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Stress Analysis of Underground GRP Pipe Subjected to Internal and External Loading Conditions

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Abstract

This project focuses on the stress analysis of Glass Reinforced Polymer (GRP) pipes. Pressure piping made from GRP is becoming increasingly popular due to its high corrosion resistance and high strength to weight ratio. This development is driven by the need for lighter and more corrosion resistant components. Initially, GRP piping was limited mainly to applications with moderate fluid pressurization. With increasing knowledge of failure mechanisms, improved damage predictability and pipe quality, GRP piping is increasingly being considered in the field of high pressure fluid transmission with pressurization in excess of several megapascals. Since the GRP material consists of several layers, the analysis of stresses developed in it is complicated. Therefore, as the initial approach towards the project, the stress analysis of steel pipes is performed using ANSYS, which was followed by a comparative study of steel and GRP pipes.

Keywords: Glass Reinforced Polymer, pressure piping, stress analysis, high pressure fluid transmission.

1. Introduction

A Glass Reinforced Plastic (GRP) Fibre is light in weight, very strong, a robust material. Although the strength properties are comparatively lower than carbon fiber and is less stiff, the material is typically far less brittle, and the raw materials are cheaper. When compared to metals, its bulk strength and weight properties are also very favorable and it can be easily formed using molding processes [1]. In this world of rapidly developing economy, where the prominence of Nuclear power plants and its transportation is held in the highest regard. Alternate methods of transporting large quantities of liquids (as in hot water) to the conventional options like metal pipes are studied. After a considerable amount of engineering considerations, which compared the advantages and disadvantages of various pipes, A GRP pipe is chosen as the best option because it provides lower thermal conductivity, an important factor in the transport of hotter liquids. It also offers higher strength-to-weight ratio to metal pipes. GRP, generally has a resistance to corrosion, which gives it a longer lifetime than the metal pipes [2]. To get a better understanding of the maximum stress that the pipe can take on before it subjects to failure, a study is conducted numerically using thermal-structural couple element type. The results demonstrate that the strength and stiffness. The most important requirement of a composite GRP is that it must provide considerable strength and reliability to provide safe operation. Fiber reinforcements also plays a decisive role in the development of high pressure GRP pipes. Most commonly, E-Glass has been the preferred choice of reinforcing fiber used [3]. These reinforcing composites are crucial to increasing the corrosion resistance and also contributes to the increase in lifetime of the pipe. GRP can be used for a variety of applications, above and under the ground such as in firewater systems, cooling water systems, drinking water systems, waste water systems or sewage systems and gas systems. GRP pipes can be used as a practical alternative to metal pipes in applications where corrosion, weight, environment and various other factors limit the use of metal pipes.

Glass fiber-reinforced polymer (GFRP) bars are being widely used as reinforcement in reinforced concrete (RC) structures. According to Antonio et al., these structures are subjected to flexure and shear, corrosion resistance; and, above all, electromagnetic transparency [4]. To withstand these, they are required to have good physical and mechanical properties. Still, the use of GFRP bars as longitudinal reinforcement in compression members is still not being implemented widely. Different modes of failure may occur in GRP bars in compression, depending on the type of fiber, fiber volume fraction, and type of resin. Testing of GRP bars in compression is typically complicated by the occurrence of fiber micro-buckling. These are due to the anisotropic and nonhomogeneous nature of the FRP material, and can lead to inaccurate measurements. Therefore, presently an accurate measurement and prediction of failure is not possible.

2. Theoretical Modelling and Analysis

2.1. Material Properties

Glass fibres (GF) are the most common reinforcement for polymeric matrix composites. Their principal advantages are the relationship between their low cost, high tensile strength, high chemical resistance, and insulating properties. The disadvantages are low tensile modulus, relatively high specific gravity, sensitivity to abrasion during handling, low fatigue resistance, and high hardness. E-glass and S-glass are the types of fibres more commonly used in the fiber reinforced plastic industry. E-glass fibres have the lowest cost of all commercially available reinforcing

GFs, which is the reason for their widespread use in the fiber reinforced plastic industry.

Epoxy is the cured end product of epoxy resins, as well as a colloquial name for the epoxide functional group. Epoxies are widely used in industry. However, many epoxies are brittle and have poor fracture toughness, weak impact strength and low resistance to fatigue crack propagation [5]. The composites selected was e-glass as the fiber and epoxy as the matrix element.

