Efficient finite element modeling of the static collapse of complex bonded structures

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ABSTRACT.

The paper deals with the application of an efficient finite element (FE) model for the failure analysis of bonded structures. Aim of the work is to assess the accuracy and applicability of the computational model in the prediction of the post-elastic response of complex bonded structures, having large dimensions. In order to overcome the limitations retrieved in the technical literature, such as the use of special elements, the present work assesses the applicability of a reduced computational method, previously presented by the authors. The method is based on standard modeling tools, which are available in most of commercial FE softwares. The method describes the adherends by semi-structural elements (plates or shells), and the adhesive by means of a single layer of cohesive elements.

This work applies the proposed reduced method to a complex, industrial-like structure. A square thin-walled beam is considered, made of two different portions joined head to head by overlapping thin plates on each side. The beam is loaded by a three point bending fixture up to failure and originates a complex stress field on the bonded region.

The benchmark for the computational analyses are the force-displacement curves obtained by experimental tests on two different geometries. The comparison with the experimental data shows a good accuracy of the proposed method in terms of the prevision of the structure stiffness, the maximum load (error below 10%) and post-elastic behaviour up to the breakage of the structure. The numerical precision and the computational speed make the proposed method very useful for the efficient analysis of complex bonded structure, both in research and industrial world.

INTRODUCTION

The paper deals with the application of an efficient finite element (FE) model, previously assessed by the authors in the elastic field, for the failure analysis of bonded structures loaded monotonically. Aim of the work is to assess the accuracy and applicability of the computational model in the prediction of the post-elastic response of complex bonded structures, having large dimensions.

The motivation of the research comes from the need of simple, fast and accurate design methods in the industrial word to assess the mechanical strength of structural joints in order to increase their applicability. A lot of finite element method for the analysis of bonded joints can be retrieved in the literature [1-8]. Many of these methods are based on special elements in order to describe the adhesive or the overlap region. The main drawback of these methods is the difficulty to implement special elements in commercial FE software usually available in the industrial world. As a consequence their application is limited to the research field. In recent works, on the contrary, the proposed methods mostly apply a fracture mechanics approach [6-8]. In these cases, the failure criterion employed needs data that are not provided by the adhesive manufacturer so ad-hoc experimental tests have to be performed.

In order to overcome these limitations, the present work assesses the applicability of a reduced computational method, presented by the authors in [9] for the analysis of thin walled structural joints. The method is based on standard modeling tools and common finite elements, which are available in most of commercial FE software. The method describes the adherends by semi-structural elements (plates or shells), the adhesive by means of a single layer of solid elements and applies internal kinematics constraints to reproduce the structural continuity. In [9] the efficiency and accuracy of the reduced model in the prediction of the elastic stress distribution on the mid-plane of the adhesive layer has been assessed for many 2D and 3D geometries. Then the authors have applied the method in the post-elastic field [10, 11] using a simple regularized stresses failure criterion as proposed in [12, 13] and obtained encouraging results.

This work extends the application of the reduced method to a square thin-walled beam, made of two different portions joined head to head by overlapping thin plates on each side. The beam is loaded by a three point bending fixture up to complete failure and originates a complex stress field on the bonded region. A cohesive zone model failure criterion has been implemented as proposed in [14] in order to combine the accuracy of the model with the computational speed. The benchmark for the computational analyses are the force-displacement curves obtained by experimental tests performed on joined thin-walled beams with the same geometry as the one considered in the computational model.

The originality of the work consists in the simplicity of the proposed computational tools, which relies on standard modeling options available on commercial FE software. The proposed method is general, easy to apply and allows a dramatic reduction of the computational effort (computational time elapsed and dynamic memory allocated), due to the minimization of the degrees of freedom of the model. Efficiency, generality and simplicity make the proposed method a valid industrial tools to simulate the mechanical behavior of wide and complex bonded structures.

