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Experimental investigation and numerical modelling of spot welding–adhesive joints response

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ABSTRACT

Hybrid joints obtained by a combination of two simple techniques, e.g. by spot welding and adhesive, are relatively modern joints developed especially for application in aerospace industry. This contribution describes the modelling and testing of structural elements by application of an angle bar and spot welding techniques with the introduction of adhesive layers between adherends.

Numerical modelling of the mechanical response using the Finite Element Analysis requires a description of 3 different damage processes: (1) plastic degradation of the spot welded points, (2) plastic deterioration of the joined parts around the regions of spot points and (3) degradation of the adhesive layer.

The whole uniaxial deformation process of samples was experimentally investigated with the application of 2 Digital Image Correlation systems to monitor the development of deformation up to the final failure. The first damage process starts within the adhesive layer, much below the maximum force that can be carried by the specimen. The second damage process activated in the joined adherends surrounding the spot welded points – near the maximum of the carrying force. The failure of the specimens took place when the adhesive layer was almost totally degraded and the welded spots were subjected to intensive plastic degradation.

1. Introduction

Hybrid joints obtained by a combination of 2 simple joining techniques [1], e.g. by:

- Weld–adhesive, e.g. [1–10].
- Rivet-bonded, e.g. [11–17].
- Clinch-adhesive, e.g. [12,18–22].
- Bolted-bonded, e.g. [23,24].
- Mixed-adhesive, e.g. [25].

are relatively modern techniques developed especially for application in aerospace and car industries to get safer and more durable joined structural parts of aircrafts or cars. The advantages of the application of two different techniques simultaneously to create hybrid joints include a significant increase of static strength, fatigue strength, energy absorption (e.g. [8]) and corrosion resistance. This modern technique is important for many branches of engineering like aircraft manufacturing, automotive industry, civil engineering, etc.

In this paper a detailed analysis of the behaviour of the weld–adhesive complex joint will be presented. The joint is made of two adherend strips connected by an angle bar with the application of 2 weld spots and adhesive bonding by “in-flow technique”, Fig. 1. A systematic description of the spot welding–adhesive joint technique as well as an experimental characterisation of the joints response due to mechanical loading still requires new investigation. The most difficult task in the numerical modelling of the joint deformation process is the description of progressive damage behaviour of joined parts and the adhesive. Up to now most papers deal with a modelling of single lap hybrid joints without consideration of the damage processes which develop in many parts of the joint subjected to mechanical loading, e.g. [2,5–8]. The results obtained in [7] revealed premature adhesive layer debonding, while the maximum load was governed by the spot weld.

Up to now, however, the whole gradual degradation process of weld-bonded joints is still not fully understood and established failure criteria cannot be applied, e.g. [9]. There is only one paper dealing with the description of the damage processes with the application of the Cohesive Zone Model (CZM) to the analysis of the spot-welded/bonded single lap joint [10]. However the description of the degradation process in this complex joint requires taking into account also damage process of the joined adherends.

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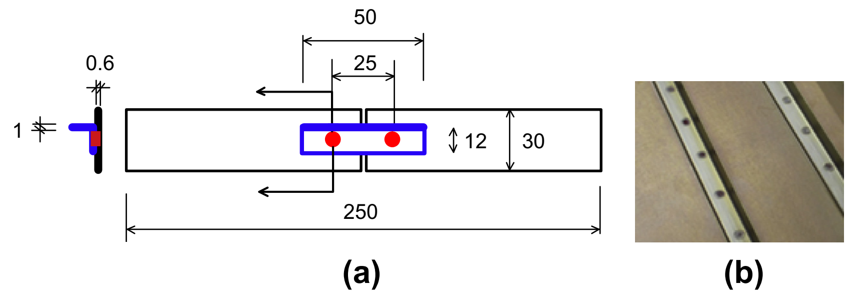

Fig. 1. Geometry of the sample.

Therefore here we propose the most generalised description of the damage in numerical modelling of weld–adhesive joints by Finite Element Analysis (FEA). A full description of the hybrid joints response under a whole monotonic quasi-static deformation requires an inclusion of the damage processes of:

- adhesive layer;
- weld nuggets;
- joined metallic adherends.