Table 2.1: Properties of Unidirectional Composites (Two Dimensional)

Property	E-glass / Epoxy Composite
Fiber volume ratio, Vf	0.55
Density, ρ, g/cm3	1.97
Longitudinal modulus, E1, GPa	41
Transverse Modulus, E2, GPa	10.4
In-plane shear modulus, , G12, GPa	4.3
Major Poisson's Ratio, v12	0.28
Minor Poisson's Ratio, v21	0.06
Longitudinal tensile strength, F1t, MPa	1140
Transverse tensile strength, F2t, MPa	39
In-plane tensile strength, F6, MPa	89
Ultimate longitudinal tensile strain, εu1t	0.028
Ultimate transverse tensile strain, εu2t	0.005
Longitudinal compressive strength, F1c, MPa	620
Transverse compressive strength, F2c, MPa	128

3. Modelling and Analysis

Underground pipelines must be capable of resisting both internal and external pressures. The three principal stresses in a cylindrical pipe are defined initially. The stress acting in a direction parallel to the axis of the pipe barrel, is termed the longitudinal stress σ_a, the stress acting in the circumferential direction, is called the circumferential or tangential stress σ_c and the stress acting in the radial direction and varying through the thickness of the pipe wall, is termed the radial stress σ_r. The stress acting in a direction parallel to the axis of the pipe barrel, is termed the longitudinal stress σ_a, the stress acting in the circumferential direction, is called the circumferential or tangential stress σ_c and the stress acting in the radial direction and varying through the thickness of the pipe wall, is termed the radial stress σ_r [6].

In this theoretical model, the support and loading variations along a run of pipe will be assumed to be indistinguishable at a specific cross section where the longitudinal load variation will be ignored. The bending stresses in the pipes are not considered in this analysis. The load does not vary along the length of the pipe and the material composition is assumed to be uniform for the whole pipe [7]. It will also be assumed that the pipeline will remain at a constant and uniform temperature with its cross section in a state of plain strain (i.e. longitudinal movements or deformations being ignored) [8]. The effects of stresses exerted by external load and by internal fluid pressure on underground-pressurized pipelines are considered. Internal pressure produces uniform circumferential tension stress across the wall. External loads produce circumferential stresses on the walls of the pipe [9].

The circumferential stress due to internal pressure can be estimated using the following expression:

$$\sigma_l = \frac{Pr}{t} \qquad (1)$$

where, 'σ_f' is the hoop stress due to internal fluid pressure, 'P' is the internal fluid pressure, 'r' is the radius of pipe, and 't' being the thickness of pipe wall.

According to Tsai Wu Failure Criterion, for failure to occur, the following condition must be satisfied:

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\,\sigma_1\,\sigma_2 \geq 1 \qquad (2)$$

where, F_{11}, F_{22}, F_{66}, F_1, F_2 and F_{12} are the strength parameters given by:

$$F_{11} = \frac{1}{X_t X_c}\,,\ F_{22} = \frac{1}{Y_t Y_c}\,,\ F_{66} = \frac{1}{s^2}\,,\ F_1 = (\frac{1}{X_t}) - (\frac{1}{X_c})\,,\ F_2 = (\frac{1}{Y_t}) - (\frac{1}{Y_c})\,,\ F_{12} = \frac{1}{2}\sqrt{(F_{11}\,F_{22})}$$

where, σ_1 and σ_2 are the on-axis stresses in the longitudinal and transverse directions and σ_6 is the on-axis in-plane shear stress. X_t and X_c are the longitudinal tensile and compressive strengths, respectively. Y_t and Y_c are longitudinal tensile and compressive strengths in the transverse direction. s is the in-plane shear strength [10].

Substituting X_t = 1140 MPa, X_c = 620 MPa, Y_t = 39 MPa, Y_c = 128 MPa, s = 89 MPa from the table 2.1 to equation (2), the failure index = 2.4047 was obtained.

For this analysis purpose, ANSYS 14.5 was used to test a GRP pipe consisting of 3 layers. A quarter of the pipe (cylinder) was selected as it is symmetrical. The internal radii of the 3 layers, starting from the innermost layer are 79mm, 86mm and 93mm. The orientation of these layers are 90°, 0° and 90° respectively. An internal pressure of 25MPa and an external pressure of 100MPa was assumed. Also the pressure applied is assumed to be uniform throughout. The properties used for the analysis are shown in table 2.1.

4. Results and Inference

The solution of the above problem gives a deformed pipe which bends inward uniformly (because of uniformly applied pressure on both sides). This is illustrated in the figure 1.3. The solution shows that the maximum stress lies in the innermost layer. The values of these stress are equal to 553.572MPa. It can be seen the least stress is in the middle layer.

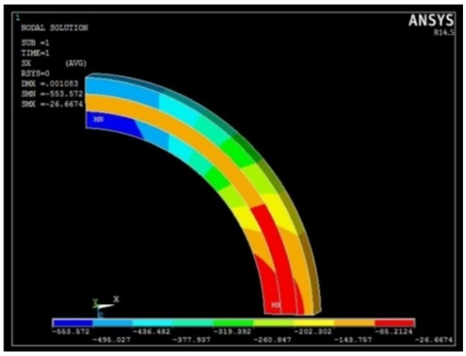

Fig. 3.1: Nodal Solution in the X-Axis.

