CHAPTER 3

Literature Survey

3.1 Literature Review

D Chen and S Cheng \[^{[5]}\] in their paper titled "Torsional stresses in tubular lap joint" \(^1\) analysed the stress distribution in adhesive bonded tubular lap joints subjected to torsion. The two adherends may be having different thicknesses and consist of different materials. The analysis was based on the elasticity theory where circumferential stresses in the two tubular adherends are taken into consideration in conjunction with the variational principle of complimentary energy and a closed form solution was obtained. In view of symmetric property in geometry and loading it was assumed that there are only two stress components existing in the joint in the \(\theta\)-axis (i.e. \(\tau_{r\theta}, \tau_{\theta z}\)) and \(\tau_{\theta z}\) in adherends considered varying linearly with radius and in adhesive layer taken as vanishing. Special attention was given to the high stress intensities in the end zones of the joint and stress concentration factor was deduced as stress concentration in the adhesive layer of a tubular lap joint under torsion is in fact more serious than it actually is.

Shrink fitted joints have been widely used in mechanical structures such as railway vehicles, automobiles and so on. Bonded shrink fitted joints, in which a shaft and a ring gear are shrink fitted after being applied an anaerobic adhesive to the shank of the shaft are used in automobile differential gears in order to improve joint strength and reduce assembly weight. Thus, it is important for mechanical design engineers to understand the interface stress distribution and the joint strength of the bonded shrink fitted joint. Hiroshi Kawamura, Toshiyuki Sawa, Masahiro
Yoneno, Takeshi Nakamura\textsuperscript{[17]} in their paper titled \textbf{“Effect of fitted position on stress distribution and strength of a bonded shrink fitted joint subjected to torsion”} have analysed the effect of fitted position on the characteristics of the bonded shrink fitted joints. The stress distributions at the interface of the joints were analyzed using axisymmetric theory of elasticity. In the numerical calculations, the effects of the fitted position, Young’s modulus of the adhesive and the ring, the outer diameter of the ring, and the engagement length on the interface stress distributions were examined. Using the interface stress distributions, joint strength was predicted. For verification of the strength estimation, the strengths of the bonded shrink fitted joints subjected to torsional loads were measured experimentally by applying torsional load $T$ gradually to the joint by using hydraulic ram and torsional load was measured by using torque transducer. It was found that the effect of shrink fitted position is negligibly small.

From the interface stress distributions obtained from the analysis, it was concluded that the joint strength increases when Young’s modulus ratio, outer diameter ratio of ring and shaft increases.

The numerical results of the joint strength showed more conservative values than the experimental results.

Kozo Ikegami\textsuperscript{[14]} in his paper titled, \textbf{“Tensile and Torsional Strength of Metal Shaft Joint Connected Adhesively with Cylindrical Coupling”} investigated the strength of adhesive shaft joint under combined axial tensile and torsional load analytically and experimentally to study effect of overlap length and cross sectional ratio. The joint considered was consisting of two steel shafts and a coupling bonded with adhesive. The stress strain distributions were computed by the elastic Finite Element Method with the assumption of symmetric three dimensional conditions. For strength evaluation Von-Mises conditions were applied to the outer and inner adherends and to the adhesive layer. The analysis resulted in the following conclusions –

For combined axial and torsional loads the adhesive interface is the critical position for the initial failure.
The joint strength for torsional load is saturated by certain overlap length which depends upon the cross-sectional area of shaft and coupling.

The joint strength for tensile load is also saturated by certain overlap length but the overlapped length at the saturated joint strength is longer for tensile load than for torsional load.

H. Nayeb Hashemi [27] in their paper titled “Multiaxial fatigue life evaluation of tubular adhesively bonded joints” obtained the shear stress distribution in adhesively bonded tubular joint under axial and torsional loadings using shear lag model. The shear stress under Torsional loading was obtained by assuming the adhesive to shear in the circumferential direction only and neglecting its other deformations. The analysis considers variation of shear stress across the adhesive thickness. The nondimensional parameter $\theta$ was defined which combines adherend and adhesive mechanical properties and geometries and it was shown that shear stress in the bonded area not only depends upon $\theta$ value but also depends upon moment of inertias ($J_1, J_2$) of the tubes.

