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Effect of FRP parameters in strengthening the tubular joint for offshore structures

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Abstract. This paper presents the strengthening of tubular joint by wrapping Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). In this study, total number of layers, stacking sequence and length of wrapping are the different parameters involved when fiber reinforced polymers (FRP) composites are used for strengthening. For this, parameters where varied and results were compared with the reference joint. The best stacking sequence was identified which has the highest value in ultimate load with lesser deflections. For determining the best stacking sequence, numerical investigation was performed on CFRP composites; length of wrapping and number of layers were fixed. Later, the studies were focused on CFRP and GFRP strengthened joint by varying the total number of layers and length of wrapping. An attempt was done to propose a parametric equation from multiple regression analysis, which can be used for CFRP strengthened joints. Hashin failure criteria was used to check the failure of composites. Results revealed that FRP was having a greater influence in the load bearing capacity of joints, and in reducing the deflections and stresses of joint under axial compressive loads. It was also seen that, CFRP was far better than GFRP in reducing the stresses and deflection.

Keywords: tubular joints; CFRP; GFRP; numerical investigation; Hashin failure; multiple regression

1. Introduction

Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) are used in retrofitting of structures and strengthening a new one. Advantages of fiber reinforced polymer (FRP) include high strength to weight ratio and controlled anisotropy. Behavior of FRP is entirely different as that of metals, because of its orthotropic property. Due to its ease of application, FRP can be used in aerospace, automotive, civil construction and marine field.

In early 90s strengthening of concrete structures by FRP were carried out, later this technique was used to strengthen the steel structure. Later in the 20th century, FRP were used to strengthen steel bridges, and also used for repairing corrosive steel. Sen (2003) had done external wrapping of

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FRP to repair damaged concrete structures by corrosion and found that the performance of the column after wrapping was excellent. Many experiments and field study were carried out by strengthening with FRP for steel and concrete structures, this led to the conclusion that it was an efficient method for increasing its durability. Chalmers (1991) had used FRP in the design and production of marine structures. He discussed about the design principles, methods and material properties, production techniques and applications.

Zhao and Zhang (2007), Teng *et al.* (2012) and Gholami *et al.* (2013) had studied on the strengthening of steel structures using CFRP and found that it was an efficient method. Jones and Civjan (2003) had found that fatigue life of steel can be increased by wrapping CFRP. Al-saidy *et al.* (2004) had done studies on CFRP plates, and found that the strength of damaged beams can be fully restored to its original strength by wrapping with CFRP. Ghafoori and Motavalli (2015) had found that strengthening with CFRP increased the yield and ultimate load of steel beams. Narmashiri and Mehramiz (2016) had shown that by increasing the number of CFRP layers wrapped on steel hollow pipe sections the load bearing capacity can be increased. Haedir and Zhao (2011) shown that, CFRP sheets delayed the buckling of steel tube while the bare steel tube buckled at its ultimate load. By wrapping HSS with GFRP, they found that when the transverse load is applied to the joint, its bearing capacity got increased. Lesani *et al.* (2013, 2014, 2015) had done numerical and experimental work on GFRP wrapped tubular T-joint, they explained about the specimen preparation, wrapping of FRP and length of FRP to be reinforced. Fu *et al.* (2016) wrapped CFRP sheets onto a tubular joint and concluded that it can only delay its primary failure mode. He and Xian (2016) had done studies on delamination of CFRP-steel joints with linear and nonlinear adhesives. They found the different failure for CFRP delamination and presented its failure modes.

A thorough literature review has been carried out in the area of FRP strengthening in steel and concrete structures. An experimental investigation was also performed by the authors on the behavior of CFRP strengthened tubular joints, and found that the stresses and deflections were less compared to the non-wrapped joint under the same loads Prashob *et al.* (2017). Neser (2017) had done research on the future trends of FRP applications in marine industry in terms of materials, production methods and environmental issues. Islam (2018) had used FRP to strengthen a marine riser for an offshore structure and also designed a composite marine riser. The researcher found that this technique can be successfully employed in the offshore industry for strengthening a marine riser.

This paper deals with the comparison of CFRP and GFRP wrapping technique used for strengthening a tubular joint under axial compressive load. So far no attempt was made to compare CFRP and GFRP for the strength assessment in tubular joints. Numerical investigation was performed for the joint by wrapping with CFRP and GFRP, to find the optimum design in FRP wrapping. The different parameters considered were: the wrapping length, number of layers in wrapping, orientation of layers and failure of composites employing Hashin criteria. A parametric equation was developed to find the ultimate load of CFRP strengthened joints using multiple regression analysis. The results of the findings can be used as a reference for wrapping FRP on a tubular joint.

2. Details of tubular joint specimen

The tubular joint dimensions for the numerical investigation were taken from the experiments performed by the authors Prashob *et al.* (2017) in their previous study. Table 1 shows the particulars of the tubular T-joint. Fig. 1 shows the schematic diagram of the tubular joint defining the salient points and its dimensionless parameters (X/√DT). Lesani *et al*. (2013) had defined a dimensionless parameter called effective chord shell width X, which is the distance measured from the tubular joints plug center towards the chord end. RΦ is the distance measured from the plug center towards the chord quadrants on the curved surface in the hoop direction. A tubular joint strengthened with CFRP is shown in Fig. 2.

