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# DESIGN OF SINGLE LAP JOINTS WITH MILD STEEL ADHERENDS

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**Abstract:** *Adhesively bonded single lap joints are a candidate structure fastening technique to riveted, welded and bolted joints, attaining a better load transfer and more uniform stress distributions. It is quite important to establish a relationship between static strength of a single lap joint and design parameters such as geometrical parameters, material response, type of loading and etc. This paper presents a conceptual design methodology for single lap joints with mild steel adherend S255 considering geometrical and material parameters. In order to perform this task, ductile (Veropal Super HE-20) and brittle (Carboresin) two component structural epoxy adhesives are implemented to examine influence of material behavior. Single lap joints are manufactured at various overlap lengths and undergone simple uni-axial tensile tests to identify static tensile strengths. Then a numerical model is created in a commercial finite element package program (ABAQUS™) to make a comparison between experimental and numerical failure loads, which implements well-known maximum value criteria for both adhesive and adherend failure. The results express that the material response and overlap length plays a substantial role in the design stage of bonded structures up to a certain point. Consequently, strength of a single lap joint is no longer dependent on increase of overlap length at which the failure mechanism is dictated by adherend yielding.*

**Keywords: Single lap joint, Epoxy adhesive, Static strength, Mild steel, Finite element method**

## 1. Introduction

Adhesively bonded joints are practical, economical and easy to manufacture and thus have been commonly implemented in a variety of engineering applications including railway, automotive, aircraft and other mechanical industries. The strength estimations and failure analysis of adhesively bonded structural joints in numerous applications are critical point of interest. For the prediction of failure loads of single lap joints, geometrical design parameters such as overlap length, adhesive and adherend thickness, type of loading and environmental conditions are critical issues as much as the material behavior of both adhesive and adherend.

For the case of low strength steel, adherend yielding occurs during the joint loading and the interpretation of the joint failure mechanisms is radically different from that seen with high strength (elastic) steel adherends (da Silva et al., 2013). Adherend yielding often occurs in engineering structures where metals such as aluminum and mild steel (automotive) are used (Harris JA and Adams RD., 1984). There are many researchers in the literature that include adherend yielding using finite element (FE) analysis with a continuum mechanics approach (Dorn L and Liu W., 1993), or alternative tools such as cohesive zone modelling (Zhao X, et al., 2011). It was first recognized by Hart-Smith (Zhao X, et al., 2011), Adams et al. (Clarke JD and Mcgregor IJ., 1993), (Grant et al., 1981) and da Silva et al. (Hunston DL. et al. 1984 and Duan K. et al., 2004) that adhesive yielding could be rather simple and solely controlled by adherend yielding.

This paper aims to contribute design of the single lap joints considering the effect of overlap length and material response (ductile or brittle adhesive). A simple failure theory based on maximum equivalent stress and strain values is presented to evaluate failure loads of the single lap joints under uni-axial tensile

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loading. It is quite advantageous that the presented approach only requires such mechanical properties to estimate failure strength, which can be obtained from a basic stress-strain diagram of corresponding bulk samples of adhesive and adherend.

## 2. Material and Methods

### 2.1. Materials

Two different types of structural epoxy adhesive, Veropal Super HE-20 (ductile) and Carboresin (brittle), were used to manufacture single lap joints. Adherend material was selected to be S255 mild steel with a low yielding strength of 255 N/mm$^2$ to asses influence of adherend yielding on static strength of single lap joints.

Since the main objective is to evaluate failure mechanism of both adhesive and adherend, the bilinear elastic-plastic material properties are needed. For this case, bi-linear material properties (Tab. 1.) of both adherend and adhesive materials were specified as a result of true stress-strain diagrams of bulk samples. The Poisson's ratio values of adherend, Veropal Super HE-20 and Carboresin are 0.3, 0.34 and 0.28, respectively.

