1
Introduction

1.1 Introduction

In response to significant corrosion problems with metallic pipes due to the chemical processes in pulp and paper industries, composite piping systems were developed using fibre glass reinforced thermoset plastics (FRP). Subsequently, with advancement of material science and manufacturing processes, the mechanical properties of composite pipes have been dramatically improved by way of using carbon/graphite-epoxy and boron-epoxy composites.

As the usage of composites is increasing in piping systems, study of joining methods for composites has become an important research area (Nanda Kishore et al. (2009)). Although joints are not desirable still are inevitable in the piping systems due to limitations of component size imposed by manufacturing processes and requirement of inspection, assembly, repair and transportation. Adhesive bonding is becoming a primary connection method in composite pipe joints (Fu and Mallick (2000)) because it can effectively lower the stress concentrations through smoother load transfer between the connecting members. In addition to this, adhesive bonds are generally corrosion free as compared to mechanical fasteners. Laminated FRP composite adherend pipes are vulnerable for various interlaminar failures and delaminations, etc., besides the conventional cohesion and adhesion failures. Initiation of such failures and their propagations can be effectively characterized by evaluation of fracture mechanics parameters such as Strain Energy Release Rate (SERR), J-integral and Stress Intensity Factor (SIF). Some industry specific applications require that high thermal stress gradients be reduced through the thickness of the adherend pipe structural components. Although the laminated FRP composite material may have better tailored mechanical properties, the mismatch of their material properties across an interface introduces large interlaminar stresses that could cause severe delamination. Therefore, in recent years, this adverse effect has been overcome by way of using Functionally Graded Materials (FGMs). FGMs are designed as high performance heat resistant materials. Their manufacturing proportions can be suitably tailored through Power Law variations to achieve better crack growth resistant capabilities. This Thesis deals with the finite element (FE) based computations of SERR for adhesion failure and delamination damage analyses of adhesive bonded tubular single lap and socket joints made with laminated FRP composites and FGMs.

1.2 FRP composites: Constituents and characteristics

Composite materials are composed of two or more materials on a macro-scale resulting in a macroscopically homogeneous medium. Fibre reinforced composite materials consist of fibres of high strength and modulus bonded to a matrix with distinct interface between them. In this form, both fibres and matrix retain their physical and chemical identities. Thus, FRP composites exhibit the best qualities compared to its constituents and hence, find tremendous applications in the aircraft (S.W. Tsai (2003)), aerospace and automobile structures. In general, fibres are the principal load carrying members, whereas the matrix keeps them at the desired location and orientation, acts as a load transfer medium between them, and protects them from environmental damages. The basic constituents of composite material systems are the reinforcements, the matrix (usually epoxy or polyester) and the coupling agents (coatings/fillers). Depending on the reinforcement type, they are classified as:

Fibrous	:	Composed of continuous or chopped fibres
Particulate	:	Composed of particles
Laminated	:	Composed of layers or laminae with desired fibre orientation
Flake	:	Composed of flat flakes reinforcements

The FRP composites are used in large scale in the composite piping systems due to the improved properties such as specific strength, specific weight, stiffness, corrosion resistance, wear resistance, fatigue life, temperature dependant behaviour, thermal insulation, thermal conductivity, acoustical insulation, etc. Unlike traditional monolithic materials, FRP composites can have their strengths oriented to meet specific design requirements. Real composite structures consist of multi layered laminae having different ply orientations of continuous fibre. A wide variety of fibres and matrix materials are available for use in the composite piping systems. The principal fibres preferably used in the composite piping systems are various types of Glass, Carbon, Graphite, Aramid as well as Kevlar. Other fibres, such as Boron, Silicon Carbide and Aluminium Oxide are used in limited applications. All these fibres are incorporated into the appropriate matrix phase in continuous or discontinuous (chopped) lengths. The matrix material may be a polymer, a metal or a ceramic. Specific fillers, additives and core materials are also sometimes added to enhance and modify the final product.

In the present Thesis Graphite/Epoxy (Gr/E) laminated FRP composite made pipes have been considered as adherends in the bonded pipe joints. Also, in order to improve the resistance of the joints, the material anisotropies of the composite pipes have been varied through use of Carbon/Epoxy (C/E), Glass/Epoxy (G*l*/E), and Boron/Epoxy (B/E) laminated FRP composites. The classifications of the FRP composites have been shown in Fig. 1.1. Schematics of various other types of composite laminates used for the piping systems are shown in Fig. 1.2.