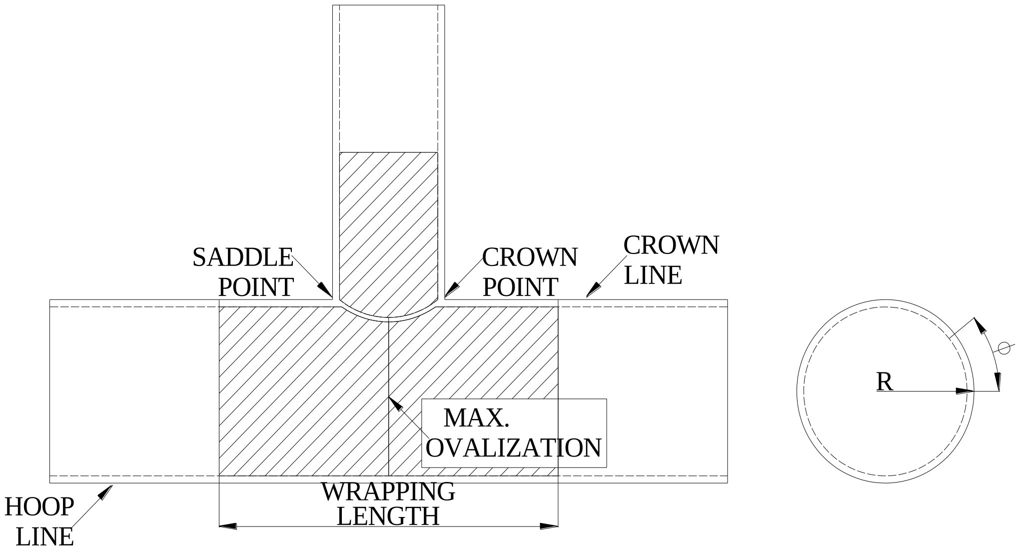
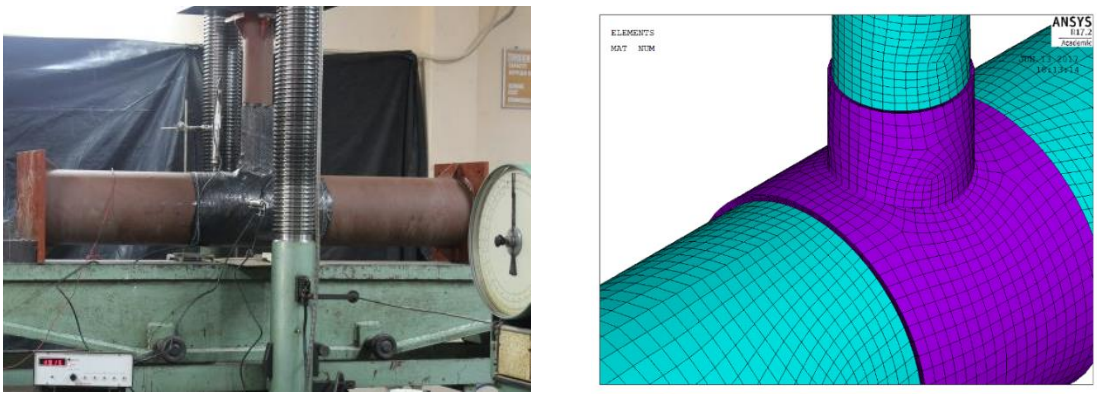


Fig. 1 Tubular joint terminology



(a) Experimental Model (Prashob *et al.* 2017) (b) Numerical Model

Fig. 2 CFRP strengthened tubular joint

Table 1 Tubular Joint Property

Details	D	d	T	t	L	θ	α	β	γ	τ	σ_y	σ_u
TJ / TJW	273.1	114.3	9.27	8.56	1740	90°	12.72	0.42	14.73	0.92	451	522

Table 2 Elastic constants of CFRP and GFRP Bhagwan *et al.* (2006)

	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{23}	ν_{13}	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)
CFRP	138	8.96	8.96	0.3	0.33	0.3	7.1	3.37	7.1
GFRP	38.6	8.27	8.27	0.26	0.33	0.26	4.14	3.1	4.14

Table 3 Strengths of CFRP and GFRP Christensen (2013)

	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_{12} (MPa)	S_{23} (MPa)	S_{13} (MPa)
GFRP	1062	610	31	118	72	32.33	72
CFRP	1447	1447	51.7	206	93	55	93

Where TJ, Tubular Joint; TJW, Wrapped Tubular Joint; D, chord outside diameter; d, brace outside diameter; T, chord wall thickness; t, brace wall thickness; L, length of chord between constraints; θ, angle between brace and chord; chord length parameter (2L/D); diameter ratio (d/D); chord thickness ratio (D/2T); wall thickness ratio (t/T); σ_y, chord yield strength; σ_u, chord ultimate strength.

3. Properties of composite material

Composites are constituents consisting of two or more chemically distinct parts on a macro scale. Fiber is the reinforcing phase, which is stronger, and due to their smaller cross sections it should be embedded in a matrix which is a continuous phase to form the composites. Tables 2 and 3 show the elastic constants and strengths of CFRP and GFRP. Longitudinal and transverse directions are denoted by 1 and 2, where 3 denote the axis perpendicular to the longitudinal and transverse axes. Longitudinal and transverse strengths are denoted by X in the fiber direction and Y perpendicular to the fiber direction, S denotes its shear strength, tension and compression are denoted by T and C. Where Ei, modulus of elasticity along axis; ν_{ij}, poison's ratio that corresponds to a contraction in direction j when an extension is applied in direction i; G_{ij}, shear modulus in direction j on the plane whose normal is in direction i.

Where X, longitudinal strength (fiber direction); Y, transversal strength (perpendicular to fiber direction); Sij, shear strength in direction j on the plane whose normal is in direction i; T and C denotes tension and compression.

4. FRP wrapping technique

The wrapping length, no of layers in wrapping and orientation of layers are the three important parameters considered when FRP is used for strengthening. Preliminary analysis was performed on a reference tubular joint without any wrapping. Detailed procedure for wrapping of CFRP on a tubular joint can be seen in Prashob *et al.* (2017). When wrapping this tubular T joint, plug area was avoided due to the presence of brace member.

To identify the best stacking sequence, other two parameters need to be fixed. Wrapping length of chord was fixed to 500 mm and wrapping length of brace was kept as half the wrapped length of chord. Second parameter considered was the number of layers, which was taken as four. Selected configurations for the study are [0/45/0/-45], [0/-45/0/45], [0/45/0/45] and [0/-45/0/-45]. To determine the best stacking sequence, a preliminary investigation was carried by strengthening the joint with CFRP. Comparison was then made with the reference joint and the four wrapped joints.

