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A novel test rig for measuring bending fatigue using resonant behaviour

C P Okeke^{a,b*}, A N Thite^a, J F Durodola^a and M T Greenrod^b^a Department of Mechanical Engineering and Mathematical Sciences, Oxford Brookes University, Oxford – OX33 1HX, UK^b Wipac Ltd, London Road, Buckingham, MK18 1BH, UK

Abstract

A novel test rig for bending fatigue test that based on specimen resonant behaviour has been developed. Determining bending fatigue properties of polymer materials with the standard test systems is challenging, and in some cases results are unattainable. This is particularly true of polymers that exhibit a high level of non-linearity and large deflection. This novel test setup is similar to that of four point bending arrangement resulting in a simple support. The loading is achieved by inertial effect of small masses mounted on the test specimen. A vibration shaker is used to base excite the specimen at the first resonance frequency until it breaks. The proposed test setup reduces the time taken to obtain Stress v/s number of cycles (S/N) curves, typically 1/10th of the universal testing machine based approach. The effect of nonlinearities can be reduced by application of larger loads at higher frequencies using large acceleration and smaller deflection combination. The results based on the proposed approach are in good agreement with tensile fatigue results. It has been successfully used to determine the bending fatigue properties of Polycarbonate (PC) of which determining the tensile fatigue properties were difficult to obtain. The significance of this novel test rig is that it accelerates the fatigue testing and allows the determination of the fatigue properties of some materials that cannot be obtained with existing systems.

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1. Introduction

Determining bending fatigue properties of polymer materials with the standard test systems is challenging, and in some cases results are unattainable. This is particularly true of polymers that exhibit a high level of non-linearity and large deflection. These characteristics have a significant influence on the determination of bending fatigue properties.

* Corresponding author. Tel.: +44-(0)1865-423011

E-mail address: c.okeke100@gmail.com, 14101309@brookes.ac.uk

There are different ways in which bending fatigue load can be generated; these include centrifugal forces, dead weights electro-magnetic forces, pneumatic forces, hydraulic forces etc. These methods were discussed in Weibull (1962). Most of these methods of bending fatigue load application are particularly designed for metallic materials; they may not be suitable for characterising the bending fatigue of polymers due to their large driving load. Polymers have low bending load and therefore require a system of low load application. Currently, the hydraulic and pneumatic mechanisms are the most commonly used load applications in the fatigue of polymers. However, they come with challenges, the minimum rating force for servo-hydraulic system is typically 5kN and some polymers have lower bending load than this. For this reason, the hydraulic system is mostly used for measuring the tensile fatigue of polymers. The servo-pneumatic system has the potential to achieve minimum load down to 1kN, however, due to the compressible nature of air, the operating frequency is low and the performance can be unstable. With low test frequency, the time taken to obtain fatigue property (S-N curve) is longer. To reduce the time taken to characterise the fatigue life of polymers, high frequency system is required. This is where the use of specimen resonant frequency as a test frequency offers significant advantage. The resonant fatigue test system allows the application of larger loads at higher frequencies. There has been some recent work on the development of resonant bending fatigue test rig; however, they are largely focused on the large scale structures. Schneider (2018) developed a resonant bending fatigue testing system to measure the fatigue life of a large-scale structure. The imbalance rotors were used to generate vibrational driving force. The system was able to determine the fatigue life of a structure four times faster than the standard hydraulic system. Maillet et al. (2013) developed a new test methodology based on structural resonance for mode 1 fatigue delamination growth in a unidirectional composite. The set-up which is a mass-spring-specimen dynamic system designed to resonate, was ten times faster than the standard system without heat generation. Bertini (2007) were able to characterise the resonant fatigue property of full scale oil drill string connections in a very short time by using a resonant test rig. The resonance fatigue test system offers a great advantage over standard fatigue test systems by exploiting specimen resonance to accelerate testing.

