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Fatigue crack growth of filament wound GRP pipes with a surface crack under cyclic internal pressure

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Abstract In this study, fatigue damage behavior of ($\pm 75_3$) filament wound composite pipes with a surface crack under alternating internal pressure was investigated. The specimens were tested at room temperature and exposed to open ended fatigue tests in which the pipe can be deformed freely in the axial direction. The tests were carried out in accordance with the ASTM D-2992 standard. The alternating internal pressure was generated by conventional hydraulic oil. The low cycle tests were performed with 0.42 Hz frequency and $R = 0.05$ stress ratio. Glass reinforced polymer pipes (GRP) are made of E-glass/epoxy and have ($\pm 75_3$) configuration. Surface cracks were machined in the axial direction of the pipes which have depth-to-thickness ratios $a/t = 0.25$–0.38–0.50 and depth to length ratio of $a/c = 0.2$. Tests were performed at three different loads of 50%, 40%, and 30% of ultimate hoop stress strength of unnotched pipes. The failure behavior of GRP pipes during the test was observed and fatigue test results were presented by means of (S–N) curves and delamination damage zone area-cycle (A–N) curves.

Introduction

Glass reinforced polymer (GRP) tubes are increasingly used and have become an important class of engineering materials for a wide range of applications. These types of materials can be used as high pressure containers, gas and liquid transfer pipes, mobile bridging components, and trusses owing to their high strength-to-weight ratio and good corrosion resistance.

A review of the literature revealed a number of studies focused on GRP pipes but there were fewer studies on the fatigue and monotonic behavior of GRP pipes with surface crack. The majority of the research into filament wound GRP composite pipes was performed under open-ended, close-ended, biaxial, and axial loading conditions [1–7].

Kaynak and Mat [8] studied the uniaxial fatigue behavior of filament-wound glass-fiber/epoxy composite tubes. They determined the fatigue life of the epoxy matrix ($\pm 55_3$) glass fiber-wound specimens for stress levels of 60, 70, and 80% of tensile strength and applied three different frequencies for the constant amplitude sinusoidal loading with a stress ratio of $R = 0.1$. Perreux and his co-workers [9–12] conducted the most intensive research on filament-wound fiber-glass/epoxy composite tubes. The effect of frequency on the fatigue performance of ($\pm 55_3$) laminated composite pipes under biaxial loading has been investigated by Perreux et al. [13].

Tarakcioglu et al. theoretically and experimentally investigated the effect of surface cracks on strength of glass/epoxy filament wound pipes [14], fatigue failure behavior of glass/epoxy ($\pm 55_3$) filament wound pipes under internal pressure [15], and fatigue behavior of ($\pm 55_3$) filament wound GRP pipes with a surface crack under internal pressure [16]. Fatigue behavior of surface cracked filament wound pipes in corrosive environment was investigated by Avci et al. [17].

In this study, the fatigue tests of ($\pm 75_3$) filament wound GRP pipes with a semi-elliptical surface crack were carried out under open-ended internal pressure. The effect of notch depth-to-thickness ratios and hoop stress level ratios were

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investigated. The relationship between delamination areas versus fatigue cycle (*A*–*N*) was also investigated.

Experimental

Filament wound GRP pipes were manufactured using a CNC winding machine by İZORELL Co İzmir-Turkey. Vetrotex 1200 tex E-glass fiber and CIBA-GEIGY LY 556/HY 917/DY 070 Bisphenol-A epoxy resin system was used for production. Filament wound composite pipes were produced with six layers which have a ($\pm 75_3$) configuration with dimensions of 1 m in length, 72 mm inside diameter, and 2.25 mm in average thickness. After production the pipes were cured for 2 h at 135 °C on the mandrel in a slow motion rotary oven. After pulling out the mandrel, the pipes were post-cured for 2 h at 150 °C. The pipes were cut into the designed test length of 300 mm. A burn-off test was applied according to ASTM-D2584 and fiber volume fraction was found to be 51%. The properties of glass and matrix materials are given in Table 1.

The elliptical surface notches were cut in the axial direction of pipes by using a 1 mm thick diamond grinding disc. The machined surface notches have a depth-to-length ratio of $a/c = 0.2$ and depth-to-thickness ratios of $a/t = 0.25$–0.38–0.5, where a is the crack depth, $2c$ is notch length on the pipe surface, and t is wall thickness. After the formation of the surface notches, they were sharpened by a doctor blade in order to change them into surface cracks.