*Tab. 1: Mechanical properties of adhesive and adherend materials.*

| | Modulus of elasticity, E (MPa) | Yield Strength, $S_y$ (MPa) | Tensile strength, $S_u$ (MPa) | Elongation at break, $\varepsilon_f$ (%) |
|---|---|---|---|---|
| Mild Steel S255 | 200000 | 255 | 380 | 20 |
| Veropal Super HE-20 | 1150 | 31.2 | 34.7 | 12.5 |
| Carboresin | 7460 | 20.9 | 23.6 | 1.5 |

### 2.2. Joint Geometry

The same geometry as that prescribed in ASTM D1002 were used for manufacture of the joints (Fig. 1.). Single lap joints were manufactured and modelled for four different overlap lengths of 20, 30, 40 and 50 mm, respectively. Two alignment tabs 25mm in length were placed equally at the both ends of each adherend material in order to avoid eccentricity, which creates a high amount of peeling stresses at the joint extremities. The joints were manufactured with an adhesive bond-line thickness of 0.2 mm.

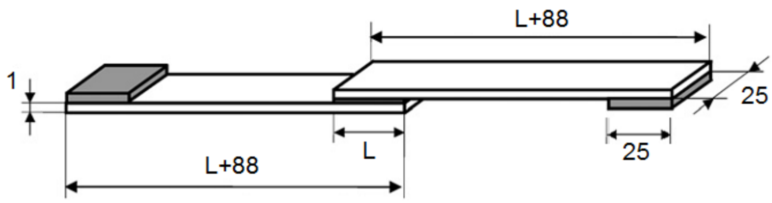



*Fig. 1: Single lap joint geometry (Dimensions in mm).*

### 2.3. Numerical Model

The finite element analysis was performed to estimate failure loads and details were covered in this section. The strength of the joint is highly affected by the plasticization of mild steel adherend material since they have quite ductile and relatively low yield stress. Beyond a critical point of adherend material stiffness, the joint strength remains almost the same. For this reason, bi-linear elastic-plastic material model, which is nearly exhibited by low strength mild steels, was implemented in the numerical analysis. In the same way, structural epoxy adhesives are mainly characterized by bi-linear material model. After reaching a critical stress value, the joint can sustain no extra load, global stiffness dramatically decreases then failure is assumed to be completed as a result of limit state consideration. For the numerical analysis, the single lap joint geometry (Fig. 2.) was created in 2-D since the static strength of bonded joints are almost directly proportional to width of the joint. In order to stimulate real case, displacement constraints are applied over the grip lengths and loaded in the uni-axial direction. A refined mesh zones were created at the joint extremities (Fig.2) where shear and peeling stresses attain the highest peak values.

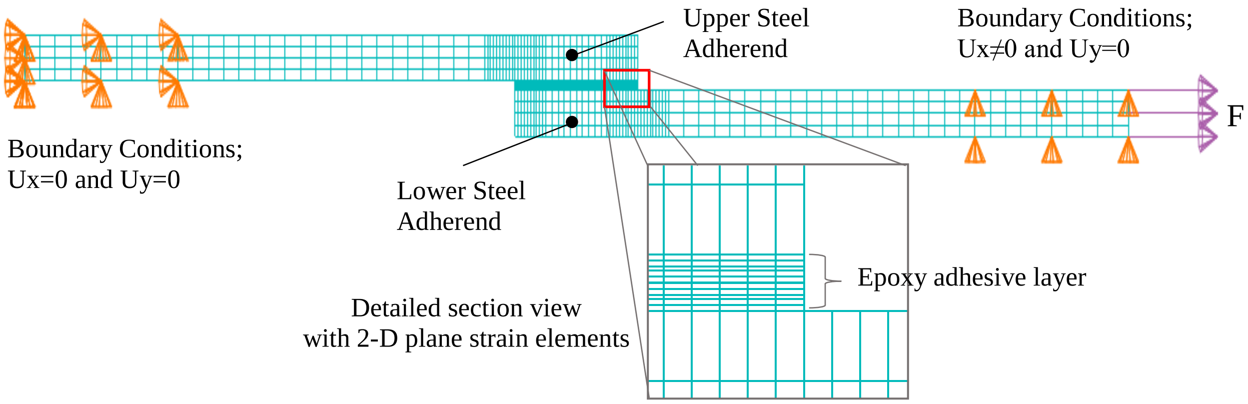



*Fig. 2: Two dimensional numerical model of the single lap joint with mesh structure.*

