

# Numerical Investigation of Balanced Boron/Epoxy Single Lap Joints with Different Bond Thicknesses

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**ABSTRACT:** The present study concerns with the numerical investigation of balanced Boron/Epoxy single lap joints subjected to tensile loading. FM94, a high strength adhesive produced by Cytec, was used for bonding. Four different bond thicknesses (0.04, 0.1, 1 and 2 mm) have been analyzed extensively, while two overlap lengths have been used (13mm and 40mm, respectively). A geometrically nonlinear, two-dimensional (2D) finite element analysis has been employed to determine the hydrostatic stress and the shear strain distribution across the two interfaces of the single-lap joints, while a 3d representation of the interfaces also presented. The results mainly prove that the overlap thickness directly affect the joint tensile strength, while an optimum value of the overlap thickness can be defined.

**KEYWORDS:** Bonded joints, Thickness effect, FEA, Boron/Epoxy.

## I. INTRODUCTION

Adhesive bonding is a material joining process in which an adhesive, placed between the adherend surfaces, solidifies to produce an adhesive bond. The use of adhesives has many advantages over other methods of fastening. For instance, strain concentration around joint hole can reduce static and phatic strengths. Potential micro or macro defect during perforation process will lead to further damage of joint [1], while adhesively bonded joints develop smooth load transfer and have fewer points of stress concentration when compared to mechanically fastened joints [2, 3]. However, it is quite important to be able to predict the mechanical behaviours of adhesively bonded joints particularly under service loading condition. For these reasons, methods based on the strength of materials [4 - 7], as well as, fracture mechanics approach, which can be used when the adherends undergo only elastic deformation [8 - 10]. Bonded joints strength strongly depends on the type and thickness of the adhesive layer, and sometimes adhesives are quite tough [11-12]. That means, an extensive in elastic deformation may be induced in the adherends during joint failure [13]. It has been established that high peel and shear stress concentrations develop in bonded joints close to the ends of the joints and this is available especially in bonded composites. When composites are involved in joints structure the problem becomes complex, as they have relatively low interlaminar shear strength. The geometry of the structure is a very important aspect, especially for the service performance [14, 15]. Theoretical and finite element investigations, also, obtained in order to determine the influence of the adhesive thickness [16 - 19].

## II. OBJECTIVES

The present study describes an analytical investigation of adhesive bonded boron/epoxy-to-boron/epoxy lap joints tested in tension. A geometrically nonlinear, two-dimensional (2D) finite element analysis has been employed to determine the hydrostatic stress and the shear strain distribution across the two interfaces of the single-lap joints.

### III. MATERIALS AND METHODS

#### Joint Configuration

The configuration was based on the ASTM standards D 1002-01 for metal-to-metal single-lap joints and D 5868-01, which completes the D 1002 standard and extends the application to composite-to-composite single-lap joints. A typical specimen configuration is shown in Fig 1.