MATERIALS AND METHODS

The work is divided in two steps: computational analyses and preliminary experimental tests, these ones performed only on two different geometries. A beam structure has been considered (Fig. 1), made of two square thin-walled beams joined head to head by thin plates bonded with single overlap on each side. The structure is loaded under three point bending. The eccentricity of the bonded joint with respect to the loading axis, originates an indirect and complex stress field in the adhesive layers. The structure, simple to manufacture, aims to resemble a real bonded construction and provides a good benchmark for the proposed method. Both the computational and experimental tests have been performed quasi statically up to failure of the structure.

Experimental tests

The performed experimental tests are preliminary in order to evaluate how many and which factors have to be considered in a subsequent systematic test campaign. Fig. 1 represents a sketch of the geometry which was considered for the bonded joint. Moreover the same beam without joint has been considered as reference in order to evaluate the influence of the joint on the strength of the structure.

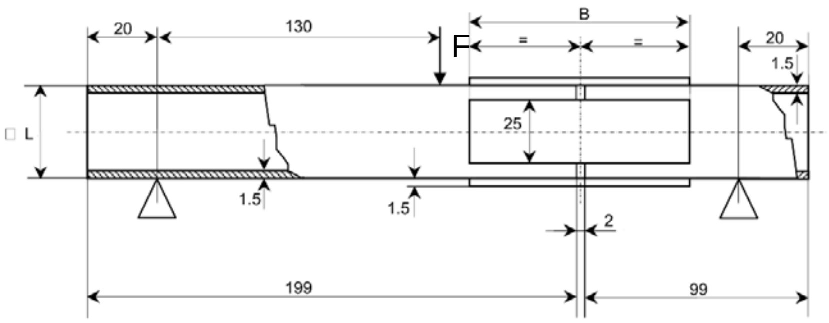


Figure 1. Sketch of the bonded thin-walled beam structure

Two different adherend dimensions have been considered for each configuration. Table 1 presents the chosen dimensions and materials. The adherends are thin walled square beams, made of mild steel Fe510 and the adhesive is a high-strength two-part epoxy (Henkel 9466 [15]). Table 1 collects the elastic properties of the adherends and of the adhesive while their post elastic behavior is described by the diagrams of Fig. 2a and 2b. The width of the joining plates is 25 mm with a nominal thickness of the adhesive layer of 0.05 mm, imputable to the adherends roughness.

The adherends have been prepared, before bonding, through mechanical grinding with abrasive paper (P200) and then cleaned with degreasing solvent Henkel Loctite 7063 [16], in order to ensure a better adhesion. The experimental tests have been performed at a constant cross-head speed of 60 mm/s up to complete failure of the joint. The tests were performed on a servo-hydraulic testing machine, MTS-MINI BIONIX 858, with an axial capacity of 25 kN.

Computational analysis

The aim of the computational analysis is to obtain the force-displacement curve up to complete failure, thus allowing a direct comparison with the experimental results.

Three-dimensional computational models have been developed both for the bonded tubular structure and for the undivided one. The adherends are described by semi-structural shell elements lying on the mid-surface either of the beam or joining plates. The adhesive layer is described by a single layer of cohesive solid elements. Modeling the adherends by means of structural elements introduces a virtual gap between the adhesive and the adherends. In order to enforce the structural continuity internal kinematic constraints are employed. These kinematic constraints make equal the corresponding degrees of freedom of the linked parts.

Table 1: Geometric variables and mechanical properties of the materials

	Geometry	
L (mm)	25	40
B (mm)	50	100
Adhesive thickness (mm)	0.05	
	Adherends	Adhesive
Materials	Steel	Henkel Loctite 9466
Young modulus (MPa)	206.000	1718
Poisson ratio	0.3	0.3
Maximum elastic stress (MPa)	500	60