5. Numerical investigation

For mathematical modeling of the tubular joint and FRP, Shell281 element capable of modeling curved structures was used Ansys inc. (2010). This element has got eight nodes with six degrees of freedom. Wrapping of FRP on steel surface was taken as a contact analysis problem. Some assumptions for modeling the tubular joint were made i.e., welds at the intersection, and plates at the chord ends were not modeled. Fine mesh was made in the brace-chord intersection regions, while mesh size were made coarser as it reached the chord ends. Translations were arrested at the chord ends, while rotations were permitted. For the brace member only vertical displacements were allowed. Dimensions of the tubular joint were the same as that of the experiments performed by the authors.

Tubular joint was divided into different sections; the FRP wrapped region, the brace-chord intersection and the non-wrapped area of the joint. The plug area of tubular joint was not modelled with FRP. Arc length method was used for this non-linear analysis in which the arc length termination criteria and convergence criteria was used.

6. Results and discussions

The results in the following sections involve comparison of chord surface deflection, ovalization, and stresses of the FRP wrapped joint with the reference joint. Hashin (1980) failure criteria for composites were employed to determine the failure pattern of CFRP and GFRP composites.

6.1 Orientation of layers

In this study, the wrapping length was kept constant to 500mm ($10\sqrt{DT}$), and the numbers of layers were fixed to four. Altering the ply orientation, three different configurations of CFRP were selected, i.e., [0/45/0/-45], [0/-45/0/45] and [0/45/0/45]. The vertical surface deflections along the crown line and ovalization along the hoop line for all these four cases were compared with the reference joint. Fig. 3 shows a basic wrapping sequence of a four layer FRP.

Comparison of these four cases with the reference joint shows that by wrapping the joint with CFRP, the deflection in the crown line was reduced by 54% and the ovalization to 41%. [0/-45/0/45] was the best sequence which gives a lesser deflection for the tubular joint, so this sequence was selected for further studies. Chord surface displacement and ovalization of the four sequences were compared with the reference joint and shown in Figs. 4 and 5.

