Multiwalled Carbon Nanotube Reinforced Composites for Strengthening Adhesive Tubular Joints

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Adhesives are widely used for making joints in various structures. A strong and durable joint is required for heavy duty structures. Various reinforcement materials are being used for improving the strength of adhesives. Carbon nanotubes (CNTs) are observed as strong reinforcing material in the development of nanocomposites. In this work multiwalled carbon nanotube (MWCNT), reinforced epoxy adhesives are used for strengthening tubular joints in pipe sections. Continuum modeling approach using finite element method is applied for the design and analysis of tubular joint. Stresses at the joint section are analyzed under tensile and torsion loading conditions. Effect of geometrical parameters such as adhesive thickness, overlap length and pipe material in the strength of the joint is determined. The results obtained can be used to optimize the joint. The simulation technique used in this work is found to be useful for the composite pipe designers for designing joints for pipe applications. A comparison of von mises stresses for MWCNT-reinforced epoxy adhesive and epoxy adhesive indicates that MWCNT filled epoxy joints provide higher bonding strength than the epoxy joints. The present model is validated with Lubkin and Reissner's model. The plot of normalized stresses for both models reveals that the finite element results are in good agreement with the theoretical results.
[DOI: 10.1115/1.4054369]

Keywords: MWCNT, adhesive joint, epoxy adhesive, finite element modeling, tensile loading, torsional loading, adhesion, analysis and design of piping, composite materials, finite element analysis, nanomaterial, numerical simulations, pressure

1 Introduction

Adhesive bonding is emerging as a promising technique to join tubular pipe structures. Adhesively bonded joints are found to be beneficial in many applications as they provide smooth continuous sealing with no complex parts such as threaded joint, riveted joint, etc. Thus, the stress concentration is reduced in the case of adhesive. The higher stresses are observed at the edges of the joint [1,2]. Epoxy-based adhesives are been used in various applications like automobile, aeronautics, defense, and medicals.

Volkersen O. investigated the torsional stresses in the tubular lap joint. Adhesive joint between the tubular adherents is analyzed using the concept of mechanics of materials [3]. The adhesive layer is modeled as a "shear spring" between the adherends, and the effect of circumferential stresses is neglected. Adams and Peppiat N.A. observed that there is a stress gradient through the thickness of the adhesive layer [4]. The analysis of the adhesive layer is performed for a single lap joint using the finite element method. They also studied the adhesive yielding using an iterative elastoplastic finite element (FE) program. Terekhova and Skoryi found the stress distribution within the adhesive joints subjected to internal and external pressure [5].

Composite shafts or tubular sections with adhesive joints are studied for torque transmission capabilities [6–9]. Experimental work done by Choi and Lee [7] is extended to single-lap composite joints to cover adhesively bonded tubular sections [9]. The torque transmission capacity of epoxy adhesives single lap tubular joints is determined under the effect of thickness and thermal stresses. Closed-form solution and numerical techniques were used to analyze the elastic and plastic behavior of adhesive joints.

Various researchers have investigated the single lap joints for longitudinal loading conditions [10–12]. Guess and coauthors [11,12] investigated a single lap joint between metal pipe composite pipe. The joint is analyzed under three loading conditions, i.e., axial tension, compression, and bending. Both experimental and numerical simulation techniques were used to analyze the joint. The two sets of joints are analyzed between E-glass fabric/epoxy and aluminum; and triaxially reinforced E-glass/polyester and steel. The results reveal that the failure initiated due to delamination at the inner part of the joint. Metal to composite joints were observed to possess higher tensile strength than the compression strength except in the case of tapered aluminum pipe sections. Using steel adherend in place of aluminum does not affect the joint strength under compressive loading conditions.

Most of the adhesive joint failure occurs due to the high peel stress developed at the joint and low transverse strength at the bonding connection which results in delamination [13]. It is been investigated that the adhesive joints having higher overlap length are more susceptible to delamination failure for composite adherends [14]. Hence, it is required to design novel material for the adhesive joint so that the load-carrying capacity of the joint can be improved, and the effect of delamination can be minimized.

Carbon nanotubes (CNTs) are extensively used in reinforcing the polymer and metal composites as they possess excellent mechanical, thermal, and electrical properties [15–19]. Many researchers developed CNT/epoxy composites for various applications [20,21]. In these papers, enhancement in the mechanical properties of CNT/epoxy adhesive is observed and techniques to improve the dispersion of CNTs in epoxy are investigated. Although various

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Manuscript received November 22, 2021; final manuscript received April 11, 2022; published online May 2, 2022. Assoc. Editor: Erdogan Madenci.

researchers have worked on CNT/epoxy composites, very little work is done to analyze the multiwalled carbon nanotube (MWCNT)/epoxy adhesives for joining tubular joints.

