CHAPTER 8

Results and Discussions

8.1 Variation of torque along bond length

Fig. 8.1(a) : Torque Variation along bond length for different G1J1/G2J2 ratio’s
Fig. 8.1(b) : Rate of change of torque along bond length for different G1J1/G2J2 ratio’s

From the graph of % Torque Vs Bond length obtained in fig.(8.1(a)) and Rate of change of torque Vs bond length obtained in (8.1(b)) the following conclusions can be drawn:

- Torque transfers gradually from shaft1 to shaft2.
- In case of torsional stiffness of both shaft is same (i.e. \( G_1 J_1 = G_2 J_2 \)) the variation of torque along bond length in shafts is uniform.
- In case of torsional stiffness of both shaft is different (i.e. \( G_1 J_1 \neq G_2 J_2 \)) the variation of torque along bond length in shafts not uniform and the torque variation becomes steeper near the edges of bond length which is clearly seen from the graph of \( dT_1/dz \).
8.2 Variation of shear stress in adhesive layer along bond length

![Graph showing variation of shear stress in adhesive layer along bond length for different G1J1/G2J2 ratio's](image)

Fig. 8.2: Variation of shear stress in adhesive layer along bond length for different G1J1/G2J2 ratio’s

From the graph of Shear stress in adhesive layer Vs Bond length obtained in fig. (8.2) the following conclusions can be drawn:

- The maximum interface shear stress occurs at the ends of the joint.
- Depending upon the ratio of $G_1J_1/G_2J_2$ in the bond area the maximum interface shear stress can occur at right end, left end or simultaneously at both ends.
- The maximum interface shear stress occurs at the end of stiffer shaft.
- The maximum value of shear stress in the case of $G_1J_1= G_2J_2$ is found to be minimum as compared to maximum values of shear stresses in the cases $G_1J_1 > G_2J_2$ and $G_1J_1 < G_2J_2$. 
8.3 Effect of variation of Bond Length on shear stress in adhesive layer along bond length

From the graphs obtained in fig. (8.3(a)) and (8.3(b)) the following conclusions can be drawn:

- As the bond length increases the maximum shear stress induced in adhesive layer decreases and after certain bond length it remains constant.
- And hence increasing the bond length beyond this limit will not be beneficial in reducing the stresses in the joint.
- The equation derived for $c_{\text{optimum}}$ can be used to determine optimum bond length for design of adhesively bonded shafts for maximum torque transmission capability.
- Also it should be noted that the joint strength cannot increase indefinitely with adhesive bond length because as the adhesive bond length increases the number of defects become significant and the joint strength decreases and there is limitation of shear strength of adherend materials.
8.4 Effect of variation of Bond thickness on shear stress in adhesive layer along bond length

![Graphs showing effect of Bond thickness on shear stress](image)

Fig. 8.4(a) : Effect of variation of Bond thickness on shear stress in adhesive layer along bond length

Fig. 8.4 (b) : Effect of variation of Bond thickness on maximum shear stress in adhesive layer

From the graphs obtained in fig. (8.4(a)) and (8.4(b)) the following conclusions can be drawn:

- As the bond thickness increases the maximum shear stress induced in adhesive layer decreases and after certain bond length it remains almost constant.
- And hence increasing the bond thickness beyond this limit will not be beneficial in reducing the stresses in the joint.
- The equation derived for $t_{opt}$ can be used to determine optimum bond length for design of adhesively bonded shafts for maximum torque transmission capability.
- The joint strength cannot increase indefinitely with adhesive thickness because as the adhesive thickness increases the number of defects become significant and the joint strength decreases.
Also it should be noted that the bonding clearance recommended by different manufacturers for their different anaerobic adhesive products are in the range from 0.05 to 0.5 mm.

8.5 Effect of variation of $G_{1}J_{1}/G_{2}J_{2}$ ratio on Stress Concentration Factor (SCF)

From Fig. (8.5) it can be observed that Stress concentration factor (SCF) is minimum when $G_{2}J_{2} = G_{1}J_{1}$.

Shear stress in adhesive layer depends upon the rate of change of torque in shaft 1 and shaft 2 along bond length and torque variation is steeper at the end of stiffer shaft when $G_{1}J_{1} \neq G_{2}J_{2}$ as compared to rate of change of torque in case of $G_{2}J_{2} = G_{1}J_{1}$. And hence the value of SCF is higher when $G_{1}J_{1} \neq G_{2}J_{2}$.