The objective of this paper was to develop a test rig for measuring bending fatigue using resonant behavior. This novel test setup is similar to that of four point bending arrangement resulting in a simple support. The loading is achieved by inertial effect of small masses mounted on the test specimen. A vibration shaker is required to base excite the specimen at the first resonance frequency until it breaks. The proposed system was validated using fatigue property tests on Polymethyl-methacrylate (PMMA) based on the standard test system. After proving the validity of this novel rig, it will then be used to determine the bending fatigue properties of Polycarbonate (PC) of which determining the tensile fatigue properties with the standards test system was not successful. The significance of this novel test rig is that it accelerates the fatigue testing and allows the determination of the fatigue properties of materials that cannot be obtained using existing systems.

2. Resonant fatigue test rig design

The design of the proposed fatigue test system uses similar support conditions to that of four point bending arrangement ASTM (D7774-12) resulting in a simple support. The loading is based on inertial effect by having two double sided small masses mounted on the test specimen. The schematic diagram of the test set-up is shown in Fig 1. The supports and the loading masses are designed to have cylindrical surfaces; this is to avoid undesirable failure of the test specimen as a result of surface wear induced stress concentration. The clamping of the test specimen to the supports and the attachment of the loading masses to the specimen are achieved with minimal tightening torque. The value of torque to be used is dependent on the material to be tested. In accordance to the four point loading principle, the maximum axial stress on the test specimen is constant between the two loading masses. However, when a notch is introduced at the midpoint of the specimen (centre of the two loading masses), the maximum stress on the specimen will be located at the root of the notch. The total input force required to drive the system is the sum of the forces on the double loading masses which is given as:

$$F = F_1 + F_2 \quad (1)$$

$$F_1 = m_1\ddot{y}, \quad F_2 = m_2\ddot{y} \quad (2)$$

where m and \ddot{y} are the additional mass elements on the specimen and the drive acceleration, respectively. The use of a notch ensures that the fatigue failure occurs at the desired place. However, the stress concentration factor due to the notch has to be accounted for. The maximum stress at the root of the notch is given as:

$$\sigma_{max} = K_t \sigma \tag{3}$$

where K_t is stress concentration factor and for U-type notch used in this study Pilkey (2004), it is given as:

$$K_t = 0.998 + 0.790 \sqrt{\frac{h}{r}} \tag{4}$$

h and r are the depth and radius of the notch, respectively. The nominal stress is defined as:

$$\sigma = \frac{6M}{d^2} \tag{5}$$

And the bending moment M is given as:

$$M = \frac{P}{2} \cdot \frac{L_1}{3} = \frac{FL_1}{6} \tag{6}$$

where F and L_1 are applied force and support span, respectively.

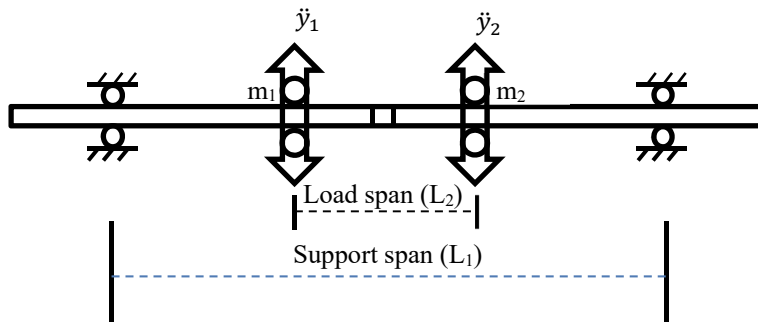


Figure 1: Four-point based resonant, fatigue test specimen and loading

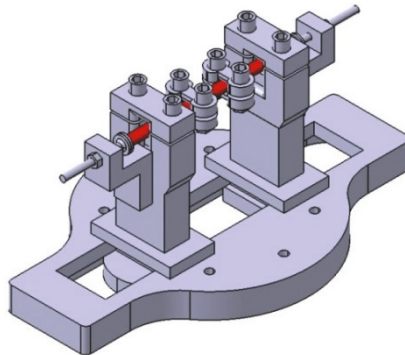


Figure 2: Shaker table adaptor and the test specimen along with fixture.