2 Modeling Approach

Adhesively bonded joints are extensively used in various piping applications. The adhesive joints used for joining the metal pipes possess very less strength and stiffness in comparison with the adherends. To enhance the mechanical properties of adhesives, additives are used such as carbon, nylon, liquid rubber precipitates, glass microfibers, etc. Improvements have been observed in the bonding properties of adhesive [22,23]. These additives also reduce the effectiveness of high-temperature service capabilities, low impact strength, and poor shrinkage characteristics [24]. Since the discovery of carbon nanotubes, they have been explored for various applications. CNTs are observed as an excellent reinforcing agent in the development of nanocomposites. They have also been used as filler in adhesives to improve their strength [25]. Despite having a wide variety of applications for tubular adhesive joints, CNT/epoxy adhesive tubular joint has not been much explored in the literature.

In this work, MWCNT-reinforced epoxy adhesive is analyzed for joining metal pipe structures using the finite element method. The analysis is performed on hyperworks. The model consists of three components two metal tubes constitute the adherends and MWCNTs reinforced epoxy as the adhesive. The continuum modeling approach is used for the modeling of three components. The adherend and adhesive layer is modeled with three-dimensional brick elements. The modeling and computational effort may become prohibitively large, by using more layers of brick elements through the thickness of the model. Therefore, layered volume elements are used to improve computational efficiency without compromising the accuracy of the FE analysis. The FE model of an adhesive joint between tubular pipes is shown in Figs. 1(*a*) and 1(*b*).

3 Comparison of the Present Model With the Results Available in Literature

From the available literature on adhesive joints, few theoretical models are there in which the researchers have determined the stresses in adhesive joints under tensile and torsion loading conditions. Lubkin and Reissner have done some pioneering work in the field of adhesive tubular joints [26]. In their model, they considered the adherend pipes under axial load, bending, and shear load conditions. They developed a model to determine the peel and shear stresses in the adhesive due to the displacements in the outer and inner adherend tubes. The relationships for the peel and shear stresses obtained are

$$\sigma_p = \frac{E_{adh}}{t_{adh}}\,(r_o - r_i) \tag{1}$$

$$\tau = \frac{G_{adh}}{t_{adh}}\left[\left(a_o + \frac{t_o}{2}\frac{dr_o}{dx}\right) - \left(a_i - \frac{t_i}{2}\frac{dr_i}{dx}\right)\right] \tag{2}$$

σ_p is the peel stresses; τ is the shear stresses; t_{adh} is the adhesive thickness; r_o, r_i are radial displacements of adherend outer and inner pipes; E_{adh} is Young's modulus of adhesive; G_{adh} is the shear modulus of adhesive; a_o, a_i are the axial displacements of adherend outer and inner pipes; t_o, t_i are the thickness of adherend outer and inner pipes; x is the axial axis of the coordinate system.

The FE results obtained from the present model are compared with Lubkin and Reissner's results by taking present parameters into account.

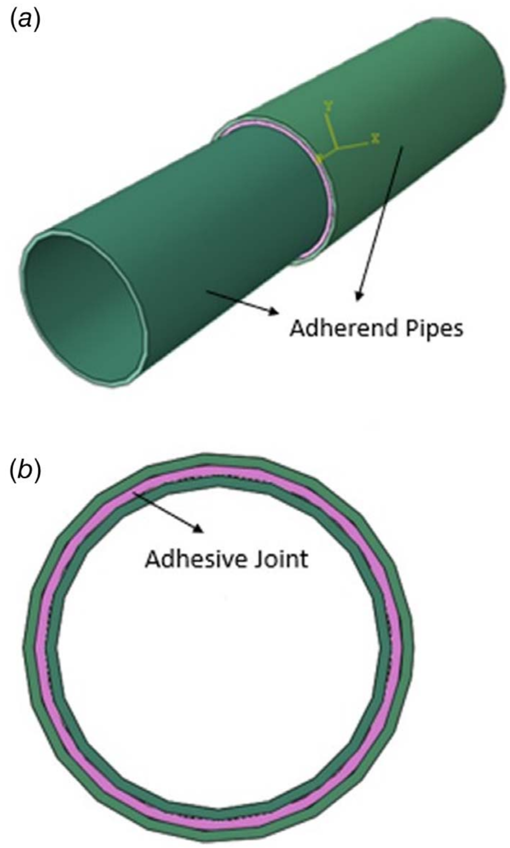

Fig. 1 Finite element model of the adhesive joint in tubular pipe: (*a*) three-dimensional model and (*b*) cross-sectional view of the adhesive layer between tubular pipes

