# Effect of Mechanical Properties of Adhesives on Stress Distributions in Structural Bonded Joints

Xiaocong He

*Abstract*—**Influence of mechanical properties of adhesives on stress distributions in single-lap jointed cantilevered beams is investigated in this paper. Numerical examples are provided to show the influence on the stresses of the beams using adhesives of different characteristics which encompass the entire spectrum of viscoelastic behavior. Finite element solutions of the stress distributions in the adhesive layer have been obtained for four typical characteristics of adhesives. The results indicate that Young's modulus and Poisson's ratios of adhesives strongly affect the stress distributions of the beams.**

*Keywords*—**Structural adhesive joints, structural adhesive characteristics, FE analysis, stress distribution.**

## I. Introduction

The need to design lightweight structures and the increased use of lightweight materials in industrial fields, have led to wide use of adhesive joints in recent years. Some applications of adhesive joints include bonding of metallic and composite body panels for automotive and flight vehicle structures in which lightweight and high fatigue strength are prime requirements. A considerable amount of theoretical and experimental research has been carried out on the static and dynamic behaviors of adhesive joints [1-11].

The present author and co-worker [12] investigated in detail the influence of the characteristics of structural adhesives on the free vibration of single-lap adhesive joints and found that the transverse natural frequencies of the single-lap cantilevered adhesive joints increase with increasing adhesive Young's modulus whereas any significant change was not observed with increasing Poisson' ratio. In present author's recent study [13], the forced vibration behaviour of single lap-jointed cantilevered beams has been investigated theoretically and validated via experiments. The results show good agreement between the measured and predicted characteristics.

The focus of this paper is on numerical investigation of the influence of the characteristics of structural adhesives on stress distributions in single-lap jointed cantilevered beams. These investigations are performed by means of the three dimensional finite element method (3D FEM). The results indicate that Young's modulus and Poisson's ratios of adhesives strongly affect the stress distributions of the beams.

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## II. Configuration, Properties and FE Model

### A. Configuration and Properties

The single lap-jointed cantilevered beam studied in the present work includes the upper adherend, adhesive and lower adherend, as shown in Figure 1. The two adherends used were 2024-T3 aluminium alloy beams of dimensions 200 mm long ×25 mm wide ×4 mm thickness. Table 1 shows the mechanical properties of the adhesives and adherends. The range of mechanical properties of the structural adhesives encompass the entire spectrum of viscoelastic behavior ranging from the rubbery region at the lower values of Young's modulus (down to 0.001 GPa) and higher values of Poisson's ratio (up to 0.5), to the rubber-to-glass transition region at the intermediate values of Young's modulus and Poisson's ratio, to the glassy region at the higher values of Young's modulus (up to 10 GPa) and lower values of Poisson's ratio (down to 0.3). The value of Young's modulus $E_{ad}$ =70 GPa is not realistic for any polymeric structural adhesive or epoxy. It represents aluminium alloy "adhesive" which is in fact aluminium alloy welding. This value was used in the analysis in order to obtain a reference value for the maximum stresses of a single lap-jointed aluminium alloy cantilevered beam.

### B. Finite Element Modelling

The original finite element mesh is shown in Figure 2 which also shows the directions of the coordinate axes x, y, z. The components of stress in a body are defined by considering the forces acting on an infinitesimal cubical volume element whose edges are parallel with coordinate axes 1, 2, 3 which are equivalent to the coordinates x, y, z. As the cube is in equilibrium, the components of stress are therefore defined by six independent quantities: normal stresses $S_{11}$, $S_{22}$, $S_{33}$ and shear stresses $S_{12}$, $S_{13}$, $S_{23}$. The adhesive layer was divided into 64 equal parts along its length (x-direction) and 20 equal parts along its width (y-direction) in order to obtain an accurate indication of the variation of stresses in the lengthwise and breadthwise directions. Along the thickness (z-direction), the adhesive layer was divided into 5 equal layers of elements.

The finite element (FE) mesh was created using the ABAQUS FE pre- and post-processing program operating in X-window environment. Small finite elements were used within the adhesive layer and around the adhesive-adherend interfaces and larger elements were used in the outer regions of

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the adherends. This model was expected to be a good one as it had enough accuracy and a moderate number of elements [14]. In the present study, a distributed load of 1000N was applied at the right end face of the upper adherend in the x-direction, as shown in Figure 1.