Olcay Ersel Canyurt [4] in their paper titled “Fatigue strength estimation of adhesively bonded tubular joint using genetic algorithm approach” used stochastic search process to investigate effect of surface roughness, bonding clearances, interference fit, temperature, and material of the joining parts. Nonlinear estimation models were developed using GA. Developed models were validated with experimental data. Genetic Algorithm Fatigue Strength Estimation Model (GAFSEM) is developed to estimate the fatigue strength of the adhesively bonded tubular joint using several adherent materials, such as steel, bronze and aluminium materials.

N. Pugno and G Surace [41] in their paper titled “Tubular bonded joint under
torsion: theoretical analysis and optimization for uniform torsional strength

“analysed the problem of torsion in an adhesive bonded tubular joint. The stress field in the adhesive is obtained by assuming that all three of the materials making up the joint (tubes and adhesive) are governed by an isotropic linear elastic law and a stress concentration factor which indicates the extent to which maximum stress departs from the mean was derived. For uniform torsional strength the value of stress concentration factor should have unit value and accordingly modifying the joint design a new kind of tubular joint of tapered profile is proposed.

Zhenyu Ouyang, Guoqiang Li\cite{33} in their paper titled “Interfacial debonding of pipe joints under torsion loads: a model for arbitrary nonlinear cohesive laws” obtained Cohesive Zone Model (CZM) based analytical solutions for the bonded pipe joints under torsion. The concept of the minimum interfacial cohesive shear slip is introduced and used in the fundamental expression of the external torsion load. The results obtained from Cohesive Zone Model were in good agreement with finite element analysis (FEA) results. Also parametric studies of various cohesive laws were conducted.

Philip Portillo, Dr. Jesa Kreiner, Dr. Timothy Lancey\cite{39} in their paper titled “Torsional fatigue behavior of adhesively joined tubes” made effort to investigate experimentally fatigue behaviour of a bonded aluminium tubular joint. In spacecrafts the composite tubular struts are employed throughout the structure and these struts undergo torsional adhesive fatigue. It is critical for engineers to know what kind of behavior adhesives will exhibit under fatigue loading. For experimental investigation the test rig used was consisting of air cylinder to load the test specimen for high cycle fatigue and load cell to measure force exerted by the air cylinder. Two strain gauges were bonded to the inner shaft where bond was located and to control the bond gap wire was used around bond area. An analytical analysis assuming the system in plane strain was conducted to make a handshake with the experimental strain results.
Luis Ernesto Mendoza-Navarro, Alberto Diaz-Diaz, Ruben Castaneda-Balderas, Stephane Hunkeler, Romuald Noret \cite{25} in their paper titled “Interfacial failure in adhesive joints: Experiments and predictions” developed a method to predict interfacial failure in adhesive joints by application of a twofold criterion involving stress and energy conditions simultaneously to predict adhesive failure onset in different geometries of adhesive joints subjected to diverse loadings. Butt joints and double lap joints with adherends made of elastic materials were tested in tension and torsion. The failure predictions were based on finite element calculations and a twofold criterion involving stress and energy conditions.

Naveen Rastogi \cite{43} in his paper titled “Design of Composite Drive shafts for Automotive Applications” presented comprehensive approach to design drive shafts for automotive applications. Based on the closed-form analytical solutions, preliminary design tools were developed to aid quick analysis and design of composite driveshaft for automotive applications. Detailed finite element analysis was performed to validate the preliminary design tools.

