

Stress analysis of Steel/Steel Adhesive Bond Double Lap Joints

Najeeb Ali Yahya, Mutyaa Mohamed Ehmaida

Department of Mechanical and Industrial Engineering, Faculty of Engineering, University of
Zawia, Zawia, Libya
nyahya@zu.edu.ly

Abstract

Structural defects such as cracks and corrosion are a common problem experienced within many different engineering fields. Where the marine industry and the oil and gas industry are known to suffer greatly for those defects. Traditionally these were repaired using welding techniques or mechanical fasteners such as bolts and rivets. The related fire hazard within the oil and gas industry requires large areas of production to be shut down before welding can take place. This causes delays and can lead to large financial implications. Mechanical fasteners also have the disadvantage in that they require holes to be drilled in the component. Undesirable stress concentrations can form around these holes when the joint is under load. Therefore a method of repair which doesn't produce harmful stress concentration and wont delay production is desirable. Adhesively bonded patch repairs satisfy both of these requirements and are gaining interest within many sectors of industry.

A double lap shear joint is considered to be a good representation of an adhesively bonded patch repair.

In this paper, numerical investigations into the behaviour of the Double Lap Joint (DLJ) will be conducted, with the aim of analysing its strength and failure characteristics. The main objectives of this work are to create a valid numerical representation of the joint using ABAQUS modelling software. The main conclusions drawn are: The stress distributions observed within the numerical model could be considered a reliable indication of the stresses present in the real joint. This helped to confirm the location of a stress concentration on the lower adhesive/adherend interface at the end of the strap overlap.

Key Words: Stress analysis, double lap joints, adhesive joint, finite element analysis, ABAQUS.

1. Introduction

Structural defects such as cracks and corrosion are common problems in the automotive, aerospace and marine industry. In the past, welding and mechanical fasteners such as bolts or rivets were seen as the most viable solution. However, these fastenings require holes to be drilled in the component around which large stress concentrations exist when the joint is under load. The mechanical joint (especially weld joints) were still prevailing, while adhesive joints became popular mainly for thin-walled components and in the case of strengthening of steel structures. Adhesive joints for steel structures have been recently studied and analysed. Some research covering primarily thin-walled structures are presented in [1][2][3]. Such a specialization results from advantageous proportion between the load-bearing capacity of a thin-walled component and its surface area (which also translates into the bond surface), as well as extensive experience in gluing structures used in aviation and automotive industries. The main problem in obtaining a full value adhesive joint featuring required load-bearing capacity and durability is to identify an appropriate glue. This issue has been already tested and analyzed [4]. The load-bearing capacity of the joint, failure mode and the distribution of shear stresses within the adhesive layer were analyzed and discussed [5]. However, still no universal solution is available which results from a variety of steel grades and applications, as well as the mode of loading and the working conditions of structures.

Adhesive bonding, as a method of patch repair, eliminates such drawbacks and also avoids the fire safety hazard associated with welding. This technique has been increasing in popularity with recent improvements in their load carrying capacities and predictability of failure. Advances in Finite Element Analysis (FEA) software has allowed the failure modes of such joints to be studied in far greater detail than was ever previously possible. Numerical modelling also saves on time and cost when compared to experimental methods. In order to validate the numerical results however, we must first confirm that the modelling software is an accurate representation of the experimental work.

More advantages of adhesive bonding over traditional methods include: cost and weight reductions, water tight joints and good sound and vibration absorption [6]. For these reasons adhesive joints are fast becoming a more attractive method of repair within industry [7] [8]. This work contains numerical investigations into the behavior of a high strength steel Double Lap Joint (DLJ) under tensile loading. The overall aim is to

investigate the strength and failure characteristics of this type of joint and identify possible areas of failure initiation.

This investigation looks at high strength carbon steel as the upper and lower adherends and a commercially available 2-part epoxy adhesive as the bonding agent. The findings from this work will hopefully act as guide for future analysis of similar joints.

The stress analysis of the interior bonding region is one of the most important aspects of design procedures based on the joint strength prediction and evaluation. How to impose the external loads to a joint defines the stress states which may be produced [9]. Pickett and Holloway presented the classical and finite element analyses for determination of the stress field in adhesive layer of single-, double-, and tubular-lap joints [10].