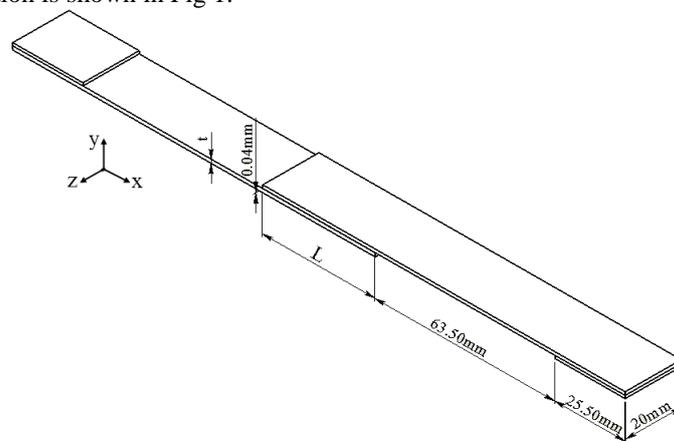


Fig. 1 Typical test specimen configuration based on the ASTM standard D1002

In adhesive bonding, the aim is to transfer the load smoothly from one adherend to the other, minimizing the peak shear stresses and peel stresses in the adhesive layer. Increasing the overlap length reduces the maximum peel and shear stresses and also the average shear stresses in the middle of the overlap region. In this context, in order to investigate the influence of overlap length on the two interfaces, four different bond thicknesses were used: 0.04, 0.1, 1 and 2 mm, respectively. The free length was kept constant at 63.5 mm for all the joint configurations while the “specimens” width was maintained at 20 mm.

#### Materials

Adherend material was Boron/Epoxy, where eight layers of  $0^\circ$  resulted in a layer thickness of 1.14 mm. FM94, a high strength adhesive produced by Cytec, was used for bonding. The mechanical properties of the materials are given in Table 1, while the stress – strain curves for both materials presented in fig 2 and 3, for boron/epoxy and FM94, respectively.

Table 1 Materials properties: Boron/Epoxy and FM94 Cytec [20]

Properties	Boron/Epoxy	FM94 CYTEC
Longitudinal Modulus $E_1$ (GPa)	208	3.5
Transverse Modulus $E_2$ (GPa)	25.4	-
Shear Modulus $G_{12}$ (GPa)	7.2	1
Poisson's Ratio $\nu$	0.1677	0.35

The mechanical behaviour of the adherend is linear elastic, fig 2. The uniaxial tensile stress-strain curve of an adhesive cannot be easily obtained due to the fact that the manufacturing of adhesives in a bulk form is usually complex. In order to characterize an adhesive in shear, it is assumed that the shear behaviour by the uniaxial curve used in the finite

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element analysis represents well the shear measured in a real shear test. FM 94 adhesive is formulated to exhibit superior elongation, toughness and shear strength properties. A tensile stress-strain curve for the adhesive material, FM94 Cyttec can be seen in Fig 3.

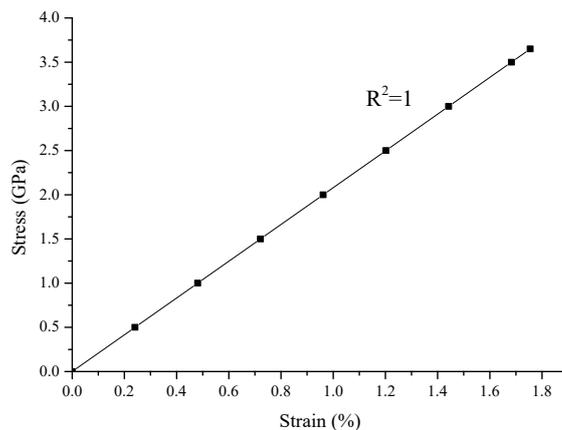


Fig. 2 Tensile stress-strain curve for the Boron/Epoxy adherend material

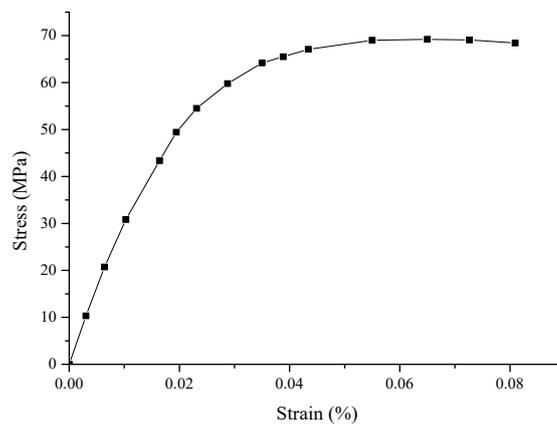


Fig. 3 Tensile stress-strain curve for the FM94 Cyttec adhesive material

## IV. FINITE ELEMENT ANALYSIS

Finite element simulations were carried out by using ANSYS Code Version 10. An eight-nodedisoparametric quadratic element with four integration points has been used to model the adhesive layer and the adherend simulating the large stress variation through the two interfaces (loaded-unloaded) as shown in Fig 4. The 8-node element (PLANE 82) is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions. Four elements were placed across the thickness of the adhesive. In order to determine the conditions for the yielding and subsequent plastic deformation, a yield criterion is required for each of the materials. For the adhesive a Von Mises

criterion (includes a component dependent on the hydrostatic stress) was used which includes a component dependent on the hydrostatic stress.