3. Experimental

The materials used in this study were PMMA and PC respectively. The PMMA specimens of rectangular shape were cut out from an optical plate that was injection moulded at Wipac, while PC specimens were cut out from standard A1 injection moulded dumb bell specimens supplied by manufacturer, Albis. The dimensions of the specimens of both materials apart from PMMA of 2.8mm thickness were 170mm x 10mm x 4mm. A U-type notch of 2mm radius and 6mm depth was introduced at the centre of the specimen as shown in Fig 3.

The fatigue testing was based on three load levels - 80%, 60% and 40% material yield strength. At every load level, five specimens were tested and the number of cycles to failure was logged for every specimen. The input acceleration

for all three load levels was obtained by taking the ratio of the calculated specimen response acceleration to the experimentally obtained transmissibility of the first resonance. The loading was achieved by inertial effect of two small masses mounted on the test specimen. A V721 electrodynamic vibration shaker was used to base excite the specimen at the first resonance frequency until it breaks. The testing was conducted at the room temperature. The complete test set-up is shown in Fig 4.

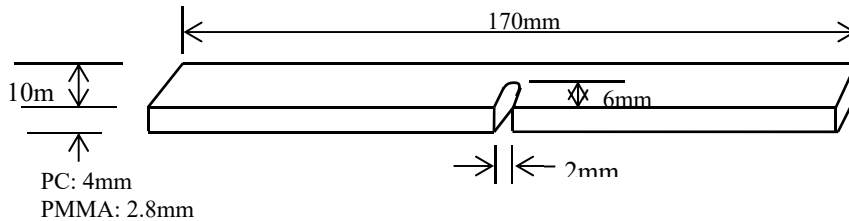


Figure 3: Test specimen

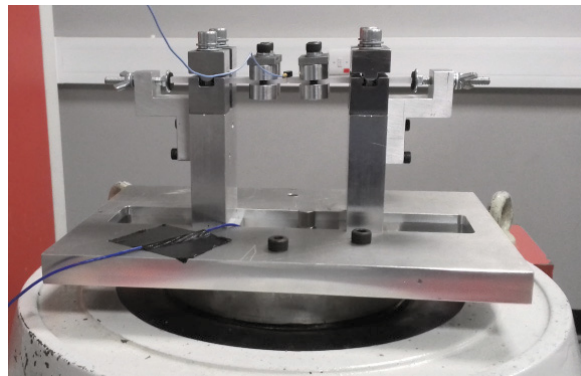


Figure 4: Experimental test set-up

4. Results and validation

4.1. Fatigue life of PMMA – tensile vs resonance bending

Fig 5(a) shows acceleration–fatigue life curve (a-N curve) of PMMA material obtained using the new resonance bending fatigue test rig with resonance of 45Hz. This acceleration-fatigue life curve was converted to stress-fatigue life (S-N curve) and validated with S-N curve of the same material obtained with standard tensile method; both curves are shown in Fig 5(b). The tensile fatigue test was performed under the room temperature in accordance to standard ASTM (D7791-12) using computer controlled SI-Plan servo hydraulic machine. A sinusoidal load waveform with fixed frequency of 5Hz was used. The fatigue life obtained using the novel resonance bending fatigue rig was in excellent agreement with that of standard tensile method. The difference in stress amplitude was that the stress amplitude of resonance bending fatigue was based on bending strength while for tensile fatigue it was based on tensile strength. The bending strength is always higher than the tensile strength and for this material, the bending strength was 1.27 higher than the tensile strength. The curve shows scatter in the fatigue life which increases as the stress amplitude decreased. This is a known phenomenon in characterising the fatigue life of materials. This phenomenon was attributed to the specimen surface condition Schijve (2001). At a high stress the effect of specimen surface imperfection to the crack nucleation is less significant as the loading is more dominant. However, as the stress amplitude decreases, the surface condition starts to play a role in the fatigue life as the crack nucleation can be enhanced by the surface imperfection. The surface conditions can vary between specimens which results in variations of fatigue life between specimens at low amplitude. One of the important contributing factors in this scatter that must not be ignored is inter-sample variations. Polymers are prone to manufacturing variability; this means that material properties will vary across specimens of the same material batch.