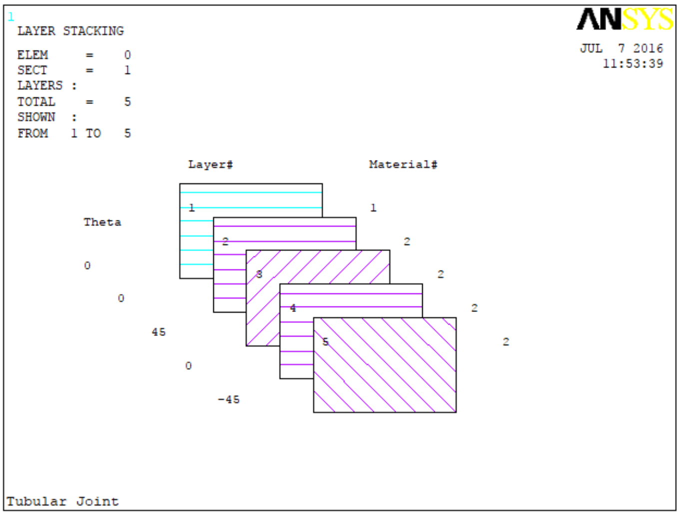


Fig. 3 An orientation of four layers in wrapping

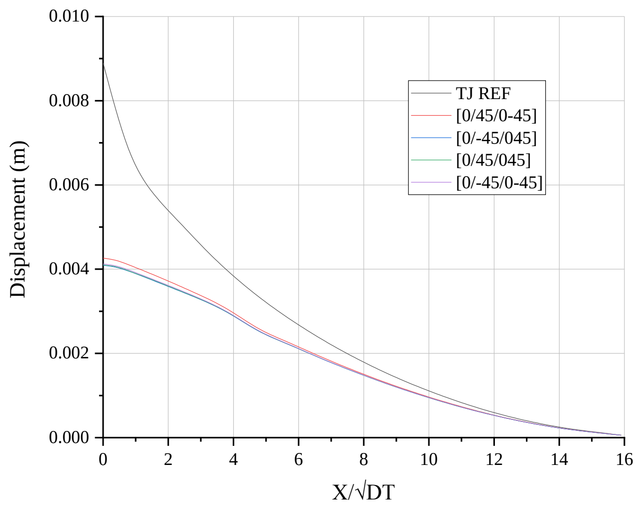


Fig. 4 Displacement along crown line for orientation of layers

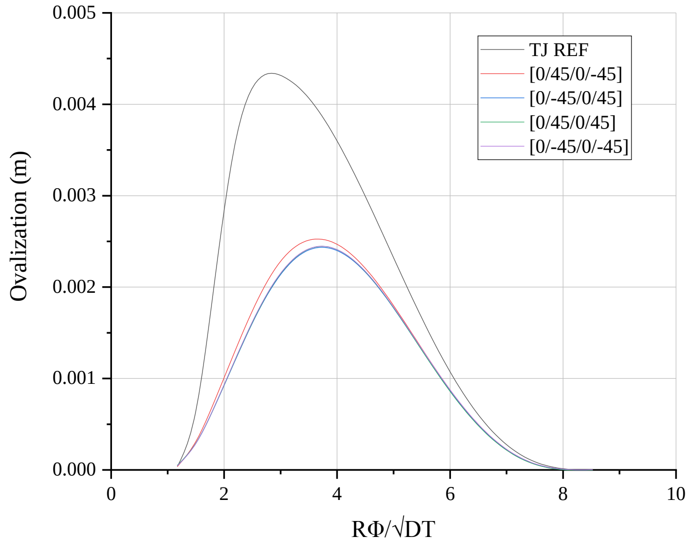


Fig. 5 Displacement along hoop line for orientation of layers

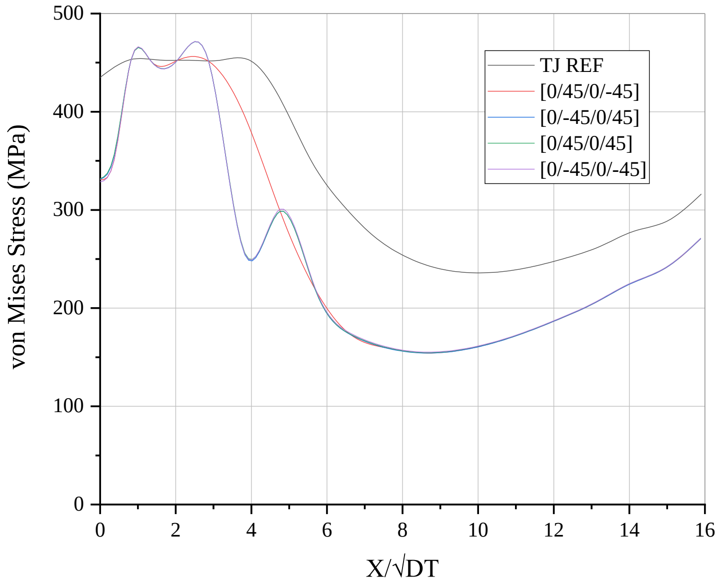


Fig. 6 von-Mises stress along the crown line for orientation of layers

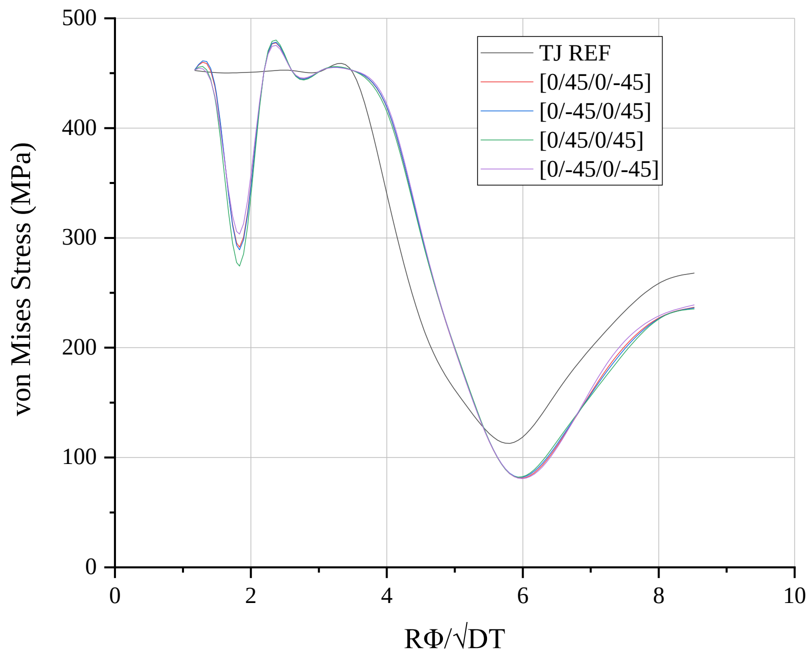


Fig. 7 von-Mises stress along the hoop line for orientation of layers

von-Mises stress is defined as the stress at which the materials start yielding. By wrapping CFRP composites, it was found that the von-Mises stress value got reduced at the crown line after the wrapping area. Figs. 6 and 7 shows the von-Mises stresses acting on the joint at the crown line and hoop line location for different orientation of layers. Much difference in stress value was not observed in the hoop line.

6.2 Number of layers

For the different orientation of layers mentioned in the above subsection, the configuration which takes maximum ultimate load was considered for layers 8 and 12. In this section, the parametric study involves the comparison of CFRP and GFRP with 4, 8 and 12 layers with the reference joint.

- [0/-45/0/45]
- [(0/-45/0/45)2]
- [0/-45/0/45/0/-45/0/45/0/-45/0/45]

Following the above configuration, six parameters were chosen, the wrapping length for each case was fixed to 500 mm. The six parameters are:

- 4C Layers - 4 layer of CFRP following [0/-45/0/45] configuration
- 8C Layers - 8 layer of CFRP following [(0/-45/0/45)2] configuration

- 12C Layers - 12 layer of CFRP following [0/-45/0/45/0/-45/0/45/0/-45/0/45] configuration
- 4G Layers - 4 layer of GFRP following [0/-45/0/45] configuration
- 8G Layers - 8 layer of GFRP following [(0/-45/0/45)2] configuration
- 12G Layers - 12 layer of GFRP following [0/-45/0/45/0/-45/0/45/0/-45/0/45] configuration

Among CFRP and GFRP, 12 layers of wrapping provide less deflection in the crown and hoop line. The deflection of CFRP wrapped joint when compared to the reference joint shows that the surface deflection reduces by 54%, 60% and 65% and ovalization reduces by 44%, 54% and 63% for a 4, 8 and 12-layer wrapping. The deflection of GFRP wrapped joint compared with the reference joint, shows that the surface deflection reduces by 47%, 53% and 58% and ovalization reduces by 31%, 40% and 48% for a 4, 8 and 12-layer wrapping.

Stresses were maximum in wrapped length region of the reference joint, but when CFRP and GFRP was wrapped this stresses gets reduced. Figure 8 shows the chord surface displacement along the crown line and Fig. 9 shows the ovalization along the hoop line for different number of layers.

From the comparison of CFRP and GFRP, it can be seen that 8 layer of GFRP wrapping and 4 layer of CFRP wrapping has got almost the same surface displacement and ovalization. By wrapping 12 layers of CFRP, stresses can be reduced to a greater extent in the crown line than 4 and 8 layers of CFRP. 8 layers of CFRP wrappings are better than 12 layers of GFRP. Figs. 10 and 11 shows the von-Mises stresses acting on the joint at the crown line and hoop line location for number of layers.

