Study on fatigue failure of glass fibre-reinforced thermoplastic pipe

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Abstract

The long-term fatigue performance of a glass fibre-reinforced thermoplastic pipe (RTP) is mainly determined by that of its glass fibre reinforcement layer. Glass fibre has an irregular network structure consisting of SiO₄ tetrahedrons. In this network structure, there exists numerous defects. Under cyclic loading, cracks are initiated at these defects and grow steadily and perhaps even disruptively, ultimately leading to the fracture of the glass fibre. The mean stress corresponding to the occurrence of disruptive crack propagation is referred to as the critical fatigue stress. When the mean cyclic load is smaller than the critical value, the growing cracks stop propagating when in contact with high-energy chemical bonds. When the mean cyclic load is larger than the critical value, the glass fibre is doomed to fracture. In the present study, a series of fatigue tests was performed on a RTP subjected to cyclic loadings of different mean stresses. The numbers of cycles to failure at different mean stresses obtained from the tests were then used to estimate the critical fatigue stress of the RTP. The mechanism underlying the fatigue failure was analysed using fatigue mechanics and chemical bond theories.

1. Introduction

Glass fibre-reinforced thermoplastic pipe (RTP) is a composite pipe with inner and outer layers of high-density polyethylene (HDPE) and an intermediate reinforcement layer of glass fibres that are bound to the inner layer at a certain angle and covered by the outer layer [1–4]. A RTP has the advantages of pressure resistance, high pressure rating, corrosion resistance, low weight, fewer joints required for installation, and low cost. These pipes have a wide range of potential applications in on- and off-shore petroleum exploration and transportation, municipal water infrastructure, and chemical industries.

The long-term fatigue failure performance of RTP is mainly determined by that of its glass fibre reinforcement layer [2, 5, 6]. The most common source of RTP failure is glass fibre damage. Relatively limited research has been carried out on the fatigue performance of RTP and the mechanism underlying its fatigue failure. The service life of RTP under fatigue stress remains unclear. In the present study, a series of long-term fatigue tests was performed on a RTP subjected to cyclic loading at a constant minimum to maximum stress ratio but at different mean stresses. The resulting numbers of stress cycles to failure at different mean stresses were then used to estimate its critical fatigue stress. To ensure a desirable service life of a RTP, the maximum mean stress of the cyclic loading must be smaller than the critical fatigue stress.

2. Test

2.1. Testing materials

Glass fibre strip: Glass fibre bundles were wetted via soaking in a batch solution and then baked dry in an oven. The pre-treated bundles were bonded with molten HDPE in a mould. The resulting composite material was rolled into strips. The glass fibre (2400 TEX) measured 0.6 mm in thickness and had a density of 1.3373 g cm⁻³ and vertical fracture stress of 300 MPa.
RTP: Samples were made using HDPE as the inner and outer layers and the glass fibre strip as the intermediate reinforcement layer, which was bonded with the inner layer and covered by the outer layer (figure 1). The extruder extrudes HDPE, cools and shapes the inner tube, and the winding machine winds the glass fibre composite tape around the inner tube at a certain angle, and the outer layer is coated with polyethylene. The RTP measured 110 mm and 10 mm in outer diameter and overall wall thickness, respectively. The inner, reinforcement, and outer layers measured 6, 1.2, and 2.8 mm in thickness, respectively.

2.2. Testing equipment
Tests were conducted on a XGNB-P burst test machine and a XGNB-Y fatigue test machine (Chengde Precision Testing Machine Co., Ltd, China). Scanning electron microscopy (SEM) observations were conducted with an APREO scanning electron microscope (FEI, USA).

2.3. Testing conditions
The two ends of the RTP samples were sealed for the subsequent tests.

2.3.1. Parametric setting for burst test
Main pressure: 12 MPa; pressure loading rate: 1 MPa s⁻¹; testing temperature: 20°C; and effective length of sample: 1,000 mm.

