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MIE 320 - Lab 6 report

1.0 Introduction

The objective of this lab was to construct a joint that has the maximum strength to weight ratio while under axial loading. The joint is made with one plate of PMMA and one plate of of aluminum. ANSYS simulated the axial loading test and we constructed our geometry based on the results. After manufacturing the joint, it was physically tested to see if our design was valid.

2.0 Design Geometry

A lap joint was designed with epoxy as an adhesive in between the plates. The geometry and arrangement are shown in Fig. 1, and the material properties in Table 1. The design was made to maximize the adhesive area, to ensure that the plates would stay bonded. Epoxy would be applied as thinly between the plates, as it is at maximum strength at a thickness below 0.4mm. It would also be applied on the edges of the overlapping area, as a chamfer; This was to avoid stress concentrations due to a rapid change in material rigidity. Finally, the slot in the PMMA was made to reduce the mass of the overall design.

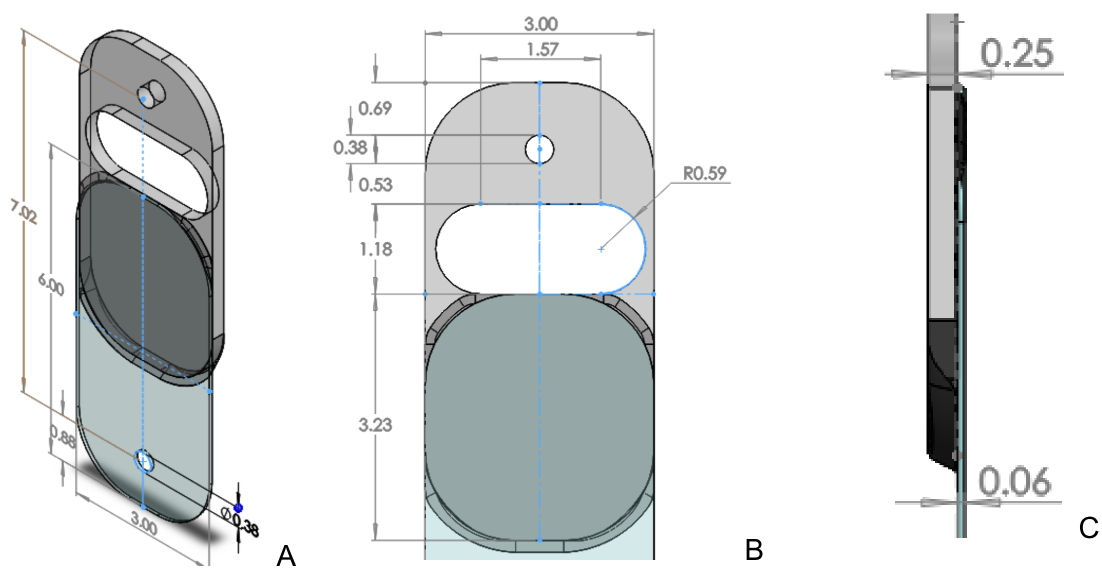


***Figure 1:** Schematics of the joint, in inches; Teal is aluminum, grey is PMMA and black is the epoxy. (A) Dimensions of the aluminum plate. (B) Dimensions of the PMMA plate. (C) Side view of the joint, showing the thickness of the plates. The thickness of the epoxy was modeled as 0.2 mm or 0.001 in between plates.*

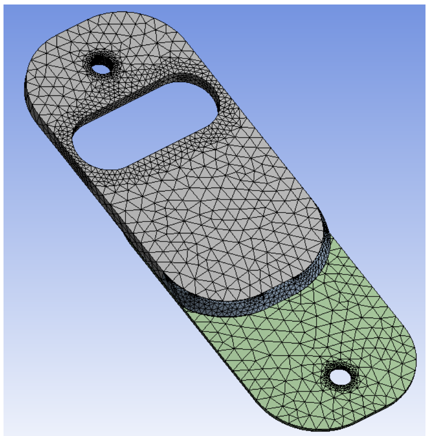
***Table 1:** Material properties of the PMMA and aluminum plates [1].*

	Young's Modulus	Yield Strength	Poisson's Ratio	Density
PMMA	3.1 GPa	70 MPa	0.35	1.19 g/cm^3
AA110-O	68.9 GPA	34 MPa	0.33	2.77 g/cm^3
Epoxy	3780	16.7 MPa	0.35	1.16 g/cm^3

3.0 FEA

The geometry of the joint was made and assembled in Solidworks, then exported to ANSYS. To ensure accuracy, mesh refinement was used at the holes, slots and the adhesive layer as seen in Fig2. A load of 1000N and of type force was applied at the PMMA loading hole, and a fixed-support was applied at the other hole as seen in Fig.3; This mimics the testing conditions, where the machine would hold at the aluminum hole, and pull at the PMMA hole.

