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Effects of thermal conditions on fatigue behaviour of laminated glass/epoxy plates under tension-tension cycle

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A B S T R A C T

The fatigue behavior study on laminated glass/epoxy composite plates at elevated temperature is attempted in the present research work. INSTRON 8862 servo-electric universal testing machine with hydraulic suspension is utilized to perform low cyclic tension-tension fatigue tests at 0.5Hz and 0.7Hz frequencies. Bluehill universal software compatible with INSTRON 8862 is employed to obtain the relationship of fatigue stress upon cycles to failure (S – N) for each specimen. The parametric investigation is done for the loading frequency, lamination sequence and number of layers to understand their effects on fatigue behavior of composite laminated plates under ambient and thermal environment. The elicited results lead to the conclusion that above parameters greatly influenced the fatigue behavior of composite laminated plates under thermal loading. The rising temperature has significant adverse effects on fatigue life. The present research is beneficial for the analysis and design of laminated composite plate or plate-like structures in the domain of fatigue analysis.

1. Introduction

Laminated composite introduces excellent tailoring ability along with high strength and high specific stiffness for which it has a wide fundamental application in applied engineering fields. To this end, aerospace engineering, civil infrastructure, marine and mechanical machineries consume a high level of application of fiber laminated composite plates (FLCP) in assembly. Such wide engagements of FLCP inevitably experience different conglomerations of static and dynamic loads along with the temperature variations due to which crack or crack-like structural irregularities cannot be avoided. But in crack propagation, the tension-tension cyclic loading affects the FLCP significantly. In this context, fatigue behavior study is a prime concern for FLCP as it has a rigorous utilization in aerospace applications. The failure in composite panels in most aircrafts attributed to fatigue behavior. Apart from good mechanical and physical strengths, the FLCP requires good fatigue resistance for safe operational life of such structures. Thus, the fatigue behavior study of FLCP presents significant scientific research importance.

The fatigue behavior of composite laminates has been the subject of interest for many investigators. In this context, Degrieck and Paepegem (2001) presented a review study for fatigue damage analysis of composite laminates. Performing a strain energy density study, Ellyin and Ei-Kadi (1990) developed a fatigue failure norm for FLCP. Soutis et al. (1991) used finite element method (FEM) to investigate the fatigue behavior under compression for notched carbon/epoxy laminates. Xiao and Bathias (1994) analyzed the behavior of woven fabric composites by performing the fatigue tests on notched and unnotched laminates. Caprino and Giorleo (1999) used stress ratios for carrying out the 4-point bending fatigue tests on a glass/epoxy composite laminate. Using analytical solutions, fatigue tests were performed by Ferreira et al. (1999) on glass-polypropylene fiber composites. Hansen (1999) investigated the fatigue damage initiation and growth in a woven fabric composite using Infrared thermography. Experiments were carried out by Tsai et al. (2000) to study the damage initiation in

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multi-layer woven 3D composite plates during fatigue. Using FEM, Shokrieh and Lessard (2000) presented a progressive simulation model to investigate the fatigue in composite laminates. Muc and Krawiec (2000) presented life estimation of composite laminates during fatigue when subjected to shear loading through experimental work along with finite element predictions.

The fatigue prediction model by experimental investigation was presented by Epaarachchi and Clausen (2003) using different frequencies and stress ratios. Clark and Mouritz (2008) experimentally analyzed the 3D orthogonal woven composite under tensile fatigue. Taking a circular graphite/epoxy plate into consideration, Minak et al. (2009) examined the residual fatigue strength using probabilistic failure analysis. Jweeg et al. (2010) presented an experimental fatigue behavior study under normal loading conditions for FLCP. Developing a finite element model, Bizeul et al. (2011) addressed the fatigue crack growth study for notched glass FLCP under tensile loading. Employing the numerical solutions using FEM, Selmy et al. (2013) carried out flexural fatigue experiments on unidirectional glass FLCP. The tension-tension fatigue behavior was addressed for woven hemp/epoxy composite laminate by Vasconcellos et al. (2014) employing a multi-instrumented damage analysis process. The fatigue life constraints for composite materials was addressed in the research study by Muc and Muc-Wierzgoń (2015) through an optimization design methodology. The issue of damage progression under fatigue for matrix composite was also illustrated through FEM and experimental non-destructive tools in some research works (Stens & Middendorf, 2015; Montesano et al., 2015).

