also observed at a preliminary stage of FE simulations, compared to 1/4 the nominal geometry, the latter assumption allows in fact to preserve the accuracy of FE analyses, hence to properly account for local bending phenomena in the joint components as well as to avoid possible local stress peaks deriving from symmetry boundaries. Mesh size and pattern are defined on the base of a variable brick scheme, so to ensure a refined mesh pattern especially in the region of adhesive layers (0.5mm the reference size), with up to 5mm the brick size towards the external surfaces of glass and steel components respectively. The final FE assembly consists of $\approx 95,000$ solid elements and $\approx 330,000$ DOFs, see Figure 3(a).

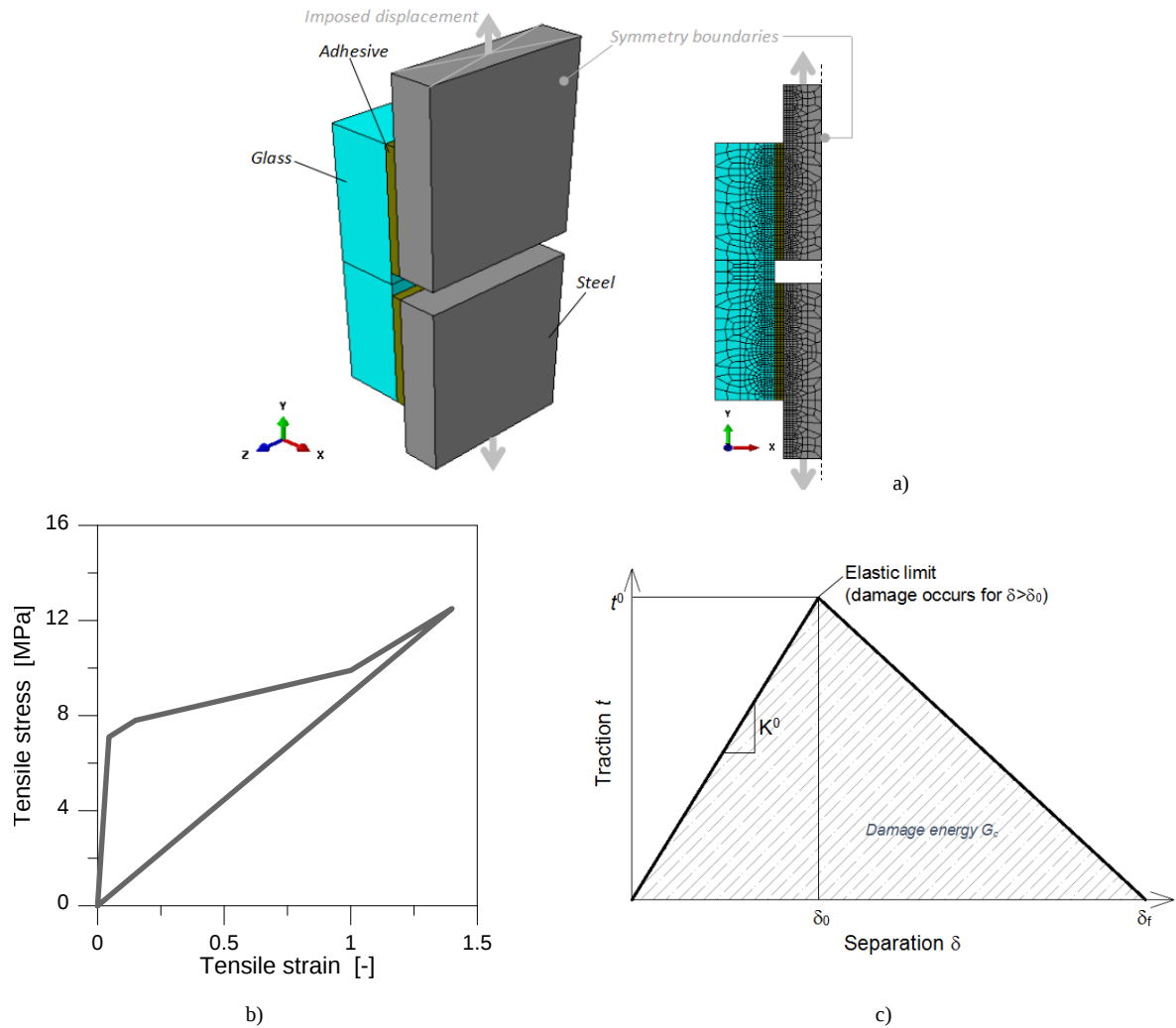


Fig. 3 a) Reference M0R numerical model (ABAQUS), with b) Von Mises input data for the adhesive layers (Machalická et al., 2016) and c) typical bi-linear traction-separation law for the CZM approach.

The mechanical interaction between glass, adhesive and steel model components is then implemented by means of *surface-to-surface* constraints. Based on past experimental and FE observations (see Section 2), the steel-to-adhesive interfaces are described in the form of rigid *tie* connections, hence enabling possible relative displacements and rotations of the involved nodes. In the case of glass-to-adhesive surface contacts, careful consideration is indeed spent

for the calibration of appropriate interactions (see Section 3.3). In the latter case, while rigid *tie* constraints are used for a preliminary reference model only ('M0R', in the following), cohesive surface interactions are in fact implemented for FE sensitivity studies ('M0C' model, in the following). The final effect of such a modelling assumption is a rigid mechanical interaction between the involved surfaces (i.e. as in the case of rigid *tie* constraints), but including also possible damage initiation and propagation once exceeded a certain critical stress-strain condition.

3.2. Materials

The mechanical characterization of materials is carried out in accordance with earlier literature references, so to account also for possible damage effects.