An eight node quadrilateral plane strain element was selected with the element dimensions of 0.01x0.1 $mm^2$ and 0.2x0.25 $mm^2$ for refined and coarse meshed zones, respectively. For the modelling of metal adherends, classical Von-Mises yield criterion is used with isotropic hardening which is offered by ABAQUS™. Adhesive failure is estimated based on peak values of longitudinal plastic strain together maximum stresses at the local elements for both ductile and brittle yielding mechanisms.

## 3. Results and Discussion

Experimental tensile test results for both adhesive type are given in Fig.3. It was clearly observed that the failure load remains nearly constant beyond a critical overlap (40mm) for ductile adhesive. Contrary, the joint strength with brittle adhesive is still sensitive to overlap length, for the case of loading under the yielding limit of adherend material. Hence, it may be effective for high strength brittle adhesives.

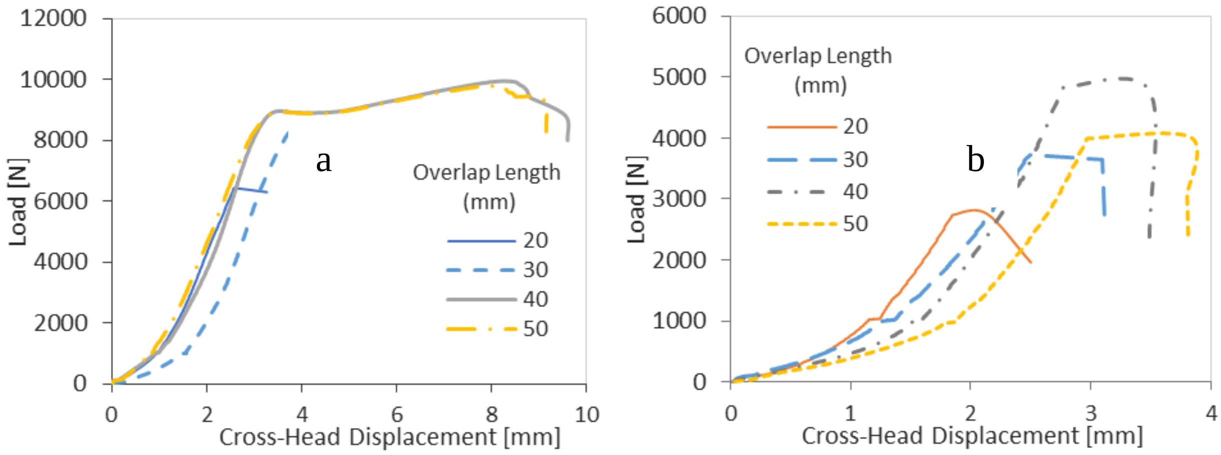
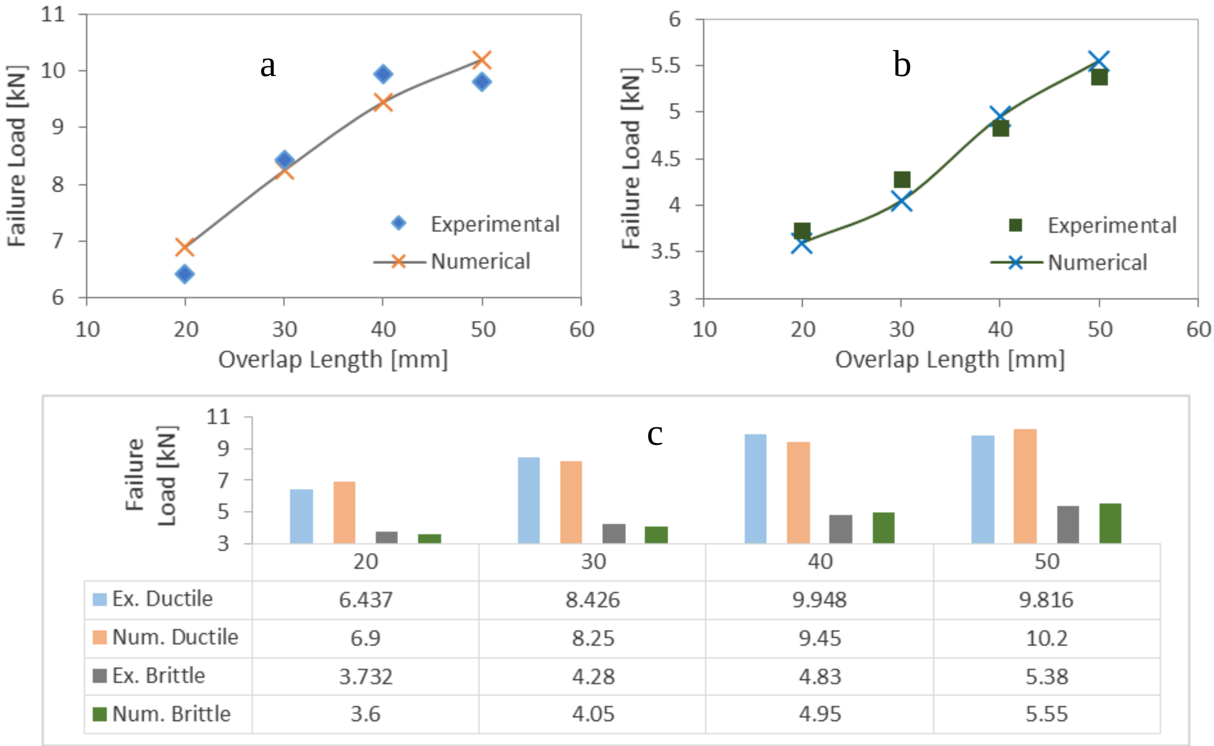