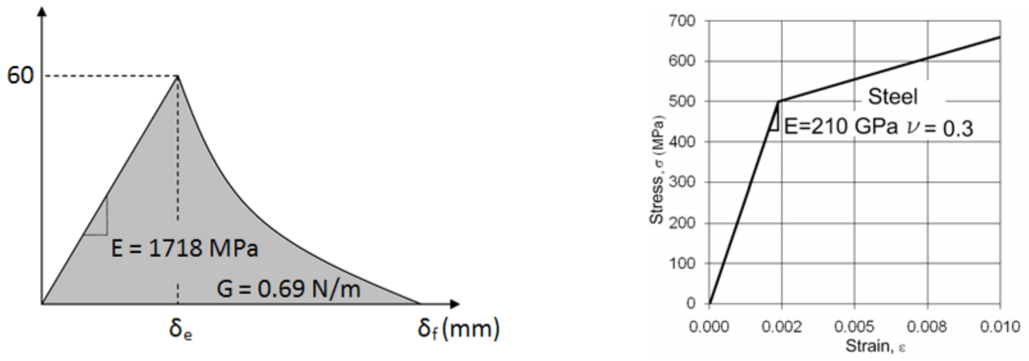
Both the adherends and the adhesive have been modeled by means of linear square elements with reduced integration. The elements dimension on the adherends is equal to the distance between the mid-planes of the adherends itself, while the adhesive elements dimension is equal to a quarter of such distance. This choice, which was previously discussed in [16], ensures a good tradeoff between accuracy of the results and the computational speed.

The computational models have been developed for all the joint configurations considered in the experimental tests and have been implemented through the explicit solver of the FE software ABAQUS 6.8. The adherends have been modeled with a simple bilinear elasto-plastic constitutive behavior with hardening (Fig. 2a), while the adhesive has been described by means of a cohesive zone model (Fig. 2b). The yield stress of the adherends have been obtained by commercial datasheet, while the parameters which characterize the cohesive zone model (maximum stress = 60 MPa, fracture energy = 0.69 N/m) have been assumed as proposed in [15] for the same adhesive. The chosen criterion assumes that when the elastic limit is reached, in mode I, II or III the mechanical properties of the adhesive gradually reduces with an exponential law. In the FE model a constant speed of 150 mm/s has been applied on the central vertical plane and mass scaling option has been activated in order to reduce the computational time, without significantly affecting the accuracy of the results. The analysis provided the reaction force of the structure up to failure. All the models have been run on a notebook equipped with an Intel Core Duo Mobile T7200.

RESULTS

Fig. 3 presents the experimental results as force-displacement diagrams, for all the thin-walled beam configurations considered. Fig. 3a refers to the thin-walled beam having a side length of 25 mm, while Fig. 3b refers to the one having a side length of 40 mm. In each diagram both the curve obtained by the thin-walled beam without joint (thin black line) and that obtained by the joined one (thick gray line) are displayed.

Fig. 4 presents the comparison between computational analysis (thick black line) and experimental test (thin gray line) for the bonded thin-walled beam.



(a) (b)

Figure 2: adhesive cohesive model (a) and adherends constitutive behaviour (b)

Table 2 reports the computational time for the numerical tests. Fig. 5 presents the comparison between the deformed configuration of the thin-walled beam in the experimental tests and the corresponding one provided by the finite element simulation. Fig. 5a and 5b display the experimental tests respectively on the beam with a side length of 25 mm and 40 mm, while Fig. 5c and 5d show the results coming from the computational analysis respectively for the side length of 25 mm and 40 mm.

DISCUSSION

Experimental tests

The diagrams of Fig. 3 show that the load carrying capacity of the joined thin-walled beam is slightly higher than the one of the beam without joint. This behaviour is imputable to the higher bending modulus of the overlapped bonded region and testifies the good structural performance of the adhesive in transferring the load. It's worth of notice that the adherends go plastic before the adhesive fails due to crack propagation (Fig. 3).