They numerically solved differential equations expressed in their classical analysis. The effects of different thicknesses of adhesive and adherends on the stress distributions in adhesive layer of symmetrical lap-joints with thick adherends and symmetrical DLJs were investigated [11][12]. The mechanical behavior of adhesive joints was investigated through the double-lap shear tests for different temperatures and extension rates[13]. Also presented a semi-analytical solution procedure considering the material's nonlinearity in order to predict the mechanical behavior of adhesively bonded shear DLJs using the von Mises and Raghava's yield criteria. A two-dimensional (2-D) stress analysis of adhesively bonded DLJs subjected to combined thermal loadings through a thermal stress analysis conducted by the finite element software ABAQUS[14]. Those studies already found the stress fields produced in the adhesive layer and on the interfacial surfaces [15] [16]

An analytical investigation on the stress analysis of DLJs with constant adherends' thicknesses using a layer wise model based on the tacking of the Reissner Mindlin plates presented in [17]. The stress distribution and the strength of adhesively bonded steel-composite DLJs, theoretically and experimentally studied [18]. And presented a new nonlinear elasto-plastic stress analysis considering the shear deformation of the adhesive and shear and normal deformations of the adherends.

Based on the Volkersen's theory, introduced an analytical approach in which the adhesive was assumed to have a piece-wise linear mechanical behavior in order to find the shear stress distribution along the adhesive bond-line[19].

2. Joint Details

The four metal bars used to make the joint were made out of high strength carbon steel. The Araldite 2015 epoxy based adhesive used in this study is a commercially available structural adhesive.

The dimensions of the double lap shear joint (DLJ) are shown in Figure 1. It consists of two inner adherends and two outer adherends (straps), all of which are made from high strength carbon steel. The width of the joint is 25mm.

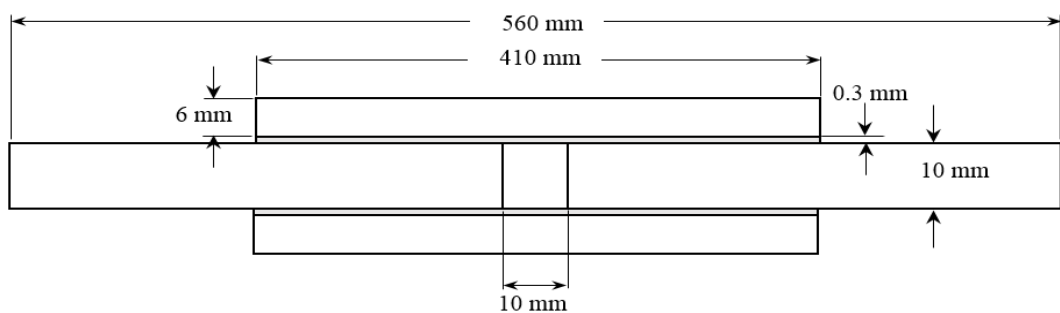


Figure (1): Double lap shear joint dimensions

The adhesive and adherends components were modelled separately and assembled within Abaqus. The adhesive's material behavior was modelled as elastic fully plastic and the maximum shear strength and maximum tensile strength was taken as 26MPa and 40MPa respectively. Material data used for the numerical model is shown in Table (1).

Table (1):Material properties of adhesive and high strength carbon steel.

| Property | Epoxy Adhesive (Araldite 2015) | High Strength Carbon Steel |
|------------------------|-----------------------------------|-------------------------------|
| Young's Modulus (GPa) | 2 | 210 |
| Poisson's Ratio | 0.36 | 0.3 |
| Tensile Strength (MPa) | 40 | 450 |
| Shear Strength (MPa) | 26 | - |

3. Numerical Analysis of DLJ

Due to the symmetry conditions in the DLJ, using a quarter model in order to reduce the complexity of the FE simulation and reduce computation time. In order to gain the most

accurate representation of the stresses in the quarter model of the DLJ, the 8-noded plain-strain quadratic elements, CPE8R (reduced integration), which capture the stresses Prominent more accurately than using 4-noded plain strain linear elements, CPE4R. Non-linear static analysis steps were used along with taking into account for the non-linear behaviour of the adherents and adhesive via means of using the non-linear geometry function (NLGEOM). Figure 2 illustrates the boundary conditions used to model the DLJ with relevant dimensions shown also. Plain strain elements were used for the adhesive and adherends due to the consideration of the thickness values compared to the width of each. The accuracy of analysis in FEM is heavily dependent on the size of the elements used. Smaller elements within a structure (using a finer mesh) will produce more reliable stress and strain results. Mesh refinement should be concentrated in areas of high stress such as fillets, sharp corners and fracture points.

In this study, a manual bias was given to the upper and lower adherends. A stress concentration was expected at the joint overlap and hence the bias was directed towards this area of interest. Figure 2 illustrates the mesh used within the DLJ.