Though there is a wide research interest for fatigue analysis of composite materials, under thermal field the research attention is scarce. Very limited research works were devoted to fatigue behavior of composite laminated plates under the influence of temperature by doing tension-compression tests (Curtis & Moore, 1983), numerical analysis using FEM (Wu, 1993), experiments under cryogenic conditions (Shindo et al., 2006) and accelerated testing for moisture ingress (Meng et al., 2016). Summarizing the review of presented literature above, there are no investigations on the tension-tension fatigue behavior of flat panels made of woven fabric laminated glass/epoxy composite that have been exposed to thermal environments in the open literature to the best of the author's knowledge. In the current work, bidirectional glass/epoxy laminated composite plates subjected to thermal stress are examined for their tension-tension low cycle fatigue behavior.

2. Experimental Study

2.1 Specimen fabrication

Two kinds of symmetric composite laminate plates having 8, 12 and 16 layers with stacking sequence [0/90] and [45/-45] were manufactured. The fabrication follows the hand lay-up process as shown in **Fig. 1** towards lamination of glass/epoxy composite plates. For lamination purpose bi-directionally woven glass fabrics (WR 360/100, Owens Corning – 360g/m2) are cut in specified sizes and layer wise arranged confirming the stacking sequences mentioned above. The adhesive matrix prepared with fusion of epoxy (Lapox L-12, Atul Pvt. Ltd., India) with hardener (K-6, Atul Pvt. Ltd., India) and splotched by means of a smooth plastic brush between every two consecutive layers of glass fabric. The inter laminar voids were removed by pressing the laminated sample through a hydraulic press applying a pressure of 5kgf/cm^2 at 60 ^{0}C for 20 minutes. Prior to sample cutting, the fabricated samples were put under normal temperature for curing for 24 hours. The samples are mechanically engineered by means of a diamond saw to produce the samples of size 250mm × 25mm towards tensile testing. The thicknesses of the 8-layer, 12-layer and 16-layer sample were measured through a digital caliper as 3 mm, 4.5 mm and 6 mm correspondingly.

Fig. 1. Fabrication process using hand lay-up method

2.2 Experimental setup and testing details

The experimental work was carried out focusing on static tensile test and tension-tension fatigue test. To this end the servo-electric hydraulic press INSTRON 8862 universal testing machine (UTM) was employed.

2.2.1 Static tensile test

It is essential to determine the static ultimate tensile strength (UTS) to explain the different stress levels for fatigue testing. Following the testing procedure laid in ASTM D3039 (Standard, 2008) the fabricated samples were put in the threshold of static tensile tests using INSTRON 8862 UTM. A constant strain rate loading 1mm/min was applied during the test to record the UTS. Earlier the test samples were fabricated for 8-layer, 12-layer and 16-layer samples confirming [45/-45] symmetric angle-ply and [0/90] symmetric cross-ply orientations. The test results were considered for the mean of three samples for each symmetric angle-ply and cross-ply orientation.

2.2.2 Low cycle tension-tension fatigue test

Low cycle tensile-tensile fatigue tests are carried out under load control, depending on the tensile strength, employing a sinusoidal waveform with constant amplitude and a range of maximum applied stress levels. The test plates are put through stresses that are no more than 60% of UTS. The test frequencies are set at 0.5 Hz and 0.7 Hz with thermal impressions at 300K and 350K. The low cycle tension-tension fatigue tests were carried out on different-layered fabricated glass/epoxy plates with aforesaid symmetric cross-ply and angle-ply orientations. All specimens are subjected to a temperature bath at 350K for 12 hours in order to evaluate the thermal effects on the fatigue behavior of glass/epoxy plates. The laminated composite plate underwent fatigue testing until it broke, as seen in **Fig. 2**.

Fig. 2. Tension-tension fatigue test

3. Results and Discussions

For the experimental research of the low cycle tension-tension fatigue test, flat composite glass/epoxy lamination panels exposed to high temperatures are taken into consideration.

3.1 Static tensile test results

The results of static tensile test for UTS and maximum tensile load (MTL) are detailed in **Table 1**. It is noted from the summary that a symmetric cross-ply composite plate bears greater tensile strength than a symmetric angle-ply plate. This reflection is observed as the fibers and loading are placed in the same direction for all the layers for cross-ply composite plates. It has been shown that elevating the stacking layers from 8 to 12 or 16, correspondingly, results in an increase in the maximum tensile stress of symmetric cross-ply plates of between 43% and 74%. When compared to a symmetric 8-layer angle-ply lamination, the increase is 82% for 12 layers and 157% for 16 layers.

Table 1. UTS and maximum tensile load of glass/epoxy composite panels.