For each of the eight Poisson's ratio of the adhesives, results for ten maximum stresses values, corresponding to various Young's modulus of adhesive $E_{ad,}$ ranging between 0.001 GPa and 70 GPa are presented in tabular and graphical forms.

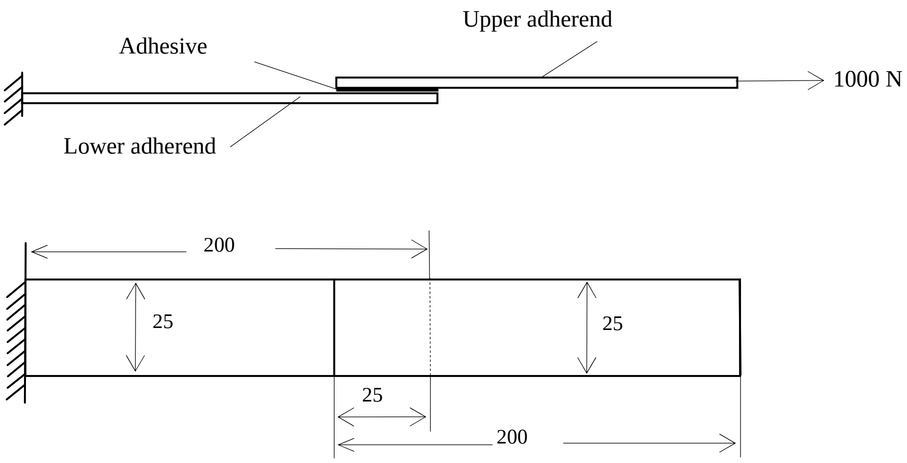


Fig. 1. A single lap-jointed cantilevered beam

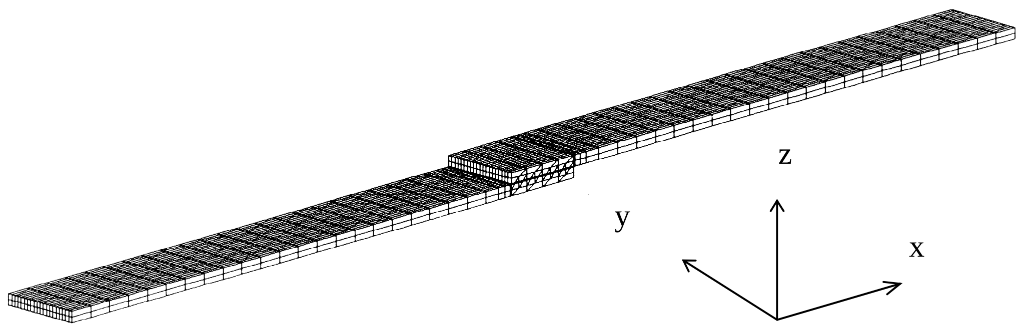


Fig. 2. Original finite element mesh and coordinates

TABLE 1. MECHANICAL PROPERTIES OF ADHESIVES AND ADHERENDS

| | | |
|---|---|---|
| Adherends | E (GPa) | 70 |
| | ν | 0.33 |
| Adhesives | $E_{ad}$ (GPa) | 0.001, 0.01, 0.1, 1, 2, 5, 10, 20, 50, 70 |
| | $\nu_{ad}$ | 0.30, 0.35, 0.40, 0.45, 0.49, 0.499, 0.4999, 0.49999 |