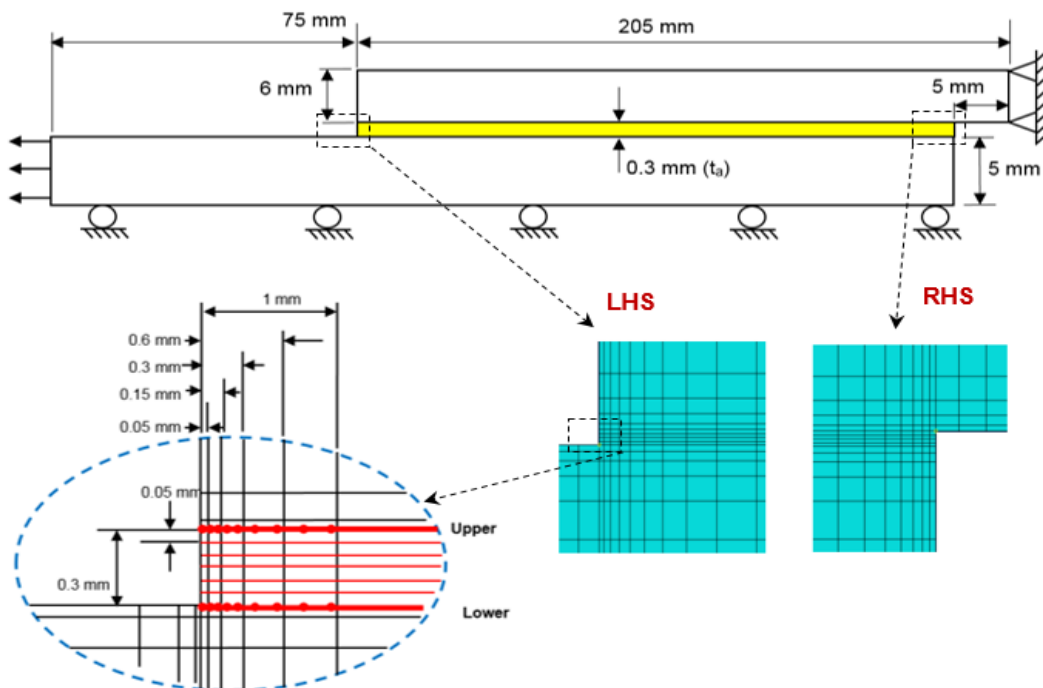
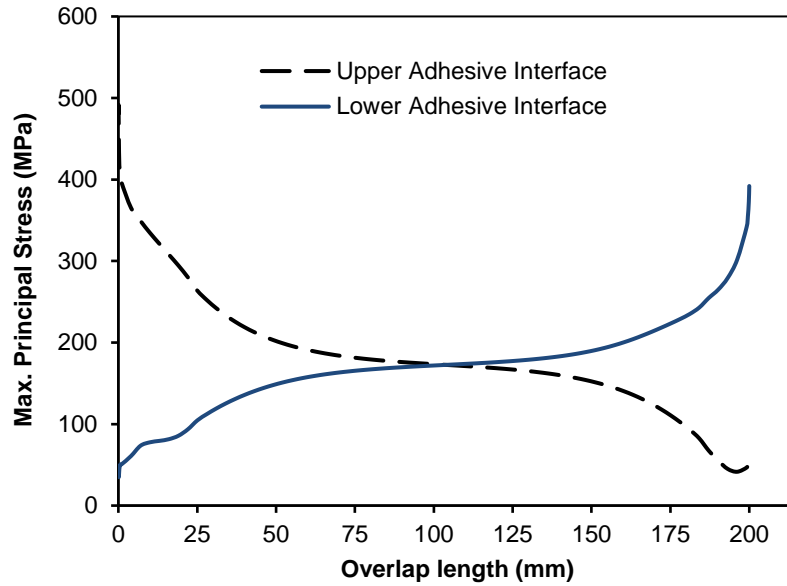
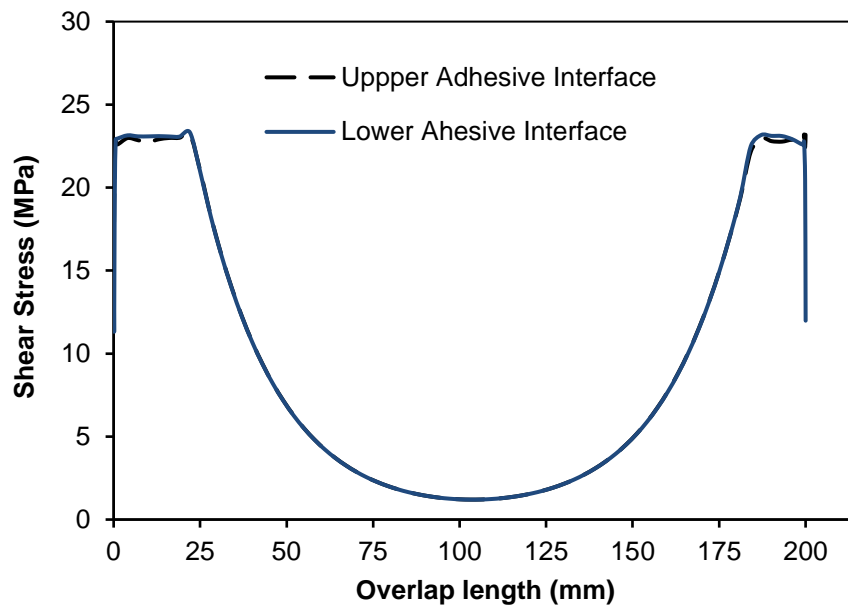


