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Adhesively bonded composite tubular joints: Review

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ABSTRACT

The aim of this review article is to examine solutions and challenges associated with adhesively bonded fibre reinforced polymer (FRP) pipe sections. FRP materials have been used in piping systems for more than 40 years. Higher specific mechanical properties and corrosion resistance of FRP makes it a potential candidate for replacing metallic piping structures. Another advantage of FRP structures is the large number of design variables available. Despite the advantages associated with FRP structures, their application is still limited, partly due to unsatisfactory methods for joining composite subcomponents and inadequate knowledge of failure mechanisms under different loading conditions. Adhesively bonded joints are attractive for many applications, since they offer integrated sealing and minimal part count and do not require pipe extremities with complex geometries such as threads or bell and spigot configurations. Normally, an adhesive joint results in more uniform stress distribution, undamaged fibre architecture, and smooth surface contours. In the present article, a comprehensive review of various joining techniques for FRP piping through adhesive bonding is presented and damage mechanisms for different loading conditions are examined.

1. Introduction

Fibre reinforced polymer (FRP)/composite material has many inherent qualities, including high specific stiffness and strength. These special properties make composites ideal candidates for replacing metallic piping structures in industries such as chemical, petrochemical, and energy. Composite structures are being intensively studied as replacements for metallic structures, as metallic structures are considered more prone to corrosion and wear under such harsh environments.

The complex layout of industrial piping systems, along with limitations associated with composite pipe manufacturing, demands repeatable and durable joining mechanisms. It is a known fact that joints are the weakest links of such composite structures. Composite pipe joints can be accomplished either mechanically or adhesively. Mechanical joints are associated with trimming, bolting, and fastening, which result in localised stress concentration in the structure and often weaken the joint as well as the whole structure. Drawbacks associated with the mechanical joining of composite tubes divert the research towards adhesive bonding of tubular sections.

Adhesive bonding of FRP structures was studied by a number of researchers [1–4]. With advancements in filament winding technology, ongoing efforts are also being made to study the adhesive bonding of tubular structures [5–9]. Lubkin and Reissner [10] may be considered among the pioneer researchers in the field of adhesively bonded tubular joints. They experimentally investigated the stresses developed in an adhesive joint, which were further validated with the finite element model developed by Adams and Peppiatt [5]. The first theoretical analysis of the tubular single lap joint was performed by Volkersen [11] and further modified by Adams and Peppiatt [5]. The numerical expression proposed by Adams and Peppiatt for shear stress in adhesive bondline subjected to torsion loading T is given in Eq. (1), and an illustration is provided in Fig. 1.

$$\tau_a = \frac{T\alpha}{2\pi\alpha^2}\left[\frac{1-\varphi(1-\cos\boldsymbol{h}(\alpha L))}{\sin\boldsymbol{h}(\alpha L)}\right]\cos\boldsymbol{h}(\alpha z)-\varphi\sin\boldsymbol{h}(\alpha z) \tag{1}$$

where

$$\delta = \frac{2\pi r_{1o} G_a a^2}{G_1 J_1 \eta}$$

$$\varphi = \frac{G_2 J_2 r_{1o}}{G_1 J_1 r_{2i} + G_2 J_2 r_{1o}}$$

$$\alpha = \left(\frac{\delta}{\varphi}\right)^{0.5}$$

r_{1o}, r_2: outer and inner radius of cylinder adherend and tube adherend, respectively, a: average radius of the adhesive, J_1, J_2: polar moment of inertia for cylinder adherend and tube adherend, respectively, G_1, G_2: shear modulus of cylinder adherend and tube adherend, respectively, G_a, η: shear modulus and thickness of adhesive, respectively.

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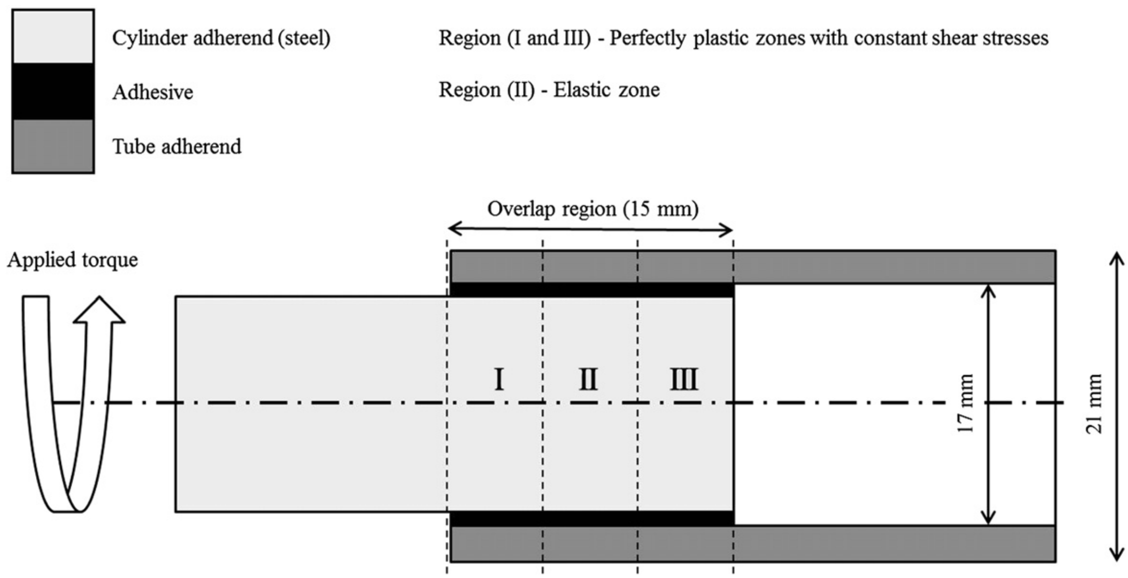