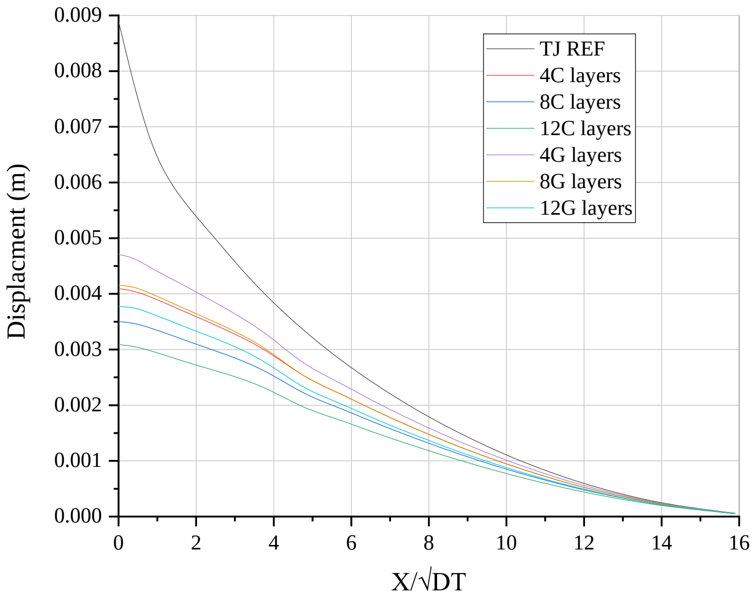


Fig. 8 Displacement along crown line for number of layers

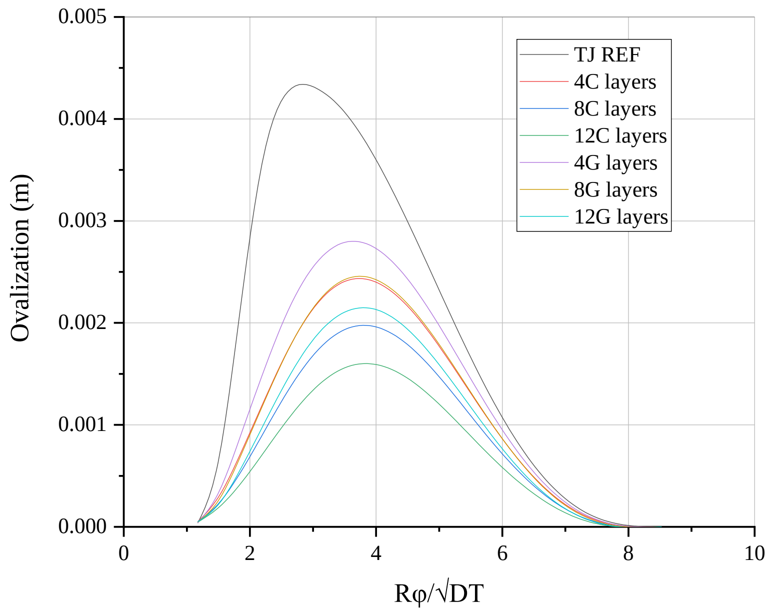


Fig. 9 Displacement along hoop line for number of layers

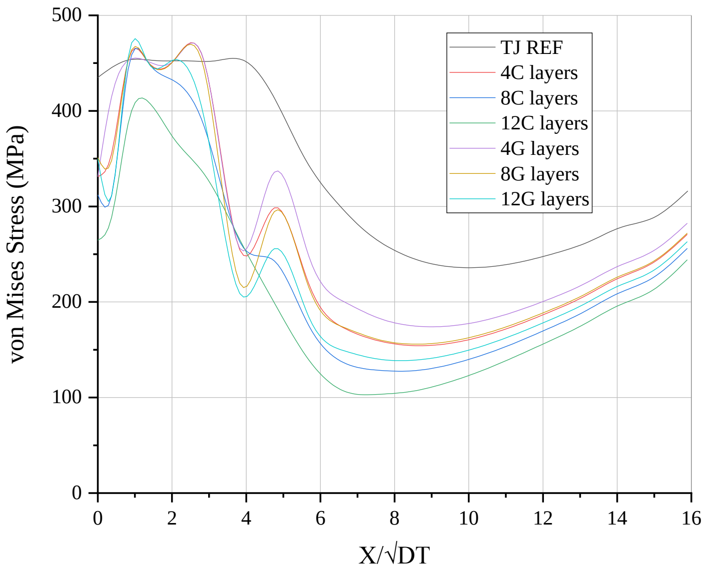


Fig. 10 von-Mises stress along crown line for number of layers

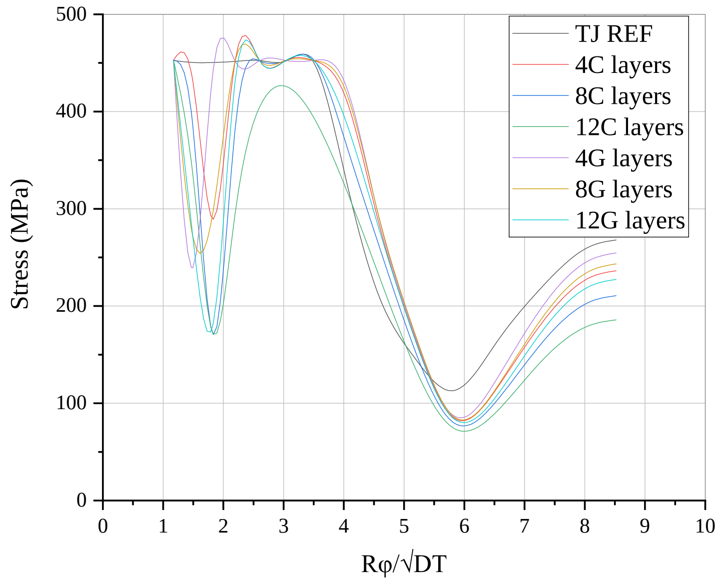


Fig. 11 von-Mises stress along hoop line for number of layers

6.3 Length of wrapping

For wrapping the tubular joint both CFRP and GFRP was considered by changing the total reinforcement length from 250 mm to 1000 mm (5√DT to 20√DT). In this study the layers were fixed to four numbers and the orientation was [0/-45/0/45]. Parameters selected for this study are:

