Impact responses, compressive and burst tests of glass/epoxy (GRE) composite pipes

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Abstract. The paper presents the impact responses, compression and burst tests of glass reinforced epoxy (GRE) composites pipes. Impact loadings of three different energy levels (5 J, 7.5 J, and 10 J) were applied, followed by monotonic burst tests. Uniaxial compressive tests were conducted GRE samples using a universal testing machine in accordance with ASTM D695-10. In addition, the tests were also repeated with samples of different winding angles of ±45 ° and ±55 ° and tested at room temperature, and elevated temperatures of 45 °C and 65 °C. The result shows that the higher the impact energy applied to the pipes, the lower the burst strength of the pipes. The maximum burst strength found decreased with an increase in the impact energy level. The results also indicate that the strength of the GRE pipes significantly decreases with increase in temperature though, they are also found to increase as the winding angles decrease.

Keywords: Glass/epoxy composite pipes; composites materials; crushing behaviour; elevated temperatures; compression test

1. Introduction
In the current years, composite pipes are widely utilized in marine division and also as underground passage of fluid elements such as oil, firewater, natural gas, wastewater, and also drinking water. This is because of their high heat resistance, corrosion competent mechanical properties and easy to handle. They are more economical compared to steel and can be obtained at a lower price. The investigation on mechanical properties of glass fibre reinforced epoxy (GRE) pipes which including compression, tensile, and impact test have been conducted from recent studies [1,2].

The burst strength of a GRE pipes is a crucial aspect to be considered in their life cycle of service since they can be subjected to different combination of loadings. The effect of impact test and quasi-static on burst pressure have been studied by Matemilola et al. They discovered that the decline in the pressure bearing capacity is caused by fibre micro-buckling of the exterior layer at the variety of the impact point [3]. Before testing the composite tubes under internal pressure test, Curtis et al. implemented lateral indentation and low-speed impact test. They found that strain measurements confirmed compelling redistribution of strains when loading and the damage (micro-cracking) only weaken overall stiffness marginally but did result in altered strain distribution [4].
Other than that, there is also work reported on the effects of winding angles and elevated temperatures on the efficiency of the GRE pipes. The effect of winding angles on biaxial ultimate elastic wall stress (UEWS) has been studied by Abdul Majid et. al. [5], and they concluded that the different winding angles of GRE pipes have significant effect on the mechanical properties of GRE pipes. Abdul-Majid et. al [6] also looked into the performance of GRE pipes under hydrostatic and biaxial load conditioned at elevated temperatures. Similarly, the results also indicates that the failure of the GRE pipes greatly affected by the test temperatures.

2. Materials and experimental procedure

2.1 Composite fabrication
The filament-wound E-glass fibre epoxy pipes were fabricated at Advanced Materials Research Centre (AMREC), SIRIM Kulim High Tech Park. The process involved glass fibre roving wetting by passing through a resin bath. The wet fibre then wound onto the mandrel at angles of ±45° angle and ±55° to form 6 layers of composite shells. The dimension of the pipes is approximately ±1000 mm in length and ±2.5 mm in thickness. The pipes were then cured for 3 hours at 130°C. Then, the tubes were left to cool at room temperature before withdrawal from the mandrel.

2.2 Drop weight impact test
To study the impact response, a model IM10 drop weight-impact tester supplied by IMATEK was used. The impactor surface was hemispherical with a radius of 12.7 mm and the total mass including the impactor and carriage was 9.6209 kg in this experiment. Three different impact energy levels, which are 5 J, 7.5 J and 10 J were chosen and the test was performed at room temperature. A high-speed camera was used to record the movement of the impact load on the samples during the impact tests.

2.3 Burst test
As shown in Figure 1, the burst tests were performed using a in house-built pressure test rig in accordance to ASTM D1599 standard. The pipe was carefully filled with tap water from the inlet of one of the end fittings. It is of high importance to ensure that the entire system is ‘bleed-out’ for approximately 3-4 min before the test began to assure that no air bubbles were trapped. The strain gauge was installed near the impacted area on the pipe to record the axial strain experienced by the pipe. The pipes then hung in a free-free condition by using lubricated rubber rings to assure accuracy of the strain measurements. Once all checked out and the instrumentations functioning, the pipe then gradually pressurised until the it ultimately burst.