Specimens with an elliptical surface crack were exposed to fatigue tests under internal pressure at 30, 40, and 50% of ultimate hoop stress strength values of unnotched pipes. The tests were conducted under open-ended internal pressure conditions in which the pipes can extend in diameter and shrink in length freely.

Experimental results and discussions

Static internal pressure tests of intact GRP pipes

For determining the stress level to be used in the fatigue tests, it is necessary to know their static hoop strength values. Strain-gauges were located on the intact GRP pipe in axial and radial direction in order to obtain the mechanical properties and static burst strength. These specimens were loaded with internal pressure until burst was obtained at a loading rate of 1 MPa/s. The average values were found as $\sigma_{\theta\theta\text{static}} = 675$ MPa and E = 45 GPa. Tarakcioglu et al. found approximately similar results [14, 15].

Fatigue tests

Fatigue tests were performed by using a programmable logical controller (PLC) controlled servo-hydraulic testing machine. The procedure for determining the fatigue strength of a composite pipe is based on ASTM standard D2992 which requires cycling internal hydrostatic pressure at a rate of 25 cycles per minute (frequency of 0.42 Hz). The fatigue loads were applied at a stress rate of $R = \sigma_{\min}/\sigma_{\max} = 0.05$. The magnitude of the fatigue test stress levels was decided based on the strength under static internal pressure. Three different stress levels were applied in the tests. The maximum stress levels were 30% (202.5 MPa), 40% (270 MPa), and 50% (337.5 MPa) of the static strength of the specimen ($\sigma_{\theta\theta\text{static}}$).

Figure 1 shows the variation of fatigue failure cycles versus applied stress. As shown in this figure, as the applied stress increased the cycles of fatigue failure decreased expectedly. On the other hand, as the *a*/*t* ratio increased the fatigue life decreased considerably.

The applied load is in hoop direction. As the load increases, the diameter of the pipe increases. The pipe returns to its original shape when the load is released. This event leads to an interlaminar shear stress especially at the

