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Behaviour of GRE composite pipes after fire exposure under dry and wet internal conditioning

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Abstract. This paper presents the behaviour of GRE composite pipe after fire exposure under dry and wet internal conditioning. Numerous studies has been conducted in the past, however there is lack of research in the residual strength, and the damage mechanisms of the pipe due to fire exposure. Therefore, this will be the focus of the research study. The specimens were exposed to fire for a period of 10s to 90s under dry and wet internal conditioning, followed by undergoing a monotonic burst test and scanning electron microscopy (SEM) analysis. The results show that the residual strength in terms of axial stress decreases with an increase in fire exposure time. Water is found to absorb thermal energy from the fire source, hence reducing the rate of matrix breakdown and char formation of the pipe under the wet internal conditioning.

Keywords: Composite pipes, GRE pipes, fire exposure, residual strength, microstructure

1. Introduction

Glass-reinforced epoxy (GRE) is one of the composites that are widely used in low and high-pressure piping to transport fluids. This can be seen in offshore industries where GRE pipes to transport oil and water over long distances because it is easy to handle and repair [1-4]. GRE composite pipe consists of high strength fibres which are bonded to a matrix with well-defined interfaces between them. The matrix and fibres are able to retain their existing chemical and physical properties while producing a better combination of properties that cannot be achieved with either component acting alone.

An intrinsic issue with composite materials is their poor fire performance. The reason for this is because of the flammable property of the composite material organic matrix and the associated risk from fire as mentioned by Mouritz and Mathys [5]. Polyester, epoxies and vinyl ester are the most common resin systems used in composite pipes, and these polymers lose much of their stiffness and strength at temperatures close to glass transition temperature which often lies between 80°C - 150°C. Higher temperatures, more often in excess of 400°C will result in decomposition and products that may burn. These products will subsequently release heat, limiting visibility hindering escape and thus constituting a further hazard and making fire-fighting a dangerous task [6-7]. Furthermore, the behaviour also raised concerns about the integrity of the composite pipe due to degradation in the mechanical properties.

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Despite its combustibility, polymer composites have shown positive results when exposed to fire such as excellent thermal insulation and slow burn-through effect based on past research [8]. The reason for this is due to low diffusivity and conductivity of the composites, endothermic effect of the matrix decomposition, convective cooling flow of the volatiles to hot face and low thermal conductivity of residual glass depleted resin content. The most important factor supporting the composites integrity in fire is the heat absorption property due to the endothermic pyrolysis of the polymeric matrix.

Thus the current study investigates the residual strength of GRE composite pipes after being exposed to fire and pressure loading under dry and wet internal conditioning. The investigation focuses on the residual strength of GRE composite pipes after fire exposure and monotonic burst test. This takes into account the process of cutting the composite pipe into smaller specimens which were exposed to fire. The heat flux of the fire is kept constant at 112kW/m2 while varying the fire exposure time ranging from 10s to 90s to simulate in service environments. Then the burnt specimen was subjected to internal pressure loading from the monotonic burst pressure test to determine the deformation behaviour of the composite pipe.

2. Materials and method

2.1 Heat flux calibration

The heat flux of the fire source is set as a controlled variable in this study while manipulating the exposure time on the specimen. Hence, a suitable method is needed to calibrate the fire testing process. The solution is to use the copper block heat flux meter. Figure 1 shows the layout of the apparatus to calibrate the heat flux. The apparatus consists of a copper block with 3 thermocouples placed at different points within the block [9]. This will ensure a more accurate temperature sensing as the average of the temperatures is needed to obtain the heat flux. Besides that, it is important to take note that the exterior of the block is insulated with kaowool, bound together by a calcium silicate board frame. A small circular surface is left exposed at the front for heat to penetrate through during the calibration.

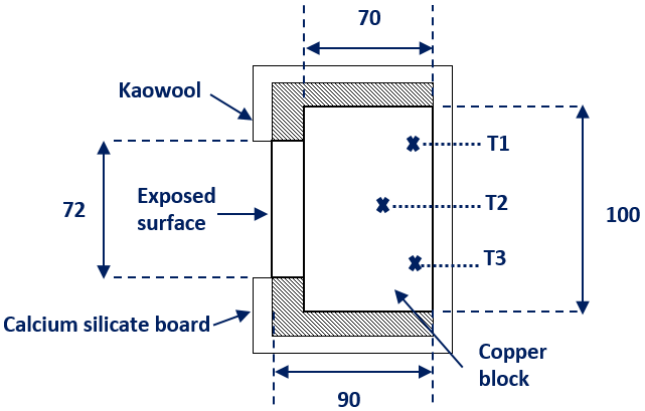


Figure 1. Schematic diagram of the copper block heat flux meter (in mm)

The calculation to obtain the heat flux is based on the following formulation:

$$Q=V.\rho.Cp.\partial T\partial t \quad (1)$$

where, Q = Energy Input (J/s)
V = Volume of the copper block ($m3$)
ρ = Density of copper
Cp= Specific heat of copper (J/kg.°C)
$\partial T/\partial t$ = Temperature change with respect to time (°C/s)

2.2. Fire exposure

This test utilises a propane fuel source to burn a pipe test specimen to simulate actual fire damage situation. The fire test rig consists of a 14kg LPG cylinder, two support stands, burner array and GRE composite pipe specimen [10]. The setup configuration of the test is shown in Figure 2. The pipe specimen is supported parallel to the burner rows and above the centre axis of the burner assembly. The pipe specimen is fixed at a 12.5 cm height from the burner array whereas the propane gas pressure is fixed at 0.25 bar.