Figure (2): Boundary conditions and element meshes in the finite element model.

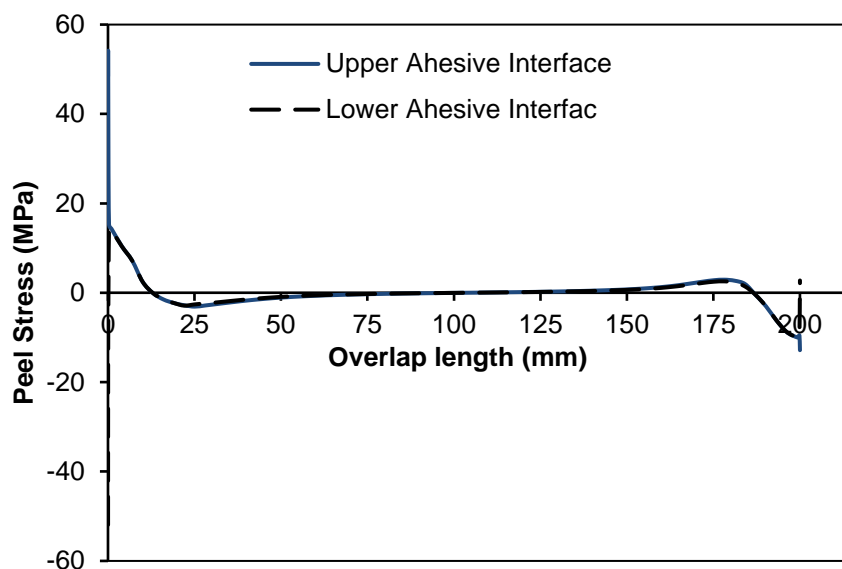
4. Results and discussion



(a) Maximum principal stresses



(b) Shear stress S12



(c) Peel stress S22.

Figure. 3: Distributions of the interfacial stresses of the lower and upper adhesive layer, (a) maximum principal stresses, (b) shear stress S12 and (c) peel stress S22.

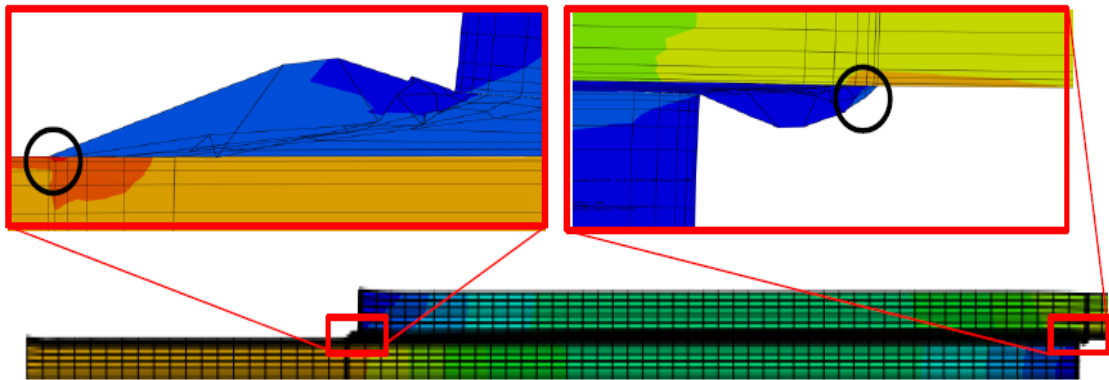
Table (3) shows the analysis results from along the two data paths described in figure 2. Images of the model simulation can be found in Figure 4. These illustrate in colour where these stress concentrations occur.