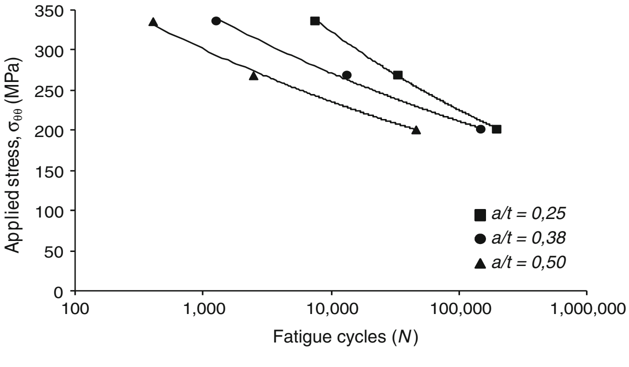


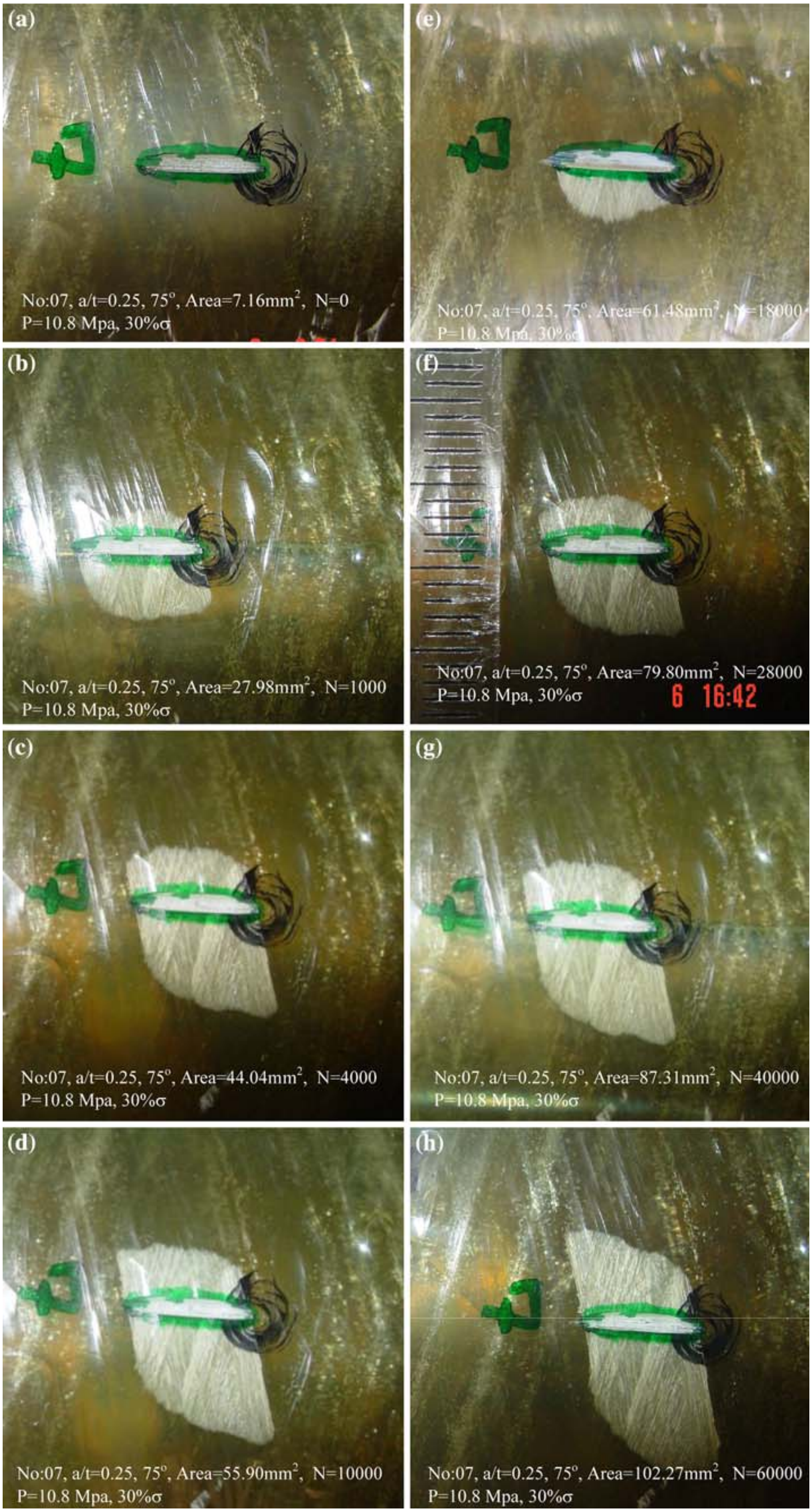
Fig. 1 Stress-life (*S*–*N*) curves of ($\pm 75_3$) GRP pipe with a surface crack at different *a*/*t* ratios

Table 1 The properties of glass fibers and epoxy resin materials

Material	*E* (GPa)	ν	σ_{ult} (MPa)	ρ (g/cm^3)	ε(%)
Vetrotex 1200 tex E-glass	73.0[a]	0.25	2400[a]	2.6	1.5–2
Ciba Geigy CY 225 epoxy resin	3.4	0.38	50–60	1.2	4–5

[a] Based on dry roving testing

Fig. 2 Progressive fatigue failure of GRP pipe with a surface crack under cyclic internal pressure of 10.8 MPa ($a/t = 0.25$, $0.3\sigma_{\theta\theta\mathrm{static}}$) (**a**) $N = 0$, (**b**) $N = 1{,}000$, (**c**) $N = 4{,}000$, (**d**) $N = 10{,}000$, (**e**) $N = 18{,}000$, (**f**) $N = 28{,}000$, (**g**) $N = 40{,}000$, (**h**) $N = 60{,}000$, $N_{\mathrm{burst}} = 200{,}000$



regions underneath the surface crack. On the other hand, as the load is applied the fiber reinforcements show a tendency to orient in hoop direction. When the load is released the fibers return to their initial orientation. At the successive plies this motion occurs at opposite directions leading to an additional interlaminar shear stress development. So it is reasonable that the damage occurs as mixed mode (Mode II and Mode III).

Figure 2 shows the propagation of delamination under fatigue loading at different number of cycles for $a/t = 0.25$ and load of 30% of static burst strength ($\sigma_{\theta\theta\text{static}}$). The failure propagated at the region where the surface crack cuts glass fiber bundles. This failure region did not exceed the distance of crack length, $2c$, and boundary of ($\pm75_3$) winding angle. As shown in this figure the crack propagation occurred in Mode II associated with delamination. After some delamination, the pipes experienced a sudden burst. The pipes with different a/t ratios showed the same failure characteristics.

In order to measure the delamination area, the damage zone was photographed step by step in high resolution. These photographs were transferred to AutoCAD. The scales of these photographs were set to 10:1 using the “scale” command. The delamination zone was surrounded by using the “spline” command and closed area was formed. Finally the area was measured by issuing the “area” command with 0.01 precision.

Figures 3–5 show the growth of delamination area versus fatigue cycles. As shown in these figures, as the applied load increased delamination spread faster. After a certain amount of delamination growth, the delamination propagation saturated and did not continue to grow any more until the end of damage process.

