Fatigue Characterization of Polycarbonate under Stress-Controlled Cyclic Load

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Abstract

Polycarbonate (PC) is a widely used engineering thermoplastic that exhibits time-dependent viscoelastic behaviour, making it highly susceptible to fatigue damage under cyclic loading conditions. Existing studies are largely restricted to simplified loading conditions and short-term fatigue investigations, and the complete characterisation of hysteresis energy strain loss under cyclic loading remains limited in the literature. In the present study, the fatigue behaviour of injection-moulded unfilled polycarbonate was experimentally investigated using specimens prepared in accordance with ASTM D638. The tensile test was conducted at a strain rate of 5 mm/min, and the fatigue test was conducted under stress-controlled cyclic loading with a stress ratio of R = 0.1, an applied stress amplitude of 30 MPa, and a frequency of 5 Hz. Tensile testing revealed the confirmation of adequate mechanical strength and considerable ductility of PC with a tensile strength of 62.8 MPa and an elongation at break of 31.5 %. Fatigue test using the proportional limit as the stress input, high-cycle fatigue tests revealed a progressive increase in maximum strain, from 0.01534 mm/mm at 1000 cycles to 0.01677 mm/mm at 32000 cycles, reflecting accumulating plastic deformation. Correspondingly, the hysteresis loop area decreased from 0.006152 to 0.005547 MJ/m^3, indicating reduced energy dissipation and initial cyclic stabilisation, followed by microstructural damage and stiffness degradation at higher cycles. These findings highlight the interplay between strain accumulation and energy dissipation in governing the fatigue behaviour of polycarbonate.

Keywords: Polycarbonate; cyclic loading; hysteresis loop; fatigue damage; viscoelastic behaviour.

Introduction

The mechanical properties of thermoplastic materials hold significant scientific and industrial importance, primarily because polymers exhibit low mechanical impedance, characterised by relatively low mass density and low elastic stiffness. Among these materials, Polycarbonate stands as a widely utilised tough engineering plastic, finding broad application across demanding sectors such as the automotive and aerospace industries, owing to its favourable strength-to-weight ratio and exceptional impact resistance. Throughout their operational service life, these materials are frequently subjected to cyclic loading conditions, which inevitably lead to the progressive accumulation of internal damage over time. Despite this, the majority of existing research has focused only on the static and dynamic stress-strain behaviour of polymers during loading phases alone. The complete characterisation of hysteresis energy loss resulting from cyclic loading has not yet been studied in sufficient detail, representing a critical gap in the current understanding of polymer fatigue behaviour. Albouy et al [1] studied the influence of matrix ductility on the high-temperature fatigue behaviour of carbon fibre reinforced PPS and epoxy composites. Their study revealed that the ductile PPS matrix delayed crack initiation and propagation, thereby improving fatigue performance. Furthermore, hysteresis loop energy dissipation was strongly correlated with fatigue damage accumulation. Calcagno et al [2] compared the viscoplastic behaviour of polycarbonate, polypropylene, and high-density polyethylene through uniaxial tensile testing conducted at various strain rates. A unified constitutive model was developed to describe the plastic deformation behaviour of all three polymers. However, the investigation was limited to monotonic tensile loading at room temperature and did not address cyclic fatigue or hysteresis loop characteristics. Chen et al [3] investigated the strain energy evolution of polycarbonate during elastic-plastic deformation using infrared thermography. The study established quantitative relationships between infrared radiation variation and both elastic and plastic strain energies. The results demonstrate that infrared thermography can effectively monitor real-time energy storage and dissipation during deformation. However, the investigation was limited to quasi-static tensile loading of polycarbonate, and the applicability of the proposed approach to other materials and complex loading conditions remains to be explored.