Won Tae Kim and Dai Gil Lee \cite{19} in their paper titled ”Torque transmission capabilities of adhesively bonded tubular lap joints for composite drive shafts” analysed the stresses and torque transmission capabilities of adhesively bonded circular, Hexagonal & Elliptical tubular lap joint by the three dimensional finite element method and compared with experimental results. In calculating torque transmission capabilities the linear laminate properties of the composite material of adherends and the nonlinear shear properties of adhesive were used. Since the shear strain was dominant in the adhesive of tubular lap joint, in their work the adhesive failure was predicted by maximum shear strain theory. The experiments revealed that the hexagonal joint had the best torque transmission capability among the single lap joints, and the double lap joint had better torque transmission capability than the single lap joint. The torque transmission capability of the hexagonal single lap joint was found to be comparable to that of the circular double lap joint.
O. Nemes, F. Lachaud, A. Mojtabic \cite{O.Nemes1} in their paper titled “Contribution to the study of cylindrical adhesive joining” developed a simple analytical model for predicting the distribution and intensity of stresses in the adhesively bonded cylindrical joint subjected to axial tensile load. The model is based on a variational method applied to the potential energy of deformation in the cylindrical assembly. The model can be used to predict the stress field in the assembly or the influence of geometrical parameters like adhesive thickness, adhesive lap length and material parameters like Young’s Modulus of adhesive, relative rigidity on the stress field.

M. A. Martinez, F Velasco, J. Abenojar, M. Pantoja, J.C. Del Real \cite{M.A.Martinez} in their paper titled “Analytical solution to calculate the stress distribution in pin and collar samples bonded with anaerobic adhesives (following ISO 10123 standard)” analysed cylindrical bonded joint with anaerobic adhesives of a pin and collar type and developed a simple analytical model for elastic adhesives (anaerobic acrylic based adhesives) predicting the distribution and intensity of stresses in the joint subjected to axial tensile load. The model is based on a variational method applied to the potential energy of deformation in the cylindrical assembly. The model can be used to predict the stress field in the assembly or the influence of geometrical parameters like adhesive thickness, adhesive lap length and material parameters like Young’s Modulus of adhesive, relative rigidity on the stress field. By knowing the failure load and the adhesive mechanical properties, the analytical model developed provides the value of maximum shear stress reached and distribution of stresses in adhesive joint. Also the model can evaluate the influence of different material and geometric parameters in pin and collar stress field avoiding important number of experiments and complicated finite element models, with consequent reduction in cost and time.

N. Pugno and A. Carpinteri \cite{N.Pugno} in their paper titled ”Tubular Adhesive Joints Under Axial Load” have considered the shear and normal stresses and strains in the adhesive layer to propose an optimization to uniform axial strength (UAS) and to reduce the stress peaks in the bond. The stress analysis confirms that the
maximum shear stresses are attained at the ends of the adhesive layer and that the peak of maximum shear stress is reached at the end of the stiffer tube and does not tend to zero as the adhesive length approaches infinity. A fracture energy criterion to predict brittle crack propagation for conventional and optimized joint is presented.

Tezcan Sekercioglu [50] in his paper titled “Shear strength estimation of adhesively bonded cylindrical components under static loading using the genetic algorithm approach” investigated effect of bonding clearance, surface roughness, adherend material and temperature on bonding strength using genetic algorithm approach. The GASSEM (Genetic Algorithm Shear Strength Estimation Model) model developed was used to estimate shear strength of an adhesively bonded cylindrical components under static loading. The GASSEM results were comparable with the experimental data obtained with adherend materials such as steel, Aluminium, bronze material and anaerobic adhesive Loctite 638. The GASSEM model indicated that the design parameters bonding clearance, surface roughness, temperature and adherend have a direct independent influence on bonding. The reason given for minimum value of surface roughness $Ra=0.45 \mu m.$ obtained from experimentation, may be from the fact that mechanical interlocking disappears due to inadequate penetration of adhesive on smooth surfaces and when the surface roughness increases more than necessary, the strength values decreases again.