Fig. 1. Schematic of joint subjected to torsional loading by Choi and Lee [20].

On practical grounds, their theory was bounded by the concept of thin-wall and Goland and Reissner [12] criteria. According to these criteria [12], normal and shear stresses in the adherend can be neglected if values of constant 'β' satisfy the condition given in Eq. (2) below

$$\beta = \frac{\eta \times E}{E_a \times t} \simeq \frac{\eta \times G}{G_a \times t} \geq 10 \tag{2}$$

here, η=thickness of adhesive layer, E_a, G_a=Young's and shear modulus of adhesive layer, respectively, E, G=Young's and shear modulus of tubular section, respectively, t=wall thickness of the tubes.

In accordance with the Goland and Reissner criteria [12], the results of Lubkin and Reissner [10] were formulated around the assumption that shear and peel stresses in tubular subsections can be neglected when compared with the same stresses in the adhesive layer.

In the research work of Alwar and Nagaraja [13], the viscoelastic behaviour of adhesive material was incorporated in the finite element analysis of the joint, subjected to different loading conditions. It was reported in their conclusion that the viscoelastic behaviour of the adhesive helps to reduce the maximum stresses at the edge of the joint. A few researchers have also come up with closed-form solutions for mapping stress distribution within adhesively bonded joints. One such solution was provided by Volkersen [11] for a tubular joint subjected to torsional loads; another was provided by Terekhova and Skoryi [14] for a joint subjected to internal and external pressure.

In 2010, Wei and Guoqiang [15] established that stress components along the thickness of the adhesive layer are not constant. These results were contrary to earlier established assumptions of constant stress values along the thickness of the adhesive layer. Wei and Guoqiang [15] used a finite difference method to calculate six stress components in the adhesive layer and came to this conclusion. The effects of fibre orientation, composite laminate stacking sequence, overlap length, and adhesive layer thickness on shear and peel stresses developed in the adhesive layer were also studied in the same research work.

The aim of the present article is to review the existing techniques for adhesive bonding of composite tubes. An attempt is also made to illustrate the challenges associated with each kind of technique. Optimisation techniques for coupler configuration as well as design aspects with respect to peel/shear stresses are also discussed in the review.

2. Classification of adhesively bonded tubular joints

2.1. Lap joints

Adhesive bonding provides a convenient method for assembling structures such as composite laminates and tubes. The typical and conventionally used joining technique for tubular structures is the lap joint. Applications of such lap joints include bonding a metal and fitting to a composite tube in space structures and automotive drive shafts.

Composite shafts are becoming common these days due to ease of manufacturing and low rotational inertia at a relatively high stiffness compared with similar metallic shafts. Torque transmission capabilities of adhesively bonded composite shafts or tubular sections are the focus of many research works [16–19]. The experimental work of Choi and Lee [18] on single lap composite joints was further extended to cover the same strength for adhesively bonded tubular sections [20]. In that research work [20], the effect of adhesive thickness was studied with respect to the torque transmission capacity of the single lap tubular joint. For the purpose of modelling, the adhesive was divided into three regions as shown in Fig. 1.

In the discussed work of Choi and Lee [20], the effects of adhesive thickness and thermal residual stresses on the torque transmission capacity of single lap tubular joints were investigated, using epoxy-based adhesive. Elastic properties were assumed for adhesive, while driving closed form solutions, whereas elastic perfectly plastic behaviour of adhesive was assumed in a numerical-based solution for investigating the effect of adhesive thickness on the torsional capacity of the joint. It was considered in the research work that adhesive failed under fracture when maximum shear strain reached its ultimate value. Contrasting trends for the torsional capacity of the adhesively bonded joint were reported in the work of Choi and Lee when the behaviour of adhesive material was modelled as elastic perfectly plastic instead of elastic. It was concluded in their work that the torsional capacity of the joint decreased linearly with respect to adhesive thickness, when adhesive behaviour was modelled as elastic perfectly plastic material properties, which was