Drozdov [4] examined the cyclic viscoelasto-plastic response and low-cycle fatigue behaviour of polymer composites through experimental testing and constitutive modelling. The proposed model successfully predicted hysteresis loop evolution and strain accumulation. And fatigue life under cyclic loading. However, the study remains limited to specific loading conditions and simplified damage mechanisms. Drozdov et al [5] explored the cyclic viscoplastic behaviour of high-density polyethylene through tensile and cyclic loading experiments. Their study demonstrated significant hysteresis loop evolution, residual strain accumulation, and creep behaviour during cyclic deformation, and a constitutive model was successfully developed to predict the observed material response. However, the investigation was limited to sub-yield uniaxial loading conditions and did not address fatigue failure mechanisms. Drozdov et al [6] investigated the cyclic viscoelastoplastic behaviour of polypropylene using tensile, relaxation and ratcheting tests. Their results showed that mellaocene polypropylene exhibited better resistance to ratcheting deformation and longer fatigue life than isotactic polypropylene due to enhanced physical cross-linking within its crystalline structure. Meneghetti et al [7] examined the fatigue behaviour of glass-fibre and calcium carbonate reinforced polypropylene composites using hysteresis energy analysis. Their study demonstrates that hysteresis energy per cycle effectively correlates fatigue life across different composite systems and was largely independent of loading frequency. However, the investigation was restricted to room temperature constant amplitude fatigue conditions. Movahedi-Rad et al [8] proposed a constitutive model to describe the interaction between time-dependent (viscoelastic) and cyclic-dependent fatigue behaviour in glass/epoxy composite laminates. The model successfully predicted fatigue stiffness degradation, hysteresis loop evolution, cyclic creep, storage modulus, loss modulus, and tan(δ) under interrupted fatigue loading. However, the study was limited to matrix-dominated ±45° glass/epoxy laminates and interrupted loading conditions. Yin et al [9] developed a fatigue life prediction method for carbon black-filled rubber based on steady-state hysteresis loss. A strong correlation is observed between hysteresis loss and temperature rise. The proposed model accurately predicted fatigue life while reducing experimental time and cost. However, the model was validated under limited loading conditions and a single material formulation. Zhang et al [10] investigated the cyclic mechanical behaviour and microscopic irreversible deformation evolution of HDPE/glass fibre reinforced thermoplastic composites through cyclic testing and multiscale numerical modelling. The study demonstrated that stress level, stress ratio, and strain rate strongly influence hysteresis energy dissipation and irreversible strain accumulation. However, the proposed model had limited capability in predicting long-term fatigue damage evolution. Andrianov (2023) studies the fatigue life of polycarbonate material, which is used for the 3D printing process, considering cyclic tension. A stress-controlled loading method was utilized to analyse the fatigue characteristics [11]. Under tensile cyclic loading, fatigue resistance and failure behaviour were predicted for compatibilized PC/ABS material blends, which also utilized a stress-controlled fatigue process [12]. Cai et al. (2024), for polymeric materials, predicted stress-controlled cyclic loading behaviour using a fractional modelling method [13]. The effect of foam morphology was quantitatively analysed considering quasi-static and cyclic dynamic tests to predict tensile properties [14]. Thermomechanical behaviour and fatigue life were predicted for ternary PC/PMMA/ABS blends considering the effect of methyl methacrylate content [15].

Existing studies on the fatigue behaviour of thermoplastic materials are generally restricted to specific materials, simplified loading conditions and short-term fatigue investigations. Furthermore, the capability to predict long-term fatigue damage using energy-based approaches remains limited. Polycarbonate, as a time-dependent viscoelastic material, exhibits characteristic cyclic deformation behaviour, including hysteresis loop formation and internal energy dissipation, which are strongly influenced by loading variables such as stress amplitude, stress ratio, loading frequency and strain rate. However, the combined influence of these variables on cyclic deformation and long-term fatigue performance is not systematically addressed in the literature. Therefore, the objective of the present study is to experimentally investigate the cyclic viscoelastic behaviour of polycarbonate under various stress-controlled tensile and cyclic loading conditions, with particular emphasis on evaluating the role of key loading parameters in governing fatigue damage accumulation and hysteresis energy loss.

Materials and Methods

In the present work, tensile and fatigue tests are carried out on polycarbonate material specimens. The unfilled polycarbonate used in this study has a density of 1.2 g/cm^3 and a melt flow index of 20 g/10 min, and is supplied by AVG Polymers India Pvt Ltd (Delhi). Dumbbell-shaped specimens are prepared in accordance with ASTM standard D638, with a length of 165 mm, a width of 13 mm, and a thickness of 3.2 mm, using an injection moulding machine. The material used is an unfilled polycarbonate of injection mould grade in granule form. Since polycarbonate is highly hygroscopic and readily absorbs ambient moisture, the granules require careful pre-drying prior to processing. The granules are dried in a dehumidifying hopper dryer at a temperature of 120°C for three to four hours, or until a moisture analyser confirms that the moisture content is reduced to below 0.02%. After drying, the granules are immediately inspected to ensure they are free from contamination, streaks, and discolouration. The injection moulded within 30 to 60 minutes of exposure to ambient air. The barrel temperatures range from 240°C at the feed zone to 300°C at the nozzle, and the mould temperature is maintained between 70°C and 100°C. These processing parameters ensure proper cavity filling and minimise residual stress in the final specimen, and also provide accurate optical clarity, dimensional stability and reliable mechanical strength. Figure 1 presents the specimen dimensions prepared according to the ASTM D638 standard (in mm). The tensile tests are performed on unfilled polycarbonate specimens, which are produced directly by injection moulding, as shown in the Figure 2. The static tests are conducted on a Tinius Olsen machine with a 50kN load capacity, at a displacement rate of 5 mm/min and at room temperature. The specimens are marked along the grip length and gauge length for both tensile and fatigue testing, as shown in the Figure 3. The fatigue tests were carried out by imposing a sinusoidal wave form characterised by a nominal stress value R equal to 0.1. A test frequency of 5 Hz is adopted depending on the applied stress value. In order to maintain the ambient temperature of the specimen throughout testing.