4 Results and Discussion

4.1 Adhesive Joints in Tubular Structures. In this work, the application of MWCNT-reinforced epoxy in enhancing the strength of adhesive joints in tubular pipes is studied. MWCNT is introduced as filler into epoxy adhesive to improve its strength. Geometrical parameters such as adhesive thickness, overlap length, and pipe material along with different loading conditions are analyzed using Hyperworks finite element software. In order to consider the influence of material properties, two commonly consumed materials, i.e., steel and aluminum, are considered in this study. To understand the factors affecting the adhesive joint, tensile and torsional loading conditions are considered. The inside radius of the inner pipe is taken as 18.9 mm, the thickness of both adherends as 1 mm, and the length of each adherend equal to 80 mm. The effective overlap length is considered in form of 2c and is varied in the range of 5–20 mm. The adhesive thickness is varied from 0.1 to 0.5 mm. The properties of epoxy adhesive and MWCNT-reinforced epoxy adhesive are taken as obtained experimentally by Wernik and Meguid [27]. The properties of steel and aluminum pipe adherend, MWCNT-reinforced epoxy adhesive, and epoxy adhesive are mentioned below:

- Aluminum adherend: Young's modulus = 70 GPa, Poisson's ratio = 0.3.
- Steel adherend: Young's modulus—210 GPa, Poisson's ratio = 0.3

The properties of MWCNT reinforced epoxy adhesive used to join metal pipes are taken as follows:

- Epoxy adhesive: Young's modulus = 1.07 GPa; Poisson's ratio = 0.3.
- MWCNT-reinforced epoxy adhesive: Young's modulus = 2.8 GPa; Poisson's ratio = 0.3.

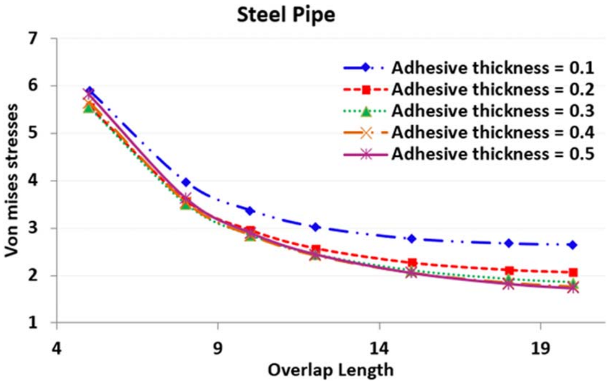

Fig. 2 Plot of von mises stresses along adhesive thickness for steel pipe adherend and MWCNT-reinforced epoxy adhesive

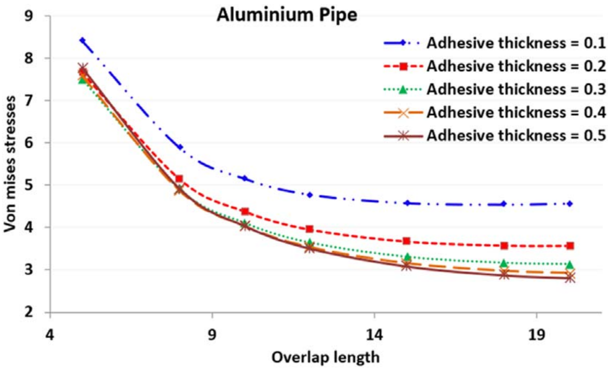

Fig. 3 Plot of von mises stresses along adhesive thickness for aluminum pipe adherend and MWCNT-reinforced epoxy adhesive

4.1.1 Tensile Loading. A tensile load of uniform intensity 10 MPa is applied at end of the inner adherend pipe. The von mises stress and shear stress distribution along adhesive thickness are determined for evaluating the strength of the joint. Figure 2 shows the effect of adhesive thickness on von mises stress distribution. Steel pipes with the joint of MWCNT-reinforced epoxy adhesive is considered. By increasing the adhesive thickness, the maximum stresses at the ends of the joint region decrease and uniform stress distribution curve is obtained. For evaluating the strength of the joint, the stresses at the joint free end region are considered crucial parameters. The failure would initiate from the joint free end regions, assuming uniform adhesive thickness and properties along the bonded length. A similar trend of results is observed for aluminum–aluminum pipe joint as well (shown in Fig. 3). Figure 4 shows the comparison of aluminum and steel pipe with MWCNT epoxy adhesive. Higher stress values are observed in aluminum–aluminum pipe joints. The plot of deformation in steel and aluminum pipe is shown in Fig. 5. The results of higher deformation in aluminum pipe joints reveal that the rigidity of aluminum is less in comparison with that of steel. This also confirms that the less rigid pipes result in greater deformation in comparison with more rigid pipes. However, for making strong and economical aluminum joints, thick adhesive joint would be required.

