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Failure Analysis of Glass Fiber Reinforced Plastic Pipes and Crack Inlet Opening with *J*-Integral Criteria Under Internal Pressure

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ABSTRACT: Inspection of the damage caused by glass fiber reinforced plastic tubes, which are subjected to internal pressure due to different angles that can be exposed under the creep phenomenon in the long-term, has not been sufficiently considered. Therefore, in the present research, it has been tried to simulate the fracture by Tsai-Wu, Hashin criterions and the crack inlet opening with *J*-integral criterion in these pipes with different layering at internal pressure using finite element method and ABAQUS. The results of this research show that the fibers under compressive and tensile stress and the resin of tube have not fractured by tensile stress, but the fracture has occurred in the resin of composite tubes that were under pressure. According to the results, the fracture index is less than one for each of ten layers, when layering angle varies from $[(\pm 30)_5]$ to $[(\pm 60)_5]$, but the fracture index is more than one, layering decoration for $[(\pm 70)_5]$, $[(\pm 80)_5]$ and $[(\pm 90)_5]$ of composite tubes has been fractured. However, the value of the stress intensity factor was immediately decreased for layering decoration angle of $[(\pm 55)_5]$, but this factor has improved when layering angle increased.

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1. INTRODUCTION

If metal pipes are buried less than freezing depth underground due to extensive thermal expansion and contraction, they undergo unwanted deformations and phenomena that affect the structural interaction of the soil. Because the potential difference between the pipe and the surrounding soil in the underground metal pipes causes corrosion in this type of pipes results in leakage of metal tubes from the vulnerable parts. While Glass Fiber Reinforced Composite Pipes (GRP) that play a major role in engineering structures in the current plumbing systems are able to withstand difficult and complex conditions, such as thermal, humidity, radiation, tensile environments, and in particular against a wide range of fluids, such as chemicals, industrial and petroleum. Therefore, they do not require additional insulation from outside or inside. On the other hand, these pipes, despite their low weight, have a lot of strength, so the sturdy structure of these pipes, their high corrosion resistance, as well as their low or light weight make it a great alternative to metal and concrete pipes [1].

2. FRACTURE MECHANICS EQUATIONS

The value of the I_F fracture index is calculated using the Tsai-Wu criterion [2] from Eq. (1)

$$I_F = F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\sigma_{12}^2 + \\ + 2F_{12}\sigma_{11}\sigma_{22} \tag{1}$$

where $F_1, F_2, F_{11}, F_{22}, F_{66}$ and F_{12} in Eq. (1) can be calculated from Eq. (2).

$$\begin{gathered} F_1 = \frac{1}{X_t} + \frac{1}{X_c}, \quad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c}, \quad F_{11} = -\frac{1}{X_t X_c}, \\ F_{22} = -\frac{1}{Y_t Y_c}, \quad F_{66} = \frac{1}{S_{12}^2}, \\ F_{12} = \frac{1}{2\sigma^2}\left(1 - [F_1 + F_2]\sigma - [F_{11} + F_{22}]\sigma^2\right) \end{gathered} \tag{2}$$

Hashin proposed two criteria for yielding of fibrous-reinforced layer composites, in which the fibers and texture fracture were independent together. These two criteria include the following four modes [3]:

1- Fracture index of composite pipe fiber under stretching (F_f^t).
2- Fracture index of composite pipe fiber under pressure (F_f^c).
3- Fracture index of the matrix composite pipe under stretching (F_m^t).
4- Fracture index of the matrix composite pipe under pressure (F_m^c).

$$\begin{aligned} &if \quad \sigma_{11} \geq 0; \qquad F_f^t = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2}, \\ &if \quad \sigma_{11} < 0; \qquad F_f^c = \left(\frac{\sigma_{11}}{X_c}\right)^2, \\ &if \quad (\sigma_{22} + \sigma_{33}) \geq 0; \\ &\quad F_m^t = \frac{(\sigma_{22} + \sigma_{33})^2}{{Y_t}^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2}, \\ &if \quad (\sigma_{22} + \sigma_{33}) < 0; \\ &\quad F_m^c = \left[\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right]\left(\frac{\sigma_{22} + \sigma_{33}}{Y_c}\right) + \frac{(\sigma_{22} + \sigma_{33})^2}{4S_{23}^2} + \\ &\qquad + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} \end{aligned} \tag{3}$$

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3. SIMULATION

Since the GRP pipes are tested separately under standard pressure conditions with standard methods, hence, in this paper, the results of each test are used for validation. GRP tube for this study consists of ten layers of reinforcing fibers in the form of axisymmetric, in which their mechanical properties are a function of the volume fraction of the fiber and the texture. The fiber used is E-Glass and epoxy matrix. The layout is considered as $[(\pm\theta)_5]$ in this research. In addition, the mechanical properties and damage fracture energy for the GRP pipe in this study is based on Ref. [4]. The studied GRP pipe, with a nominal DN500 specification with a thickness of 2 mm, is affected by the internal pressure of 5 MPa and closed-closed boundary conditions. In this research, the simulation of fracture with the mentioned criteria and crack opening at $[(\pm30)_5]$, $[(\pm45)_5]$, $[(\pm55)_5]$, $[(\pm60)_5]$, $[(\pm70)_5]$, $[(\pm80)_5]$, and $[(\pm90)_5]$ angles have been investigated.