The highlighted values in the table indicate the larger stress values detected within the adhesive. Some are greater than others. For this study however, the maximum principal stress was chosen as the most reliable indicator of failure initiation within the adhesive. It was recognised that a large stress value exists at a point on the lower adhesive interface at the end of the joint overlap. This value was by far the greatest and was therefore the most likely location for failure initiation in the joint.

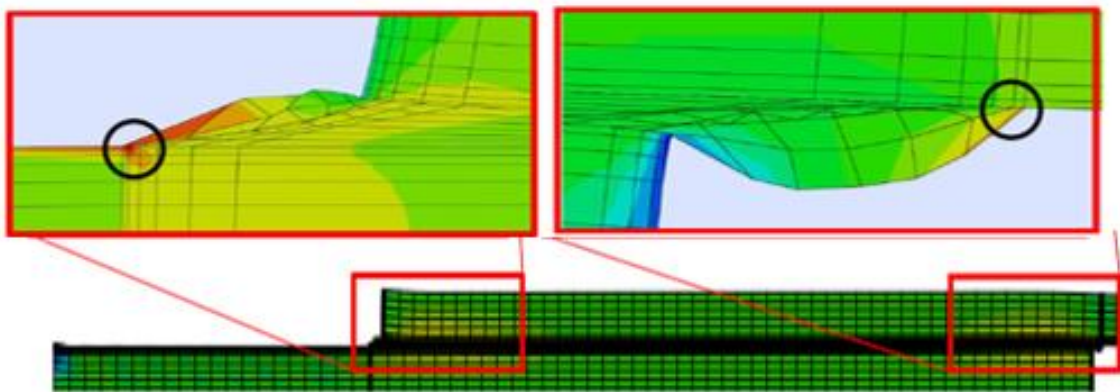
Table (3):Summary of stress analysis at adhesive layer

| Stress | Data Path | LHS (MPa) (End of Overlap) | RHS (MPa) (Centre of Overlap) |
|---------|-----------|-------------------------------|----------------------------------|
| Max S22 | Upper | 27.6 | 15.9 |
| | Lower | 54.8 | 28.8 |
| Max S12 | Upper | 12.9 | 23.1 |
| | Lower | 12.63 | 23.4 |
| | Upper | 29.1 | 409.1 |

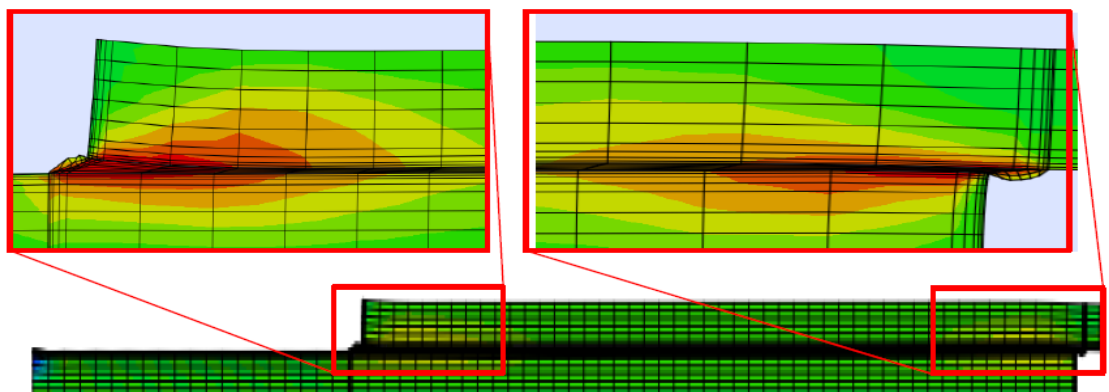
| | | | |
|---------------|-------|-------|------|
| Max Principal | Lower | 517.1 | 41.7 |
|---------------|-------|-------|------|



(a) Max Principal stresses



(b) Peel stress S22



(c) Shear stress S12

Figure 4. Distributions of stresses within adhesive layer of homogeneous DLJ subjected to uniaxial tension, (a) Max Principal stresses, (b) peel stress and (c) shear stress.