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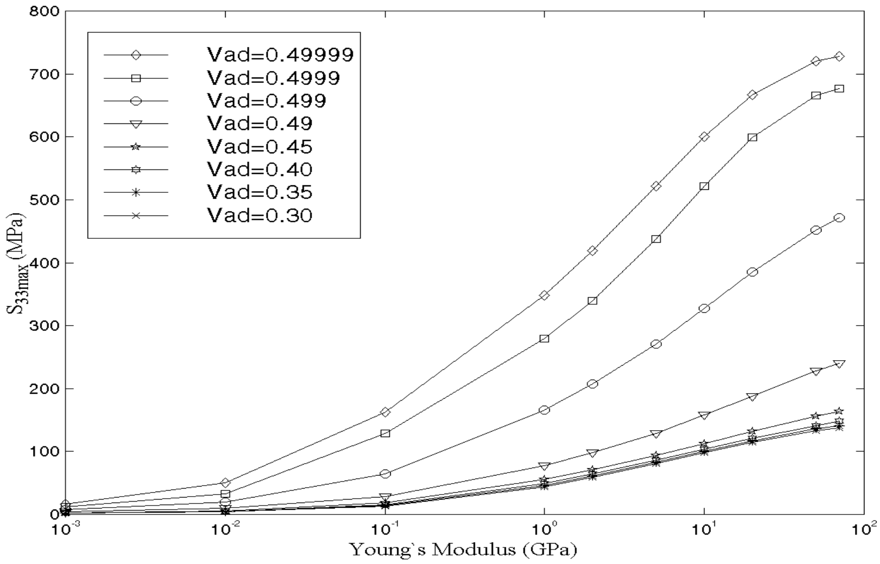


Fig. 3. Dependence of normal stress $S_{33max}$ on $E_{ad}$ and $\nu_{ad}$

## Ⅲ. Effect of the Adhesive Properties on Distributions of Maximum Stresses

Since failure of bonded joints initiates where high stresses occur, the maximum stresses are of interested. According to the previous study [14], the stress component $S_{11}$ is the biggest component of the six stress components in the order of magnitude but $S_{33}$ is potentially the most dengerous component because it is associated with the peel stress. In this section, the distributions of the stress component $S_{33}$ in the adhesive layer of a single-lap jointed cantilevered beam will be studied.

The distribution of the maximum values of the normal stress $S_{33max}$ for different adhesive properties are shown in Table 1 and Figure 3. It is seen from Figure 3, that for Poisson's ratio $\nu_{ad}$=0.30, 0.35, 0.4, 0.45, the maximum values of the normal stress $S_{33max}$ increase gradually as the Young's modulus of the adhesive increases gradually. For Poisson's ratio $\nu_{ad}$=0.49, 0.499, however, $S_{33max}$ increases quickly as $E_{ad}$ increases. Also, for $\nu_{ad}$=0.4999, 0.49999, $S_{33max}$ increases rapidly as $E_{ad}$ increases from $E_{ad}$=0.001 GPa to $E_{ad}$=50 GPa, then $S_{33max}$ increases less rapidly as $E_{ad}$ increases beyond $E_{ad}$=50 GPa.

Table 2 Maximum values of normal stress $S_{33MAX}$ induced in adhesive layer for various adhesive properties

| | Young's modulus $E_{ad}$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\nu_{ad}$ | 0.001 | 0.01 | 0.1 | 1 | 2 | 5 | 10 | 20 | 50 | 70 |
| 0.49999 | 16.48 | 50.73 | 163.30 | 347.67 | 419.32 | 522.06 | 600.00 | 667.21 | 720.38 | 727.73 |
| 0.4999 | 12.52 | 33.15 | 129.43 | 278.91 | 339.08 | 437.88 | 521.61 | 599.08 | 665.72 | 677.22 |
| 0.499 | 8.05 | 19.17 | 64.18 | 166.28 | 206.79 | 270.86 | 326.58 | 384.69 | 452.05 | 470.53 |
| 0.49 | 3.96 | 9.93 | 28.00 | 77.95 | 97.88 | 129.40 | 157.58 | 188.25 | 227.52 | 240.12 |
| 0.45 | 2.03 | 5.39 | 18.12 | 55.17 | 70.85 | 93.75 | 112.47 | 131.76 | 155.84 | 163.59 |
| 0.40 | 1.84 | 4.72 | 15.39 | 48.68 | 63.89 | 86.14 | 103.71 | 120.97 | 141.28 | 147.53 |
| 0.35 | 1.76 | 4.37 | 14.17 | 45.63 | 60.66 | 82.91 | 100.32 | 117.01 | 135.85 | 141.43 |
| 0.33 | | | | | | | | | | **139.96** |
| 0.30 | 1.72 | 4.16 | 13.49 | 43.89 | 58.82 | 81.16 | 98.61 | 115.10 | 133.16 | 138.33 |