__Figure 2:__ Mesh of the joint. The mesh was refined around the holes and at the epoxy layer.



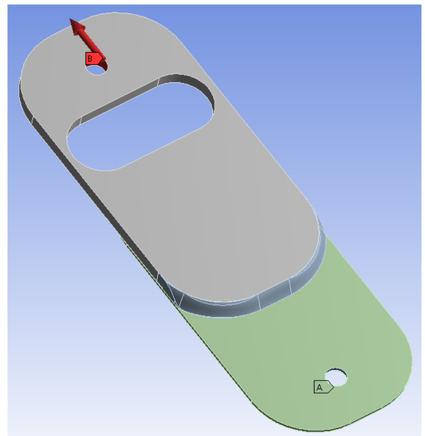


__Figure 3:__ A force type load was applied at the PMMA loading hole, seen as a red vector. A fixed support was applied at the other loading hole, indicated as 'A'.

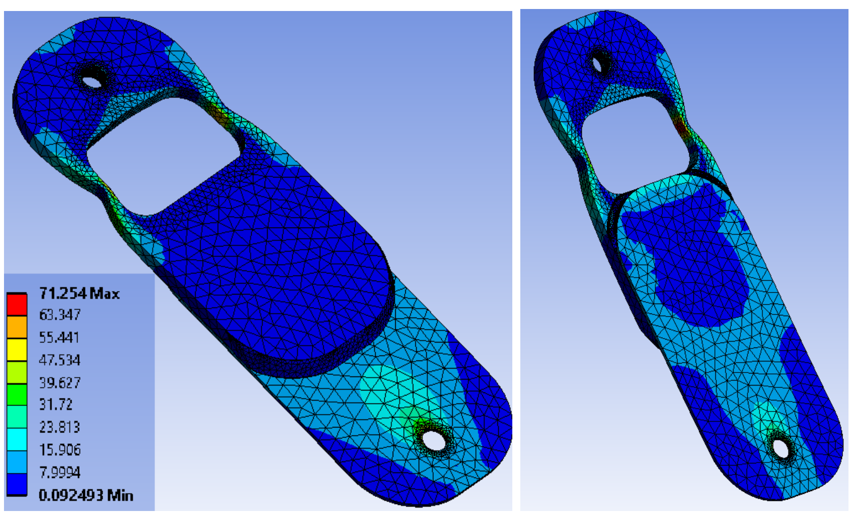


__Figure 4:__ Equivalent stress distribution of the joint at a applied load of 1, the legend in is [MPa]. (LEFT) With the PMMA side forward. (RIGHT) with the aluminum side forwards.

As seen above in Fig 4. FEA showed that a maximum stress of 71.254 MPa would occur at the edges of the slot, however it also shows that it is yielding. PMMA is brittle, so it is more likely to fail due to fracture rather than yield, and whether that occurs at the edge of the slot is unknown, as a crack will grow at any imperfection. To find the ratio of maximum load to mass, the force was increased until one of the plates failed at ultimate stress; This occurred at PMMA's slot edge with stress over 70 MPa, at a load of 1200 N as seen in Fig. 4 . ANSYS calculated the mass to be 118g. Thus, the ratio is 10.17 N/g.

To further ensure that the FEA was as accurate as possible, mesh refinement was done. The number of elements were increased by decreasing the size of the element's side at a applied load of 1000N and recorded in Table 2. As seen in Fig.5, stress converged to just below 56 MPa after 65,000 elements. Thus, the mesh was arranged properly, and the analysis was done with at least 65,000 elements.