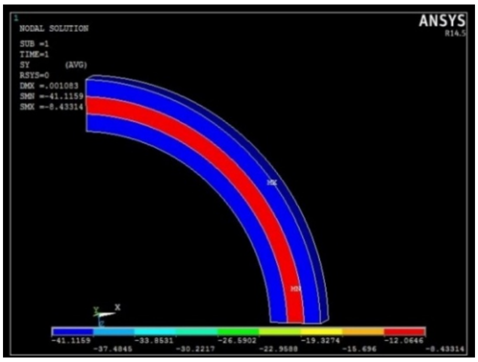

Fig. 3.2: Nodal Solution in the Y-Axis.

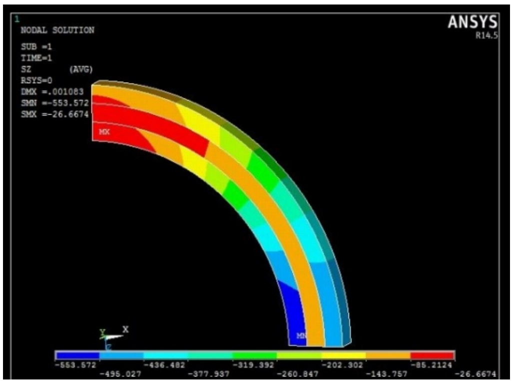

Fig. 3.3: Nodal Solution in the Z-Axis

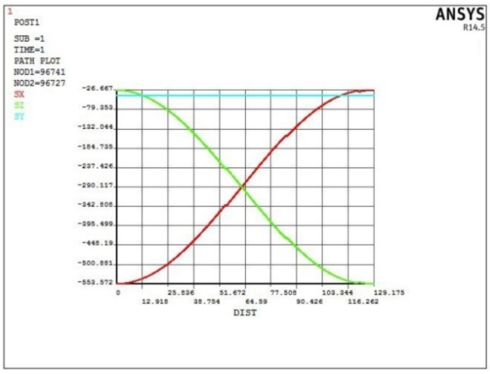

Fig. 3.4: Graph of Stress Along Inner Curve – Nodal Solution in X-Axis, Y-Axis and Z-Axis

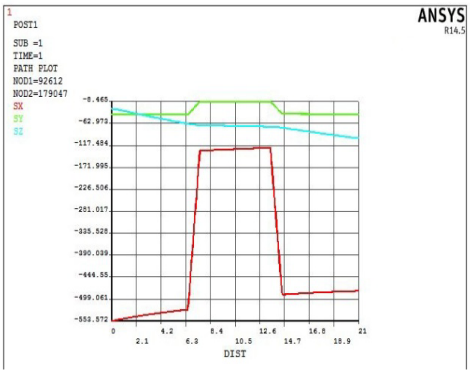

Fig. 3.5: Graph of Stress From Interior to Exterior Surface (Parallel to Z-Y Plane)

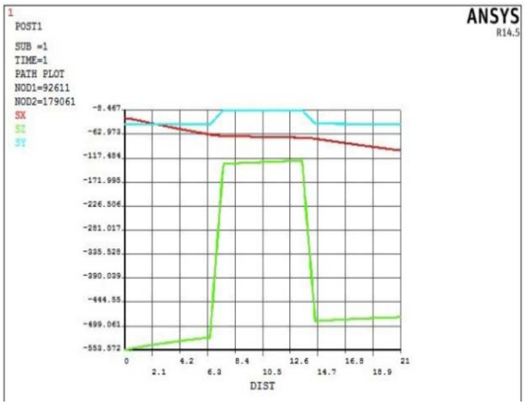

Fig. 3.6: Graph of Stress from Interior to Exterior Surface (Parallel To x-Y Plane)

The maximum value of stress i.e. 553.572MPa, is found to be the same for stresses corresponding to X axis, on the plane parallel to Y-Z plane, and for the stress corresponding to Z axis, on the plane parallel to X-Y plane i.e. the stresses are found to be symmetrical.

The variation of stresses in each direction is found to vary in a parabolic manner along the inner curve, except for the stress in Y direction which appears to remain a constant (whose value is around 35MPa).

The variation of stress in X axis on graph gives a step shape while the stresses in the Y and Z axis are somewhat linear and have low values of stress in the plane parallel to Y-Z plane. Similarly the variation of stress in Z axis gives a step shape while the stresses in the X and Y axis are somewhat linear and have low values of stress in the plane parallel to X-Y plane.

5. Conclusion

It can be concluded that the present design of the GRP pipe cannot withstand the pressure applied. Hence the present design of the GRP pipe has to be changed. Possibly, change in orientation of the fibres in the different layers of the polymer would improve the resistance to failure, also an increase in dimension could solve the problem. Combination of GRP with other kinds of reinforcing polymers could provide an alternate solution.

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