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In Table 2, the maximum value of $S_{33}$ for an equivalent, homogeneous, 'staggered' cantilevered beam without adhesive joint for which $\nu_{ad}$=0.33 and E=70GPa, is $S_{33max}$=139.96 MPa. It can be seen from the table that most of the maximum values of the normal stress $S_{33}$, which encompass the entire spectrum of viscoelastic behavior, are lower than the corresponding maximum value of a cantilevered beam without a joint except the shaded data. In fact, the shaded data are for adhesives which do not and cannot exist. For example, when $\nu_{ad}$=0.49999, it is not possible to obtain a rubber of Young's modulus $E_{ad}$=0.1 GPa or higher. Therefore all the shaded data denote adhesive joint failure. The boundary between the shaded and unshaded data, therefore, represents the limits of the normal stress $S_{33}$ for the safe design of a lap-joint which is similar to Figure 1.

## IV. Discussion of typical cases

Several parametric studies are performed and the the stress distributions corresponding to different Young's modulus and different Poisson's ratios are obtained in this section. However, only four typical cases will be discussed because of limited paper space. In order to make it easy to describe the different combinations of Poisson's ratios and Young's modulus employed, the following nomenclature is used:

RR-Beam: $\nu_{ad}$=0.49999, $E_{ad}$=0.001 GPa, bonded beam with adhesive properties in the rubbery region

TR-Beam: $\nu_{ad}$=0.40, $E_{ad}$=1 GPa, bonded beam with adhesive properties in the rubber-to-glass transition region

GR-Beam: $\nu_{ad}$=0.30, $E_{ad}$=10 GPa, bonded beam with adhesive properties in the glassy region

H-Beam: $\nu_{ad}$=0.33, $E_{ad}$=70 GPa, homogeneous beam without joint

$S_{33maxRR}$: The maximum value of stress component $S_{33}$ for RR-Beam

$S_{33maxTR}$: The maximum value of stress component $S_{33}$ for TR-Beam

$S_{33maxGR}$: The maximum value of stress component $S_{33}$ for GR-Beam

$S_{33maxH}$: The maximum value of stress component $S_{33}$ for H-Beam Helpful Hints

The predicted variation of the stress component $S_{33}$ for the four different combinations of Young's modulus and Poisson's ratios employed are shown in Figure 4. Figure 5 shows the two-dimensional plots, in which the maximum stresses occur, of the normal stress $S_{33}$ against the non-dimensional distance x/c. A close examination of Figures 4 and 5 shows that $S_{33maxRR}$ occurs symmetrically near the left-rear corner (x/c=0, y/b=0.85) and near the left-front edge (x/c=0, y/b=0.15) of the adhesive layer. However, $S_{33maxTR,}$ $S_{33maxGR}$ and $S_{33maxH}$ occur at the centre of the left edge (x/c=0, y/b=0.5) of the adhesive layer. It is also clear from Figure 5 that in this case, the values of the normal stress $S_{33}$ of H-Beam are higher than that of other beams along the x direction. It can also be seen that for RR-Beam and H-Beam, the magnitude of the stress oscillates in value close to both the left and the right ends of the adhesive layer.

The stress distribution shown in Figure 5 is similar to that obtained by Adams *et al.* [1], Delale *et al.* [5] Ojalvo and Eidinoff [6] and Wah [8] using analytical methods. These previous works confirm that the left hand region of the adhesive layer is highly stressed. The additional contributions made in the current work are on the influence of the mechanical properties of adhesive on the magnitudes of the interface stress as well as on the three-dimensional distributions of this stress. The previous works concentrated on the two-dimensional distributions of the stress.