- 4C 250 - 4 layer of CFRP with 250 mm wrapping length
- 4C 500 - 4 layer of CFRP with 500 mm wrapping length
- 4C 750 - 4 layer of CFRP with 750 mm wrapping length
- 4C 1000 - 4 layer of CFRP with 1000mm wrapping length
- 4G 250 - 4 layer of GFRP with 250 mm wrapping length
- 4G 500 - 4 layer of GFRP with 500 mm wrapping length
- 4G 750 - 4 layer of GFRP with 750 mm wrapping length
- 4G 1000 - 4 layer of GFRP with 1000 mm wrapping length

Fig. 12 shows the four different configurations by varying the total wrapping length. Figs. 13 and 14 show the chord surface deflections along the crown line and ovalization along the hoop line for different wrapping length.

By wrapping CFRP composites, it was found that for 4, 8 and 12 number of layers ovalization can be reduced to 44%, 54% and 63%. For 4, 8 and 12 number of layers the chord surface line vertical displacement reduces to 54%, 60% and 65%. By using CFRP, chord surface displacements were reduced by 13%, 15% and 18% than that of GFRP for 4, 8 and 12 layers. The ovalization of CFRP was lesser than that of GFRP by 13%, 19% and 25%.

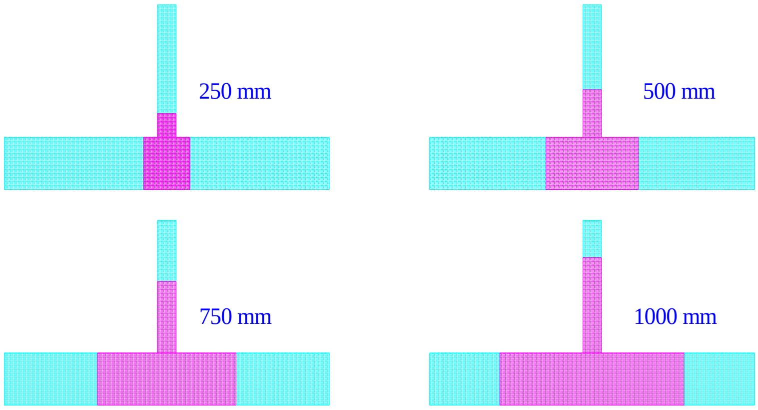


Fig. 12 CAD model of tubular joint with different wrapping length

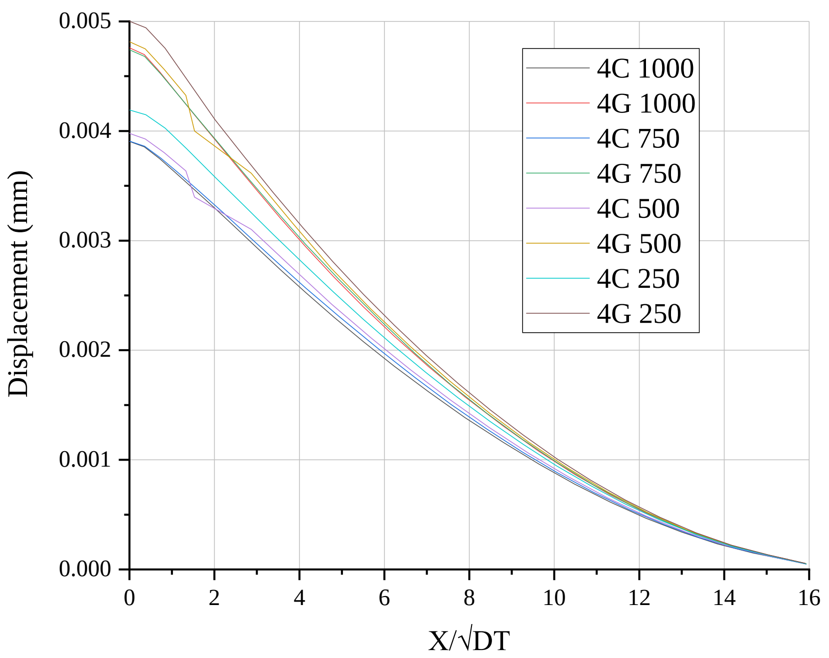


Fig. 13 Displacement along crown line for different wrapping length

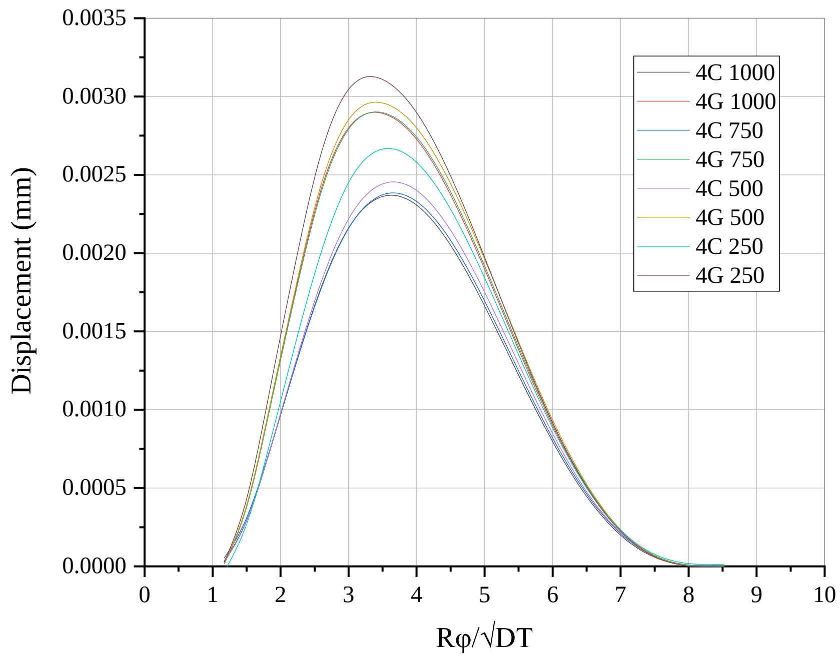


Fig. 14 Displacement along hoop line for different wrapping length

6.4 Parametric study

Parametric study was conducted on CFRP wrapped tubular joints to determine the ultimate load. Finite element model was used to capture the behavior of CFRP wrapped tubular joint and the non-wrapped joint. The load bearing capacity of these joints was determined using finite element analysis. Parameters considered for the multiple regression analysis are by varying the number of layers and wrapping length for brace and chord members. The wrapping sequence chosen was one with less deflection.

Five non-dimensional variables were defined for this parametric study (L_c/L_{cw}), (E_{frp}/E_s), (f_{frp}/f_s), (N_c) and (N_b). Where, L_c is the length of chord member, L_{cw} is the length of CFRP wrapping on chord member, E_{frp} is the modulus of FRP sheet, E_s is the modulus of steel material, f_{frp} is the yield stress of FRP sheet, fs is the yield stress of steel material, N_c is the number of layers wrapped onto chord member and N_b is the number of layers wrapped onto brace member.

Increase in load bearing capacity was evident for CFRP wrapped joints; based on this load bearing capacity, an equation was developed (Eq. (1))