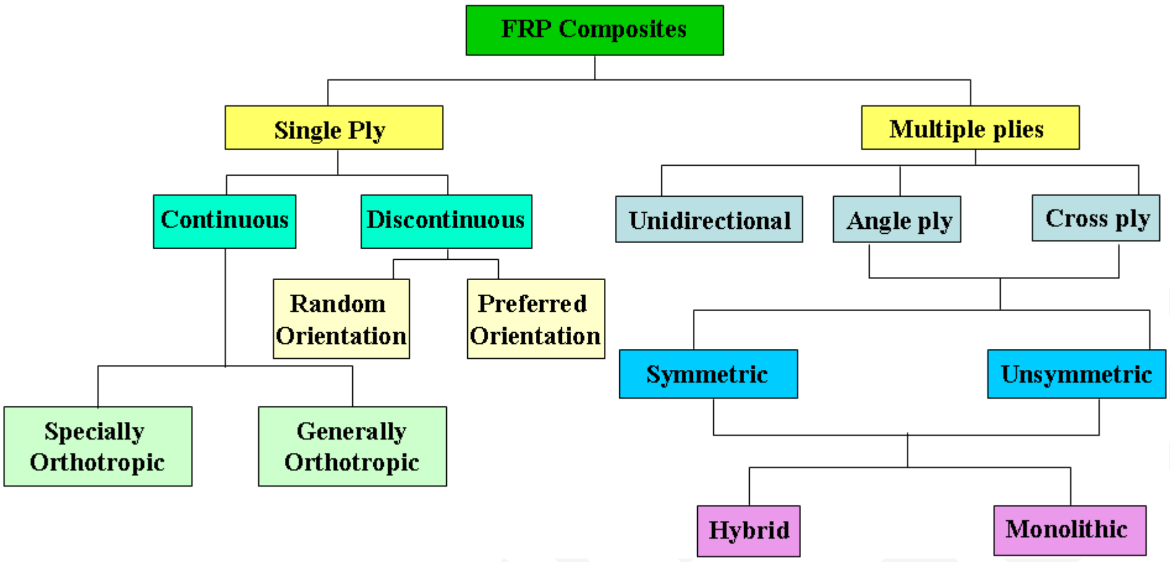

Fig. 1.1: Classification of Fibre Reinforced Plastic (FRP) composites.

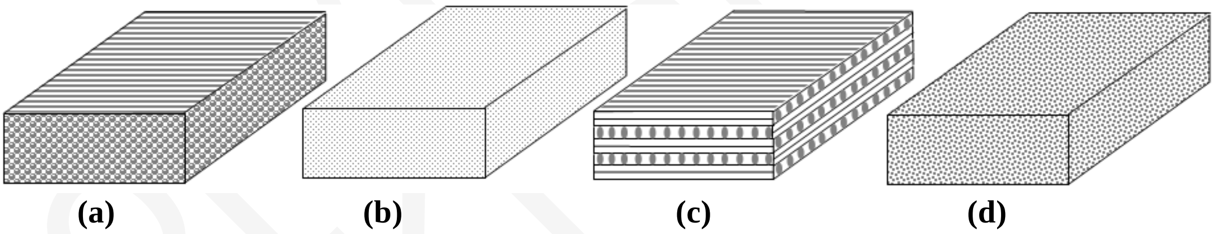

Fig. 1.2: Various types of polymeric composites (a) Fibrous, (b) particulate, (c) laminated, and (d) flake.

The selection of a specific composite material system must be carefully done in order to enhance the structural integrity and the structural efficiency of the composite piping systems. The composite used as adherends in the bonded structures must be resistant to debonding or delamination damages at the fibre/matrix interface and also to fibre breakage and matrix cracking. However, in applications where it is desired to dissipate energy during the failure process (such as crashworthy or impact resistant structures), progressive fibre failure and fibre matrix debonding are positive features because they dissipate energy.

1.3 Functionally Graded Materials (FGMs): Constituents and characteristics

Although the laminated FRP composite made tubular adherends used in the bonded pipe joints have better tailored mechanical properties, the mismatch of their material properties across the interface introduces large interlaminar stresses that could cause severe delamination. The insidious nature of the delamination damages and their detrimental effects on the strength of the joint and the adherends of the bonded tubular joints are discussed in details in subsequent Chapters (Chapters 6 and 7). These adverse effects can be overcome by replacing the laminated FRP composite adherends by Functionally Graded Materials (FGMs).

FGMs are usually composed of two or more materials whose volume fractions are made to change smoothly and continuously along desired directions in a desired manner. These multiphase composites achieve the desired variation in properties by spatial variations in the volume fractions of the constituent phases. This broad definition encompasses a wide variety of materials which have gradations in their mechanical, thermal, chemical, optical or electrical properties. The fundamental idea in generation of the FGMs came from the fibre-volume fraction concept in composites. Since the fibre volume fraction in composites plays a major role in governing its properties, it has generated the key idea that the spatial variation of fibre-volume fraction in the composites can be done for achieving desired material property gradations. The emerging new manufacturing techniques for processing of materials helped in materializing this idea of FGMs into action. In the early days the material processing techniques used for the manufacturing of the FRP composites were also implemented for the processing of the FGMs. However, because of the emergence of new methods and equipments in metallurgical process engineering it has become possible now-a-days to fabricate the FGMs through varying the proportions of constituent phases in a continuous manner.

Though the FGMs belong to the class of so called heterogeneous materials, in general they are anisotropic as well. From the micromechanical point of view, they are just composites with very special properties. The major difference between the FRP composites and FGMs is that, in composites generally bonding is at macro level, whereas in FGMs it is at atomic level. FGMs possess variations in constituent volume fractions that lead to the continuous change in composition, microstructure, porosity, etc. So they can be considered as innovative composites whose composition and micro structure vary in space following a predetermined law. Basically FGMs are made up of a mixture of two materials, i.e., the ceramics and metals. The former are capable of withstanding the high temperature and corrosive environments, while the latter act as structural elements for withstanding mechanical loads. The gradual change in composition and microstructure gives place to a gradient of properties and performances in the FGMs.

1.3.1 Advantages and applications of the FGMs

FGMs eliminate the problems of high stress concentrations due to abrupt changes in material properties at the bimaterial interfaces (Fig. 1.3 (a)) through incorporating a smooth variation of the material properties (Fig. 1.3 (b)). Due to this specific feature of the FGMs, they have been used in the present research in place of the laminated FRP composites as the adherends in the bonded tubular joints in order to make the structures completely devoid of the chances of delamination damages and improve their resistance against adhesion failures (Chapters 8 and 9).