Lamination Layers	[0/90] Cross-ply		[45/-45] Angle-ply	
	MTL (kN)	UTS(MPa)	MTL (kN)	UTS(MPa)
8	25.86	344.8	5.6	74.14
12	36.98	328.7	10.21	96.98
16	45.09	300.6	14.42	96.13

3.2 Fatigue for low cycle tension-tension test

Flat panels with Symmetric cross-ply and angle ply lamination with various stacking layer counts are subjected to tension-tension low cycle fatigue testing.

3.2.1 Fatigue in tension-tension cycle for cross-ply lamination

Figs. 3–10 show the S–N curve summarized for fatigue test results: flat composite plates with cross-ply lamination for various assembling layer counts and two different temperatures. Fig. 3 depicts the relationship on a logarithmic scale of maximum stress (S) upon number of failure cycles (N_f) for the composite plate laminated for 8-layers operating at 300K temperature (300K) and 0.5 Hz loading frequency. With the failure cycles increasing, the decline in stress turns out to be less abrupt. At this point, debonding of matrix and fiber develops that leads to the growth of fatigue damage. At 2460 cycles, the fiber ultimately fails, and it has been detected that the stress reduces sharply all through the initial 70 cycles. This is the primary stage in which the initial fatigue damage appears in the form of a transverse crack. At the final failure, there is a sharp decline in the stress value.

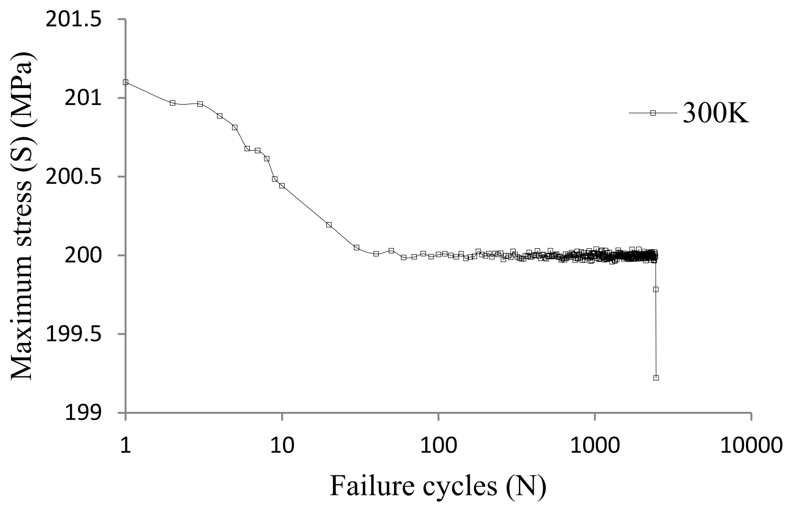

Fig. 3. Stress upon failure cycles of cross-ply 8-layered $[0/90]_{2s}$ lamination at 300K and frequency at 0.5 Hz

Fig. 4 shows the fluctuation of stress concerning failure cycle counts for an 8-layered $[0/90]_{2s}$ laminated plate under the frequency loading of 0.5 Hz at 350K temperature. The laminate composite plate in a heat environment was reported to break after 1840 cycles. By increasing the temperature from 300K to 350K, the failure cycles at high temperatures are reduced by 25%. This is because the thermal environment causes the plate's stiffness to decrease.

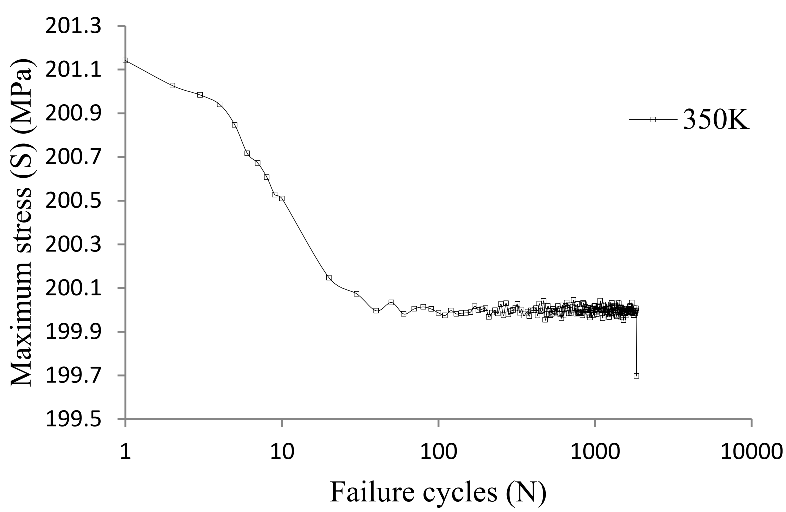

Fig. 4. Stress upon failure cycles of cross-ply 8-layered $[0/90]_{2s}$ lamination at 350K and frequency at 0.5 Hz

Fig. 5 and **Fig. 6** show the 8-layered [0/90]2s composite plate's low cycle fatigue performance at 300K ambient temperature and higher temperatures (350K). It can be seen from **Fig. 5** that the fatigue failure happened at 1810 cycles. Lower fatigue life results from a reduction in the time to failure as frequency rises. With a frequency increase from 0.5 Hz to 0.7 Hz, the failure cycle for fatigue is reduced by 26% as compared to **Fig. 3**.

