Fire exposure, impact responses, and burst tests of glass-reinforced epoxy (GRE) composite pipes

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Abstract. The paper presents the fire exposure, impact responses, and burst tests of glass-reinforced epoxy (GRE) composites pipes. Fire responses of three different fire exposure times (10 s, 20 s and 30 s) were conducted, followed by impact loadings. Three different energy levels (5 J, 7.5 J, and 10 J) were applied for impact responses and followed by monotonic burst tests. Monotonic burst tests were conducted on GRE samples using hydrostatic pressure testing equipment in accordance with ASTM D1599. The result shows that the longer the time of fire exposure towards GRE pipes, 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 fire exposure time. The results also indicated that the strength of the GRE pipes significantly decreases with an increase in impact energy level.

1. Introduction

In recent years, composite pipes are widely utilized in the marine division and also as the underground passage of fluid elements such as oil, firewater, natural gas, wastewater, and also drinking water. This is because of their excellent corrosion-resistant, good relative mechanical properties and ease of handling/maintenance. They are also better economically in the long term usage compared to steel. The determination of the mechanical properties of GRE pipes which include compression, tensile, and impact test have been of interest in the past studies [1, 2].

The burst failure pressure of GRE pipes is a crucial aspect to be considered during their life cycle of service; they are usually be subjected to different loading conditions. Matemilola and colleagues have investigated the effect of drop-impact and quasi-static responses on the pipe’s burst strength. 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 an 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].

In addition, there are also past studies concerning the influences of different winding angles of GRE pipes and elevated temperatures on the efficiency of the GRE pipes. The repercussion of winding angles on biaxial ultimate elastic wall stress (UEWS) has been explored by Abdul Majid et al. [5], and they concluded that the different winding angle of GRE pipes profoundly affected the mechanical responses of GRE pipes. Abdul-Majid et al. [6] also studied the performance of GRE pipes under
hydrostatic and biaxial load conditioned at inflated temperature. The results proved that the failure of the GRE pipes greatly affected by the test temperatures.

2 Methodology

2.1 Fire response/ Fire exposure
To simulate actual fire damage situation, a propane fuel source was used to burn a pipe’s specimen. A 14 kg LPG cylinder, two support stands, burner array and GRE composite pipe specimen are the materials and tools required in this fire test rig. Figure 1 shows the setup configuration of the test rig. The distance between the pipe specimen and the burner array was fixed at 12.5 cm whereas the gas pressure was secured at 0.25 bar. The fire exposure time on the pipe specimens was the activated variable in this test, while all the other parameters were fixed.

![Figure 1. Test rig for fire response/fire exposure.](image)

2.2 Drop weight impact test
The instrumented impact loading, a model IM10 IMATEK, was used to perform impact test after the fire exposure. The impactor surface used was hemispherical with a radius of 12.7 mm and the total mass, including impactor and carriage, was 9.6209 kg in this experiment. The test was performed at room temperature with three different impact energy levels, which are 5J, 7.5J and 10J.

2.3 Burst test
As shown in figure 2, the burst tests were executed using a pressure test rig set up in accordance with ASTM D1599. The pressurising medium used was tap water at room temperature and was carefully filled from the inlet of one of the end fittings at the closed end of the test setup. It is of particular importance to ‘bleed’ the entire system for approximately 3-4 min before the test began to assure that no air bubbles were trapped. The strain gauge was applied near the impacted area to obtain the axial strain response during pressure testing. The pipes were hung in a free-free condition by using rubber rings to assure exact strain measurements. The pipe then gradually pressurised until the test specimen ultimately burst/leaks.
3. Results and Discussion

3.1 Fire responses

A heat flux calibration was performed following ISO 14692 standard in order to acquire the standard heat flux value of $113.6 \pm 11.4 \text{ kW/m}^2$. A suitable method to calibrate a fire response test is using the copper block heat flux meter, which is designed by “Vosper Thornycroft” [7]. Parameters that influenced the value of heat flux were the gas pressure of the torch and the distance of the specimen from the propane burner. Therefore, to replicate the heat flux calibration and the actual fire response condition, the copper block position was placed exactly in the same manner as the GRE pipe in the actual fire response test. The gas pressure used in this calibration is 0.25 bar and a period of 5 minutes (300 seconds) of fire exposure time was considered to obtain a constant heat flux value within the time interval according to T.Browne [8]. The acquired heat flux was computed using the following equation:

$$Q = V \cdot \rho \cdot c_p \cdot \frac{dT}{dt} \quad (1)$$

where $Q$ is the energy input, $V$ is the volume of the copper block, $\rho$ is the density of copper, $c_p$ is the specific heat capacity of copper and $\frac{dT}{dt}$ is the temperature change with respect to time. Table 1 shows the acquired heat flux from three different tests performed. The average value of heat flux obtained was 111.92 kW/m$^2$ which within the range of the standard heat flux value by ISO 14692. Therefore, the heat flux value used in this test was 111.92 kW/m$^2$.