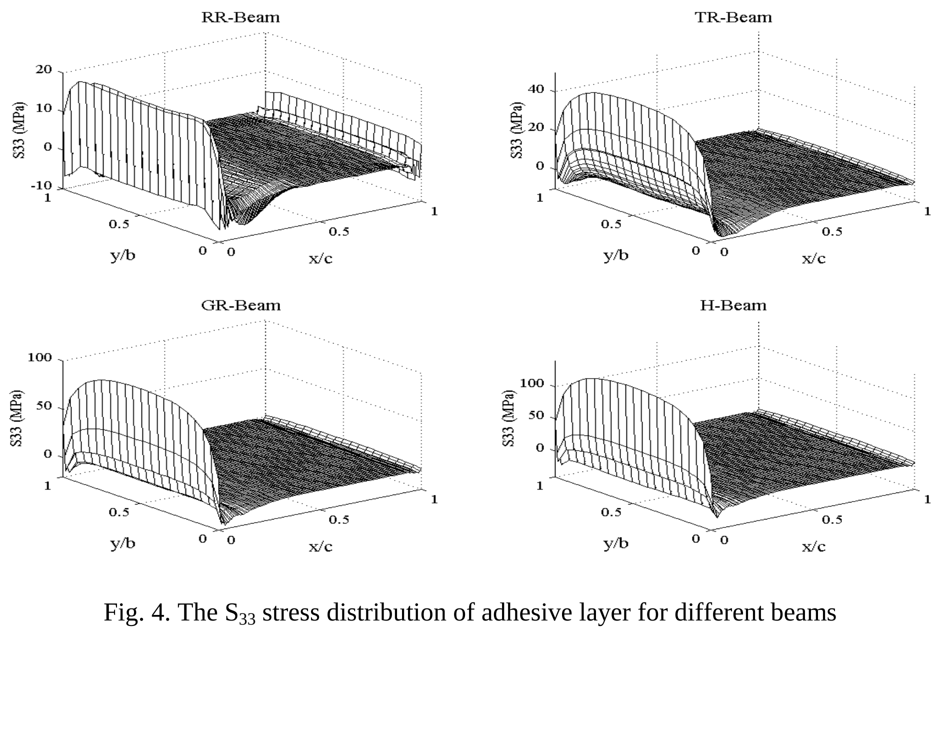


Fig. 4. The $S_{33}$ stress distribution of adhesive layer for different beams

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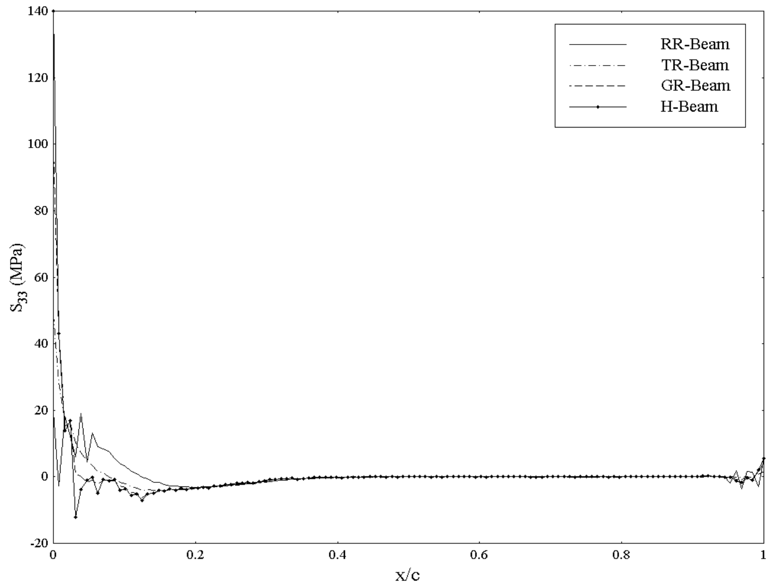


Fig. 5. The maximum stress of $S_{33}$ of adhesive layer for different beams

## V. CONCLUSIONS

The effect of adhesive characteristics on the actual stress distribution of a single lap-jointed cantilevered beam has been investigated using the three dimensional elastic finite element method. Specifically, finite element solutions of the stress distributions in the adhesive layer have been obtained for four typical characteristics of adhesives. The results indicate that the stress distributions of a single-lap jointed cantilevered beam are strongly affected by both Young's modulus and Poisson's ratios. The analysis results also show that by choosing suitable adhesive, the maximum stresses can be reduced and the strength can be improved.

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