![Diagram of test rig for conducting hydrostatic burst test.](image)
2.4 Compression test
The universal uniaxial compression tests at increased temperatures were performed using a universal testing machine (UTM, Shimadzu) in accordance with ASTM D695-10. The test temperatures were ranged from room temperature to 45°C and 65°C. These selected temperatures were based on the determined $T_g$ value obtained through differential scanning calorimetry (DSC) tests. To examine the failure of the pipes at different temperatures, the test temperatures were set at; below the $T_g$, and close to $T_g$. The tests were performed at a crosshead speed of $1.0 \pm 0.3$ mm/min as elucidated in ASTM D695-10 standard.

3. Results and discussion

3.1 Impact responses
All through the drop impact tests, the force–displacement curves of the impacted samples were documented and evaluated. Figure 2 shows the force–displacement response of the impacted pipes in the neutral settings with impact energies of 5 J, 7.5 J and 10 J. A rebounding-type curve was examined for the pipe. The closed curve obtained suggested that no severe damage that would cause functional failure was applied to the pipe [7]. At the beginning, the slope represents the elastic response, where the pipe underwent initial deformation. The intermediate slope illustrates the plastic response, suggesting the earliest permanent damages such as matrix cracking and delamination to take place. From physical assessment, it unveiled that matrix cracking occurred on 5 J impacted pipes and both matrix cracking and delamination damage were suspected for the impact energies of 7.5 J and 10 J. The final slope indicates the rebound of the striker from the pipe surface. The neutral samples force-displacement curve ended faster, yielding greater ultimate force after the onset of initial damage. The test was conducted for the chosen impact energy levels such that no fibre breakage and penetration nor perforation of the impactor was expected during the tests.

![Figure 2. Force–displacement responses of the pipe after drop impact test.](image)

The area under the force–displacement plot gives that the energy dissipated for plastic deformation as the energy absorbed by the specimen was consumed for failure. The absorbed energy by the specimen was computed mathematically from the force–displacement response curve by using the following Eq. (1):

$$W = \int F \, ds = F_m (S_f - S_i)$$  \hspace{1cm} (1)

where $W$ is the sum of energy absorbed by the impacted pipe and $F_m$ is the applied average force. $S_f$ is the maximum displacement, and $S_i$ is the initial displacement under impact loading [7].
Figure 3 shows an image of the damages that occurred near the impact point on the pipes. As illustrated in Fig. 4, the size of damage area enlarged as the impact energy increased. The lower slope illustrates, with an increase in the impact energy the evolution of matrix cracking damage and delamination will occur [4]. The size of the damaged area produced by the higher-energy impact event is an indicator of the material’s capability to absorb energy. Visual analysis of the impact-damaged specimens explained that with an increase in the impact energy will cause the damaged area tended to become more localised. Identical information were also recorded by Deniz and Karakuzu [8].

![Figure 3](image1)

**Figure 3.** Physical damage to the pipe specimen after (a) 5 J, (b) 7.5 J, and (c) 10 J impact tests.

![Figure 4](image2)

**Figure 4.** Damage area against impact energy of the impacted pipes
3.2 Burst strength

Monotonic burst tests were performed on the impacted GRE pipes in closed-ended conditions. The purpose these tests is to determine the burst strength of the pipes after they were subjected to loadings of different impact energies. Table 1 presents result analysis of the impacted specimens that underwent burst pressure tests. It shows that the increase in impact energy will decrease the burst strength. This can be associated with the decrement in the mechanical strength of the pipes due to the plasticization of the matrix, which weakens the interfacial fibre–matrix interface.