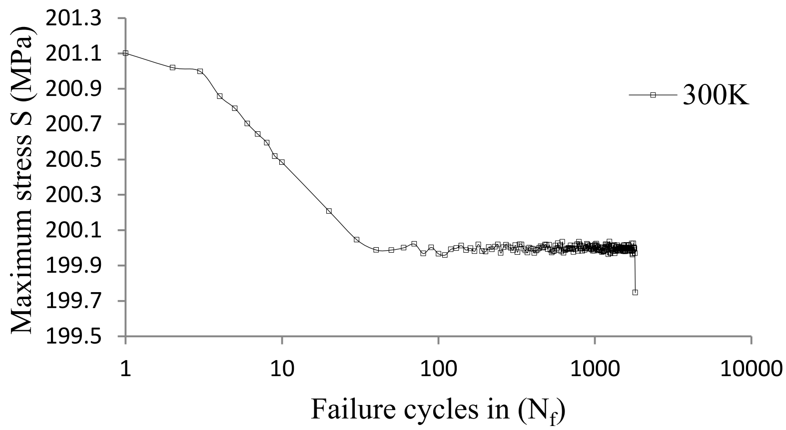

Fig. 5. Stress upon failure cycles of cross-ply 8-layered $[0/90]_{2s}$ lamination at 300K and frequency at 0.7 Hz

As shown in **Fig. 6**, the composite 8-layered plate under thermal stress at 0.7 Hz frequency demonstrated fatigue failure at 1050 cycles. Composite plate's fatigue life is declined by 42% with a shift in temperature from 300K to 350K. When there is a higher load frequency, temperature has a greater impact on shortening fatigue life.

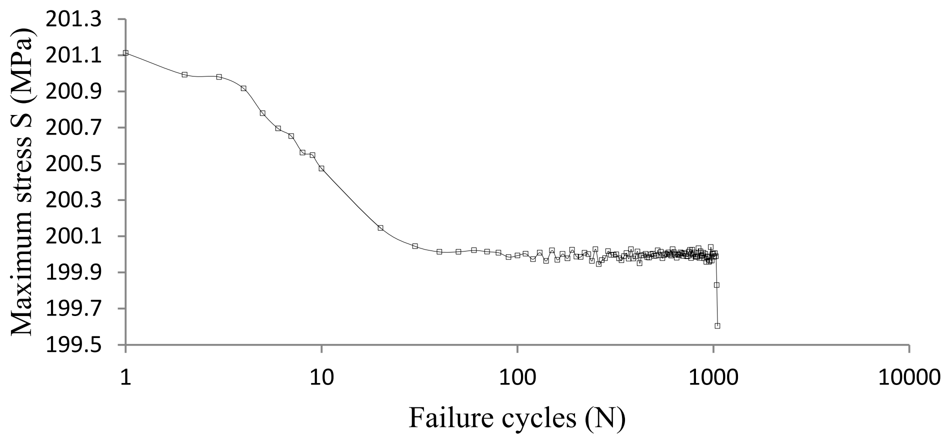

Fig. 6. Stress upon failure cycles of cross-ply 8-layered $[0/90]_{2s}$ lamination at 350K and frequency at 0.7 Hz

Fig. 7 shows a relationship between number of failure cycles and stress for the 12-layer $[0/90]_{3s}$ lamination operating at a thermal impression of 300K with a loading of 0.7 Hz frequency. Due to the increase in stiffness, the flat composite plate sees 17 times increase in the fatigue life when the number of lamination layers is increased from 8 to 12. At 30,000 load cycles, the plate finally started to break.