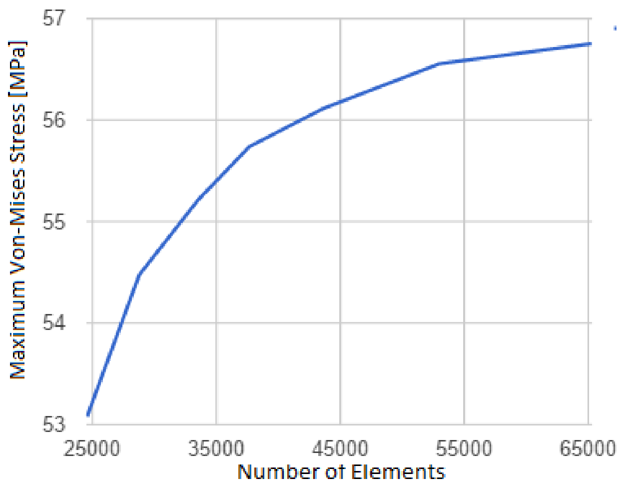


Figure 5: *Graph of number of elements vs. maximum stress.*

Table 2: *Mesh refinement results*

# of Elements	Max. Von Mises Stress [MPa]
24563	53.079
28765	54.474
33521	55.215
37648	55.739
43587	56.114
52954	56.555
65231	56.754

4.0 Experimental procedures

4.1 Link fabrication

First, the aluminum plate was cut by a water jet cutter and the PMMA plate by laser cutter. Second, the holes were reamed and notches were filed or sanded down. Next, we selected an adhesive that was easily available, cheap and had high shear and tensile strength; At our local hardware store, *JB KwikWeld twin tube adhesive* filled those requirements [2]. Having assembled the materials, we fabricated our joint. First, we marked the region where the epoxy would be applied. Second, we cleaned the plates with acetone to ensure epoxy would bond to the plates. Third, we sanded both plates with sandpaper to increase surface area for the epoxy to grip onto. Next, we cleaned the surfaced once more with acetone to remove all the dust. Meanwhile, we mixed the steel paste and hardener paste together with 1:1 ratio as instructed. As soon as the aluminum plate was ready, the adhesive was applied onto the aluminum plate. Then the PMMA plate was placed on top; We squeezed and rubbed both plates to ensure the epoxy filled in all gaps. Finally, we applied more epoxy on the joint ends so that it chamfered, as described in part 2. We held the plates for 6 minutes as instructed to ensure the adhesive had set. It was then allowed to cure for at least 6 hours.

4.2 Test procedure and results

First, we weighted our joint on the scale and found it was 124 g. Then the TA placed it in the axial loading chamber. The aluminum was placed at the fixed end at the bottom. Both ends were restrained by loading pins and clamps. After some time, the area close to the PMMA loading pin cracked and so the joint failed.

Figure 6: *Image showing the fractured area*

Our recorded max loading force was 1942 N; Thus the force to mass ratio was 15.66 N/g.

The crack is located near the loading hole of the PMMA plate. The crack starts at the filleted corner and ends at the loading hole. The crack is a clean fracture. The sticker at the back of the PMMA plate is the reason why the cracked part is still attached to the rest of the joint.

5.0 Discussion

In the discussion section, firstly, we will compare the FEA simulation results with the experimental results and talk about the discrepancies behind it and why could have caused them. Then we will go into details as how we could improve our design.

5.1 Results comparison

Table 3: *Results comparison between experimental and FEA simulation*

	Weight (g)	Axial loading force (N)	Specific strength (N/g)
FEA simulation	118	1200	10.17
Experimental	124	1942	15.66

The weight, loading force and specific strength for both FEA simulation and experimental are listed in Table 2. The highest axial loading force for FEA simulation was 1200N, which is about 61% the experimental testing result and the weight of the actual link is 6 grams heavier than the simulation model. As seen in Figure 4, the side edge of the slot had yielded and had the highest stress of 71 MPa. However, in the actual link testing, there was no yielding at that area, the fracture happens at the loading area of the PMMA plate instead.

Discrepancies are the results of multiple assumptions and lack of material property information. Static structure was used to model for this lab, however, this mode treats the entire joint as one part by assuming perfect bonding between each part which eliminates possible shear stress between the epoxy adhesive and plates. In addition, the epoxy adhesive we used provided very little information regarding its yield stress and density. We were only given the shear stress and cure time and had to estimate its values with the information already provided by ANSYS's database. Most importantly, FEA was not set to model failure due to fracture, which was how the joint failed in reality. As a result, only yielding was modeled and not crack growth as would have been required due to PMMA being a brittle material.