During fatigue tests, the hysteresis loops were measured by using the signals of the load cell over a gauge length of 50 mm. Both static and fatigue tests were carried out on the specimen geometry shown in the Figure 1. Fatigue tests were carried out on Walter+bai servo-hydraulic test machine equipped with a 250kN load cell.

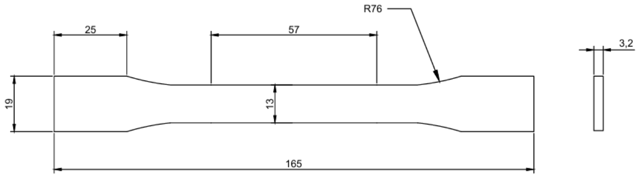

Figure 1 ASTM D638 specimen geometry adopted for static and fatigue tests. (all dimensions are in mm)

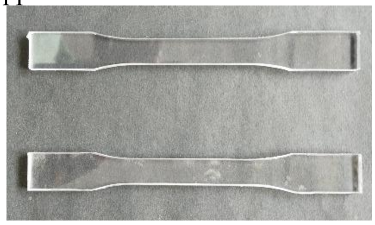

Figure 2 Samples prepared by injection moulding

Figure 3 Marked samples for the tensile and fatigue testing

Results and Discussions

Tensile Testing

The Tinius Olsen static tensile testing machine, possessing a 50 kN load capacity, is utilized for evaluating polycarbonate materials. The machine is employed to determine key mechanical properties, including Young's modulus, yield strength, ultimate strength, and elongation at break. The machine operates with the following input parameters, as shown in Table 1 below:

Table 1 Tensile Test Parameters

Strain rate, $\acute{\varepsilon}$ (mm/min)	Specimen gauge length, L (mm)	Specimen width, W (mm)	Specimen thickness, T (mm)
5	50	13	3.2

The experimentally obtained values for the proportional limit, Young's modulus, yield strength and ultimate strength are presented in Table 2. The proportional limit is subsequently utilised as the input parameter for the fatigue test. Figure 4 presents the stress-strain curve obtained from the tensile test, from which the tensile behaviour of polycarbonate is evaluated. The specimen exhibits a tensile strength of 62.8 MPa and an elongation at break of 31.5%. The relatively high elongation observed in the stress-strain response indicates that the material possesses considerable ductility and toughness. The materials are examined and tested under isotropic conditions throughout the evaluation process.

Table 2 Tensile Test Results

Young's modulus, E (MPa)	Proportional Limit, σ_p (MPa)	Yield Strength, σ_y (MPa)	Ultimate Strength, σ_u (MPa)	% of Elongation
2156	31	45	62.8	31.5

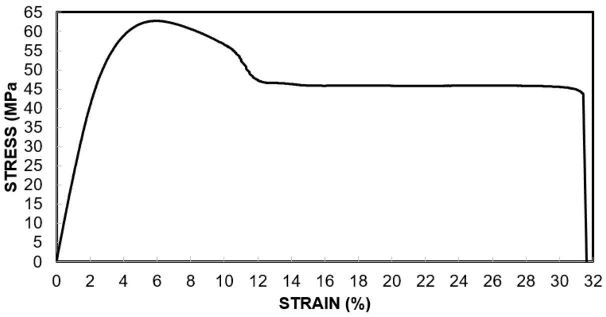

Figure 4 stress-strain graph of the polycarbonate materials

Fatigue Testing

Cyclic fatigue testing was carried out on the dumbbell-shaped polycarbonate tensile specimens using a Walter+Bai servo-hydraulic universal testing machine with a capacity of 250 kN, as shown in Figure 5. High-cycle fatigue tests are performed under stress-controlled cyclic loading conditions, which enable the determination of the load-bearing capacity of the material before failure. The input parameters adopted for the fatigue test are presented in Table 3. The primary objective of the fatigue test is to initiate cyclic loading and continuously monitor the specimen until failure occurs.