For annealed glass, the *brittle cracking* option is used, to account for possible tensile cracking phenomena. The nominal value for the characteristic tensile strength $\sigma_{tk,g}=45\text{MPa}$ is considered, with $E_g=70\text{GPa}$ and $\nu_g=0.23$ the modulus of elasticity and Poisson ratio (EN 572-2). The *brittle shear* and *brittle failure* sub-options are then used, to account for possible cracks propagation in each glass component. In doing so, a reference value $G_{f,g}=3\text{J/m}^2$ is taken into account for the fracture energy (Bedon & Louter, 2017). The cracked shear modulus $G_{c,g}$ is hence estimated - through FE simulations - as a fraction of the uncracked modulus G_g :

$$G_{c,g} = \beta(\varepsilon_{nn}^{ck}) \cdot G_{c,g} \quad (1)$$

with the shear retention factor given by:

$$0 \leq \beta(\varepsilon_{nn}^{ck}) = \left(1 - \frac{\varepsilon_{nn}^{ck}}{\varepsilon_{max}^{ck}} \right) \leq 1 \quad (2)$$

In Eqs.(1) and (2), ε_{nn}^{ck} and ε_{max}^{ck} represent the actual and ultimate crack opening strains respectively, while $p=5$ (Bedon & Louter, 2017). The physical displacement representative for the collapse configuration of a given mesh element is finally taken into account via the brittle failure sub-option, with:

$$u_{ck} = \frac{2G_{f,g}}{\sigma_{tk}} \quad (3)$$

the ultimate displacement for cracked elements. In order to minimize possible convergence issues of FE simulations, erosion from the mesh pattern of cracked glass elements is disregarded.

The small steel plates are characterized in the form of an ideal linear elastic constitutive law, with $E_s=210\text{GPa}$, $\nu_s=0.3$. Through the post-processing stage, steel plasticity proved to have null effects on the FE estimations, being the steel components subjected to limited stresses only (in the order of 40MPa), up to the collapse of adhesive layers. For the adhesive bonding layers, finally, their mechanical performance is described in the form of an equivalent, elasto-plastic material (Von Mises law). Input stress-strain data are derived from Section 2, see also Figure 3(b) and (Machalická et al., 2016).