The plot of von mises stress distribution for steel pipes with epoxy adhesive joint and MWCNT epoxy joint is shown in Fig. 6. A comparison of von mises stresses for MWCNT-reinforced epoxy adhesive and epoxy adhesive shows that MWCNT-filled epoxy adhesive joints give higher bonding strength than the epoxy adhesive joints.

Further, analysis is performed to investigate the shear strength of MWCNT-reinforced epoxy adhesives in steel pipes. The trend of results obtained for shear stresses is similar to the von mises stress (shown in Fig. 7). Higher shear stress values are observed for smaller adhesive thicknesses. A significant difference in shear stresses is observed for smaller values of an adhesive thickness (0.1–0.3 mm), while for higher values of adhesive thickness, saturation in values of shear stresses is observed. A comparison of shear stresses for steel and aluminum pipe for 0.1-mm adhesive thickness is shown in Fig. 8. Higher stresses in aluminum pipe joints are observed in comparison to steel pipe joints. These higher values of stresses can be reduced by increasing the thickness of adhesive in aluminum pipe joints. Figure 9 shows the comparison of shear stresses using MWCNT epoxy adhesive and epoxy adhesive in steel pipe. The results reveal that the addition of MWCNT as filler in epoxy adhesives improves the strength of adhesive.

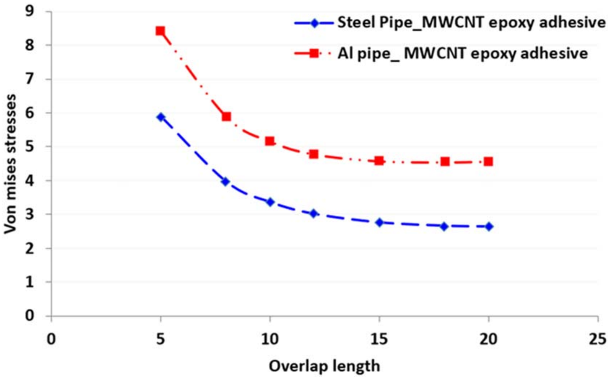

Fig. 4 Comparison of von mises stresses in steel and aluminum pipe adherend with MWCNT epoxy adhesive

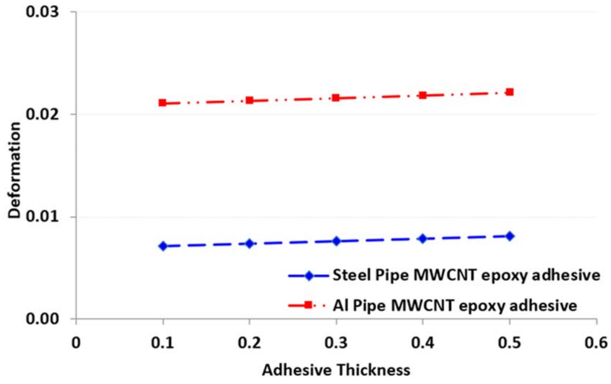

Fig. 5 Deformation in steel and aluminum pipe adherend with MWCNT epoxy adhesive

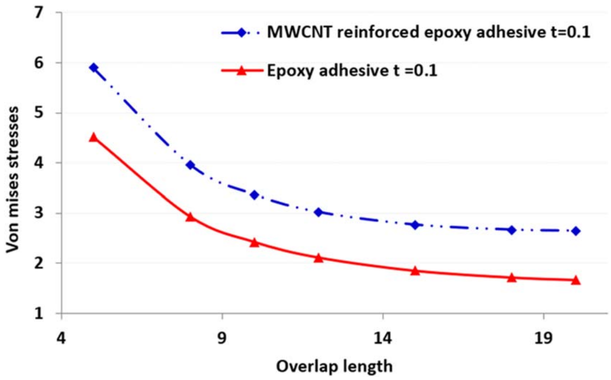

Fig. 6 Von mises stresses in steel pipe joint with MWCNT-reinforced epoxy adhesive and epoxy adhesive