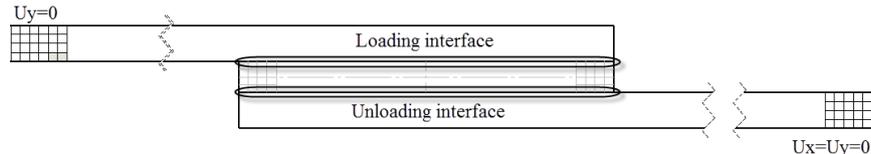


Fig. 4 Loaded and unloaded interface and boundary conditions

Furthermore, a Von Mises criterion presents an identical behaviour in tension and compression. Moreover, it is expected a large stress concentration at the ends of the adhesive. As the overall area covered by the adhesive layer behaves in a plastic way, the final failure occurs without any additional load increase. A prescribed displacement (1.1mm) for each case was applied to the joint incrementally, at the left-hand side of the model (fig4). This is a more realistic way of simulating a test machine, rather than applying nodal forces for each layer, because the stresses in each layer depend on the stiffness of the layers.

## V. RESULTS AND DISCUSSION

It is very well known that the mechanics of the lap-shear geometry can be quite complicated, owing to a great sensitivity to geometrical parameters. One of the main factors influencing the lap joint strength is the overlap length. Generally, it was observed in a series of studies that the load carried by the SLJs with the flexible adhesive increased with increasing overlap length [21, 22]. The influence of altering the overlap length is often considered a convenient means to minimizing the peak adhesive stresses. As one increases the overlap length, the adhesive shear stress is reduced. It was also affirmed that using an overlap length of about ten times the minimum adherend thickness, results to a more uniform adhesive shear stress distribution without causing the failure mode to shift into the adherend [23, 24]. Following this affirmations we must underline that the overlap length is not a parameter to be studied by its own, but rather it should be considered as one of the main factors greatly affecting the joint mechanical behaviour and it should be studied together with a group of other important parameters such as: (i) adherend material nature and especially adherend surface roughness: a rough surface will result in a better adhesion [25-32]; (ii) adherends and adhesive thicknesses; (iii) interfacial friction developed in the area between different layers etc.

### Hydrostatic stress distribution

Finite Element Analysis (Ansys) has been used to predict the hydrostatic stress distribution in the specimens. The variation of the hydrostatic stress distribution for two different overlap configurations can be seen in Figs 5 a - b. Along the length of the overlap, a large area exists where the adhesive is under hydrostatic compression. The highest hydrostatic stresses are noticed at the overlap edges while at the center of the overlap, values are quite smaller. As it can be seen from fig. 4a-b, the plasticization effect is more accentuated at the edges for the cases of 0.04mm and 0.1mm, respectively [33, 34]. In these areas of the joint, the load from one adherend to the other is mainly carried by tensile stresses, especially in the case of 40mm overlap length (fig 5b). For the case of 1mm and 2mm, respectively, the additional area is compressive. Generally, the hydrostatic stress decreases at the edges, as the bond line thickness increases from 0.04 to 2mm for both 13mm and 40mm, respectively. On the other hand, as the overlap length increases, the load increases as well. Now, as the load increases, the plastic region which starts at the edges (peak) is shifted/decreased further away from the overlap edge, towards the interior of the overlap (fig 6). This is a clear indication that in a tensile test the load is carried by the full overlap and not only by its edges [35, 36], as well as the bending moments [37, 38]. However, there is an area in the middle of the overlap that stays elastic up to the failure load of the joint. However, it is not expected this part of the joint to contribute to the maximum strength of the structure, especially when the overlap reaches longer lengths (40mm).