3.3. Cohesive Zone Modelling and damage interactions

Through the FE sensitivity study, the glass-to-adhesive adjacent timber elements are related via 'cohesive contact' interactions available in the ABAQUS library. There, a key role is assigned both to elastic stiffness features as well as to damage input data. CZM modelling, as known, is a powerful tool for predicting delamination in adhesively bonded structural components and is widely implemented in commercial FE codes. Compared to other approaches, the CZM method has intrinsic advantages in modelling, since (i) pre-existing definition of cracks is not necessary, (ii) prior assumptions for onset and growth of damage are not required, (iii) complex moving mesh techniques can be avoided, as well as (iv) strongly refined mesh elements close to cracks (to ensure local occurrence of infinite stress and strain peaks). Major structural applications available in the literature are related to various composite systems and joint types, see (Pirondi, 2004; Zhang et al., 2007; Katnam et al. 2011; Dogan et al., 2012; Perillo et al., 2012; Xu & Wei, 2013; Gato et al., 2017; Bedon & Fragiaco, 2017; etc.).

Generally speaking, within the CZM approach, fracture is assumed to occur by progressive separation of the crack surfaces ahead of the crack tip (see Figure 3(c)). The crack grows when its separation reaches a critical value. The key input into any cohesive zone model is hence represented by the traction-separation law. Such a law - aiming to accurately represent the fracture of the material or interface being modeled - is usually calibrated on the base of experimental measurements (see (Campilho et al. 2015; da Silva et al., 2009a and 2009b; etc.)).

In this research study, experimental results available for shear connections are taken into account for assessment and calibration of CZM input features. In terms of initial stiffness components of the glass-to-adhesive interactions (i.e. being representative of the interface stiffness prior to damage onset), the ‘default contact enforcement method’ was preliminary used to define the normal (K_n^0), longitudinal shearing (K_s^0) and radial shearing (K_t^0) stiffness terms. Generally speaking, the same input parameters could be estimated as:

$$K^0 = \min \left(K_n^0 = \frac{E_{adh}}{t_{adh}}, K_s^0 = \frac{G_{adh}}{t_{adh}} \right) \quad (4)$$

with E_{adh} , G_{adh} the MOE and shear modulus of the adhesive, t_{adh} its nominal thickness. Following Eq.(4) and Figure 3(b), the critical separation displacement for the n , s , t directions is then given by:

$$\delta_0 = \frac{t^0}{K^0} \quad (5)$$

where t^0 denotes the effective nominal strength in the cohesive interface.

Careful consideration should be hence spent also in terms of damage initiation and possible evolution, along the same contact surfaces. Two different stress-based *damage initiation criteria* are available in ABAQUS for cohesive elements to define the traction-separation laws: (i) the maximum nominal stress criterion (MAXS) and (ii) the quadratic nominal stress criterion (QUADS). The damage initiation criterion is a combination of stresses that satisfy a threshold value, being strictly related to material properties. As a normal failure criterion, a value ≥ 1 indicates that the initiation criterion is met, where:

$$\max \left\{ \frac{t_n}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right\} = 1 \quad (6a)$$

$$\left\{ \frac{t_n}{t_n^0} \right\}^2 + \left\{ \frac{t_s}{t_s^0} \right\}^2 + \left\{ \frac{t_t}{t_t^0} \right\}^2 = 1 \quad (6b)$$