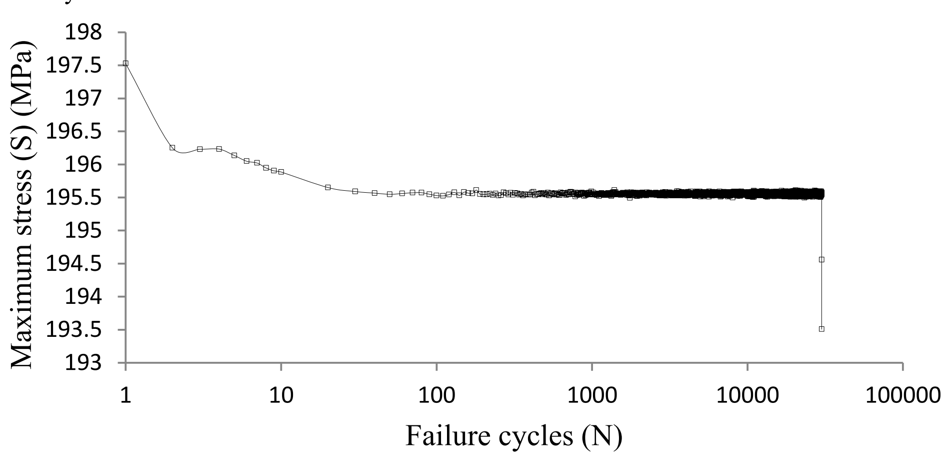

Fig. 7. Stress upon failure cycles of cross-ply 12-layer $[0/90]_{3s}$ lamination at 300K and frequency at 0.7 Hz

Fig. 8 shows the graph for Stress-Failure cycle of a 12-layer [0/90]3s fabricated composite plate evaluated at 0.7 Hz frequency and subjected to 350K temperature. By adding more stacking layers, the fatigue life of the prepared 12-layered laminate under thermal stress is further greatly increased. 25,000 load cycles later, the plate broke. When the rise in temperature jumps from 300K to 350K, the fatigue life decreases by 16.6% as a result of the plate's decreased stiffness from the thermal environment.

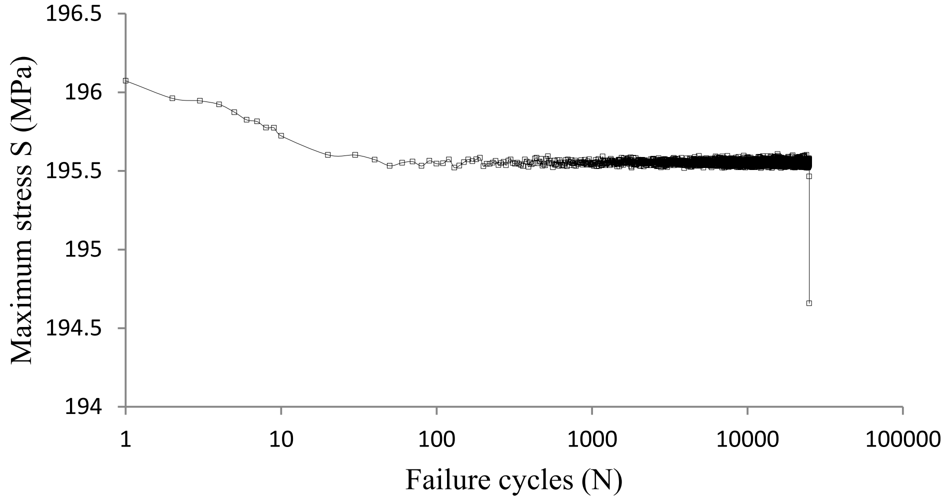

Fig. 8. Stress upon failure cycles of cross-ply 12-layer $[0/90]_{3s}$ lamination at 350K and frequency at 0.7 Hz

Fig. 9 shows the graph for the Stress upon Failure cycle for composite ($[0/90]_{4s}$) laminate with 16 layers of symmetry under 0.7 Hz stress conditions. The arrow mark significantly describes the fact that at 70,000 cycles failure did not occur for the glass/epoxy plate.

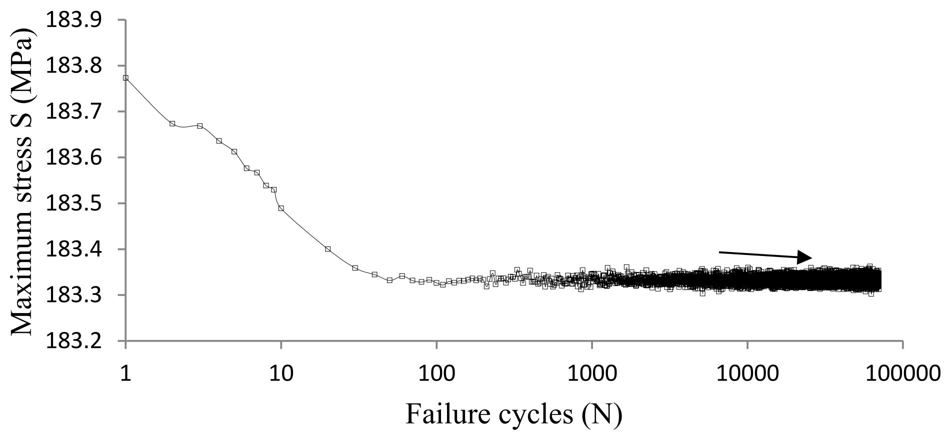

Fig. 9. Stress upon failure cycles of cross-ply 16-layer $[0/90]_{4s}$ lamination at 300K and frequency at 0.7 Hz