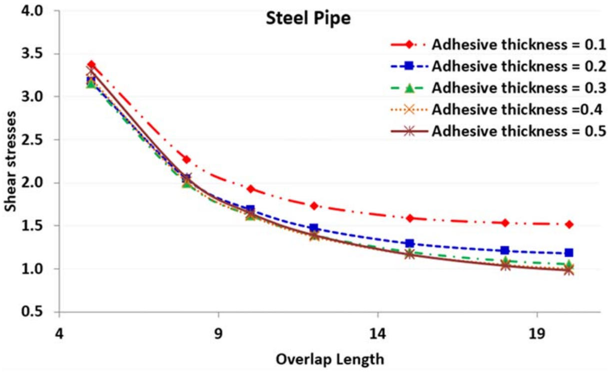

Fig. 7 Shear stresses in MWCNT-reinforced epoxy adhesive with varying thickness in steel pipe adherend

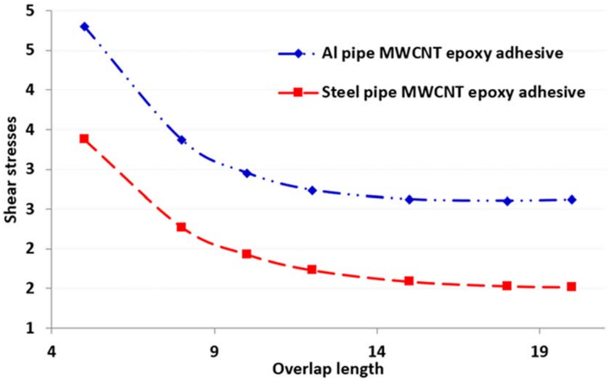

Fig. 8 Shear stresses in MWCNT-reinforced epoxy adhesive with steel pipe and aluminum pipe adherend

4.1.2 Torsion. Next analysis is performed for the torsion loading condition in adhesively bonded metallic joints. The parameters used to determine the strength of adhesive joints are normalized shear stresses and von mises stresses along the adhesive thickness. The adhesive layer shear stress was normalized with respect to the mean adhesive shear stress. The normalized shear stresses are equal to the ratio between maximum shear stresses and mean shear stresses. The mean shear stresses are obtained as

$$\tau_m = \frac{2T}{\pi D_{av}^2 L} \tag{3}$$

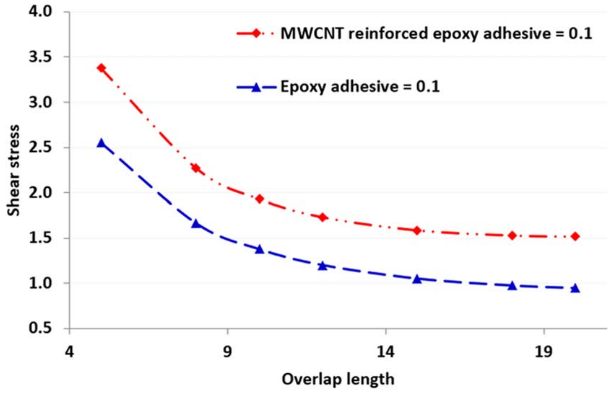

Fig. 9 Comparison of shear stresses in MWCNTreinforced epoxy adhesive and epoxy adhesive with steel pipe adherend

where $D_{av} = D_{p1o} + \eta$, and L is the adhesive length. T is the applied torsion, D_{p1o} represents pipe-1outer diameter. The geometrical parameters used for adhesive joint and aluminum and steel pipe are shown in Fig. 10. The applied torsional load at the end of pipes is 200 Nm.

The properties used for steel pipe and MWCNT epoxy adhesive are the same as in the case of tensile loading (Sec. 3.1). The plot of von mises stresses for steel pipe with MWCNT epoxy adhesive, for the variation in adhesive thickness and overlap length, is shown in Fig. 11. With the increase in overlap length and adhesive thickness, the von mises stresses along adhesive thickness decrease. The nonlinear pattern of results is observed. The effect of change in adhesive thickness is observed to be more significant for smaller values of thickness. The results obtained for aluminum pipe are of a similar pattern as obtained for the steel pipe (shown in Fig. 12). A comparison of von mises stresses for aluminum and steel pipe with the variation in thickness of MWCNT epoxy adhesive is shown in Fig. 13. Higher stress values are obtained for aluminum pipe in comparison to steel pipe. This also confirms that the less rigid pipes twist more at both sides of the joint, resulting in a more significant difference in circumferential displacements in comparison with more rigid pipes.