Next, the GRE pipes are burned and exposed to fire at three different exposure times: 10, 20 to 30 seconds. This was intended to evaluate the effect of fire exposure time of GRE pipes towards the pipe’s burst strength under hydrostatic test.
Table 1. Summary of heat flux calibration results.

| Test No. | Time interval (s) | $\Delta T / \Delta t$ ($^\circ$C/s) | Heat energy, Q (J) | Heat flux, q (kW/m²) |
|----------|-------------------|-------------------------------------|-------------------|-------------------|
| Test 1   | 0-150             | 0.1833                              | 396.09            | 97.32             |
|          | 0-300             | 0.2063                              | 445.78            | 109.53            |
|          | 60-300            | 0.2250                              | 486.11            | 119.44            |
|          | 150-300           | 0.2293                              | 495.47            | 121.74            |
| Test 2   | 0-150             | 0.1833                              | 396.09            | 97.32             |
|          | 0-300             | 0.1973                              | 426.33            | 104.75            |
|          | 60-300            | 0.2138                              | 461.80            | 113.46            |
|          | 150-300           | 0.2113                              | 456.58            | 112.18            |
| Test 3   | 0-150             | 0.1960                              | 423.45            | 104.04            |
|          | 0-300             | 0.2157                              | 465.94            | 114.48            |
|          | 60-300            | 0.2333                              | 504.11            | 123.86            |
|          | 150-300           | 0.2353                              | 508.43            | 124.92            |
| Average  |                   |                                    |                   | 111.92            |

3.2 Drop weight impact responses

Throughout the impact tests, the force-time of the impacted samples were documented and analysed. Figure 3 shows the force-time responses of the impacted pipes with impact energies of 5 J, 7.5 J and 10 J. From the figure, for each level of impact energy, the peak force was observed at 20 s fire exposure time before dropping to the lowest at 30 s. Through physical inspection, it was unveiled that matrix cracking occurred on 5 J impacted pipes and both matrix cracking, and delamination damage occurred for the impact energies of 7.5 J and 10 J. The result suggests degradation of the pipe’s stiffness during fire exposure which results in a significant loss in load-bearing capability from melting of matrix resin at elevated temperature [9].

![Figure 3. Force-time responses of impacted pipe at different energy levels](image_url)

It is possible to conclude the heat flux used in the fire response test is high enough surface temperature to damage the matrix and also the glass fibre, according to Mouritz and Mathyz [10]. Other than char formation, radiant heating can also cause delamination. In numbers of cases, this delamination can cause the char to separate completely from the unburnt portion of the composites.
Figure 4 shows images of the damages that occurred near the impact point on the pipes. 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 the damaged area tended to become more localised when the impact energy was increased. Similar findings were also recorded and reported by Deniz and Karakuzu [11].

3.3 Burst test

Finally, monotonic burst tests were executed on the GRE pipes that had undergone burning with different fire exposure time and impacted at different energy levels in closed-ended conditions. The purpose of the test was to determine the residual burst strength of the pipes after fire exposures and subjected to impact tests; tabulated in Table 2. It shows that the burst strength decreases with the increase of fire exposure time and impact energy. This was suspected due to the decrement in the mechanical strength of the pipes due to the delamination between plies which deteriorates the interfacial fibre–matrix interface.

**Table 2.** Summary of monotonic burst tests on pipes impacted at various energy levels.

| Impact energy (J) | Fire exposure time (s) | Max. burst pressure (MPa) | Axial stress (MPa) | Hoop stress (MPa) | Failure type | Failure region |
|------------------|------------------------|---------------------------|-------------------|-------------------|--------------|---------------|
| 0                | 10                     | 16.47                     | 123.88            | 247.76            | Weepage      | Near end caps |
|                  | 20                     | 4.85                      | 29.79             | 59.57             | Weepage      | Fire exposed area |
|                  | 30                     | 4.09                      | 32.51             | 65.02             | Weepage      | Fire exposed area |
| 5                | 10                     | 6.70                      | 52.89             | 105.79            | Weepage      | Fire exposed and impacted area |
|                  | 20                     | 6.11                      | 43.46             | 86.93             | Weepage      | Fire exposed and impacted area |
|                  | 30                     | 3.81                      | 29.09             | 58.18             | Weepage      | Fire exposed and impacted area |
| 7.5              | 10                     | 6.45                      | 49.56             | 99.11             | Weepage      | Fire exposed and impacted area |
|                  | 20                     | 5.35                      | 38.95             | 77.90             | Weepage      | Fire exposed and impacted area |
|                  | 30                     | 3.58                      | 28.91             | 57.82             | Weepage      | Fire exposed and impacted area |
| 10               | 10                     | 6.37                      | 48.63             | 97.25             | Weepage      | Fire exposed and impacted area |
|                  | 20                     | 5.03                      | 36.71             | 73.42             | Weepage      | Fire exposed and impacted area |
|                  | 30                     | 3.26                      | 26.18             | 52.36             | Weepage      | Fire exposed and impacted area |
For non-impacted pipes (0J), there is a significant decrease in burst strength between 10s and 20s fire exposed time. It shows that 10s fire exposed time still has a high burst strength compared to 20s and 30s pipes. The failure region for 10s pipes is also not located at the fire exposed area which means it is not as affected by the short time of fire exposure compared to 20s and 30s pipes which the failure occurs at the fire exposed area. For impacted pipes, the pipe sample impacted with the energy level of 5 J persistently displayed higher 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 52.89 MPa, but reduced to 49.56 MPa and 48.63 MPa for the 7.5-J- and 10-J-impacted specimens, respectively. This signifies a strength degradation of approximately 5% to 8% in both these cases. The authors recorded the same decrement in burst strength on impacted pipes in their report [4, 12–15].

![Impact area and fire exposure area](image)

**Figure 5.** The impacted pipe sample during monotonic burst test with weepage

### 4. Conclusions
From the research, we concluded several findings:

i. The longer the fire exposure time of GRE pipes, the lower the pipe’s burst strength

ii. Increase in the impact energy applied to the pipes will decrease the pipe’s burst strength. Pipes subjected to 5J impact energy acquire 8% more burst strength compared to pipes subjected to 7.5J and 10J impact energy.

iii. Two failure modes were observed; whitening patches in the initial monotonic burst test, and then will cause the manifestation of weepage failures.

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