Fig. 10 reports fatigue test results for stress versus failure cycle of a 16-layered $[0/90]_{4s}$ flat composite panel at 350K temperature for a frequency load of 0.7 Hz. Here, it can be seen that after exposure to 350K temperature, the plate continued to function after the experiment was terminated after 70,000 load cycles, and at that point, an arrowhead was placed at the appropriate location in **Fig. 10**.

In **Figs. 11-19**, the results of fatigue testing on $[45/-45]_{2s}$, $[45/-45]_{3s}$, and $[45/-45]_{4s}$ symmetric lamination scheme angle-ply glass/epoxy plates at thermal impressions 300K and 350K are presented. Fig. 11 shows the stress versus failure cycle graph for an 8-layered $[45/-45]_{2s}$ glass/epoxy plate evaluated for a frequency loading of 0.5 Hz at 300 K. The symmetric angle-ply plate is observed to exhibit failure due to fatigue at 1020 cycles, which is approximately 58.5% fewer than the observations for symmetric cross-ply. The altered failure mechanism is the source of this consequence. The main mechanism of fatigue in [45/-45]2s laminates is debonding of matrix to fibers brought on by standard loads. The early failure is seen on inclined planes along one of the fiber directions. The longitudinal fibers majorly contribute towards governing the normal stress in the $[0/90]_{2s}$ laminate plate, and the failure took place in the transverse planes. **Fig. 12(a)** and **Fig 12(b)** show these variations in failure mechanisms for the $[45/-45]_{2s}$ lamination panels and $[0/90]_{2s}$ lamination panels, respectively.

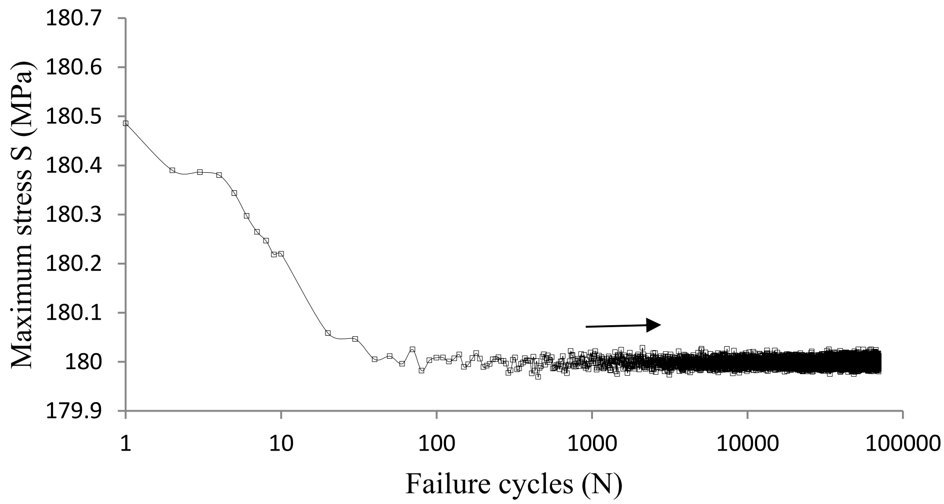

Fig. 10. Stress upon failure cycles of cross-ply 16-layer $[0/90]_{4s}$ lamination at 350K and frequency at 0.7 Hz