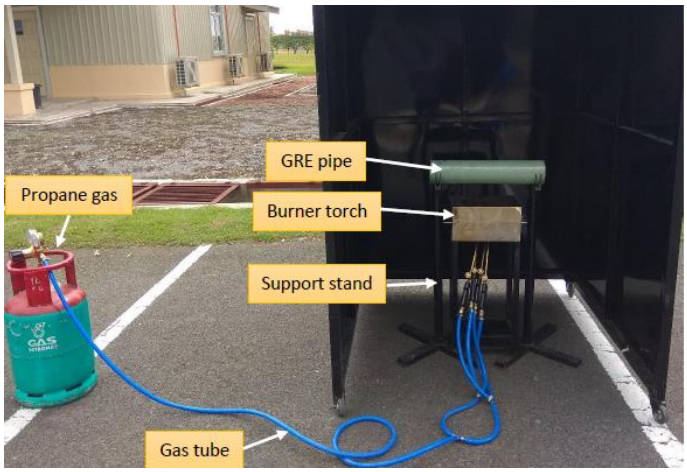


Figure 2. Propane burner conditioning setup

2.3. Monotonic burst test

The burst test is conducted on the composite pipe in 2 conditions that are before and after fire exposure. This test is done investigate the burst strength and functional failure of the specimens. The test utilises a pressure test rig developed based on ASTM D1599 (2014) standard [11]. The test rig was presented in a previous publication by the authors [12]. The concept of this test is to continuously pressurise the specimen until failure occurs. To lock the pressure in the pipe, custom designed end fittings that are based on the pipe dimensions were used. O rings are used together with the end fittings to ensure pressure leaks do not occur during the test. Besides that, tapered sleeves are placed together with the end fittings to limit external movement, acting as a mechanical lock. As a safety mechanism, clamps will be used at both ends during the testing process.

3. Results and discussion

3.1. Heat flux calibration

The heat flux calibration is performed to obtain a value of 113.6 ± 11.4 kW/m^2 based on ISO 14692. The average heat flux was calculated from the results is 111.92 kW/m^2 which is within the desired heat flux range. The calibration found that a gas pressure of P = 0.25 bar is required for the burner while the distance between the burner and pipe surface is maintained at D = 125 mm.

3.2 Monotonic burst tests

Next, the monotonic burst tests were conducted on the GRE composite pipes after exposure to fire at different time configurations under dry and wet internal conditions. This test aims to determine the pipes' burst strength after subjecting them to fire and different internal conditioning. The burst strength refers to the axial stress caused by the internal burst pressure. Table 1 presents a summary of the fire damaged specimens.

It can be observed that there is a decrease in burst strength when fire exposure duration increases. This is because of the drop in the mechanical strength of the GRE composite pipes

following the breakdown of the epoxy matrix, which deteriorates the interfacial fibre-matrix interface. For the dry condition, the pipe started off with burst strength of 123.88 MPa with 10s of fire exposure. There was a drastic decline in the burst strength to 29.79 MPa and 32.51 MPa with the 20s and 30s fire exposure respectively, indicating a strength reduction of more than 70%. The dry 30s specimen reported a lower burst pressure than dry 20s specimen although the burst strength of the dry 30s is still slightly higher, showing that the burst strength did not undergo a rapid decline from 20s to 30s of fire exposure as seen from 10s to 20s. This is due to the formation of char which has low thermal conductivity compared to the virgin composite material, which slows down thermal energy transfer and reduces matrix decomposition rate [13].

Table 1. Summary of monotonic burst tests on various condition and exposure time

Condition	Fire exposure time (s)	Max Burst Pressure (MPa)	Axial Stress (Mpa)	Hoop Stress (Mpa)	Failure Type	Failure Region
Dry	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
Wet	10	16.69	129.81	259.63	Weepage	Near end caps
	20	16.81	134.24	268.48	Weepage	Near end caps
	30	15.49	125.36	250.71	Weepage	Near end caps
	90	6.17	48.69	97.39	Weepage	Fire exposed area

Besides that, limited oxygen is being transported to the reaction zone as char covers the area and limit oxygen supply causing a slowing down in matrix decomposition. For the wet internal condition, the pipe showed burst strength of 129.81 MPa at 10s of fire exposure which is slightly higher than the same fire exposure duration in the dry condition. After 90 s of fire exposure, the burst strength reduced to 48.69 MPa. The results show that the burst strength of the wet 90 s specimen is still higher than the dry 20s specimen, indicating that the presence of water in the pipe is capable of prolonging functionality of the pipe. This is due to the water acting as a heat conduction medium by absorbing the thermal energy from the fire source, slowing down the matrix decomposition rate [14].