Figure 14 illustrates combined effect of adhesive thickness and overlap length on normalized shear stresses. A linear pattern in the results is observed for normalized shear stresses for various thickness variations. With the increase in overlap length, the normalized shear stresses increases for various adhesive thickness. A higher value of normalized stresses is observed for the smaller thickness of adhesive pipes. Normalized shear stresses are

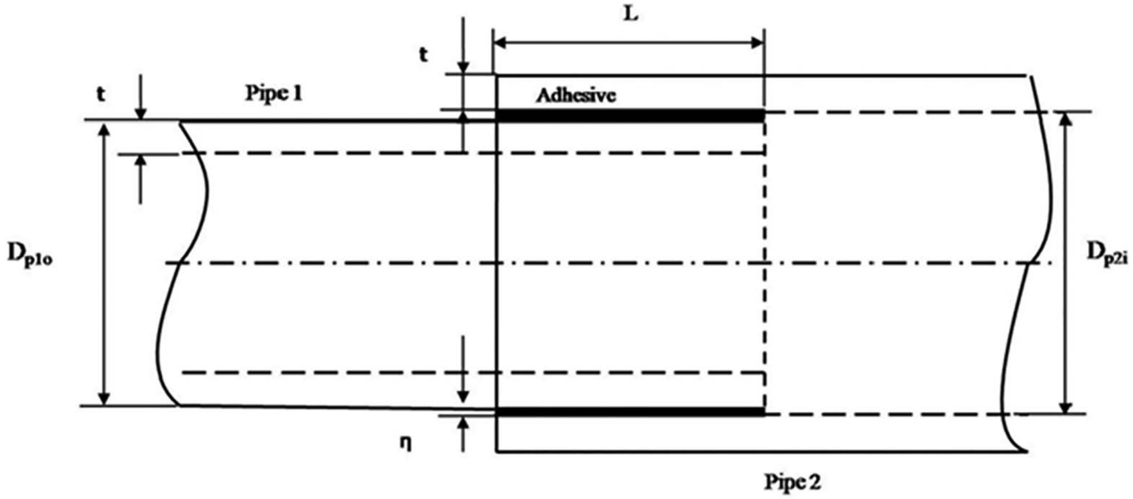

Fig. 10 Geometrical parameters for tubular pipe and adhesive layer

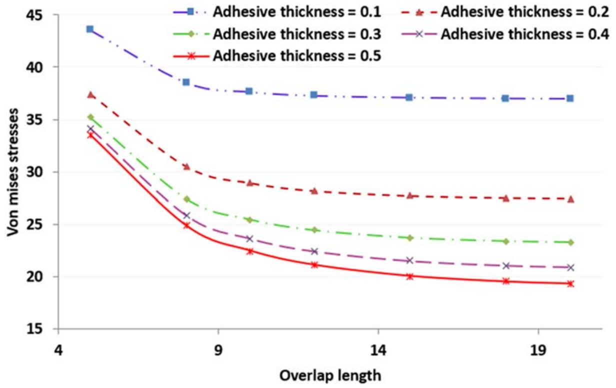

Fig. 11 Plot of von mises stresses for steel pipe and MWCNT epoxy adhesive under torsion loading

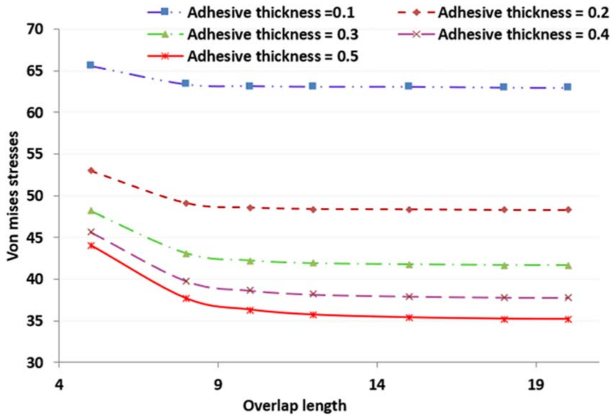

Fig. 12 Plot of von mises stresses for aluminum pipe and MWCNT epoxy adhesive under torsion loading

compared for steel and aluminum pipe with MWCNT epoxy adhesive (Fig. 15). Higher normalized stresses are produced for aluminum pipe with MWCNT epoxy adhesive. It is concluded from the results that the stress reduces when the thickness of the adhesive is increased. Maximum shear stresses are obtained for thinner adhesive.