3.2.2 Fatigue in tension-tension cycle for angle-ply lamination

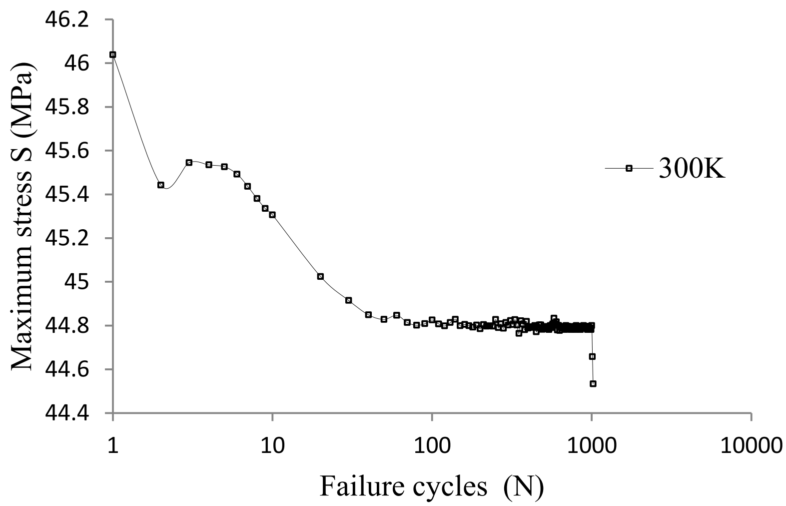

Fig. 11. Stress upon failure cycles for 8-layer angle-ply $[45/-45]_{2s}$ lamination with temperature at 300K and load frequency at 0.5 Hz

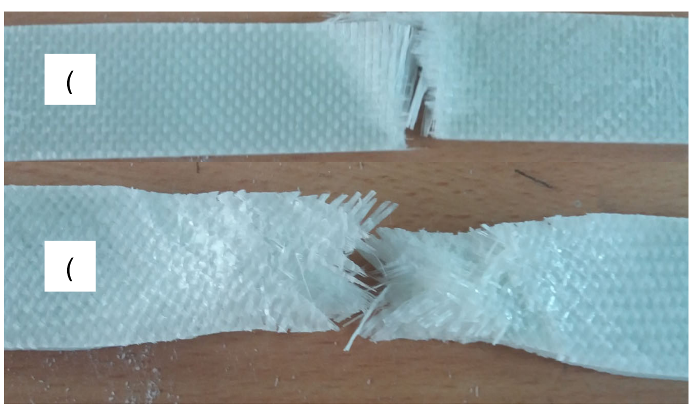

Fig. 12. Failure aspect (a) [0/90]; (b) [45/-45]

The outcomes of the fatigue assessment of a $[45/-45]_{2s}$ lamination panel for a thermal signature at 350K with frequency 0.5 Hz are shown in **Fig. 13** illustrating the curve for stress and the number of failure cycles. This proves that 570 cycles were the threshold at which the plate's fatigue broke down. With a temperature increase from 300K to 350K, the angle-ply plate's fatigue life decreases by 44.17% as a result of a decrease in stiffness under thermal stress.

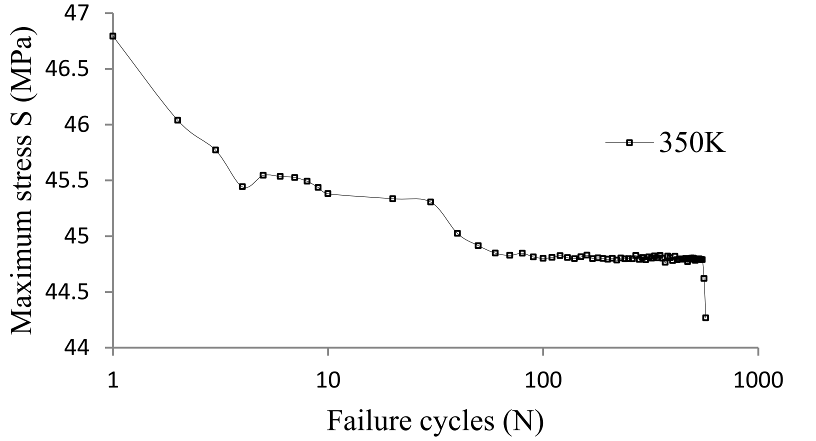

Fig. 13. Stress upon failure cycles for 8-layer angle-ply $[45/-45]_{2s}$ lamination with temperature at 350K and load frequency at 0.5 Hz

The illustration showed for maximum stress during fatigue upon failure cycles for 8-layered glass/epoxy panel($[45/-45]_{2s}$) in **Fig. 14** shows that the plate failed after 730 cycles with a 0.7 Hz loading frequency under 300 K temperatures, which is roughly 28% less cycles than with a test frequency at 0.5 Hz.