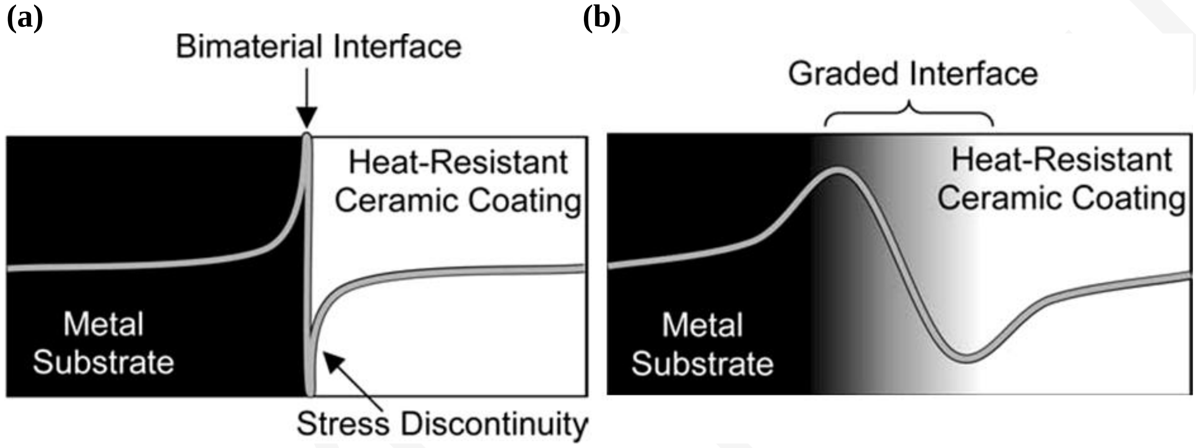

Fig. 1.3: (a) Stress concentration at the bimaterial interfaces, overcome through (b) smooth transition of material properties through the graded interface of the FGM.

FGMs are extensively used in aircraft industry for the manufacturing of wings and fuselage panels and also in the automobile industries for the fabrication of engine accessories to overcome the problems of thermo mechanical crack propagation and interfacial fracture of the joints. FGMs can also be used in the preparation of rocket engine chambers and ablative cooling equipments of space vehicles. They are also used as the shields in the nuclear fission reactors like boiling water reactor and pressurized water reactor. FGMs are also used by the biomedical engineers in the fields of artificial dental and bone related component manufacturing, as they are highly biocompatible and structurally stronger than their counterparts. All the engineering disciplines in recent days are turning their attention towards these new materials, since these materials promise the optimal functional requirement through simultaneous gathering of desired material properties in desired combinations, which cannot be achieved by the other materials. For these purposes the FGMs are now-a-days inevitable in various multi functional applications, e.g., SiC/MbS_2 or ZrO_2 /MbS_2 ceramic FGM can be used in high corrosive, high temperature, high wear resistant conditions. Ceramic FGMs are mainly used in severe thermo mechanical loading conditions. This is because ceramic FGMs can withstand high thermal stresses and they are structurally stronger than their metal counter parts. FGM coatings are very much efficient to withstand the high temperature; high corrosive environments and hence, are extensively used in chemical processing industries. In recent years FGMs are used in the development of highly efficient thermionic and thermoelectric converters (TEC) for direct conversion of thermal energy to electric energy. FGMs are also used in gear and bearing manufacturing industries to develop the components which are able to withstand high temperature and higher wear conditions.

1.3.2 Manufacturing aspects of the FGMs

The manufacturing process of a FGM has got two important aspects: (i) building the spatially inhomogeneous structure (Gradation) and (ii) transformation of this structure into a bulk material (Consolidation). Gradation processes can be classified into constitutive, homogenizing and segregating processes. Constitutive processes are based on a stepwise build-up of the graded structure from precursor materials or powders. Advances in automation technology during the last decade have rendered constitutive gradation processes technologically and economically viable. In homogenizing processes a sharp interface between two materials is converted into a gradient by material transport. Segregating processes start with a macroscopically homogeneous material which is converted into a graded material by material transport caused by an external field (e.g., a gravitational or electric field). Homogenizing and segregating processes produce continuous gradients, but have limitations concerning the types of gradients which can be produced.

Usually drying and sintering or solidification follows the gradation step. These consolidation processes need to be adapted to FGMs. Processing conditions for FGMs should be chosen in such a way that the gradient is not destroyed or altered in an uncontrolled fashion. Attention also has to be paid to uneven shrinkage of FGMs during free sintering. Since the sintering behaviour is influenced by porosity, particle size, shape and composition of the powder mixture, these problems must be handled for each materials combination and type of gradient individually referring to the existing knowledge about the sintering mechanisms. It has been demonstrated that the introduction of a controlled grain size gradient in addition to the composition gradient can balance different sintering rates.

Although many of the methods like hot pressing or hot isostatic pressing, liquid phase sintering, laser assisted sintering, spark plasma sintering for functionally graded materials were already developed in the early 1990s, there were still limitations concerning material combinations, specimen geometry and cost. Besides the well established powder metallurgical techniques other production processes suitable for metals and polymers with a low melting point were investigated.

Particular emphasis was also placed on modelling of production processes. Process simulations may allow the prediction of suitable processing parameters for FGMs in the future and reduce the considerable amount of experimental effort which is still necessary to produce a graded material free of macro defects.

1.3.3 Material property gradation schemes for the FGMs

Assuming negligible influence of the Poisson's ratio on the stress distributions, Delale and Erdogan (1983) and Konda and Erdogan (1994) have suggested an exponential mathematical profile for the spatial variation of Elastic Modulus to make the analysis of the FGM structures tractable. The profile is given by:

$$E(x) = E_1 \times e^{\lambda x} \tag{1.1}$$

where, $E(x)$ is the variation of the Young's modulus of elasticity along a specific (x) direction, λ is the material nonhomogenity parameter and expressed as: $\lambda = \frac{L}{W}\ln\frac{E_1}{E_2}$, the quantities E_1 and E_2 are the Young's moduli for the two different material phases (usually ceramic and metal) considered in the functionally graded zone of the structure. 'L' (length) and 'W' (width) are the geometrical parameters of the FGM structure.