2.3.2. Parametric setting for fatigue test
The samples (measuring 1,000 mm in length) were subjected to cyclic loadings of different mean stresses (100%, 65%, 60%, 55%, 50%, 45%, 40%, and 35% of the burst pressure obtained from the burst test). The parametric setting for the cyclic loading was kept constant except for the mean stress: magnitude, 10% of maximum stress; frequency, 10–20 cycles/min; and minimum to maximum stress ratio, 0.818. Multiple tests were performed for each mean stress. The number of stress cycles (N) to failure at a given mean stress was estimated as the average of the results obtained from multiple tests.

3. Testing results and discussion

3.1. Burst test
Multiple burst tests were performed. The burst pressure of the RTP was estimated as the mean of the burst pressures obtained from the multiple tests (8.32 MPa) (Table 1).
3.2. Results of fatigue test

A series of fatigue tests was performed under the testing conditions described above. The samples were subjected to cyclic loading at a frequency of 20 cycles/min until they failed, as shown in figure 2. When approaching failure, the samples exhibited bubbling (figure 3) but no discernible pattern in the location of the bubbles. Additionally, the time from the occurrence of bubbling to failure is very short, accounting for only a very small portion of the overall time to failure.

Table 2 shows the number of cycles (N) to failure at different mean stresses (S) and at a constant minimum to maximum stress ratio (0.818). Figure 4 is the S–N curve based on the data in table 2. The number of stress cycles to failure increased as the mean stress decreased. More specifically, at higher mean stresses (corresponding to the high-slope section of the S–N curve), fatigue failure occurred after fewer cycles. At smaller mean stresses (corresponding to the small-slope section of the S–N curve), fatigue failure occurred after a much greater number of cycles.

![Figure 2. Cyclic loading for fatigue test.](image)

![Figure 3. Cracking and bubbling of RTP prior to failure.](image)

| Mean pressure (% burst pressure) | Mean stress (MPa) | Magnitude of cyclic loading | Minimum to maximum stress ratio | Minimum stress (MPa) | Maximum stress (MPa) | Number of cycles to failure |
|---------------------------------|-------------------|-----------------------------|--------------------------------|----------------------|----------------------|-----------------------------|
| 100%                            | 8.32              | 10%                         | 0.818                          | 7.49                 | 9.15                 | 1                           |
| 65%                             | 5.41              | 10%                         | 0.818                          | 4.87                 | 5.95                 | 4973                        |
| 60%                             | 4.99              | 10%                         | 0.818                          | 4.49                 | 5.49                 | 10142                       |
| 55%                             | 4.58              | 10%                         | 0.818                          | 4.12                 | 5.04                 | 16284                       |
| 50%                             | 4.16              | 10%                         | 0.818                          | 3.74                 | 5.58                 | 30777                       |
| 45%                             | 3.76              | 10%                         | 0.818                          | 3.38                 | 4.13                 | 68047                       |
| 40%                             | 3.33              | 10%                         | 0.818                          | 3.00                 | 3.66                 | 230266                      |
| 35%                             | 2.91              | 10%                         | 0.818                          | 2.62                 | 3.20                 | 604648                      |
The $S \sim N$ curve was fitted to obtain the following logarithmic equation:

$$y = -0.049 \ln(t_1) + 1.0213, \quad R^2 = 0.9827,$$  

where $y$ is the ratio of the mean stress to the burst pressure of RTP; $t_1$ is the number of cycles to failure at a cyclic loading frequency of 20 cycles/min; and $R^2$ is the curve-fitting coefficient, with a value closer to 1 indicating better fit.

In real-world applications, a RTP with $t_1 > 10^7$ can be assumed to have an infinite fatigue life. For the RTP considered in the present study, when $t_1 = 10^7$, $y = 0.2315$. In other words, the RTP can be assumed to have an infinite fatigue life when subjected to cyclic loading with a mean stress lower than 23.15% of the burst pressure. In summary, the burst pressure of the RTP considered in the present study (outer diameter = 110 mm; overall wall thickness = 10 mm) was 8.32 MPa. Its critical fatigue stress was 1.926 MPa when subjected to cyclic loading with a magnitude of 10% of the maximum stress, frequency of 20 cycles/min, and minimum to maximum stress ratio of 0.818.