*Fig. 3: Experimental load-displacement curves for a) Ductile Veropal HE-20 b) Brittle Carboresin adhesive at various overlap lengths.*

In order to replicate the case, a numerical failure approach based on the maximum value of plastic principal strain in longitudinal direction ($\varepsilon_{11}$) was considered as a failure parameter at the critical zones positioned at the interfaces of steel and adhesive gometry. Failure parameter corresponding to 0.12 and 0.015 plastic strain for ductile and brittle adhesive, respectively was utilized. The model is also checked to ensure yielding stress is reached for each load step. Then, the trends of numerical failure load with respect to overlap length is presented (Fig. 4) with the deviations from experimental work.

Deviations of numerical results is found out to be lower than roughly 10% assumed to be in acceptable limits. From both experimental numerical results, strength of the joints with ductile adhesive exihibit an increasing trend upto a critical overlap length of 40mm where adherend yielding appeared then becomes nearly the similar. However, brittle ones have almost linear response with overlap length since the yielding point of




| | 20 | 30 | 40 | 50 |
|---|---|---|---|---|
| Ex. Ductile | 6.437 | 8.426 | 9.948 | 9.816 |
| Num. Ductile | 6.9 | 8.25 | 9.45 | 10.2 |
| Ex. Brittle | 3.732 | 4.28 | 4.83 | 5.38 |
| Num. Brittle | 3.6 | 4.05 | 4.95 | 5.55 |

*Fig. 4: Trends of the experimental and numerical failure loads for (a) Veropal HE-20 ductile, (b) Carboresin brittle adhesive, (c) the discrete failure load values for each configuration.*

adherend is not reached. Failure mode of the joints is mainly dictated by interfacial failure mode due to lack of adhesion at the interfaces.

## 4. Conclusions

It is concluded that the determining of critical overlap length depends on adherend yielding point. Simply, the strength of the brittle joint has emerged a quasi-linear trend with increasing overlap length if the adherend remains in the elastic region. Failure estimation for brittle material behavior is very conservative since the maximum principal strain parameter is very small comparing to ductile material model.

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