Table 3 Fatigue Test Parameters

Stress ratio, R	Strain rate, $\acute{\varepsilon}$ (mm/min)	Specimen gauge length, L (mm)	Specimen width, W (mm)	Applied stress, σ_p (MPa)	Test Frequency, f (Hz)
0.1	5	50	13	30	5

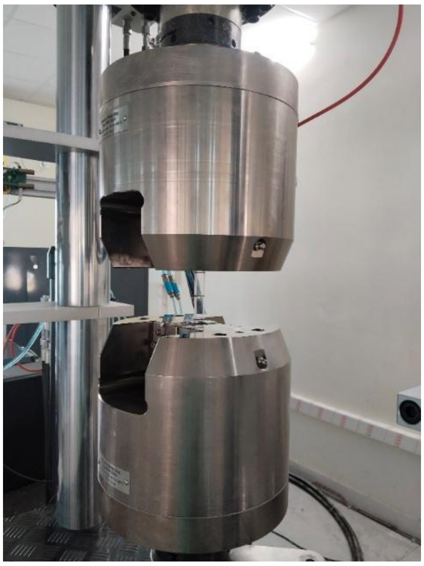

Figure 5 Walter+bai servo-hydraulic UTM testing machine

During the fatigue test, the characteristic features of the hysteresis loop were studied at selected cycle intervals. The proportional limit, determined from the tensile test, is utilised as the stress input to evaluate fatigue life and hysteresis loop behaviour in the polycarbonate material. Figure 6 illustrates the determination of the hysteresis loop area at specific cycles derived from the stress-strain response. The cyclic tensile stress-strain response showed a progressive increase in maximum strain with increasing fatigue cycles, from 0.01534 at 1000 cycles to 0.0158 at 15000 cycles and 0.01677 at 32000 cycles, corresponding to a cumulative increase of 9.322%. This trend reflects the accumulation of irreversible plastic deformation under repeated loading, consistent with progressive material softening behaviour typically observed in cyclic loading conditions. The hysteresis loop area decreased from 0.006152 MJ/m^3 to 0.05547 MJ/m^3 over the same cycle range, indicating a gradual reduction in energy dissipation during cyclic deformation. This trend suggests that the material initially exhibited cyclic stabilisation but subsequently experienced greater energy dissipation due to progressive microstructural damage, plastic deformation, and stiffness degradation at higher fatigue cycles.

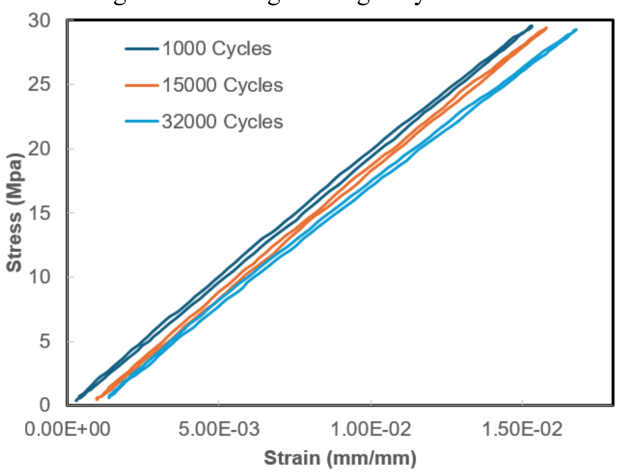

Figure 6 Fatigue stress-strain graph of the polycarbonate materials

Conclusions

The tensile and fatigue evaluation of polycarbonate reveals a transition from cyclic stabilisation to progressive damage-induced degradation under increasing fatigue cycles. The main conclusions of this study are as follows.

- Polycarbonate exhibited a tensile strength of 62.8 MPa and an elongation at break of 31.5%, indicating considerable ductility and toughness. The proportional limit from the tensile curve was used as the stress input for fatigue testing.
- High-cycle, stress-controlled fatigue tests were conducted to evaluate load-bearing capacity and hysteresis loop behaviour at selected cycle intervals until failure.
- A progressive increase in maximum strain was observed with increasing cycles, from 0.015343 mm/mm (1000 cycles) to 0.01677 mm/mm (32000 cycles). This behaviour is attributed to the accumulation of plastic strain and consequent cyclic softening of the material.
- Hysteresis loop area decreased from 0.006152 to 0.005547 MJ/m^3 over the same range, indicating reduced energy dissipation and initial cyclic stabilisation.
- Despite this stabilisation, signs of microstructural damage, plastic deformation, and stiffness degradation emerged at higher fatigue cycles, marking a shift from cyclic loading to a progressive degradation-dominated regime.

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