![Effect of variation of $G_{1}J_{1}/G_{2}J_{2}$ ratio on SCF](image)
8.6 Cylindrical Joint with Uniform Torsional Strength

- Varying torsional stiffness profile for shaft 1 and shaft 2 as determined by the equations (6.23), (6.24) gives joint of uniform torsional strength (i.e. the shear stress is constant along the bond length).

- For cylindrical joint with uniform torsional strength the Stress Concentration Factor (SCF) is unity.

- For cylindrical joint with uniform torsional strength the torque transmission capability increases as compared to the constant diameter profile.

- The torque transmission capability increases by the ratio of maximum value of shear stress with constant diameter profile to the mean or average value of shear stress. This is because of the torque transmission capability is limited by the maximum value of shear stress in the adhesive layer.

- When shaft 2 is solid (i.e. $R_{2i}=0$ or $\eta=0$) the outer radius of shaft 1 is minimum but the joint weight is maximum. For minimum weight hollow shafts are preferred and hence when shaft 2 is made hollow (i.e. $\eta \to 1$) the outer radius of shaft 1 increases but joint weight decreases. The joint weight is proportional to

$$\text{Joint Weight} \propto \sqrt{\frac{(G_1 + G_2 - G_2\eta^4)}{G_1} - \eta^2}$$
8.7 Torque transmission Capability

From fig. (8.6) it can be observed that maximum torsion load capacity is obtained when torsional stiffness (GJ_l) for both the shafts is same in the bond area regardless of other parameters.

If the shafts are of identical materials, the shaft dimensions should be such adjusted that J_1 = J_2 in the bond area for maximum torsion load capacity.

\[
\left( R_{2o}^4 - R_{2l}^4 \right) = \left( R_{1o}^4 - R_{1l}^4 \right)
\]

If R_{2l} = 0 and R_{2o} = R_{1l} then \( R_{1o} = \sqrt[4]{2} \times R_{2o} \)

For maximum torsion load capacity Optimum Bond Length should be used and which can be determined from the equation derived in analytical section.

For maximum torsion load capacity Optimum Bond Thickness should be used and which can be determined from the equation derived in analytical section.

As the adhesive used are generally costlier so use of Optimum Bond Length, Optimum Bond Thickness results in saving of cost.
8.8 Discussions based on experimental results

Figure 8.7(a) Comparison of analytical and experimental values of failure torque for Case-1 to Case-8
There is a reasonable agreement between the predicted failure torque by Analytical method and the experimental results. (% relative error is less than 16 %). The difference in the values may be because of mainly the assumption of elastic behaviour of adhesive layer while determination of analytical model. Experimental values of failure torque obtained are less than analytical values this may be because of likely defects incorporated during specimen preparation. As bond length increases failure torque also increases but after certain bond length it remains almost constant. Also it should be noted that the joint strength cannot increase indefinitely with adhesive bond length because as the adhesive bond length increases the number of defects become significant and the joint strength decreases and strength of adherend also limits the maximum value of torque that can be transmitted. As bond clearance increases failure torque also increases but after certain bond clearance it remains almost constant. Difference between analytical and experimental values of failure torque increase with increase in bond length this may be because as the adhesive bond length increases the number of defects become significant and the joint strength decreases. Difference between analytical and experimental values of failure torque is almost constant with increase in bond clearance this may be because rate of increase of defects with increase in bond clearance is less as compared to rate of increase of defects with increase in bond length.
Although the derivations are based on isotropic materials a better perspective of the response of actual joint could be obtained by first understanding how different parameters affect the torsion load capacity of isotropic shaft joint.

8.9 Discussions based on Finite Element Analysis results

In Finite Element Analysis Von Mises theory is used which assumes failure on the basis of distortion energy and which happens when the adhesive is a toughened adhesive and the failure is ductile. With Loctite 620 and Loctite 638 the failure is near to brittle and hence the failure torque values obtained on the basis of FEA are on the lower side.

From figures (7.7 (a)(b)(c)) and (7.9 (a)(b)(c)) it can be seen that the maximum interface shear stress occurs at the ends of the joint and it occurs at the end of stiffer shaft which is in line with the analytical results obtained.

As the bond length increases the torque transmission capacity increases this is because the maximum stress in adhesive layer decreases which can be seen from figures (7.7 (a)(b)(c)). Increase in torque transmission capacity with increase in bond clearance is not significant as seen from figure 8.8(b).

There is a significant influence of Surface treatment, Curing method, period, temperature on the consistency of the experimental data. Therefore, finite element simulation can only effectively mimic the behaviour of the 'ideal’ joints that are prepared and assembled with utmost care.