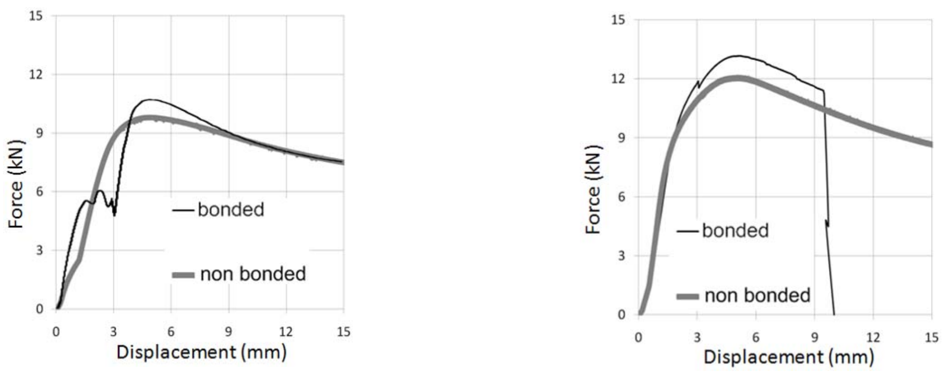
For the thin-walled beam with side length of 25 mm (Fig. 3a), no catastrophic failure occurred in the adhesive and the test was stopped due to a stroke limit. The initial oscillation of the curve in Fig. 3a was probably due to a small movement on the supports. Fig. 3b, moreover, shows that the joined beam, with side length of 40 mm, despite the higher maximum load with respect to the non joined one, presents a sudden breaking due to adhesive failure.

The lack of test repetitions makes this statistically irrelevant, but this behavior can be explained due to two main geometrical differences. As first for the beam with a side length of 25 mm (Fig. 5a) the plastic hinge develops far from the bonded zone than for the one with a side length of 40 mm (Fig. 5b) thus it does not influence directly the adhesive behavior as it does in the second configuration. Second, the bonded patch has the same width of 25 mm for both configurations so the reinforce ratio between the beam side length and the patch is 0.625 for the 40mm side length beam and 1 for the 25mm side length beam, which makes the last one stronger.

Simulation against experimental

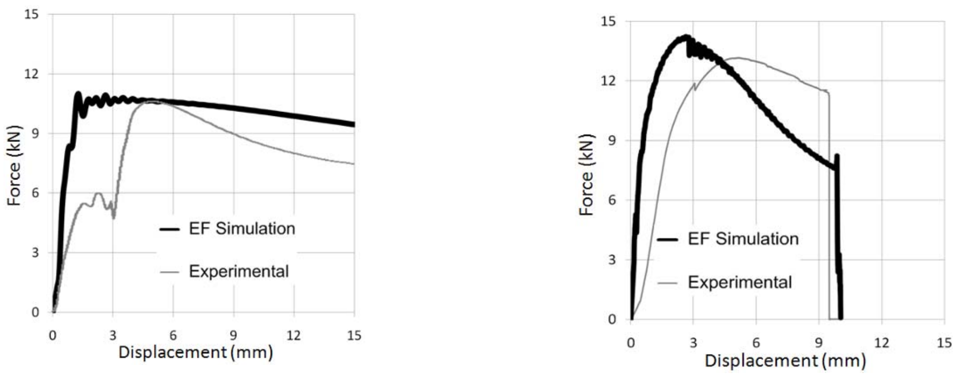
The curves of Fig. 4 show a quite good agreement between the experimental tests (thin grey curves) and numerical finite element simulations of the joined thin-walled beam (thick black curves). The oscillations in the FE curves are characteristic of the inertial effects in the dynamic procedure adopted and should not be considered. Moreover these oscillations are increased by the adoption of mass scaling option in order to speed-up the analysis. In Fig. 4a the adhesive had not collapsed and no information are available about the energy adsorbed from the adhesive layer. The same behaviour was provided by the FE analysis. The only conclusion that can be drawn from this test is that the bonding is strong enough to resist the bending moment that produces the full collapse of the beam.

The numerical FE simulation shows a stiffness quite similar to the bending experimental test and a maximum load of 10.98 kN quite above the experimental load of 9.8 kN, with an error of 10%. The post elastic behavior is quite above the experimental response but this is due to the model used to describe the adherends, which is bilinear with hardening and may be too simplistic.