In order to have a radial (r) gradation of the material properties (E, υ) form the metallic (Ni) to ceramic (Al_2O_3) phases in the functionally graded tubes used in the bonded single lap joints subjected to a thermal field Apalak et al. (2007) have utilized the modified rule of mixtures suggested by Tamura et al. (1976) for the Modulus of Elasticity given by:

$$E(r) = [(\frac{q+E_c}{q+E_m})V_m(r)E_m + (1-V_m(r))E_c]\times[(\frac{q+E_c}{q+E_m}) + (1-V_m(r))]^{-1} \tag{1.2}$$

where, E (r) is the Young's modulus of elasticity which is a function of the radial distance through the thickness of the functionally graded tubular adherends, 'q' is the stress~strain transfer ratio given by: $q = \frac{\sigma_c - \sigma_m}{\varepsilon_c - \varepsilon_m}$ ($0<q<+\infty$), where, σ_c, σ_m and ε_c, ε_m are the stresses and strains corresponding to the purely ceramic and purely metallic phases. The choice of value of 'q' affects the averaged modulus of elasticity based on the modified rule of mixture. For a well-dispersed metal-Al_2O_3 composite, a value of 'q' of 500 GPa is recommended by Cho and Ha (2001). $V_m(r)$ is the volume fraction of the metal phase at any radial position 'r' through the thickness (t) of the tube which varies as per a Power law variation given by:

$$V_m(r) = (\frac{t-r}{t})^n \tag{1.3}$$

where, 'n' is the compositional gradient exponent. The overall Poission's ratio in the functionally graded tubes has also been varied as per the mathematical expression:

$$\bar{\nu} = \frac{3\bar{k} - 2\bar{\mu}}{2(3\bar{k} + \bar{\mu})} \tag{1.4}$$

where, the overall bulk modulus $\bar{k}$ is given by, $\bar{k} = k_m + \frac{aV_c k_m (k_c - k_m)}{V_m k_E + aV_c k_m}$ (1.5)

and the shear modulus $\bar{\mu}$ is given by, $\bar{\mu} = \mu_m + \frac{bV_c \mu_m (\mu_c - \mu_m)}{V_m \mu_c + bV_c \mu_m}$ (1.6)

where, a and b are

$$a = \frac{k_c\left(3k_m + 4\mu_m\right)}{k_c(3k_c + 4\mu_c)},\ b = \frac{(1+e)\mu_c}{\mu_m + e\mu_c} \text{ and } e = \frac{9k_m + 8\mu_m}{6k_m + 12\mu_m}, \text{ respectively.}$$

FGMs with ceramic (Al_2O_3) and Metal (Ni) phases as considered by Apalak et al. (2007) have been considered in the present Thesis. The gradation of the material properties have been considered to be along the axial direction of the bonded tubular joints in order to enhance the resistance of the joints against the adhesion failures propagating inside the joints. The gradation of material properties of the tubular adherends in the present Thesis have been done as per the fundamental Power law variations:

$$E(z) = E_m + (E_c - E_m) \times (\frac{z}{2c})^n \tag{1.7}$$

$$\upsilon(z) = \upsilon_m + (\upsilon_c - \upsilon_m) \times (\frac{z}{2c})^n \tag{1.8}$$

where, E_m, E_c and υ_m, υ_c are the Young's moduli and Poisson's ratios of the metal and ceramic phases, '2c' is the overlap or coupling length of the pipe joints. The material property gradation schemes for the different adherends of the bonded tubular joints considered in the present Thesis have been discussed in details in the subsequent Chapters (Chapters 8 and 9).

1.4 Joining of laminated FRP composites

Adhesive bonding represents one of the most important enabling technologies for developing innovative design concepts and structural configurations as well as exploiting the new materials. The evolution of the adhesive bonding method and its current knowledge were made possible by the explosive growth in the adhesive applications in a great variety of industries over the past few decades. While it is easy for everyone to identify examples of adhesive bonding in the world around us, analysis and design of structural bonded joints represent one of the challenging jobs in terms of analysis, design and structural integrity assessment. Compared to other mechanically fastened joints, adhesive bonded joints can offer substantially improved performance and economic advantages. Adhesive bonding is the most attractive connection method in composite pipe joints because it can effectively lower the stress concentration effects as compared to mechanical fasteners (Fig. 1.4) through smoother load transfer between the connecting members. In addition, adhesive bonds are generally corrosion free as compared to mechanical fasteners.

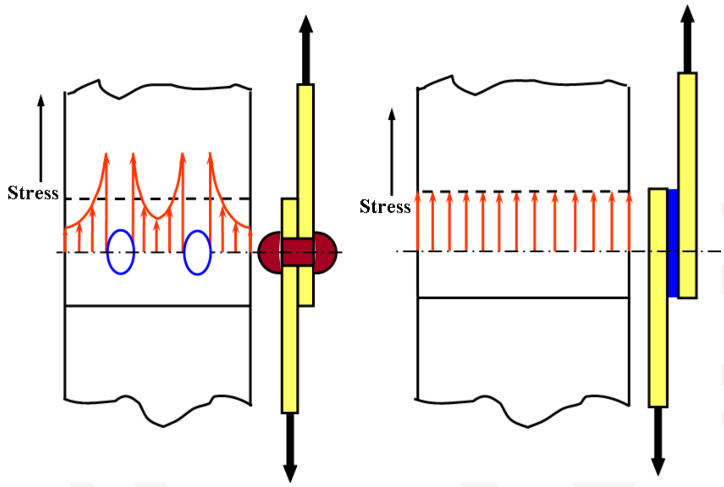

Fig. 1.4: Comparison of stress distribution in (a) mechanically fastened joint and (b) adhesive bonded joint.