| Impact energy (J) | Max. burst pressure (MPa) | Axial stress (MPa) | Hoop stress (MPa) | Strain (%) | Failure type |
|-------------------|--------------------------|-------------------|-----------------|------------|--------------|
| 5                 | 10.50                    | 113.80            | 227.60          | 0.32       | Weepage      |
| 7.5               | 6.57                     | 75.78             | 151.55          | 0.18       | Weepage      |
| 10                | 6.04                     | 69.92             | 139.84          | 0.17       | Eruption     |

The results shows that the pipe samples impacted with the energy level of 5 J persistently displayed greater burst pressure compared to specimens impacted by energy levels of 7.5 J and 10 J. The 5-J-impacted sample yielded a burst strength of 113.8 MPa, but reduced to 75.78 MPa and 69.92 MPa for the 7.5-J- and 10-J-impacted specimens, respectively. This signifies a strength degradation of more than 30% in both these cases. The authors recorded the same decrement in burst strength on impacted pipes in their report [4], [9]–[12].

**Figure 5.** The impacted pipe sample during monotonic burst test with (a) weepage and (b) eruption damage.

3.3 Compressive properties

Figure 6 displays the stress-strain response of a GRE pipe sample during the uniaxial compression test. The sample was taken from a ±45 ° angled pipe crushed at 65 °C. The uniaxial load increased continuously until it come to the failure point during the compression process. Abrupt cracks appeared when the specimens experience failure, and this caused the upper segment to lose its structural integrity. As a result, the strength drops swiftly before stabilising at a constant strength. Nonetheless, the load is still exerted on the specimen causing it to keep on crushing as the strain increases.
As shown in Fig. 6, the stress increased linearly with the strain until it reached the highest peak. During this phase, the pipe is still in an elastic state, which indicates that the pipe can still turn back to its original state. As soon as the stress reached the peak, the stress reduced speedily. Now, the pipe is in a plastic state, which implies that the pipe can no longer turn back to its original state. It is permanently deformed, and buckling usually begins at this point. As the crushing process continues, the stress retained at a low but steady value following the initial failure. Following the initial failure, the stress decreases, and the load starts to propagate progressively. As the pipes reach ultimate failure, the stress begins to increase speedily. The rapid surge is because of the cumulative effect of the specimen materials, which causes to exhibit a greater value of stress compared with that of the initial failure. At this point, the pipes cannot deform anymore.

At the onset of failure, the pipe displays local buckling and the unsteady response. As the crushing progresses, more buckles formed which eventually lead to progressive buckling. As for low temperatures (RT, 45 °C), the stress-strain behaviour exhibited lower strain responses. It is suspected that, at low temperatures, the material is rigid thus after initial deformation, the brittle-like material would quickly fracture thus no further deformation could be observed.

Fig. 7a, in the case of the ±45° angled pipes, the maximum compressive stresses of the pipes compressed at RT, 45 °C, and 65 °C were 118.9 MPa, 57.3 MPa, and 23.9 MPa respectively. Figure 7b shows the compressive strength of the ±55 ° angled pipes. These outcomes show an noticeable pattern, where the ±45 ° angle pipe has a higher compressive stress at RT, 45 °C and 65 °C compared to pipes at an angle of ±55 in the respective temperatures.
4. Conclusion
The effects of impact loading on burst failure pressure and compression tests were investigated. Impact energy of 5 J, 7.5 J and 10 J were applied to the pipes. Later, all the impacted pipes were tested with burst pressure test to test their burst strength. The higher the impact energy applied to the pipes, the lower the pipe’s burst strength. Pipes subjected with 5 J impact energy acquire 30% more burst strength compared to pipes subjected to 7.5 J and 10 J impact energy. Three failure modes were detected; whitening spot in the early monotonic burst test, and then will cause manifestation of weepage and eruption failures. The effects of elevated temperature and different winding angles on the pipe compressive strength were also investigated. The results obtained show that pipes with ±45 ° angle have higher compressive strength compared to ±55 ° angle pipes. Besides, the elevated temperatures applied to the pipes also affects the pipes compressive strength where the strength of the GRE pipes found substantially degraded as the test temperatures is increased.

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