for MAXS (Eq.(6a)) and QUADS (Eq.(6b)) criteria respectively. Afterwards, the material response changes in accordance with the chosen damage evolution law. For both the MAXS and QUADS initiation criteria, the values t_n^0 , t_s^0 and t_t^0 in Eqs.(6a)-(6b) represent the maximum permissible values for the nominal stresses, when the deformation is purely normal (n) to the bonding interface or purely in the first (s) or second (t) shear directions. Even both the criteria are stress-based, the MAXS criterion disregards any possible relation between the different stress directions, while the QUADS approach assumes a quadratic relation between the stresses recorded in all the different loading directions. Within the ABAQUS CZM formulation, the *damage evolution law* describes the degradation of material stiffnesses after the damage initiation criterion is reached. To this aim, a scalar damage variable ($0 \leq D \leq 1$) is used as damage parameter, being representative of undamaged ($D=0$) or fully damaged material ($D=1$). Both linear and power damage evolution laws can be defined, being representative of damage evolution as a function of a reference interface displacement or fracture energy value.

In this research study, the MAXS method is used, as discussed in Section 4. In terms of damage evolution, the linear degradation laws for contact mechanical properties is taken into account, with full residual stiffness in the cohesive bonding ($D=1$) at the attainment of a given failure separation displacement δ_f (see also Figure 3(c)). Such an approach is in accordance with inverse calibration CZM methods, namely consisting in iterative curve fitting procedures of input CZM data based on experimental results (da Silva & Campilho, 2012).

4. Discussion of parametric FE results

The analysis of FE results includes comparative observations on the obtained stress-strain curves, evolution and distribution of maximum stresses in the specimens components as well as a qualitative discussion of observed failure mechanisms, with respect to the experimental findings.

4.1. Reference M0R model

For preliminary comparative studies and validations, the M0R model with rigid tie constraints on both the steel-to-adhesive and glass-to-adhesive interactions is first analyzed. Comparative results are collected in Figure 4. There, major variations include modifications in the input mechanical properties of annealed glass, as well as loading protocol (compressive vs. tensile loading). Actually, the reference experiments on double lap joints gave in fact no evidence of possible sensitivity of stress-strain results to the loading protocol, while the analysis in (Guo et al., 2006) indicates that axial compression applied on single lap joints may result in higher strengths in compression than in tension due to development of compressive peel stresses.