Analysis and design of adhesive bonded joints is a multi disciplinary task, and it can involve concepts from the surface and polymer chemistry, stress analysis, manufacturing technology and fracture mechanics. The following important aspects need to be considered for designing the adhesive bonded joints when used in structural applications.

- Selection of suitable adhesive and its characteristics
- Appropriate surface preparation of adherends
- Development of design based on stress and failure analyses

This Thesis is intended to focus on various aspects of analysis and design of adhesive bonded tubular joints made with laminated FRP composites and FGMs including stress analysis, strength prediction and failure analysis.

1.4.1 Bonded joint constituents

Any rational design of structural bonded joints must be based on adequate knowledge of the stresses and strength in the joint. To determine the stresses and to predict the performance (strength, stiffness and service life, etc.) of the bonded joint, it is inevitable to know the material characterization of the constituents. In general, the bonded joint is composed of two distinct constituents: (i) the adhesive and (ii) the adherend. It is necessary to discuss the material characterization of bonded joint constituents.

1.4.1.1 Adhesive

According to the need, adhesive materials are considered to be isotropic. For linear stress analyses, Young’s modulus and Poisson’s ratio are the two input data, whereas for non-linear analyses, stress-strain curves may be considered and material yielding and hardening rules may also be needed. Fracture toughness and fatigue properties are required to characterize the failure strength and service life of the adhesive, respectively.

A great variety of test methods have been developed by researchers to characterize the adhesive material when sandwiched between the laminated FRP composite adherends. Accurate test methods are published in ASTM (American Society for Testing and Materials) standards, BS (British Standard), ISO (International Standards Organization) standards and the EU (European Units) standard. These tests evaluate not only the material properties of adhesive such as strength, modulus and fracture toughness but also the bonding techniques, effectiveness of surface preparations and curing cycle, etc. All the tests are generally classified into four different groups, i.e., shearing, tension, peeling, and fracture toughness. Adhesive materials can be classified into two categories; (i) brittle adhesive and (ii) ductile adhesive. For a brittle adhesive, a proportional linear relationship exists between the stress and the strain, while for a ductile adhesive, a non-linear stress strain relationship is generally observed. For brittle adhesives Young’s modulus and Poisson’s ratio are the two properties required for linear analyses of bonded joint.

1.4.1.2 Adherend

One of the major advantages of the adhesive bonding is that it enables orthotropic materials to be joined, even though it can be used for metallic adherends or combination of both. In many applications, laminated FRP composites are used as adherends for joining. The techniques of analyses are essentially same as when isotropic adherends are used, although due attention must be paid to the low longitudinal shear stiffness of unidirectional composites. With unidirectional composites the shear modulus is of the order of 25-30% of Young’s modulus. It may be as low as 2%, and so the adherend shear becomes extremely important. The use of lamination techniques in which fibres are placed at different orientation to the tube axis leads to reduced longitudinal and increased shear moduli. However, transverse modulus remains low. In addition, the transverse strength of FRP composite adherends is low, usually being the same order or less than that of the matrix. Thus, if the joint experiences transverse (peel) loading, there is a strong likelihood that the composite will fail in transverse tension before the adhesive fails. Adhesive peel stresses should therefore be minimized when composite adherends are used, lest this leads to adherend failure. Specifically for this purpose FGMs are proposed in place of the FRP composites in the present Thesis, and are found to have significant effects on reducing the peel stress concentrations at the critical locations in the pipe joints (Chapters 8 and 9).

Compared to isotropic materials, the analysis of joints between FRP composites is complicated by the anisotropy and heterogeneity of the adherends. A rigorous analysis may also be carried out to include the effects of residual thermal strains arising from curing and thermal mismatch when bonding to metals. When laminated FRP composite adherends are used, there are such additional variables of lay-up, i.e., combination of ply orientation, and stacking sequence as the order in which the plies are placed through-the-thickness, it being possible to change the latter without altering the former. Both these parameters affect the performance of the bonded joints, the stacking sequence playing the important role with thin adherends particularly because of its remarkable effect on bending stiffness which in turn determines the deformation of the joint and subsequent failure.

Various types of failures encountered in FRP composite adherends used in the bonded joints are, tensile failure in the fibre direction, tensile failure perpendicular to the fibre direction, interlaminar shear failure, cohesion failure, and adhesion failure. However, since the laminated FRP composites have comparatively low interlaminar strength, the three prominent modes of failures in FRP composite bonded joints are shown in Fig. 1.5.

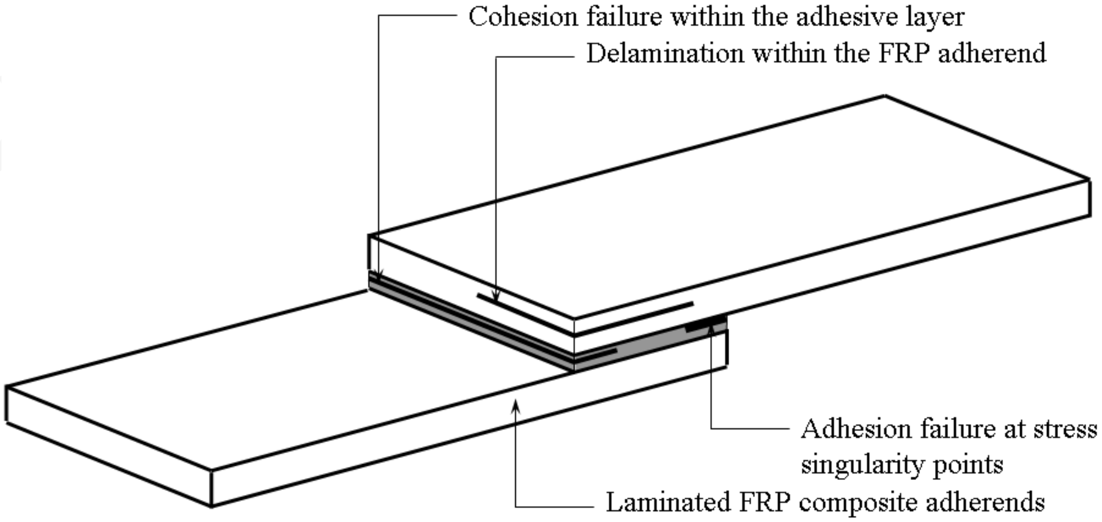

Fig. 1.5: Prominent failure modes in an adhesive bonded single lap joint made with laminated FRP composite adherends.