It is also seen in Figs. 3–5 that the delamination area rapidly increased at the beginning of the process and then slowed down. At high stress the delamination propagation saturated quickly and then propagation stopped, while at low stresses, delamination takes much more time to attain saturation. It is also seen that as the a/t ratio increased the cycles to saturation decreased.

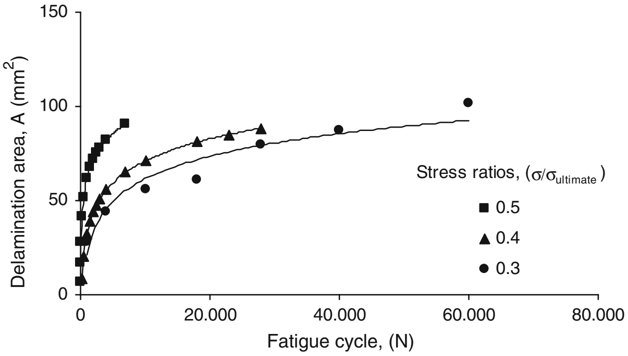


Fig. 3 Delamination area versus number of fatigue cycles (A–N) for $a/t = 0.25$

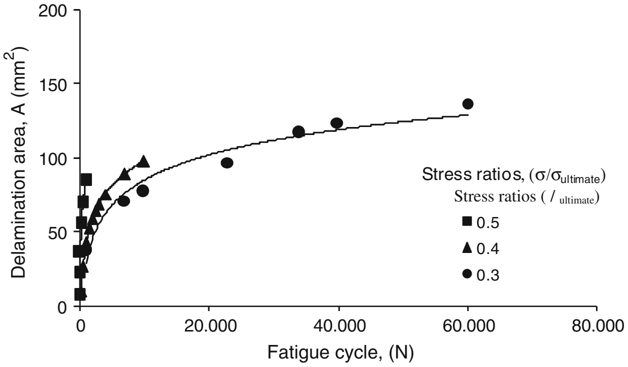


Fig. 4 Delamination area versus number of fatigue cycles (A–N) for $a/t = 0.38$

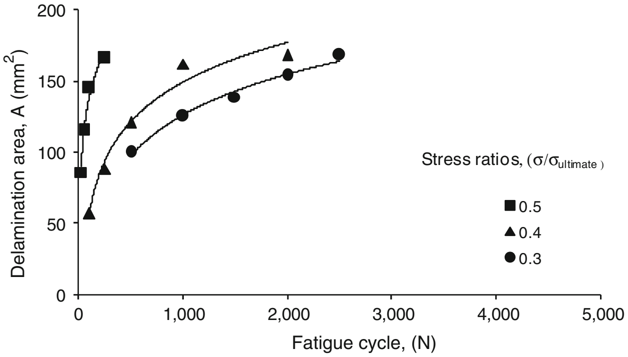


Fig. 5 Delamination area versus number of fatigue cycles (A–N) for $a/t = 0.5$

Three damage stages were observed during fatigue of the intact portion of the pipe under the surface cracks. The first stage is “white zone formation” associated with debonding between fiber and matrix and delaminations as stated by Tarakçıoğlu et al. [15].

The second stage was matrix cracking. In this region microcracks propagate in radial direction by the effect of internal pressure. These microcracks coalesced other and grew by the effect of each loading cycle (opening and relaxing). The last stage was “oil leakage initiation” and final failure with burst. The leakage starts as small droplets at points where microcrack coalescence occurs, and immediately after leakage initiation, a rapid burst damage took place. These damage stages were also reported by Tarakçıoğlu et al. [15].

Conclusions

In this study, the fatigue behaviors of ($\pm75_3$) filament wound GRP pipes with a semi-elliptical surface crack were investigated under open-ended internal pressure. It was concluded that;

- Failure mainly occurred at the region where the surface crack cuts glass fiber bundles. This failure did not exceed the crack length $2c$ or the direction of the ($\pm75_3$) winding angle.
- Crack propagation effectively occurred as delamination (Mode II).
- As the a/t ratio increased the fatigue life decreased considerably.
- The delamination area begun to increase rapidly and then slowed down.
- As the applied load increased the delamination propagated faster.
- After a certain amount of growth, delamination propagation slowed down and finally completely stopped, and did not show any further increase until the final damage is reached. At high stress the delamination propagation rate decreased quickly and then propagation stopped, while at low stress delamination saturation takes much more time, and cycles to delamination saturation decreased considerably with increasing a/t ratio.

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