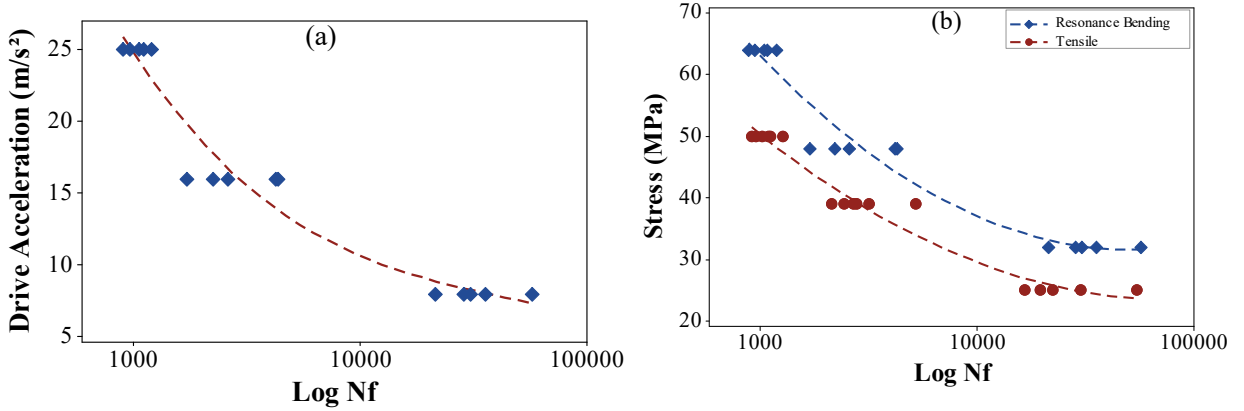


Figure 5: Fatigue life curve of PMMA (a) a-N curve, (b) S-N curve

4.2. Fatigue life of PC – tensile vs resonance bending

The tensile fatigue of polycarbonate (PC) material was carried out in accordance with standard ASTM (D7791-12). Again a test frequency of 5Hz and three levels of stress amplitude, 80%, 60% and 40% of material yield strength were used to determine the S-N curve. The test specimens were standard A1 injection moulded dumb bell BS EN ISO (527-2) supplied by manufacturer, Albis. The length, width and thickness of the narrow portion of the specimen are 80mm, 10mm and 4mm respectively. As can be seen in fig 6(a), at the load level corresponding to 80% and 60% material yield strength, realistic fatigue property could not be obtained. The specimens failed outside the gauge length and the life cycles were significantly higher than expected - similar life was obtained at the three load level which could not be true. The minimum and maximum number of cycles to failure at 80% loading is 18453 and 35143 respectively. At 60% loading, the minimum and maximum number of cycles to failure is 20428 and 34711, and at 40% loading it is 26059 and 39547 respectively. This does not represent the true fatigue failure of crack initiation and propagation and therefore thermal effect was examined. The specimen surface temperature was determined during fatigue test using a thermocouple and an infrared camera – Keysight U5856A. At 80% loading, the temperature of the sample rose to 37.2°C leading to specimen temperature difference of 15.7°C. The specimen temperature rise at 60% loading was 5.3°C, and at 40% loading, it was 0.5°C which can be considered as insignificant. At 80% and 60% loading, the specimen failed outside the gauge length, the region of the fracture showed melted texture. It was considered that the higher number of cycles to failure seen at these load levels was due to thermal softening. The specimen became more ductile as a result of heat build-up and the tendency to stretch maximised in a way that it became more ductile. Test frequency of 5Hz may seemed low to generate thermal failure, however, it should be noted that load amplitude play an important role in thermal failure, so it is the combination of frequency and loading. As a viscoelastic material, PC is sensitive to test frequency and load amplitude. In some polymers, where viscoelastic effects are large, a notable temperature rise can take place at a very low frequency as observed by Sauer et al. (1980). Crawford (1998) noted that even at a lower frequency, the thermal softening failure can take place at a high stress level.