To determine the improvement in the strength of epoxy adhesive by using MWCNT as filler, a comparison of tubular steel pipe joint with epoxy adhesive and MWCNT epoxy adhesives is done.

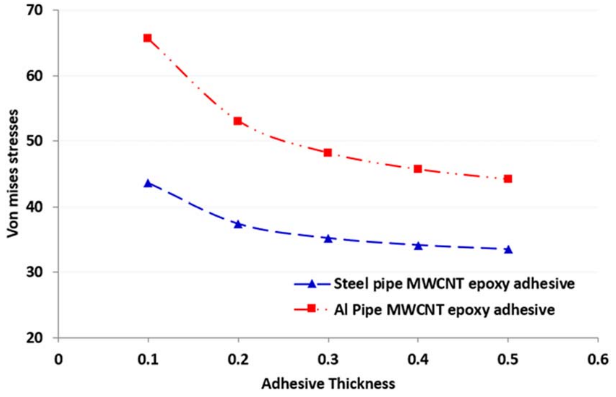

Fig. 13 Comparison of von mises stresses for steel and aluminum pipe with MWCNT epoxy joint under torsion loading

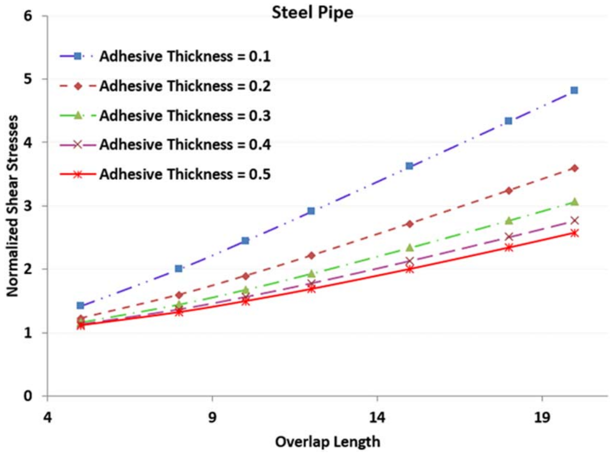

Fig. 14 Normalized shear stresses for steel pipe with MWCNT epoxy joint under torsion loading

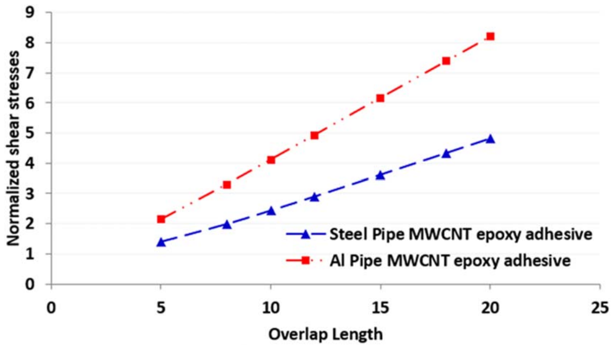

Fig. 15 Comparison of normalized shear stresses for steel pipe and aluminum pipe under torsion loading

Figures 16 and 17 show the comparison of von mises stresses and normalized shear stresses for epoxy and MWCNT-filled epoxy adhesive. The values for von mises stresses and normalized shear stresses obtained for MWCNT epoxy adhesive are greater than for epoxy adhesives

The result obtained from the present finite element model is validated with Lubkin and Reissner's model as shown in Fig. 18. The pattern of the graph shows that the mesh generated in the finite element model is quite suitable for obtaining accurate results. The values of stresses in the middle of the thickness of the adhesive are considered for comparing with Lubkin and Reissner's model [26].

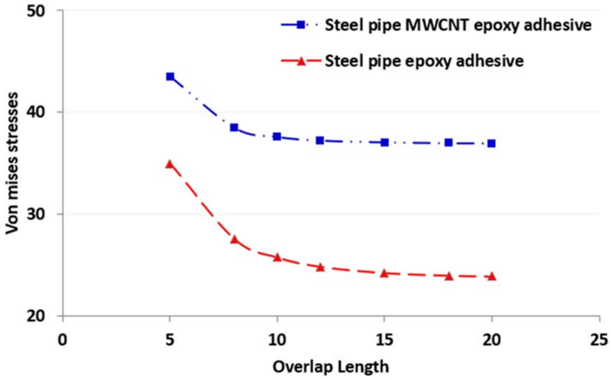

Fig. 16 Comparison of von mises stresses for epoxy adhesive joint and MWCNT epoxy adhesive joint for steel pipe under torsion loading