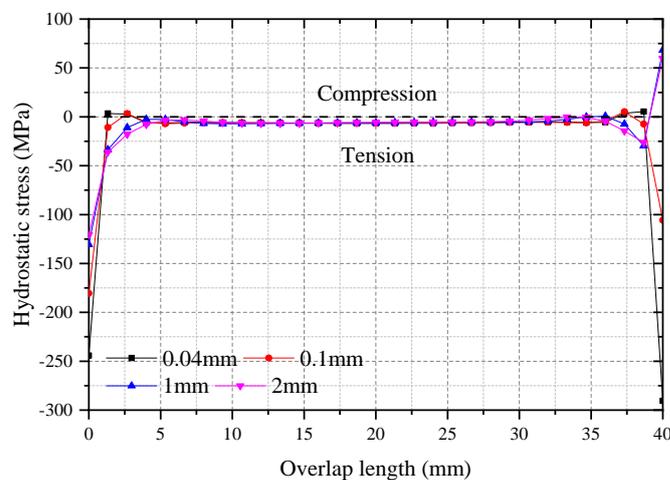
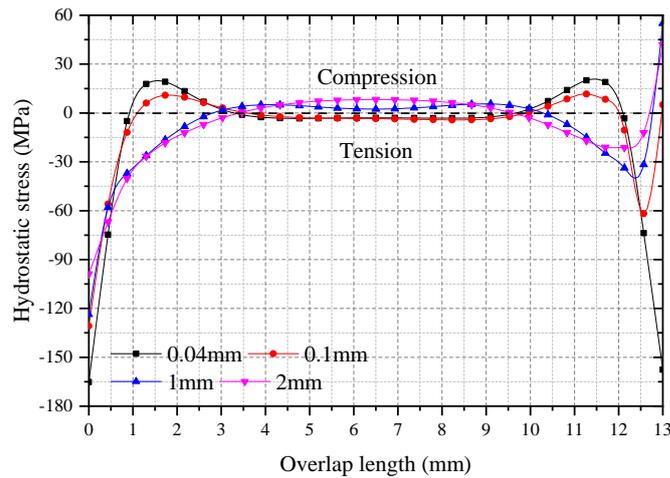


Fig. 5. Hydrostatic Stress distribution at interface for (a) 13 mm overlap length and (b) 40 mm overlap length, respectively

### Shear strain distribution

Boron/epoxy plates are quite stiff, that means the shear deformation is obtained mainly by the adhesive. As it can be seen, from figure 8 a-b, the maximum shear deformation appears near the ends of the joint. As the overlap length increases, the distortions in the middle of the interface decreases. In case, of adhesive thickness is greater than 1mm, the shear stress-strain distribution is presented as "flat plateau" regardless of the joint length. That means, by increasing the thickness of the adhesive layer, joint fails due to the increased bending moment [39]. Thin adhesive layers provide no microcracks or voids. At the same time, plastic region along the joint, "travels" much faster, as the interfacial stresses increase. Moreover, as the adhesive layer decreases from 2 to 0.04mm the magnitude of the stresses decreases at the ends of the adhesive, whereas for  $\tau_{\max} \rightarrow \infty$ ,  $\sigma_{\max} \rightarrow \infty$ .