3.3 Residual burst strengths

The evaluation of the residual strength of fire exposed pipes was conducted by slowly pressurising the GRE pipes until failure by weepage occurred. The tests were stopped once the rate of weepage equals the delivery from the pump. The criterion to determine the increased damage upon the residual pressure capacity of the pipes is the residual strength capability that is expressed in percentage with the following formulation:

$$\text{Residual Strength Capability} = \frac{\text{Axial Stress (Fire damaged specimen)}}{\text{Axial Stress (Nondamaged specimen)}} \times 100\% \quad (2)$$

Figure 3 presents the relationship between the residual strength capability and fire exposure time of the GRE composite pipe. The residual strength of the pipes decreases with increasing fire exposure time under both dry and wet internal conditioning. The trends for these two conditions are similar with the main difference being the rate at which the residual strength is decreasing. For the dry internal conditioning, the plot is characterised into two distinct regions whereby there is a rapid reduction of residual strength by 76-80% within the first 20s of fire exposure. This is followed by a slower depletion of residual strength by another 20% until no structural integrity is present. The trend indicates that the pipe will lose total functionality at 39.4s. The behaviour is caused by the rapid degradation of the polymer matrix and fibre bonding at the outer pipe surface which then spreads towards the inner pipe surface which explains the rapid reduction for the first 20s. The matrix decomposition produces char which continues to build up from the outside. The char acts as a thermal insulation layer because the thermal conductivity is much lower compared to the virgin composite

material. This effect slows the matrix decomposition rate, hence reducing the damage to the internal matrix layer of the pipe from 20 s to 30 s as seen in the trend.

In the wet conditioning samples, the first region is from 0s to 30s where the pipe maintains a residual strength capability of above 90% with very small decrement. The trend decreases gradually from 30 s onwards until no structural integrity is present. The trend indicates the pipe will lose total functionality by 112.7s when there is water present in the pipe during exposure to fire. The water absorbs thermal energy by heat conduction through the pipe thickness, thus very effectively protecting the matrix-fibre bonding on the inside of the pipe during the first 30s of fire exposure. As water continues to absorb thermal energy, the water temperature increases rapidly and slowing down the energy absorption process [15]. The temperature within the inner matrix-fibre layers starts to increase to above 70 ºC, exceeding the T_g of the epoxy which begins the decomposition process of the matrix.

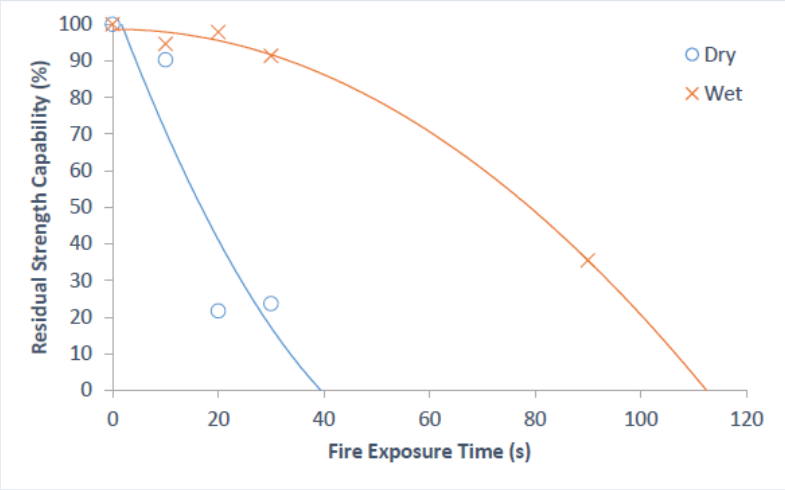


Figure 3. Residual strength capability of fire damaged specimen at all conditions

4. Conclusion

The paper presents the experimental investigation of monotonic burst test performed on fire exposed composite pipes under dry and wet internal conditions. The conclusions are as follows;

1. The average heat flux from the calibration is 111.92 kW/m^2, which is within the desired heat flux range based on ISO14692. The calibration found that a gas pressure of P = 0.25 bar with the distance between the burner and pipe surface of D = 125 mm are required to obtain the required heat flux.

2. The burst strength decreases when fire exposure time increases. For the dry internal conditioning, the plot is characterised into two distinct regions whereby there is a rapid reduction of residual strength in the first 20s due to the quick degradation of the epoxy matrix and fibre bonding at the outer pipe surface. This is followed by a slower reduction of residual strength from 20s to 30s due to the accumulation of char which acts as a thermal insulation layer. This slows down both the matrix decomposition rate and residual strength reduction.

3. In the wet conditioning samples, the first region is from 0s to 30s where the pipe maintains high residual strength capability with very small decrement. The trend decreases gradually from 30s onwards until no structural integrity is present. The pipes under wet internal conditioning exhibit stronger residual strength compared to the dry condition of the same fire exposure time due to the water absorbing thermal energy from the heat source, reducing the temperature distribution along the thickness of the composite laminate, thus slowing down the matrix decomposition rate of the epoxy.

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