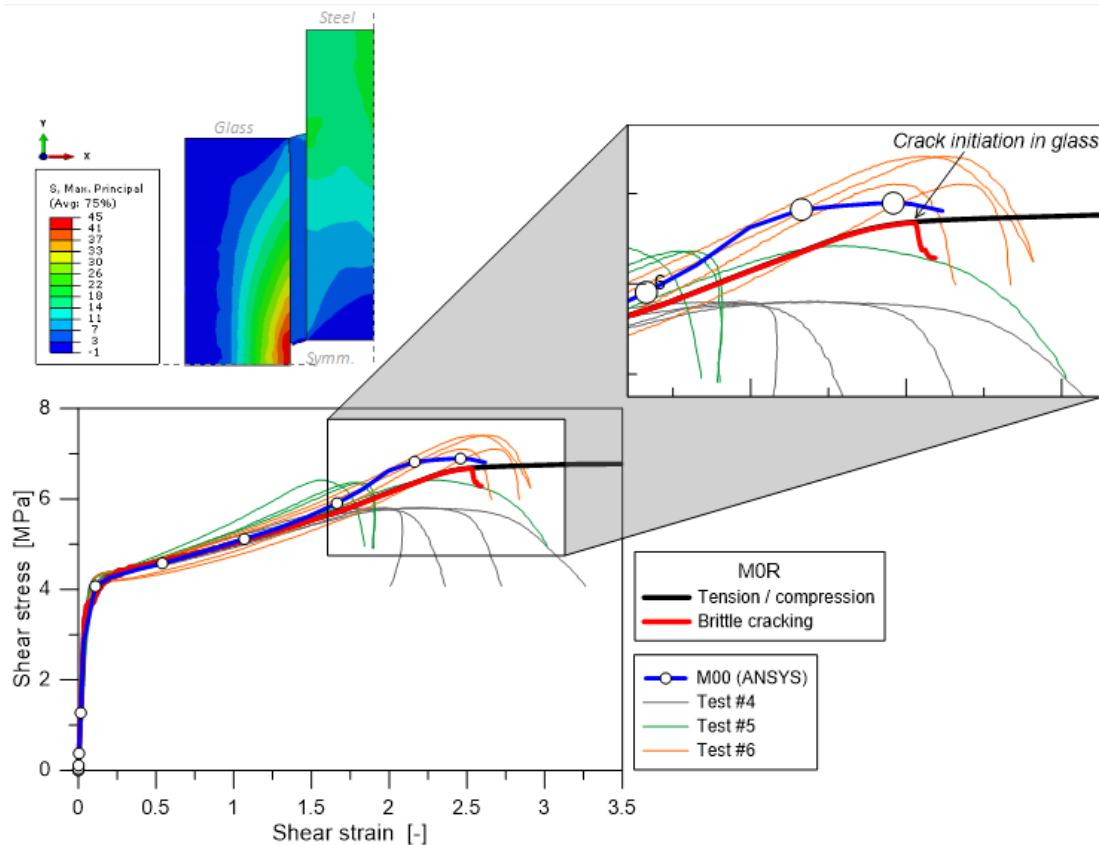


Fig. 4 Preliminary numerical assessment of the M0R model (ABAQUS), with respect to earlier experimental and FE studies (Pravdová et al., 2016; Machalická et al., 2016).

Accordingly, no sensitivity of FE stress-strain results to tensile or compressive loading is noticed from the numerical investigation. Rather close correlation is also observed between ABAQUS and earlier ANSYS models (see ‘M00’ and ‘M0R’ curves in Figure 4).

Possible tensile cracking of glass components, finally, proves to have important effects in the ultimate stage only of the assigned displacement paths. Such a finding is emphasized in Figure 4 (detail plots and FE contour plot of maximum stresses (legend in [MPa])), highlighting a mostly identical stress-strain response of M0R models with elastic or brittle glass behaviour. For strain ratios higher than ≈ 2.5 only, partial tensile cracking of glass components in bending was numerically observed, with subsequent decrease of the actual load bearing capacity for the examined connection.

4.2. Cohesive M0C model

Further parametric studies are hence carried out by including CZM methods and damage interactions at the glass-to-adhesive interfaces. In doing so, the tensile brittle constitutive law for glass is taken into account, as in the case of the 'M0R Brittle cracking' model in Figure 4. In accordance with Section 3, moreover, parametric variations are considered for the input mechanical features representative of the CZM damage initiation and evolution.

The nominal resistance value from Sika manufacturer is first taken into account (Sika, 2013) as a key influencing parameter for damage occurrence, hence resulting in $t_s^0 = 8\text{MPa}$ of shear tensile resistance for the bonding surface (with $t_n^0 = t_s^0 = t_t^0$), see Figure 5. Damage propagation - and critical separation values δ_f in particular - is hence numerically assessed based on curve fitting of the experimental results. In doing so, a linear degradation of adhesion bonding properties is considered.

As shown in Figure 5, rather marked sensitivity of FE predictions can be noticed, based on the assigned separation values. FE results are proposed for the 50x50mm bonded joints). Following Eq.(5), in particular, the reference elastic separation value δ_0 would result in 0.25mm, hence the failure separation one δ_f is parametrically assumed in the range $0.5-8\delta_0$. As shown, best correlation between numerical and experimental stress-strain data is obtained for ultimate separation values δ_f in the order of 4-6 times the δ_0 analytical estimation ($>8\delta_0$, for the specimen #6). Ultimate δ_f values $<4\delta_0$ hardly fit the selected experimental curves.