1.5 Adhesive bonded joint design philosophy

The design of adhesive bonded joints must be based on; (i) the nature of the materials to be joined, (ii) the geometry and configuration of the joint, (iii) the joining methods, and (iv) the strength and failure analysis. So for a structural bonded joint, a designer should consider the following aspects:

- Service conditions such as stresses and environmental conditions which are likely to be encountered in service.
- Selection of material combinations such as suitable adhesive and FRP composite adherends.
- Selection of specific joint configuration according to the need.
- Manufacturing specifications such as surface pre-treatment and fabrication procedures.

Many theories for adhesive bonded joints have been developed for stress and strength analysis. Many authors have made various assumptions regarding the behaviour of adhesive and adherends in terms of differential equations and have investigated the effects of various factors on the strength and stress distributions in the bonded joint. These factors are the adhesive plasticity, large deformations and rotations, satisfaction of the boundary conditions at the overlap ends, spew fillet and geometry, bondline thickness, overlap length, etc. It has been shown that, in addition to the large deformation, adhesive plasticity is another important factor and can not be ignored for appropriate prediction of joint strength. While implementing the non-linearity to the adhesive, the analytical solutions of the joint become cumbersome. Analytical and closed form solution analysis would be very difficult or may be impossible when material (both adhesive and adherend) non-linearity, delamination and debonding damages are considered. The mechanics of materials and fracture mechanics based approach are considered as the most suitable analysis tools for prediction of strength of adhesive bonded joints.

It has been observed that adhesive bonded joints often fail due to the damages initiated from the stress singularity locations and propagate either in the adhesive layer or along the interfacial surfaces or in a combination of both. Thus, fracture mechanics has been widely used to correlate damage propagation behaviour in adhesive bonded joints. For characterizing the strength, service, life, and designing rationally adhesive bonded joints, the main governing parameter is Strain Energy Release Rate (SERR). The three individual modes of damage propagation in the laminated FRP composite joints are: (i) opening mode called Mode I (G_I), (ii) shearing mode known as Mode II (G_{II}), and (iii) tearing mode designated as Mode III (G_{III}).

During the last few decades, numerous joint theories have been developed by a large number of authors using a lot of simplifying assumptions concerning the behaviour of the adherend and the adhesive. These assumptions may enable to remove the stress singularities which occur at the stress singularity locations. These stress singularities are due to many factors like dissimilar material properties at the interface, discontinuities of geometry, loading and material heterogeneity, etc. The details of assumptions made for stress analysis of bonded joints have been discussed in the pioneering work by Carpenter (1991) for obtaining a closed form solution. He concluded that the effect of a given assumption on predicted adhesive stress is difficult to determine from the differential equations.

1.5.1 Stress analyses

Stress analysis is one of the important steps for any structural design. It provides much vital information about the stresses and the strains in the real structures made of adhesive bonded joints subjected to specified loading and service conditions. This information enables the designer to predict the strength and the life of a bonded joint. The stress analysis of bonded joint is a real challenge for two important aspects of joint design: (i) bi-material interfaces and geometric discontinuities create stress concentrations and material behaviour uncertainties and (ii) the stress gives the idea of failure initiation in terms of failure index. Failure index refers to a parameter which characterizes the location of failure or damage initiation. Particularly the out-of-plane stresses are most important factors responsible for the propagation of initiated damages. In case of laminated FRP composite adherends, delamination induced damages are the major threat to the bonded joint applications. The details of methodology to predict the location of damage initiation in adhesive bonded joint made with laminated FRP composites have been discussed in Chapter 3.

Stress analysis techniques can generally be classified into two major categories, i.e., analytical solution which is based on a number of mathematically simplified assumptions and numerical solutions using the Finite Element Analysis (FEA). Because of the complexities, analytical solutions of the bonded joint exist for simple geometry, loading and boundary conditions. Therefore, more emphasis is put on the use of numerical methods when laminated FRP composites are used as adherends and the joint involves complicated geometry, loading and boundary conditions. Among various numerical techniques available, it is seen that the FEA is not only simple and robust but also straight forward and versatile enough to cover all types of bonded joint problems relevant to practical situations. The FEA, as described by Zienkiewicz (2002), is a well established numerical means for stress analysis of bonded joints. The FEA avoids the approximation of the closed form theories. Many authors like Adams (1989) have used finite element techniques exclusively for the bonded joint problems.

1.5.2 Adhesion failure and delamination damage analyses

Since fibrous composite laminates are most commonly used as adherends, they are susceptible to internal defects such as delamination during manufacture or in service. The stress analysis of laminated composites with defects for predicting the mechanical behaviour of bonded structures is also important and has received considerable attention. However, due to the anisotropic properties of laminated FRP composite adherends, the stress distribution around the defects is complex and a global theory for precise prediction of delamination due to such defects in composite materials is not available. Finite Element Method, because of its ability to model real life structures has been extensively used for stress analysis of such laminates with defects. However, for complete understanding of behaviour of such FRP composite laminates and delamination initiation from such defects, a 3D finite element analysis is necessary. In fact, with the popularity of damage tolerance, fracture mechanics concepts have been in use for analysis of such structures. However, effective analytical and numerical methods are necessary for analysis of adhesive bonded joints made with laminated FRP composite adherends along with defects.