(a) (b)

Figure 3: Experimental curves of the beam: side length of 25mm (a) and 40mm (b)

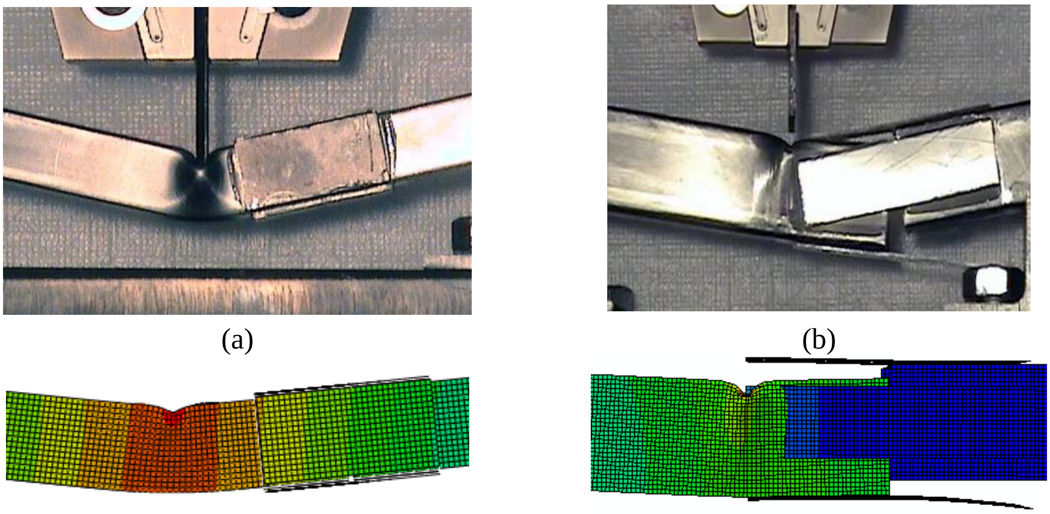


(a) (b)

Figure 4: Comparison for the joined beam: side length of 25mm (a) and 40mm (b)

Table 2: Computational times (s) – Intel T7200 1.99GHz processor, Ram 2Gb

	Thin-walled beam side length (mm)	
Thin-walled beam type	25	40
Without joint	96.5	340.3
Joined	5085	5438



(a) (b)

(c) (d)

Figure 5: Experimental tests and computational analyses on joined thin-walled beam, side length 25 mm (a), (c) and 40 mm (b), (d)

In Fig. 4b it is worth noting that for the beam of side length of 40mm a low difference exists in terms of stiffness between numerical simulation and the experimental test, both for mentioned mesh problem and for the compliance of the experimental set up. Considering the thin walled beam with side length of 40mm the maximum load in the experimental test is 13.2 kN while the FE simulation provides 14.2kN, with an error of 7.5%. In the post elastic range the FE curve show an early fall of the load sustained by the structure with respect to the experimental, but it provides quite exactly the sudden crack of the adhesive.

Fig. 5c shows excellent agreement between the displacement map of the numerical simulation of the bonded beam (side width 25mm) and the experimental test of Fig. 5a. Similarly Fig. 5d testifies a good agreement between the FE displacement map in the joined beam (side width 40mm) and the displacement configuration observed in the experimental test (Fig. 5b). The only difference is imputable to the absence of the gravity in the FE simulation, which causes the adherends to separate from each other in opposite directions when complete failure occurs, while in the experiment the two sides of the beam fall down on the supports.

The computational time needed for the analyses of these structures by means of the reduced method here proposed is in average 5000 s (Table 2). Thus this method suits well for the structural analysis of bigger and more complex bonded structures, typical of the industrial context.

CONCLUSIONS

The work assesses the applicability of a reduced finite element model for the structural analysis of complex bonded structures. The model is tested on a bonded thin-walled beam structure and it is compared directly with explorative experimental tests.

The model applies shell element to describe the adherends and cohesive elements to describe the adhesive layer. The corresponding nodes on the bonded parts are linked using internal kinematics constraints (tied-mesh). The comparison with the experimental data shows a good accuracy of the proposed method in terms of maximum load and post-elastic behaviour. In particular the relative errors are always below 10%, the prevision of the structure stiffness is quite good and it's well captured the breaking instant of the structure.

The accuracy of results and the low computational cost (in terms of allocation of dynamic memory and CPU time) make the proposed method very useful for the efficient analysis of complex bonded structure, both in research and industrial world.

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