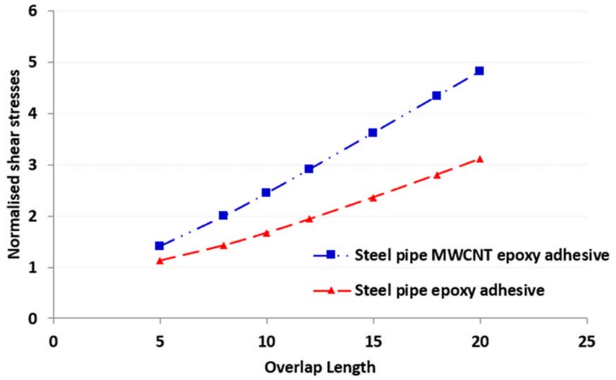

Fig. 17 Comparison of normalized shear stresses for epoxy adhesive joint and MWCNT epoxy adhesive joint for steel pipe under torsion loading

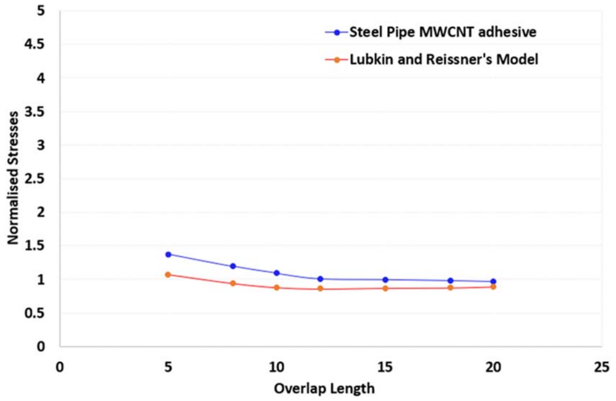

Fig. 18 Comparison of present result with Lubkin and Reissner's model [26]

By performing parametric analysis to study the effect of the thickness, overlap length, material properties of adherends and thickness of adhesives, the adhesive joint can be optimized. The simulation used for adhesive joints can be helpful to a pipe designer for optimizing joints in piping applications.

5 Conclusion

- MWCNT-reinforced epoxy adhesives are used for enhancing the strength of tubular joints in pipe sections. The model is developed using a continuum modeling approach. Various parameters such as adhesive thickness, overlap length, and pipe material along with different loading conditions are analyzed. To understand the factors affecting the adhesive joint, tensile and torsional loading conditions are considered.
- From the results, it is observed that as the adhesive thickness is increased, the maximum stresses at the end of the joint decrease. The plot of decrease in maximum stresses smoothens toward a constant curve after a certain overlap length. The maximum stress at the joint-free end region is a critical parameter that determines the strength of the joint. The failure would initiate from the joint free end regions due to high-stress concentration.
- A comparison of von mises stresses in MWCNT-reinforced epoxy adhesive and epoxy adhesive indicates that the adhesive joint strength increases with the use of MWCNT filler. Therefore, MWCNT-filled epoxy joints provide higher bonding strength than epoxy joints.
- In the case of torsional loading, higher stresses are observed in aluminum pipe adhesive joint in comparison to steel pipe joint. Higher deformation in aluminum pipe joints results from the fact that aluminum pipes are less rigid in comparison with steel. Also, the less rigid pipes twist more at both sides of the joint, in comparison with more rigid pipes. The results reveal that the aluminum joints show lesser strength in comparison with the steel joints; however, for making strong and reasonable aluminum joints, thick adhesive joint would be required.
- A linear pattern of results is observed for normalized shear stresses for various thickness variations. With the increase in overlap length, the normalized shear stresses increases for various adhesive thickness. A higher value of normalized stresses is observed for the smaller thickness of adhesive pipes. Normalized shear stresses are compared for steel and aluminum pipe with MWCNT epoxy adhesive. Higher normalized stresses are produced for aluminum pipe with MWCNT epoxy adhesive. It can be concluded from the results that the rate of change of stresses decreases with the increase in adhesive thickness. The highest shear stresses are found in the case of thin adhesive.
- The result obtained from the present finite element model is validated with Lubkin and Reissner's model. The present results are observed to be in good agreement with the analytical results.

The simulation technique is found to be an efficient and effective method for designing joints for piping applications.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent is not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

L = adhesive length
T = applied torsion
D_{av} = average diameter
D_{p1o} = pipe-1 outer diameter
τ_m = mean shear stresses

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