Such extension, in comparison to [10], is necessary when the spot-welded adhesive joints have a very complex geometrical shape (Fig. 2), in relation to single lap joints. In order to point out the advantages of the hybrid joints we analyse a simple spot welding joint by angle bar and complex joint obtained by combination of spot welding technique and adhesive bonding. In particular, we consider the whole deformation process of the joints up to the final failure with application of during experiments the 3-D Digital Image Correlation (DIC) Aramis system to monitor on-line displacement fields. For the FEA modelling we used the CZM to describe degradation of the adhesive layer, similar to [10], whereas the damage weld nuggets were modelled by point-to-point connection between joined metallic parts applying connector elements with the force failure criterion. The damage process of the adherends was modelled by the application of ductile damage based on [26,27]. Alternatively, for modelling of the adhesive cracking one can apply the X-FEM approach, e.g. [28].

The proposed general numerical approach, which includes 3 damage models, was verified by experiments. The visible correlations confirm the correctness of the formulation of the advanced numerical model of the hybrid joint with very complex shapes.

2. Numerical model of the hybrid joint

In order to create FEA numerical model of the hybrid joint 3 kinds of finite elements (FE) were used:

- Cohesive elements – for the modelling of the adhesive layer.
- Mesh-independent fasteners – for the modelling of pure spot weld joint.
- Solid elements with ductile damage – for the modelling of the degradation of the adherend strips.

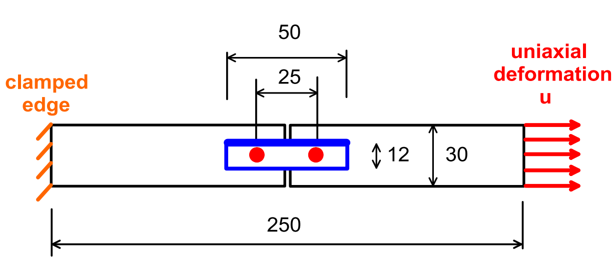

Fig. 2. Boundary condition for deformation of the hybrid joint.

2.1. FEM model of the adhesive in the hybrid joint

Gradual decohesion and failure process of the adhesive layer was described by CZM with the application of the triangular stress-separation law, Fig. 3, for the uniaxial case. λ is non-dimensional opening displacement of the adhesive layer equal to:

$$\lambda = \frac{u_n}{\delta^{max}} \tag{1}$$

where u_n is the normal opening displacement and δ^{max} is a maximum opening displacement. σ^{max} is the maximum stress threshold for the modelled material, whereas λ_{in} corresponds to the non-dimensional displacement indicating damage initiation in the material. G_{Ic} is the area under the curve corresponding to fracture energy. In 3D cases, Figs. 4 and 5 (e.g. [29,30]), where a complex mode of damage growth occurs, it is necessary to introduce a normal opening displacement u_n for the tension mode and a tangential displacement u_τ for the shear mode. Similar to (1) it is possible to define non-dimensional displacements λ_n and λ_τ:

$$\lambda_n = \frac{u_n}{\delta_n^{max}}, \quad \lambda_\tau = \frac{u_\tau}{\delta_\tau^{max}} \tag{2}$$

where δ_n^{max}, δ_τ^{max} are respectively the maximum opening and shear displacements. We assume for the considered 3D case that the damage initiation criterion will depend on the current state of stress $\{\sigma_n, \sigma_t, \sigma_s\}$, Fig. 4, and is expressed by:

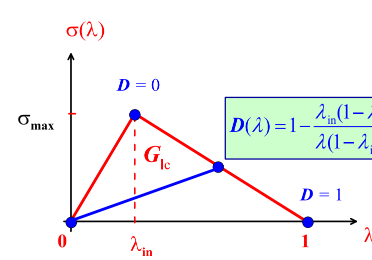

Fig. 3. Triangle-separation low for the adhesive layer.

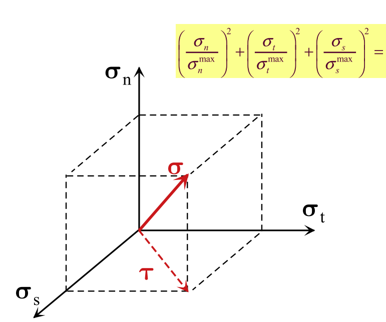

Fig. 4. Damage initiation criterion for the adhesive layer.