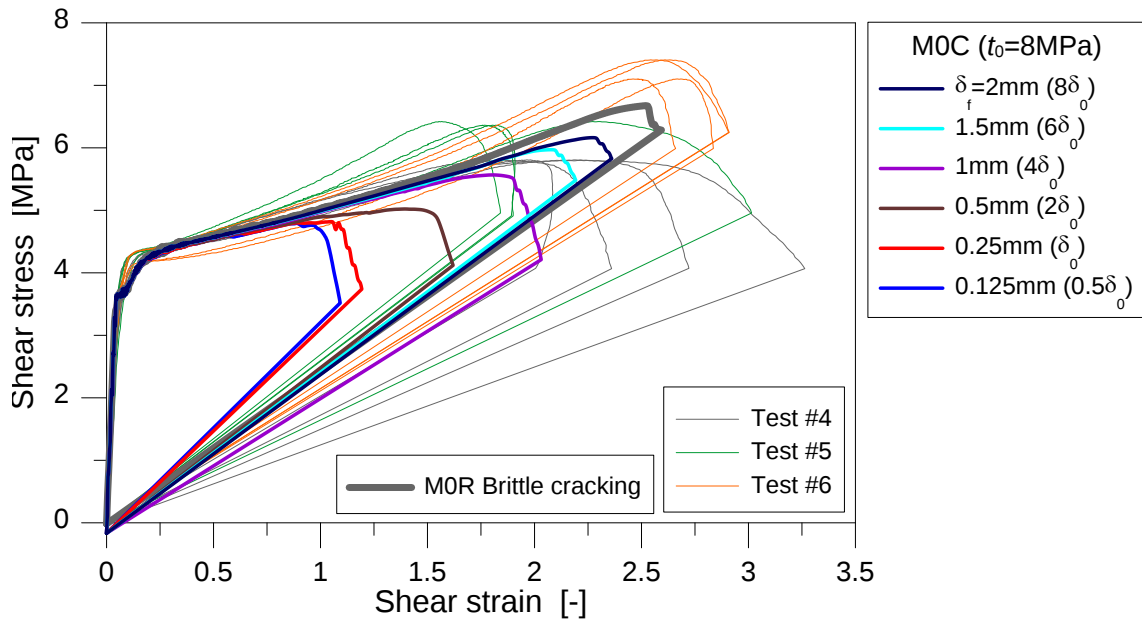


Fig. 5 Comparative numerical assessment of the M0C model (ABAQUS), with respect to earlier studies (Pravdová et al., 2016), as a function of CZM failure separation δ_f .

The sensitivity of the same FE results to the assigned t^0 resistance values is also assessed (with 4, 6, 8 and 10MPa respectively the assigned input references), by keeping constant the other mechanical properties (with $\delta_f = 1.5\text{mm}$, as selected from Figure 5). Also in this case (see Figure 6, with #6 experimental curves only in evidence), the best correlation with test predictions is obtained with a cohesive resistance of 8-9MPa, which agrees with the nominal shear strength provided in (Sika, 2013). Worth of interest, in the same Figure, is in fact the high sensitivity of the numerical stress-strain curves to even small variations in the input CZM t^0 values. Input resistance values in the order of 10MPa, for example, proved to offer stress-strain curves in close correlation with the M0R model, hence resulting in mostly null traction-separation damage propagation, compared to the M0R assembly with fully rigid *tie* constraints. In this sense, failure would be expected as a major effect of glass rupture only, rather than a mixed cohesive/adhesive failure mechanism. A certain correlation can be hence perceived with the experimental observations at collapse, for the same specimens.