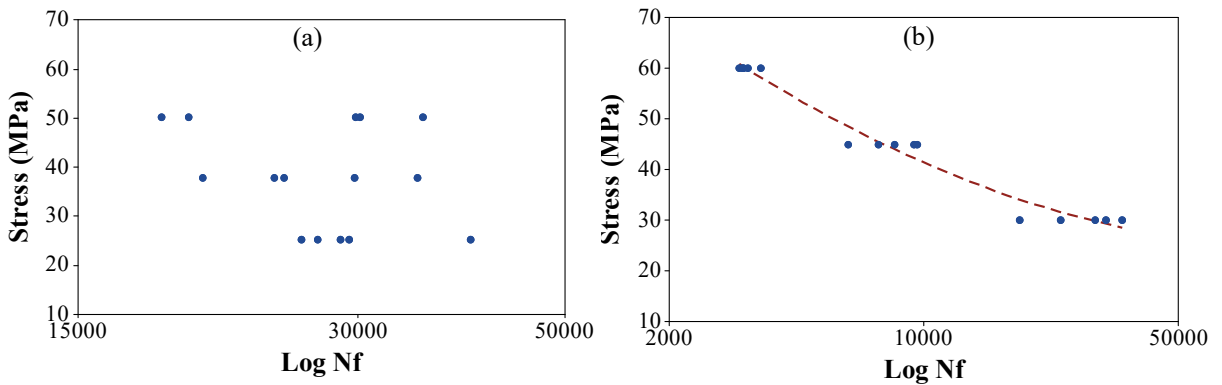


Figure 6: Fatigue life of PC – (a) Tensile fatigue, (b) Resonance bending fatigue

The difficulty in obtaining the tensile fatigue property of PC inspired the development of this resonance fatigue test rig. The resonance bending fatigue test was performed as described above. The specimen was prepared as in fig 3. A cycling frequency of 50Hz which was the resonance frequency of the specimen and three levels of stress amplitude, 80%, 60% and 40% of material yield strength were used to determine the S-N curve. The specimen temperature was measured at every load level. The measured specimen temperature varied in opposite directions to that of tensile fatigue, instead of rising, the temperature was falling, but with a smaller difference. This is an evidence of self-induced cooling. At 80% loading, the specimen temperature dropped from ambient of 22.57°C to 16.93°C giving a 5.64°C temperature difference. At 60% and 40% load levels, specimen temperature difference of 2.19°C and 0.21°C were measured. It appears that the new resonance test set-up does not only accelerate the fatigue test but also eliminates the concern of specimen internal heating by means of self-induced cooling due to the specimen vibration, which results in true fatigue curve. It can be seen from Fig 6(b) that the true fatigue life curve was obtained at every load level.

5. Conclusions

A novel test rig for bending fatigue test that is based on specimen resonant behaviour has been developed. This novel test setup support conditions are similar to that of four point bending arrangement. The loading is achieved by inertial effect of small masses mounted on the test specimen. A vibration shaker is required to base excite the specimen at the first resonance frequency until it breaks. The time taken by the new setup to obtain S/N curves was ~1/10th of the universal testing machine based approach. The fatigue properties obtained were comparable to the results based on tensile fatigue properties. Furthermore, the setup was successfully used to determine the bending fatigue properties of Polycarbonate (PC) of which determining the tensile fatigue properties with the standards test system was not successful. The specimen temperature decreases with increased load amplitude by means of self-induced cooling due to the specimen vibration, which eliminates concerns of thermal failure. The significance of this novel test rig is that it accelerates the fatigue testing and allows the determination of the fatigue properties of materials that cannot be obtained with existing methods.

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