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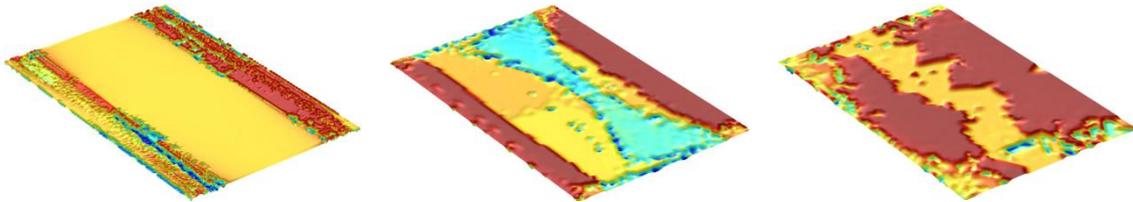


Fig. 6. Hydrostatic Stress distribution at interface for 13 mm overlap length, as the load increases

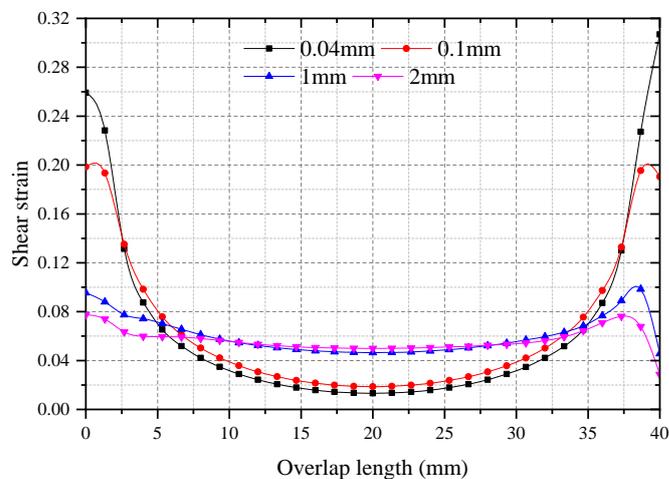
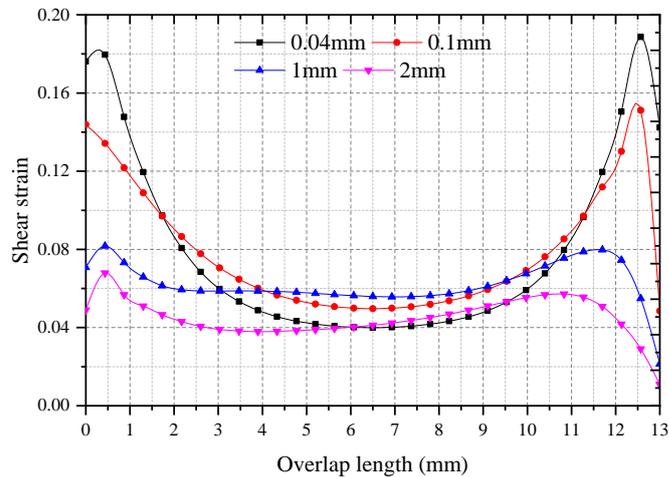


Fig. 5. Shear Strain distribution at unloaded interface for (a) 13 mm overlap length and (b) 40 mm overlap length, respectively

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## VI. CONCLUSION

The adhesive bonding is a viable technique for joining composite materials though the low inter-laminar shear and tensile strength limit the joint efficiency. The effect of the adhesive thickness (0.04, 0.1, 1 and 2mm, respectively) on the lap shear strength was investigated in this study, while the overlap length varies from 13 to 40mm. A prescribed displacement for each case was applied to the joint incrementally which is a more realistic way of simulating a test machine. It is well known, that proper design of a joint is necessary to maximize durability. The following conclusions can be made:

- The lap shear strength increases as the adhesive thickness decreases.
- The bending of one or both adherends is a dominant factor on the stress distribution in the adhesive joints.
- The shear deformations along the thickness of the adherends do not significantly influence the  $\sigma(x)$  and  $\tau(x)$  distribution in the adhesive layer. For practical purposes shear deformations along the thickness of the adherends can be neglected unless the adherends are extremely thick and deformable in shear.
- By increasing the overlap length of the single lap joints, the shear strength increases. The failure cause was in almost all cases the adhesive.

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