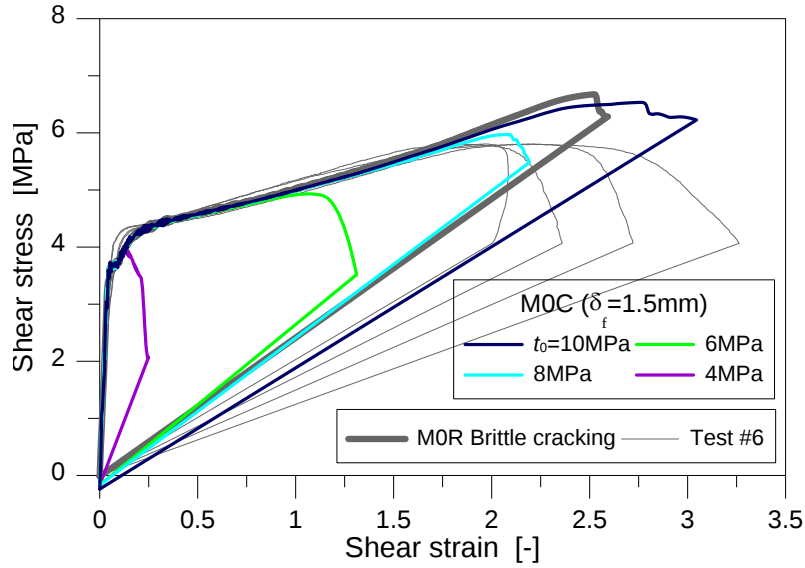


Fig. 6 Comparative numerical assessment of the M0C model (ABAQUS), with respect to earlier studies (Pravdová et al., 2016), as a function of CZM resistance t^0 .

In terms of stress evolution and propagation, selected contour plots and vectorial paths are finally collected in Figures 7-to-10 (selected FE results are proposed for the M0C model with $\delta_f=1.5\text{mm}$ and $t^0=8\text{MPa}$).

Mostly stable damage scenario were obtained for all the examined FE models. In Figure 7, stress distributions give evidence of the transmission of shear loads within the joint components, as far as the adhesive provides mechanical interaction between the bonded glass and steel plates. The tensile resistance of glass is achieved for even small strain ratios (in the order of 0.5), while partial debonding of the adhesive layers begin from shear strains higher than 1.