5.3.2 Effect of Overlap length

The metal bars will be used as outer adherends with five overlap length values of 50mm, 75mm, 100mm, 125mm and 200mm modelled as adhesively bonding joints. The adhesive thickness 0.3 mm was used in each model. Every model analysed used identical boundary conditions. The same standard mesh was used in each model as can be seen in figure 2.

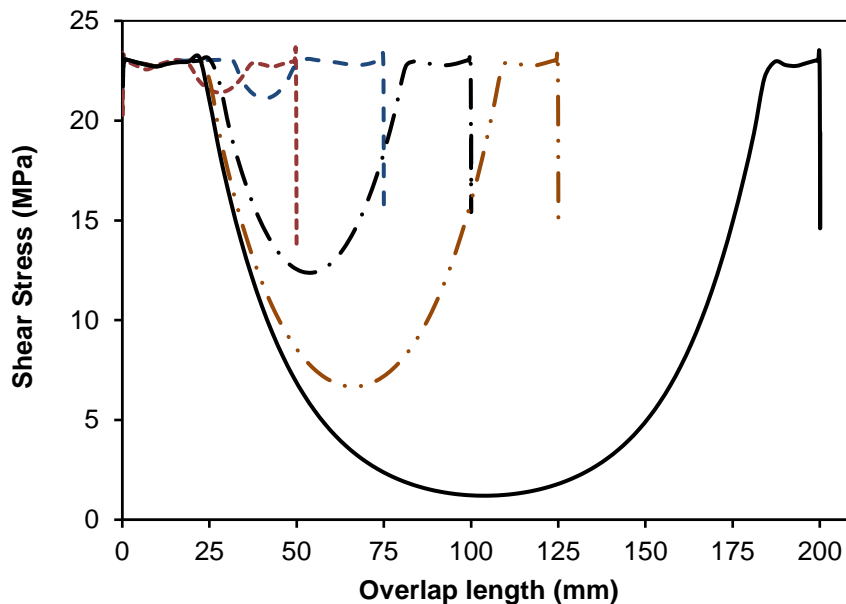


Figure 5: Shear stress distributions with various overlap lengths

Figure 5 shows all five models with contain the largest peak shear stress values. The shear stress value exists at a point on the lower adhesive interface at the end of the joint overlap. One conclusion from these results is that the adhesive seems to reach plasticity in the maximum shear stress within the adhesive. The length of plastic zone of 50mm and 75mm overlap is about 50% of overlap length joint. For long overlap 100mm and above the plastic zone length is constant for all models.

The peel stress distributions in the adhesive layer for different overlap lengths are presented in Figure 6. The stress peaks located on the edge of the overlap region. And stress values on the left edge were slightly higher.