Sublaminate techniques (Sec. 3.8.2) are generally used for evaluating the severity of damage growth mechanism in laminated FRP composite bonded joints. The interfacial resin rich layer is presumed to contain the delamination. The problem of delamination in laminated FRP composite adherends is very complex in nature and difficult to solve, because it not only involves geometric and material discontinuities, but also internally coupled mode I, mode II, and mode III fractures in layered composites. The mixed mode interlaminar fracture characteristics are investigated by retrieving the stress and displacement field results from the numerical FE analyses using transformed coordinate system. Finite Element Method (FEM) is an approximate numerical method for solving field problems. In principle the analysis domain is divided into finite number of non-overlapping sub-domains of polygonal shapes called the finite elements. First an approximate solution is sought for each element and the behaviour of the element is characterized by a finite number of unknown parameters. Then by a suitable assembly procedure the relations between the individual elements are combined into a system of equations, which are used to solve these unknown parameters. With the use of finer elements the discretization errors of the field variables can be reduced considerably and near exact solution can be obtained. The unknown parameters are usually the values of the field variables at a finite number of nodal points. Interpolation of these field variables within each element yields the approximate solution. A stationary condition of a functional based on variational principle, characterizes the equilibrium for the element and subsequently establishes the system of equations for the unknown parameters. The most important feature of the FEM is that it can be realized by using flexible and parametric design concepts and can be applied to a wide range of practical problems.

1.6 Joining methods used in composite piping systems

Use of composite pipes has been established in wastewater treatment, power, and petroleum production. Most recently, composite pipes are becoming popular in the offshore oil and gas industry due to the new invention of Tension Leg Platforms (TLPs) which have made deepwater oil and gas exploration and production more economical and affordable. The TLPs are very weight sensitive because of the special ‘‘floating’’ design. Composite pipes have found many applications on TLPs due to its unique directional properties, seawater corrosion resistance, and light weight. After 40 years of process and materials development, the mechanical properties of composite pipes have been dramatically improved. However, the limitations of the overall system performance usually come from the capacity of the joints. The estimation that one joint is installed for every 4 ft of composite pipe for marine services further emphasizes the importance of reliable composite pipe joints. As shown in Fig. 1.6, the most commonly used joining methods for composite pipes are (a) adhesive bonded single lap/socket joints, (b) butt-and-strap joints, (c) heat-activated coupling joints, and (d) flanged joints.

The first three types of joints are considered as permanent joints, whereas the flanged joints provide the ease of quick assembly/disassembly for installation, inspection, and repair. However, most composite flanges are connected to composite pipes with one of the three permanent joining methods. Among the three permanent joints, the heat activated coupling joining method is the only method capable of joining composite pipes with alloy pipes. The same joint mechanism is found in the adhesive bonded single lap/socket joints, butt-and-strap joints, and heat-activated coupling joints. Basically, there are two pieces of composite pipes to be joined, a coupling to carry the load at the connection, and a medium to transfer the load from the pipe to the coupling. Therefore, a general adhesive bonded single lap and socket joint analysis can be used to analyze all three types of permanent composite pipe joints.

Hence, the present Thesis deals with the design and failure analyses of the two major types of bonded joints, i.e., Tubular Single Lap Joint (TSLJ) and Tubular Socket Joint (TSJ) considered for the composite piping systems.