Tezcan Sekercioglu, Alper Gulsoz, Hikmat Rende [51] in their paper titled “The effects of bonding clearance and interference fit on the strength of adhesively bonded cylindrical components” investigated experimentally five different diametrical clearances and two different interference fits with adherends of structural steel and anaerobic adhesive Loctite 638 and established using regression analysis a numerical relationship between bonding clearance and bonding strength.
Tezcan Sekercioglu, Alper Gulsoz, Hikmat Rende [52] in their paper titled “The effect of surface roughness on the strength of adhesively bonded cylindrical components” investigated experimentally effect of different surface roughness values on bonding strength for both static and dynamic loading conditions. For experimentation adherends of structural steel and anaerobic adhesive Loctite 638 were used. The following conclusions were drawn from their investigations –

- The low shear strength obtained for both of the very smooth surface (Ra < 1 µm) and very rough surface (Ra > 2.5 µm).
- The reason of minimum value for surface roughness Ra = 0.45 µm may be from the fact that the mechanical interlocking disappear due to inadequate penetration of adhesive on smooth surfaces. When the surface roughness increases more than necessary, the strength values decreases again may be due to the fact that adhesive cannot spread on the substrate surface.
- For the high bonding strength the optimum surface roughness were obtained in the range from Ra =1 µm to 2.5 µm.

Reda Hadj-Ahmed, Gilles Foret, Alain Ehrlacher [11] in their paper titled “Probabilistic analysis of failure in adhesive bonded joints “ proposed a strength probability law to estimate shear strength of an adhesive joint which accounts the scale effects experimentally established for the adhesive joints shear strength and leads to studying the influence of both adhesive thickness and overlap length on joint strength. The strength probability follows Weibull’s law on tensile force applied on the adhesive joint. For experimentation the adhesive joint considered was with steel adherends and epoxy adhesive.
3.2 Closer Review

The increasing use of adhesive technology requires simple but reliable methods to predict the strength of adhesively bonded cylindrical joint.

Adhesive joints have been previously designed empirically. Now a day's data is available to design adhesive joints in an optimum manner. Both adhesion and cohesion play their part in maximizing the strength of the bond. Better adhesive strength can be obtained by proper surface preparation whereby the adherend surface is cleaned and/or chemically treated to promote better adhesion. Furthermore, the adhesive strength is in general sufficiently high. The cohesive properties of an adhesive are determined by the manufacturer and are available for design. Now by proper designing of the joint and curing under optimum conditions the user is to try and attain those. For optimum design of adhesive joint, complete knowledge of stress distribution and the parameters affecting stress distribution in adhesive joint is necessary.

A significant amount of research has been dedicated to the study of lap, butt adhesive joints of rectangular plate’s subjected to tensile, bending, cleavage and shear loads. However a comparatively less investigations have been carried out on adhesively bonded cylindrical joints subjected to torsion loading. An exact solution for the stress field of these joints is difficult to obtain due to geometric complexities and material nonlinearity of the adhesive. This has resulted in development of wide range of mathematical and numerical methods to analyze or predict the behaviour of the joint, but nowadays also this is still an open problem.

From the literature on strength determination of adhesively bonded cylindrical joint different approaches the researchers have adopted like statistical, probabilistic, genetic algorithm, only theoretical close form solution, only experimental and/or finite element method , cohesive zone model etc. Also they have assumed different failure criteria’s for bonded joint in their analysis such as stress based criteria, strain based criteria and energy based criteria. Number of times
the data required for computation is not available easily. Hence there is need to develop simple analytical model for adhesively bonded cylindrical joints subjected to torsion loading which will be capable of designing the joint with optimum values of different geometric and material parameters for maximum torque transmission capability. Also the model developed needs to be validated with experimental results and Finite Element Analysis results.

- The project aims at the development of analytical model for adhesively bonded cylindrical joint subjected to torsion loading for parametric study and optimization of joint.

- The analytical model developed will be used for analysis of the effect of geometrical parameters namely bond length, bond clearance, polar moment of inertia and material parameters like modulus of rigidity of adherends and adhesive, on the Torque transmission capability of bonded cylindrical joint.

- Derivation of equations for optimum values of different geometrical parameters for maximum Torque transmission capability.

- For maximum torque transmission capability development of bonded cylindrical joint with uniform torsional strength.

- Experimental validation of the results obtained from theoretical analysis for different combinations of materials of shaft and adhesives.