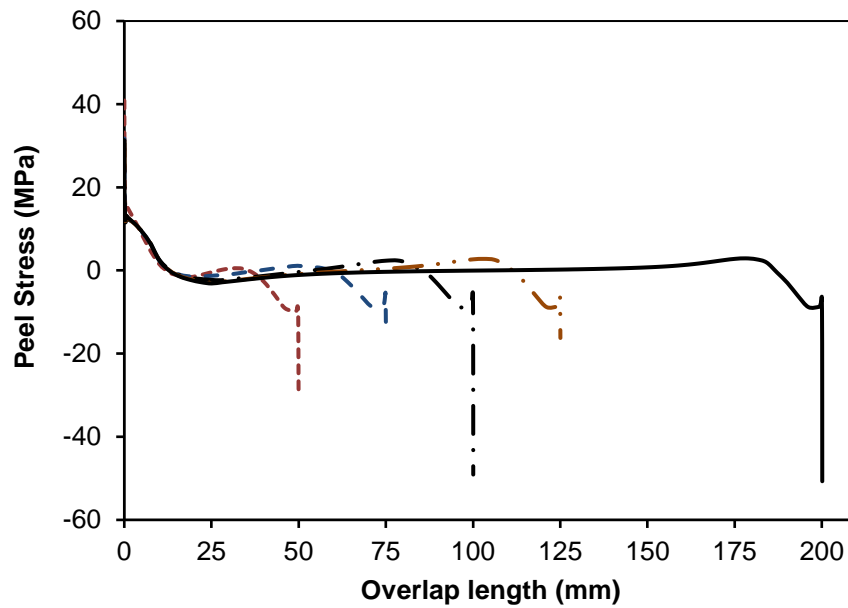
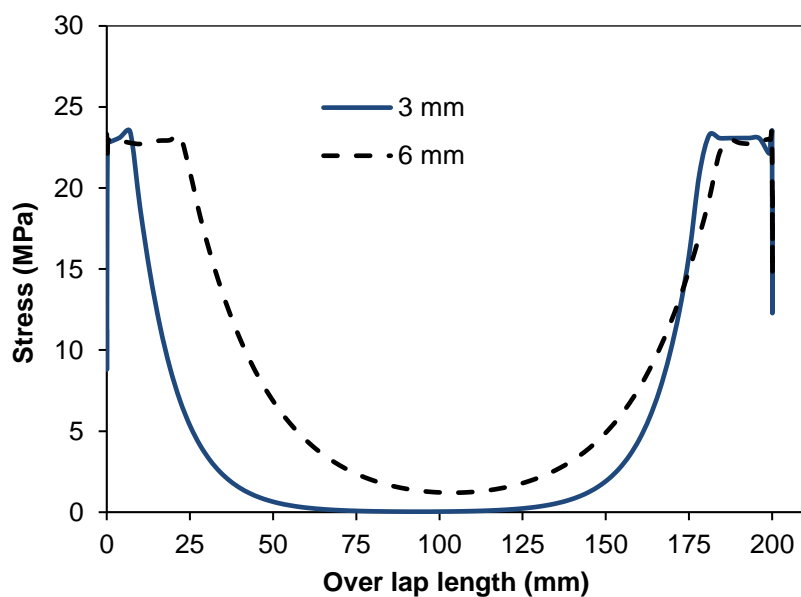
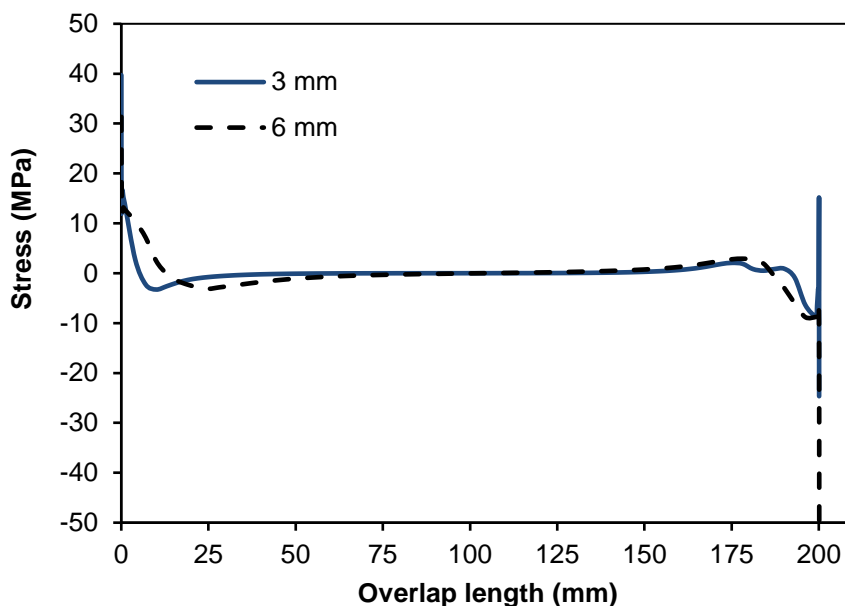


Figure 6: Peel stress distributions with various overlap lengths

5.3.2 Effect of a adherend thickness



(a) Shear stress S12



(b) Peel stress S22.

Figure. 3: Stress distributions with various adherend thickness , (a) shear stress S12 and (b) peel stress S22.

If the adherent thickness is decreased, the lever arm of the applied loads is decreased. For this reason the moment will be smaller and so the peel stresses will be smaller. But simply decreasing the adherent thickness will lead to a lower axial stiffness, which leads to higher shear stress peaks,

5. Conclusions

The paper presents the numerical solutions including the interfacial peel and shear stress distributions along the adhesive length and particularly near the edges of the bonding regions. The stress distributions are indicated, and it is shown that these phenomena can significantly affect the responses only in regions near the bond-line ends with the length of almost equal to adhesive thickness. Considerable changes in amount and sign of stresses may be responsible to debonding and failure.

The following specific conclusions might be drawn;

- As expected, the failure of the joint was within the adhesive rather than the steel.
- Modelling plasticity in the adhesive alone appears to offer accurate results within the numerical analysis.

- Failure is most likely to initiate at the end of the joint overlap on the lower adherend/adhesive interface.
- Increased joint strength is obtained with increased outer adherend thickness.
- Peel stress was the one of the main reasons of the failure in joints. According to 2D solution of the peel stress distribution graphs, peel stress was higher at the end of the overlap area compared to the centre of the joint.