### 3.3. Effect of cyclic loading frequency on result of fatigue test

Two additional series of fatigue tests was performed under the testing conditions described in section 3.2. The only difference was that the samples were subjected to cyclic loading at a frequency of 10 cycles/min and 15 cycles/min (compared with 20 cycles/min previously) until they failed, cyclic loading at a frequency of 10 cycles/min as shown in figure 5.

The samples were tested at a different cyclic loading frequency to investigate the effect of frequency on the fatigue life of RTP. Table 3 and table 4 show the numbers of cycles to failure at different mean stresses. Figure 6 is the $S \sim N$ curve based on the results shown in table 3.
The $S \sim N$ curve according to Figure 6 was fitted to obtain the following logarithmic equation:

$$y = -0.049 \ln (t_2) + 1.02, \quad R^2 = 0.98,$$

where $y$ is the ratio of the mean stress to the burst stress of RTP; $t_2$ is the number of cycles to failure at a cyclic loading frequency of 20 cycles/min; and $R^2$ is the curve-fitting coefficient, with a value closer to 1 indicating better fit.

When $t_2 = 10^7$, $y = 0.2302$. In other words, the RTP can be assumed to have an infinite fatigue life when subjected to cyclic loading at a mean stress smaller than 23.15% of the burst pressure. In summary, the burst pressure of the RTP considered in the present study (outer diameter $= 110$ mm; overall wall thickness $= 10$ mm) was 8.32 MPa. Its critical fatigue stress was 1.915 MPa when subjected to cyclic loading with a magnitude of 10% of the maximum stress, frequency of 20 cycles/min, and minimum to maximum stress ratio of 0.818.

### Table 3. Parametric setting and results of fatigue test (frequency of cyclic loading: 10 cycles/min).

| Mean pressure (% burst pressure) | Mean stress (MPa) | Magnitude of cyclic loading | Minimum to maximum stress ratio | Minimum stress (MPa) | Maximum stress (MPa) | Number of cycles to failure |
|-------------------------------|------------------|-----------------------------|--------------------------------|----------------------|----------------------|---------------------------|
| 100%                          | 8.32             | 10%                         | 0.818                          | 7.49                 | 9.15                 | 1                         |
| 65%                           | 5.41             | 10%                         | 0.818                          | 4.87                 | 5.95                 | 5238                      |
| 60%                           | 4.99             | 10%                         | 0.818                          | 4.49                 | 5.49                 | 12028                     |
| 55%                           | 4.58             | 10%                         | 0.818                          | 4.12                 | 5.04                 | 12369                     |
| 50%                           | 4.16             | 10%                         | 0.818                          | 3.74                 | 5.58                 | 28194                     |
| 45%                           | 3.76             | 10%                         | 0.818                          | 3.38                 | 4.13                 | 72510                     |
| 40%                           | 3.33             | 10%                         | 0.818                          | 3.00                 | 3.66                 | 240200                    |
| 35%                           | 2.91             | 10%                         | 0.818                          | 2.62                 | 3.20                 | 624368                    |

### Table 4. Parametric setting and results of fatigue test (frequency of cyclic loading: 15 cycles/min).

| Mean pressure (% burst pressure) | Mean stress (MPa) | Magnitude of cyclic loading | Minimum to maximum stress ratio | Minimum stress (MPa) | Maximum stress (MPa) | Number of cycles to failure |
|-------------------------------|------------------|-----------------------------|--------------------------------|----------------------|----------------------|---------------------------|
| 100%                          | 8.32             | 10%                         | 0.818                          | 7.49                 | 9.15                 | 1                         |
| 65%                           | 5.41             | 10%                         | 0.818                          | 4.87                 | 5.95                 | 5188                      |
| 60%                           | 4.99             | 10%                         | 0.818                          | 4.49                 | 5.49                 | 9186                      |
| 55%                           | 4.58             | 10%                         | 0.818                          | 4.12                 | 5.04                 | 14069                     |
| 50%                           | 4.16             | 10%                         | 0.818                          | 3.74                 | 5.58                 | 29064                     |
| 45%                           | 3.76             | 10%                         | 0.818                          | 3.38                 | 4.13                 | 57480                     |
| 40%                           | 3.33             | 10%                         | 0.818                          | 3.00                 | 3.66                 | 231636                    |
| 35%                           | 2.91             | 10%                         | 0.818                          | 2.62                 | 3.20                 | 614684                    |
According to Table 4, it was fitted to obtain the following logarithmic equation:

\[ y = -0.049 \ln(t) + 1.017, \quad R^2 = 0.9842, \quad (3) \]