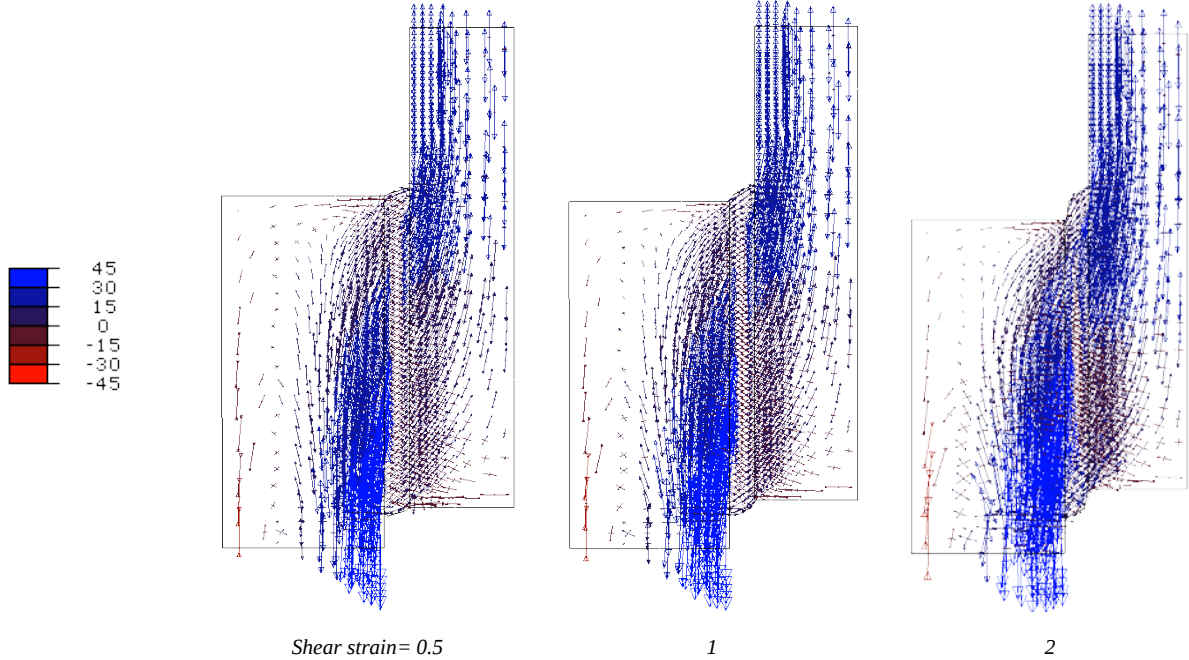


Fig. 7 Evolution of principal stresses (legend in [MPa]) in the M0C model (ABAQUS, 1/4 specimen), with $\delta_f=1.5\text{mm}$ and $t^0=8\text{MPa}$ the CZM input.

In that case, plastic yielding of the adhesive layers also manifests (see Figure 8), and further propagates up to the maximum load bearing capacity of the joint.

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As far as the MAXS damage criterion is accounted, finally, it is possible to see from Figure 10 that the bonding region is already affected by progressive degradation of adhesion properties, starting from very small strain ratio amplitudes (>0.05). In the Figure, the CSMAXCRT value is a parameter denoting the damage propagation in the CZM surface interaction, up to failure ($D=1$). In this regard, partial correlation with experimental debonding observations can be again perceived from the selected FE predictions, even in qualitative comparative terms only. In this sense, further the CZM modelling technique proved to offer a certain potential for the advanced numerical modelling of adhesive joints for structural glass applications. At the current stage, the ongoing FE investigations are aimed to assess and calibrate to experimental results the input features of several joint configurations, including variations in the joints features and material properties, as well as ageing effects (Machalická & Eliášová, 2017).

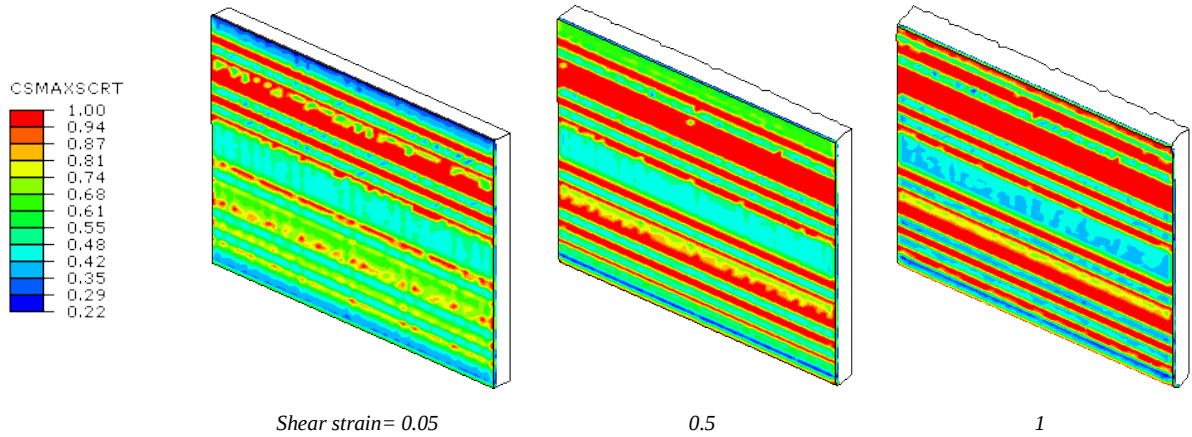


Fig. 10 Evolution of plastic yielding in the M0C model (ABAQUS, 1/4 specimen), with $\delta_i=1.5\text{mm}$ and $t^0=8\text{MPa}$ the CZM input. In evidence, the adhesive layer.

5. Conclusions

In this paper, A Finite Element numerical investigation on shear acrylate glass-to-steel connections is carried out, by accounting for cohesive modelling techniques. Taking advantage of earlier experimental and preliminary numerical studies available in the literature for the same set of experimental specimens, sensitivity studies are carried out, giving evidence of the obtained FE estimations to a set of input features having a key role on the expected calculations.

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