References

- [1] G. Kubieniec, M. Piekarczyk, "Thin-walled steel griders reinforced with use of adhesives an experimental and numerical investigation,," in *Proc. Eurosteel Conference*, pp. 1611-1616., Graz,, 2008.
- [2] M. Pasternak, G. Kubieniec, M. Piekarczyk, "Adhesives in strengthening of steel structures," *Eng. Structures and Technologies*, vol. 2, pp. 45-50, 2010.
- [3] M. Pasternak, A. Schwarzlos, N. Schimmach, "The application of adhesives to connect steel members," *Journal of Constructional, Steel Research*, vol. 60, pp. 649-658., 2004.
- [4] L.G.M. da Silva, A. Ochsner, R.D. Adams, *Handbook of adhesion technology*, Heidelberg,: Springer, 2011..
- [5] J. Hulimkaa, M. Kałużaa , "Preliminary tests of steel-to-steel adhesive joints," *Procedia Engineering* , vol. 172, p. 385 – 392, 2017.
- [6] S. Abdolmajid Yousefsani, Masoud Tahani , " Accurate determination of stress distributions in adhesively bonded homogeneous and heterogeneous double-lap joints.," *European Journal of Mechanics - A/Solids* . , vol. 39, pp. 197-208, 2013.
- [7] Mohamed N. Saleh, M. Saeedifar, D. Zarouchas, and S. Teixeira De Freitas, "Stress analysis of double-lap bi-material joints bonded with thick adhesive," *International Journal of Adhesion and Adhesives*, vol. 97, 2020.
- [8] Mariam M, Afendi M, Abdul Majid MS, Ridzuan MJM, Azmi AI, and Sultan MTH, "Influence of hydrothermal ageing on the mechanical properties of an adhesively bonded joint with different adherends. *Compos B Eng* 2019;165:572–85.," *Compos B Eng*, vol. 165, p. 572–585, 2019.
- [9] Jr. Messler, "Joining of Materials and Structures, from Pragmatic Process to Enabling Technology. .," *Elsevier Butterworth-Heinemann Publications, MA 01803, USA*, 2004.

- [10] A.K. Pickett and L. Hollaway, "The analysis of elastic adhesive stresses in bonded lap joints in FRP structures.," *Compos. Struct.* , vol. 3, pp. 55-79, 1985.
- [11] W.K. Chiu, and R. Jones, "A numerical study of adhesively bonded lap joints.," *Int. J. Adhes. Adhes.*, vol. 12, no. 4, pp. 219-225, 1992.
- [12] N.A. Yahya, and S.A. Hashim, "Stress analysis of steel/carbon composite double lap shear joints under tensile loading," *Proc IMechE Part L: Journal of Materials: Design and Applications*, Vols. 230,, no. 1, p. 88–104, 2016.
- [13] A. Deb ,L. Malvade, Biawas, I. and J. Schroeder., " An experimental and analytical study of the mechanical behavior of adhesively bonded joints for variable extension rates and temperatures.," *Int. J. Adhes. Adhes.* , vol. 28, pp. 1-15, 2007.
- [14] N.A. Yahya, and S.A. Hashim, "Delamination of thick adherend steel/CFRP laminate connections,," in " in *The European Adhesion Conference (9th EURADH), September 2012.*, Friedrichshafen/Germany,.
- [15] S. Sharifi , " Stress analysis of adhesively bonded double-lap joints subjected to combined loading.," *World Acad. Sci. Eng. Technol.* , vol. 41, pp. 758-763, 2008..
- [16] N. Yahya, "Effects of Carbon Fiber Reinforced Plastic Laminate on the Strength of Adhesive Joints," *The International Journal of Engineering and Information Technology (IJEIT)*,, vol. 4, 2017.
- [17] A. Diaz , R. Hady-Ahmed, G. Foret, and A. Ehlacher, " Stress analysis in a classical double lap, adhesively bonded joint with a layerwise model.," *Int. J. Adhes. Adhes.*, vol. 29, pp. 67-76, 2009.
- [18] H. Osnes, D. McGeorge, "Experimental and analytical strength analysis of double-lap joints for marine applications.," *Composites Part B* , vol. 40, pp. 29-40, 2009.
- [19] S. Chataigner, J. Caron, and A. Diaz , C. Aubagnac, and K. Benzarti, "Non-linear failure criteria for a double lap bonded joint.," *Int. J. Adhes. Adhes.*, vol. 30, pp. 10-20, 2010.