$$\Delta = \frac{\left(F_{uFRP} - F_{uREF}\right)}{\left(F_{uREF}\right)} \times 100\% \tag{1}$$

Where Δ is the increase in joint capacity, F_{uFRP} is the ultimate load taken by the FRP strengthened tubular joint, and F_{uREF} is the ultimate load taken by the reference tubular joint. L_{cw} and L_{bw} are expressed by (Eqs. (2) and (3)). Fig. 15 shows a schematic diagram of CFRP wrapped on a tubular joint.

$$L_{cw} = 2(L_1 + L_2) = k\sqrt{DT} + d \tag{2}$$

$$L_{bw} = (L_1 + L_2) = (k\sqrt{DT} + d)/2 \tag{3}$$

Where the value of k lies between 7.67 and 12.63.

Based on the numerical studies carried out, a multiple regression was done to propose a parametric equation for the FRP strengthened T-joints. Five non-dimensional variables were defined in this equation L_c/L_{cw}, E_{frp}/E_s, f_{frp}/f_s, N_c and N_b. For providing the data for multiple regression analysis, a set of 120 models were investigated. For different wrapping length, a 3-D graph was plotted, from this curve, a parametric equation was developed which was the product of the above non-dimensional variables. After conducting numerical studies on different additional models, an equation was proposed. Numerical values used for regression analysis is shown in Table 4.

After the regression analysis, values of constants were determined and validity range is defined for the proposed parametric equation.

The validity is as follows:

$2.35 \le L_c/L_{cw} \le 3.52$, $0 \le N_c \le 12$, $0 \le N_b \le 12$, $0.18 \le E_{frp}/E_s \le 0.97$, $2.36 \le f_{frp}/f_s \le 3.42$.

Based on the numerical investigation, the parametric equation can be expressed as the summation of the above non-dimensional terms as in (Eq. (4)).

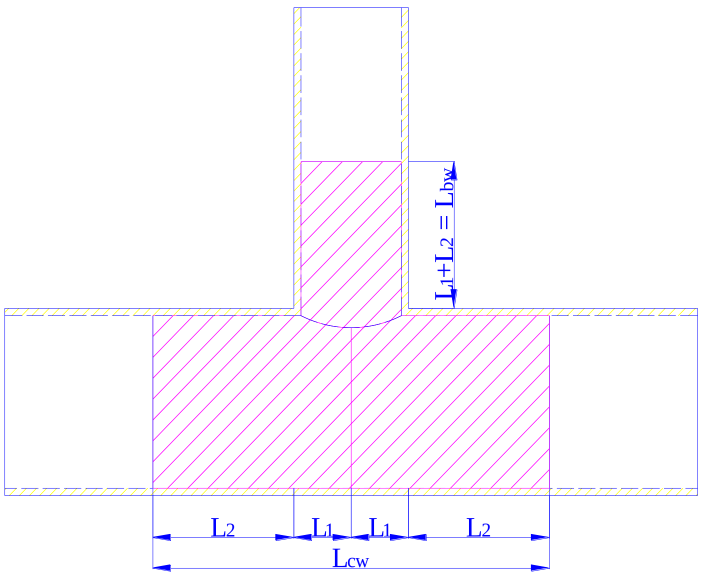


Fig. 15 Wrapping of FRP sheets on tubular joint – schematic view

$$\Delta_{frp} = a.(L_c / L_{cw})^b.(E_{frp} / E_s)^c.(f_{frp} / f_s)^d.(N_c)^e.(N_b)^f \quad (4)$$

Δ_{frp} is the increase of joint capacity after FRP wrapping, a, b, c, d. e and f are the constants used to fit the curves. After performing the multiple regression analysis, the equation can be expressed as in (Eq. (5)).

$$\Delta_{frp} = 0.008.(L_c / L_{cw})^{0.017}.(E_{frp} / E_s)^{0.138}.(f_{frp} / f_s)^{0.516}.(N_c)^{1.75}.(N_b)^{0.091} \quad (5)$$

Fig. 16 shows the effect of FRP wrapping on the capacity of tubular joints. After obtaining $\Delta_{frp,}$ the ultimate load of the joint can be calculated from (Eq. (6)).

$$F_{uFRP} = (1 + \Delta_{frp} / 100).F_{uREF} \quad (6)$$

F_{uREF} can be calculated from any of the standard design rules such as API code.