Its critical fatigue stress was 1.89 MPa when subjected to cyclic loading with a magnitude of 10% of the maximum stress, frequency of 15 cycles/min, and minimum to maximum stress ratio of 0.818.

The RTP had critical fatigue stresses of 1.926, 1.89, and 1.915 MPa at cyclic loading frequencies of 20, 15, and 10 cycles/min, respectively. The critical fatigue stress of the RTP was then estimated as the mean of the results obtained at the two different cyclic loading frequencies (1.91 MPa) to minimise the effects of testing error and other factors.

Equations (1), (2), and (3) have identical values of the coefficient, \(-0.049\), and the S-N curve at a cyclic loading frequency of 10 cycles/min almost overlaps with that at a frequency of 20 cycles/min, revealing that the RTP had similar fatigue performance at the two frequencies. This can be explained from the perspective of work transferred from the fatigue test machine on to the RTP sample. More specifically, for a given duration of cyclic loading, the energy heat transferred from the fatigue test machine on to the sample does not vary significantly with the cyclic loading frequency, especially at low frequencies.

3.4. Analysis of RTP fatigue failure using chemical bond theory

Glass fibre mainly consists of SiO2, Al2O3, and CaO. Every four silicon ions combine with one oxygen ion to form a tetrahedron \([\text{SiO}_4]\), which is the basic structural unit of glass fibre. The \([\text{SiO}_4]\) tetrahedrons are connected through bridge oxygens, with different types of connections resulting in different forms of silicon-oxygen skeletons. Each of the four corners of the \([\text{SiO}_4]\) tetrahedron is connected to an adjacent tetrahedron, forming an irregular skeleton network in the three-dimensional space. This network extends infinitely and serves as the primary structure of glass fibre. The \([\text{SiO}_4]\) tetrahedrons share different numbers of bridge oxygens and cluster in different forms, such as isles, rings, and short chains. \(\text{Ca}^{2+}\) and other ions fill the network structure uniformly but irregularly, serving to balance the electric charge in the structure, as shown in Figure 7.

In the irregular skeleton network of glass fibre, Si–O forms a covalent bond, \(\text{Ca}^{2+}\) forms an ionic bond, and the bonds between impurities, isles, and short chains satisfy the van der Waals forces, with the covalent bond being much stronger than the van der Waals forces and the ionic bond. Under cyclic loading, cracks are initiated at the voids in the irregular skeleton network. With the bonds between impurities, isles, and short chains, and between \(\text{Ca}^{2+}\) and other cations fractured, the cracks grow steadily. When in contact with the Si–O covalent bonds in the skeleton structure, the cracks are diverted or deactivated if the stress is not large enough to fracture the high-energy covalent bond. This is because glass fibre has only very low contents of impurities, isles, short chains, and cations. This mechanism serves to limit crack propagation and improve fatigue performance. Thus, if the mean stress is kept constant, the cracks stop growing after propagating for a small distance.

Owing to the presence of random defects in glass fibre, multiple cracks are initiated from different positions and grow steadily in the glass fibre when subjected to cyclic loading. Additionally, the growing cracks may be diverted when in contact with chemical bonds. Therefore, the cracks develop in random directions. More specifically, such cracks measure 10–200 nm in length. In addition to the main cracks propagating along the axis of the glass fibre, there are several micro-cracks propagating along the radial direction of the glass fibre, as shown in Figure 8.