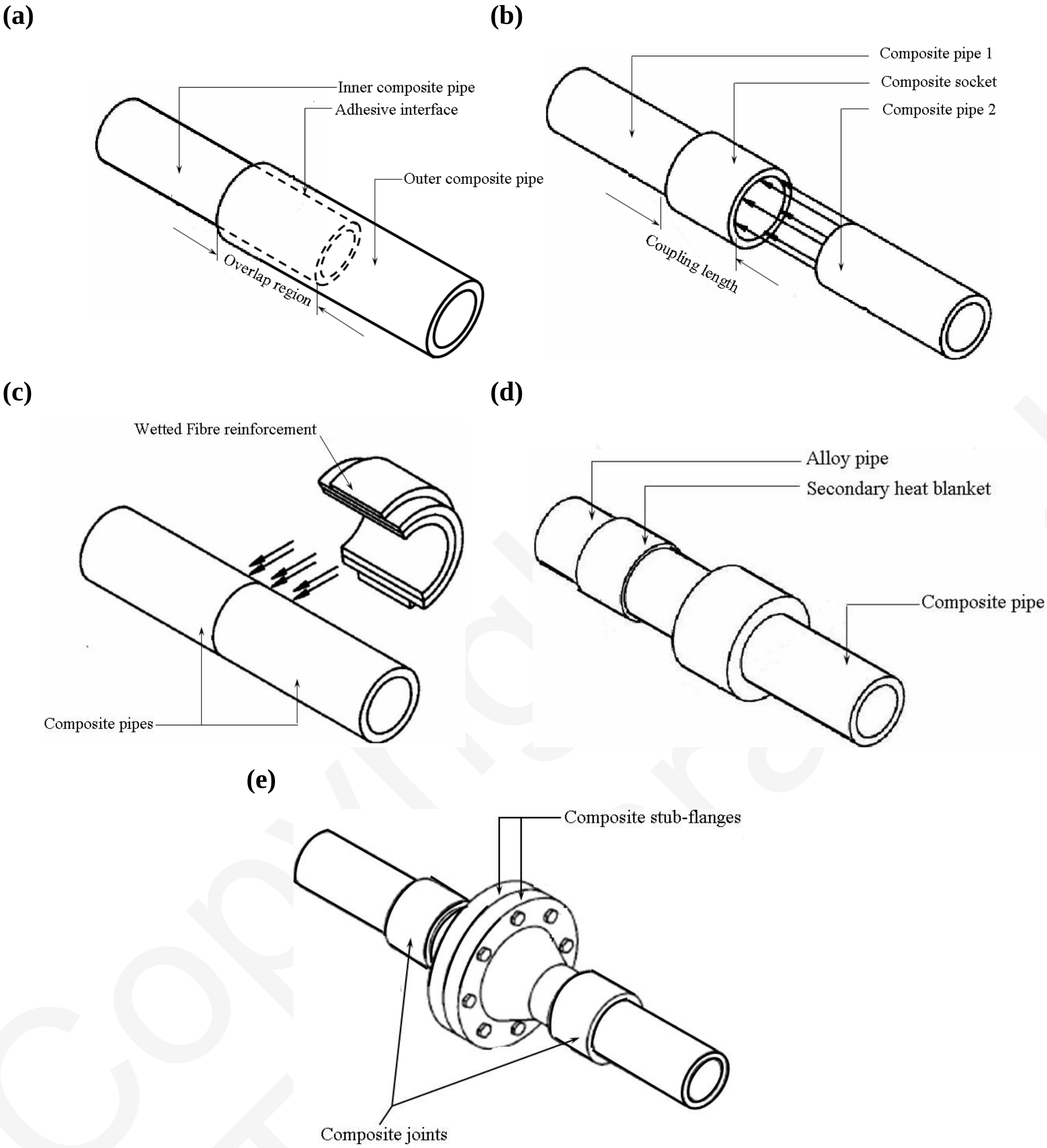

Fig. 1.6: Different types of joining methods used in the composite piping systems: (a) Single lap joint, (b) Socket joint, (c) Butt-and-strap joint, (d) Heat-activated coupling joint, and (e) Flanged joint.

1.7 Scope of adhesion failure and delamination damage analyses of bonded tubular joints made with laminated FRP composites and FGMs

All the stiffness and strength advantages of FRP composite materials can not be transformed into the structural advantages. Hence, well defined bonded tubular pipe joints must have to obtain the required joint efficiency as well as the joint strength in order to assess the structural integrity to the fuller extent. The mechanical strength of a bonded pipe joint depends essentially on four parameters: (i) the adhesion failure between the adhesive layer and the tubular adherends, (ii) the cohesion properties of the adhesive layer, (iii) the delaminated adherends, and (iv) the geometry and configuration of the joint. Understanding the fundamental nature of the damage parameters is of utmost importance in the reliability and safe design of the bonded tubular joints. For practical applications of adhesive bonded composite joints, many researchers (Kairouz and Matthews (1993), Tsai and Morton (1995), Kayupov and Dzenis (2001), Cheuk and Tong (2002), Qin and Dzenis (2003), Kim et al. (2006)) have investigated the influence of various parameters on failure behaviours of the composite bonded joints experimentally and numerically. But the failure prediction of the composite bonded joints is still difficult because the failure strength and modes are different according to the various bonding methods and parameters. According to the studies, there are broadly two kinds of failure modes in the bonded joints made of FRP composites. One is the failure of the adhesive layer, which includes interfacial failure called adhesion failure, and the other is the cohesion failure of the adhesive. The delamination induced failure which occurs in the laminated FRP composite adherends between the laminae is also very essential to be analyzed. The characteristic behaviour of the first is progressive failure and the failure propagation occurs in the adhesive layer. The characteristic behaviour of the second is catastrophic failure which occurs abruptly. The present failure prediction method utilizes a failure criterion which is considered for both the bondline failure and the delamination damages.

Performance of the composite pipe joints due to the presence of damages has not yet been properly highlighted. The detailed methodologies for the analyses of onset and growth of damages in an adhesive bonded tubular pipe joints are not available in the literature. Adhesive bonded joints having delamination mode of damages in laminated FRP composite adherends have become a subject of intensive research among the researchers. The defects which may lead to premature delamination in the FRP composites may arise from micro-cracks and cavities or voids formed during manufacturing stages, service or maintenance induced damages, or from low-velocity impact damage. The structural degradation and stability reduction of composite structures having bonded joints are more critical due to the presence of above mentioned damages.

To study the onset of damages and their growth behaviour, Strain Energy Release Rate (SERR) procedures based on the concepts of Linear Elastic Fracture Mechanics (LEFM) are found to be most suitable. It is not only based on a sound energy balance principle related to work done in new surface generation, but also the mixed mode damage progression can be separated into individual fracture modes, which can be suitably compared with experimental observations of critical SERR. Thus, the physics of stable and unstable damage growth characteristics are being modelled as a function of fracture energy release rates both by numerical and analytical approaches for understanding the interface phenomenon. Determination of joint strength for a given configuration and material property is yet to be fully understood. Several researchers have limited their bonded joint analyses pertaining to the study of stress and deformations using two-dimensional plane stress or plane strain assumptions. The three-dimensional stress analyses of adhesive bonded joints made of laminated FRP composites are very rare even today.

Although a great deal of research is devoted to the analysis of bonded flat joints made with laminated FRP composites, emphasis has not been addressed to bonded composite piping systems. The present research is based on the idea of efficient and effective design of the bonded tubular joints made with laminated FRP composites. Improving the resistance of the pipe joints against different interfacial failures is the prime concern of the present Thesis. Suitable ply-orientation and fibre-matrix compositions are adapted in order to improve the resistance and performance of the pipe joints. Also, replacement of the FRP composites by the FGMs has been found to be very much efficient. Performances of bonded pipe joints made with FRP composites and and FGMs have been evaluated in details in subsequent Sections and design recommendations have been suggested.