5.2 Improvement

Initially, we tried to maximize the adhesive bonding area so that the joint will get slightly warped due to the axial force and this rotational deflection can transform some of the normal stress into shear stress. In return, it will help relieve some stress at the loading area and increase specific strength for our link [3]. As well, we wanted to ensure that the plate would stick to each other. However, both yield strength and ultimate strength for PMMA are 70 MPa and is a very brittle material. Thus, the rotational deflection never happened which is why the joint failed very fast. Also, we thought that a bigger part can endure more normal stress than small part so we only filleted the corners of both plates.

Figure 7: *Redesign of the link. Blue lines are where the plates should be cut, the blue area the adhesive region, and the grey lines is the PMMA region to be removed.*

In terms of improving the design, we should reduce the length of the PMMA plates and tapper the adhesive end to reduce the contact area, as shown in Fig. 7 to the left. In this case, shorter joint results in a less sharp deflection angle so there will be less stress at the loading area. Also, smaller contact area will increase the stress concentration around the bounding area. However, it will help reduce the stress concentration around the loading area. So both plates can be properly stretched without cracking so soon.

Also, epoxy adhesive is a very strong bonding agent which resulted in very little movements between two plate. We can use adhesive tape so that the bonding area will be more flexible which can transform more normal stress into shear stress.

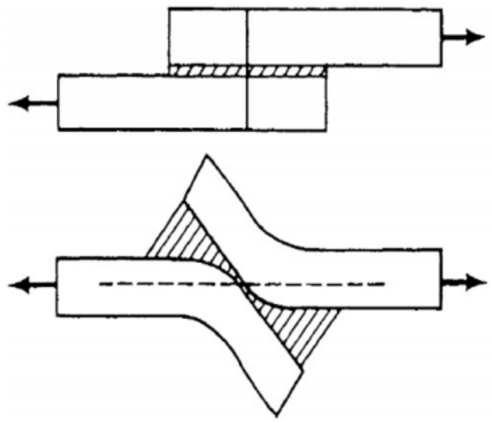


Fig. 1. Illustration of joint deformation and the creation of peel stresses at the overlap edges due to the absence of equilibrating shear stress on the free surfaces of the adhesive layer at the overlap ends, as well as due to the eccentricity induced bending of a single lap joint.

Figure 7: *Joint deflection under axial loading for ductile material* [3]

6.0 Conclusion

Brittle material behaves very differently from ductile material under axial loading. The rotational deflection we expected to see from metals will never happen to plastics like PMMA. The ductile part like aluminum can endure much higher normal stresses. The best way to increase specific strength is to reduce length and bonding area of the brittle material. The deflection is more likely to happen with a small loading area. Some of the normal stress can be transformed into shear stress for PMMA plate. Shorter part has less sharp deflection angle which prevents the part from cracking so soon. We were asked to keep the entire joint for at least 7 inches long so that it is better to keep the aluminum longer since it is more ductile.
Static structure model can be used to simulation for yield deflection. However, it is a very inaccurate reflection of fracture since it assumes that all parts are bonded perfectly. Again, static structure model treats the whole joint as one part so that it does not take rotational deflection into consideration, only yield deflection. Even with the help of FEA simulation, we still need the experimental data to confirm our theories and findings.

7.0 Reference

[1] University of Toronto. Solid Mechanics II Lab 6 manual. [Online]. Available at: https://portal.utoronto.ca/bbcswebdav/pid-5663727-dt-content-rid-35967626_2/courses/Winter-2017-MIE320H1-S-LEC0101/MIE320S%20Labs%202017.pdf

[2] J.-B. Weld, “KwikWeld Twin Tube,” J-B Weld. [Online]. Available at: https://www.jbweld.com/products/kwikweld-twin-tube.

[3] Engerer, J. D., and E. Sancaktar. "The Effects of Partial Bonding in Load Carrying Capacity of Single Lap Joints." International Journal of Adhesion and Adhesives 31.5 (2011): 373-9. Web. 7 Apr. 2017