4. RESULTS

As shown in Table 1, a composite pipe with $[(\pm70)_5]$, $[(\pm80)_5]$ and $[(\pm90)_5]$ layering angle in the all layers has the I_F fracture index more than one, therefore we can conclude the failure phenomena for these layers.

On the other hand, the highest and lowest amount of composite pipe destruction is respectively related to the tenth layer of makeup $[(\pm90)_5]$ and the sixth layer of makeup $[(\pm80)_5]$, as shown in Table 1.

Table 1. Fracture index I_F in the composite tube with Tsai-Wu criterion

Layer	$[(\pm30)_5]$	$[(\pm45)_5]$	$[(\pm55)_5]$	$[(\pm60)_5]$	$[(\pm70)_5]$	$[(\pm80)_5]$	$[(\pm90)_5]$
First layer	0.8782	0.7431	0.6573	0.7905	1.009	1.130	1.165
Second layer	0.7292	0.6637	0.5985	0.7997	1.021	1.141	1.176
Third layer	0.5620	0.6881	0.4813	0.8222	1.038	1.154	1.187
Forth layer	0.4250	0.6953	0.4258	0.8320	1.050	1.166	1.199
Fifth layer	0.2459	0.7219	0.4529	0.8564	1.068	1.179	1.210
Sixth layer	0.1957	0.7398	0.4673	0.8744	1.084	1.192	1.222
Seventh layer	0.1980	0.7478	0.4679	0.8847	1.096	1.205	1.234
Eighth layer	0.2283	0.7774	0.4981	0.9118	1.117	1.219	1.247
Ninth layer	0.2449	0.7858	0.4993	0.9224	1.129	1.232	1.259
Tenth layer	0.2779	0.8173	0.5312	0.9512	1.150	1.247	1.272

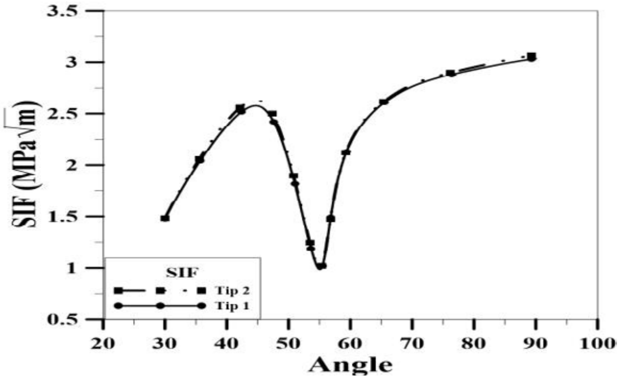

Fig. 1. Stress intensity factor variations by increasing the composite tube layering in the first and second headings

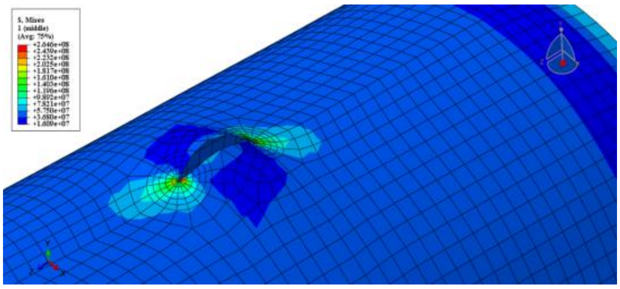

Fig. 2. Von Mises tension contour display of crack opening under internal pressure with layering angle $[(\pm80)_5]$.

In general, the increasing trend of the pipe fracture index was reduced at an angle of $[(\pm55)_5]$ and from this angle, the variations in the index of failure increased, as shown in Fig. 1.

On the other hand, Fig. 2 shows a view of the opening of the crack opening under the internal pressure with layering angle $[(\pm30)_5]$.

5. CONCLUSIONS

The main conclusions of this study can be summarized as follows:

– Based on the Tsai-Wu criterion, a composite pipe with a $[(\pm70)_5]$, $[(\pm80)_5]$ and $[(\pm90)_5]$ layering angle in each of the ten layers has been defeated. The highest and lowest amount of composite tube destruction is related to the tenth layer of makeup $[(\pm90)_5]$ and the sixth layer of makeup $[(\pm30)_5]$, respectively.

– Based on the Hashin criterion, the underlying extension tubes and the fibers of this tubing, which are under compression and extension, have not been broken, but the underlying composite pipe under pressure has failed.

– A composite pipe under internal pressure with a $[(\pm55)_5]$, $[(\pm90)_5]$ layering angle in the first and second cracks has the lowest and highest value of the J-Integral.

– The stress intensity factor at the angle $[(\pm55)_5]$ has suddenly decreased by increasing angle. The maximum value of this factor occurs in the layering angle $[(\pm90)_5]$.

– The most optimum and minimum displacement of the crack inlet opening has been occurred in the layering angle $[(\pm55)_5]$, as the angle increases, displacement increases.

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