Table 4 Numerical values used for regression analysis

FRP Material	FRP Material Properties			
	E_{frp} (GPa)	f_{frp} (MPa)	E_{frp}/E_s	f_{frp}/f_s
Carbon-epoxy AS/H3501	138	1447	0.657	3.22
Carbon-epoxy T300/N5208	181	1500	0.862	3.33
Carbon-epoxy IM6/epoxy	203	3500	0.967	3.42
Glass-epoxy E-glass-epoxy	38.6	1062	0.184	2.36

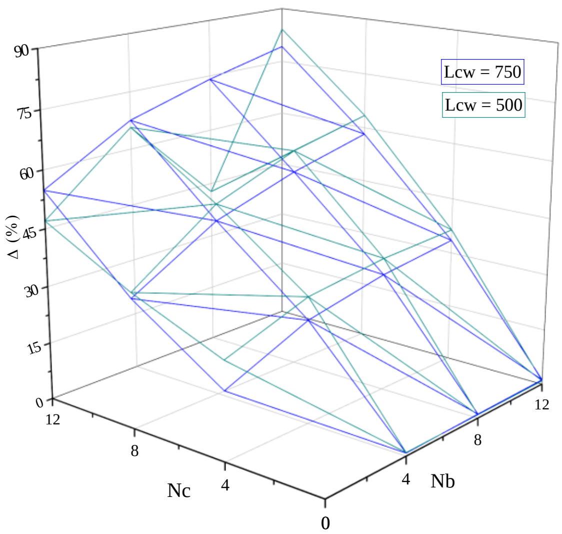


Fig. 16 Effect assessment of L_{cw} on the tubular joint (E-glass-epoxy)

Table 5 Hashin Failure of CFRP and GFRP laminates

Types of Failure	CP	MO	SP	WL
TFF	C G	C	-	-
CFF	4G	-	-	-
TMF	4CG 8CG 12CG	4CG 8CG 12CG	4CG 8CG 12CG	8G 12G
CMF	4CG 8CG 12CG	4CG 8CG 12CG	4CG 8CG 12CG	4C 8CG 12CG
ITF	4CG 8CG 12CG	4CG 8CG 12CG	4CG 8CG 12CG	8G 12G
ICF	4CG 8CG 12CG	-	-	-

*Where TFF, Tensile Fibre Failure; CFF, Compressive Fibre Failure; TMF, Tensile Matrix Failure; CMF, Compressive Matrix Failure; ITF, Interlaminar Tensile Failure; ICF, Interlaminar Compressive Failure; CP, Crown Point; SP, Saddle Point; MO, Maximum Ovalization Area; WL, Wrapping Length; C, CFRP failure; G, GFRP failure; xX, failure in XFRP for x number of layers

6.5 Hashin failure criteria

These are interacting failure criteria developed for unidirectional composites to evaluate the different type of failure. It involves six different failure modes these failure indices are related to fiber and matrix failures. For each interval of loading, stresses were noted at the salient points till its ultimate load. These stresses where then used in the failure criteria to determine its failure. Figure 1 shows the four different locations identified as saddle point, crown point, wrapping length and maximum ovalization area. Discussion on the details of six different failure modes which includes fiber and matrix failure are discussed.

Tensile fibre failure occurred at crown point and maximum ovalization area in CFRP strengthened joint. In GFRP strengthened joint the failure occurred only at the crown point. Though tensile fibre failure occurred at the maximum ovalization area in CFRP, ovalization of CFRP strengthened joint was less compared to GFRP strengthened joint.

No compressive fibre failure occurred for CFRP, but compressive fibre failure occurs at crown point location for the ultimate load in case of 4 layers of GFRP. By increasing the number of layers, compressive fibre failure can be avoided in GFRP composites.

Compressive and tensile matrix failure occurred at all the salient points in GFRP strengthened joint except for the 4 layers at the wrapped length region. This is due to the less number of layers present which may resist matrix failure. But for CFRP, compressive matrix failure occurred at all the salient points while tensile matrix failure didn’t happen at the wrapped length region.

Inter laminar tensile failure occurred at all the salient points in GFRP strengthened joint except for the 4 layers at the wrapped length region. Less number of layers prevents the GFRP strengthened joint against inter laminar tensile failure. But for CFRP, inter laminar tensile failure didn’t happen at the wrapped length region for all the layers.

Inter laminar compressive failure occurred only at the crown point location for both CFRP and GFRP strengthened joint. A detailed failure analysis of Hashin criteria is also presented in Table 5.

7. Conclusions

From the parametric studies conducted by comparing CFRP and GFRP it can be concluded that:

- By changing the orientation of layers much change in deflection cannot be seen. So, the orientation of layers is not an important parameter in strengthening when FRP composites are considered. When wrapped with CFRP, the deflection in the crown line was reduced by 54% and the ovalization to 41%.
- For CFRP wrapped joint, the chord surface deflection and ovalization was less than that of GFRP wrapped joint.
- By increasing the layers, deflections got reduced for both CFRP and GFRP. 12 layers of GFRP and 8 layers of CFRP had almost the same deflection. A wrapping length of 250 mm for CFRP produces less chord surface deflection and ovalization than a 1000 mm GFRP wrapping. From this, it can be concluded that wrapping of 4 layer of CFRP is better than wrapping with 12 layers of GFRP.
- For the optimum design, a wrapping length of $10\sqrt{DT}$to $15\sqrt{DT}$ is suggested and an ideal number of layers to 12.

8. Future scope

This work can be extended to other joints and other configuration loadings. By using the regression equation, it can be used to predict the ultimate load of the tubular T-joint strengthened with FRP.

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