When the mean stress is large enough to damage the covalent bond in the skeleton structure, disruptive crack propagation occurs. More specifically, the small cracks formed during the steady-propagation stage grow further or connect to form large cracks, leading to the ultimate fracture of the glass fibre. A large mean stress leads to a
shorter stage of steady crack propagation and shorter overall time to failure. The mean stress corresponding to the onset of disruptive crack propagation is referred to as the critical fatigue stress. When the stress is smaller than the critical value, the cracks stop propagating when in contact with the high-energy covalent bonds, and the RTP does not experience fatigue failure. When the stress is larger than the critical value, the glass fibre fractures, and the RTP is doomed to fail.

3.5. Micro analysis of glass fibre in the fatigue stress field

From the perspective of fatigue mechanics, fatigue is a process in which the damage caused by external cyclic loading accumulates. Fatigue failure occurs when the cumulative damage reaches a certain level. When the fatigue life of a RTP is greater than that expected or required for a given application, the RTP can be assumed to have an infinite fatigue life or to be fatigue-free. Generally, a RTP can be assumed to be fatigue-free if it does not fail within $10^7$ loading cycles.

Material fatigue is essentially a process in which the material micro-structure changes when subjected to a load. The load on a RTP is mainly borne by its glass fibre reinforcement layer, and hence its fatigue performance is primarily determined by that of its glass fibre reinforcement layer. The fatigue process can be divided into the following four stages: initiation of cracks, steady propagation of cracks, failure propagation disruptive propagation of cracks, and fracture [12–14]. In glass fibres, numerous micro-cracks and micro-defects exist from which the cracks are initiated. Under cyclic loading, stress concentrations are formed near the micro-cracks and micro-defects and cause local dislocations. As the cyclic loading continues, the micro-cracks grow progressively and, when the cumulative crack propagation reaches a critical level, ultimately cause material fracture. When the mean stress is small, the cracks propagate steadily. In the steady propagation stage, the cracks grow slowly. If the mean stress is constant, the crack growth is retarded after a small distance of propagation. If the mean stress is allowed to increase further, disruptive crack propagation occurs at the so-called critical fatigue stress, leading to the ultimate fracture of the glass fibre. In the present study, the time from the occurrence of bubbling of the RTP to its ultimate fracture is much shorter than the overall time to failure. In other words, the...
stage of disruptive crack propagation is much shorter than that of steady crack propagation. As the mean stress increases, the stage of steady crack growth shortens, and the time to failure decreases. Therefore, as the mean stress decreases, the fatigue life of the glass fibre increases. When the mean stress decreases to below the critical fatigue stress, the cracks stop growing and the glass fibre does not experience fatigue failure.

SEM image of glass fibre fracture surface (figure 9). The process of obvious fatigue failure of glass fibre has crack initiation and rapid expansion. In figure 9, under high cyclic stress, the crack initiation source is very small, and the rapid expansion of the crack occupies most of the surface of the glass fibre, so the fatigue failure time of glass fibre is short. With the reduction of fatigue stress (figures 10 and 11), the area of the crack initiation area is enlarged, the area of the rapid expansion area is reduced, and the fatigue failure time of the glass fibre is increased accordingly.

4. Conclusions

The long-term fatigue performance of RTP is mainly determined by that of its glass fibre reinforcement layer. Glass fibre has an irregular network structure, in which there exists numerous defects. Under cyclic loading, cracks initiate at the defects and grow, and may or may not stop growing further when in contact with chemical bonds. The burst pressure of the RTP considered in the present study (outer diameter = 110 mm; overall wall thickness = 10 mm) was 8.32 MPa. Its critical fatigue stress was 1.91 MPa when subjected to cyclic loading with a magnitude of 10% of the maximum stress, frequency of 10–20 cycles/min, and minimum to maximum stress ratio of 0.818. When the mean stress is smaller than the critical fatigue stress, the glass fibre does not fracture, and the RTP does not experience fatigue failure. When the mean stress is larger than the critical fatigue stress, the number of cycles to failure decreases as the mean stress increases. At low-cycle loading, the frequency almost does not affect the fatigue life of the RTP. To ensure a desirable fatigue life of the RTP, the maximum cyclic load must not exceed the critical fatigue stress.

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