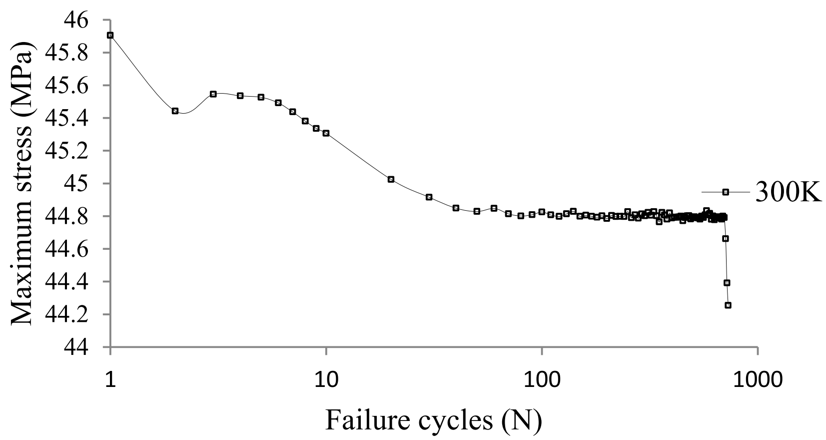

Fig. 14. Stress upon failure cycles for 8-layer angle-ply $[45/-45]_{2s}$ lamination with temperature at 300K and load frequency at 0.7 Hz

Next being exposed to 350K thermal signature, the S-N curve of a [45/-45]2s lamination panel at 0.7 Hz frequency load is shown in **Fig. 15**. A total of 410 load cycles later, the plate failed from fatigue. The fatigue failure life is lowered by 45% as a result of going from 300 K to 350 K in temperature.

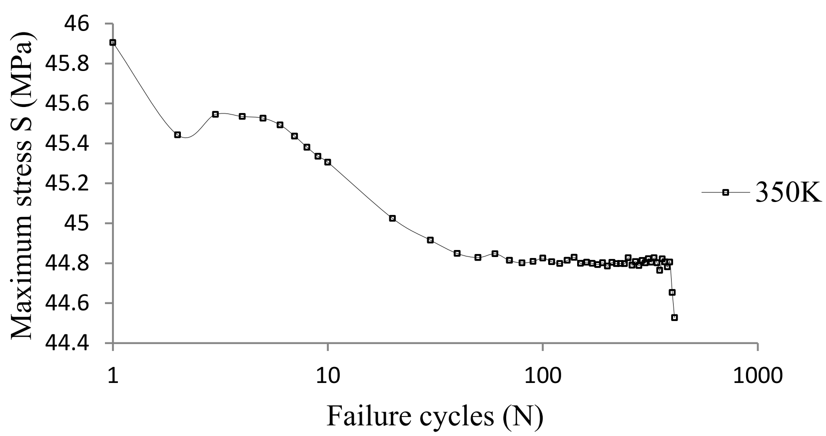

Fig. 15. Stress upon failure cycles for 8-layer angle-ply $[45/-45]_{2s}$ lamination with temperature at 350K and load frequency at 0.7 Hz

Fig. 16 and **Fig. 17** show the S-N curves for the fatigue test results for a 12-layer, symmetric angle-ply [45/-45]3s laminated plate at temperatures of 300 K and 350 K with 0.7 Hz loading frequency, respectively. **Fig. 16** confirms from the fatigue experiments that the breakdown of the 12-layer lamination panel happened at 7130 load cycles at ambient temperature conditions, the value is roughly ten times higher than that of the 8-layer fabricated angle-ply lamination.

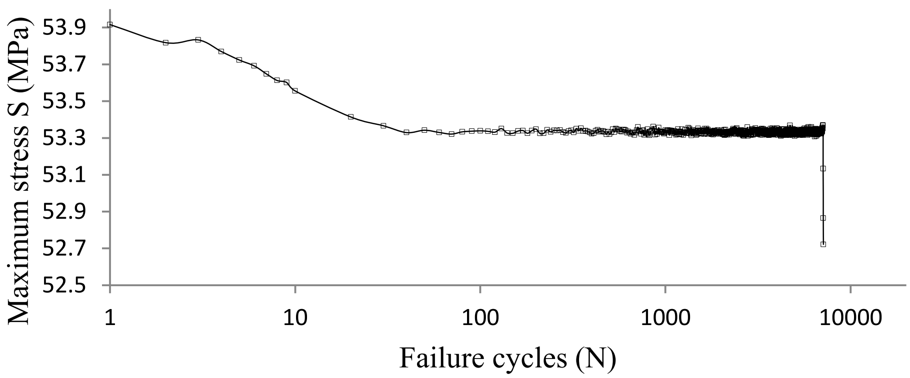

Fig. 16. Stress upon failure cycles of angle-ply 12-layer $[45/-45]_{3s}$ lamination with temperature at 300K and load frequency at 0.7 Hz

Fig. 17 demonstrates that the lamination layer numbers have a substantial effect on the fatigue life of laminated composite plates at high temperatures. At 5110 load cycles, the 12-layer laminate fails when operating at 350 K temperature at 0.7 Hz frequency. Due to the residual stress created by the thermal environment, the composite laminates' fatigue life drops by 28% as temperature rises from 300K to 350K.

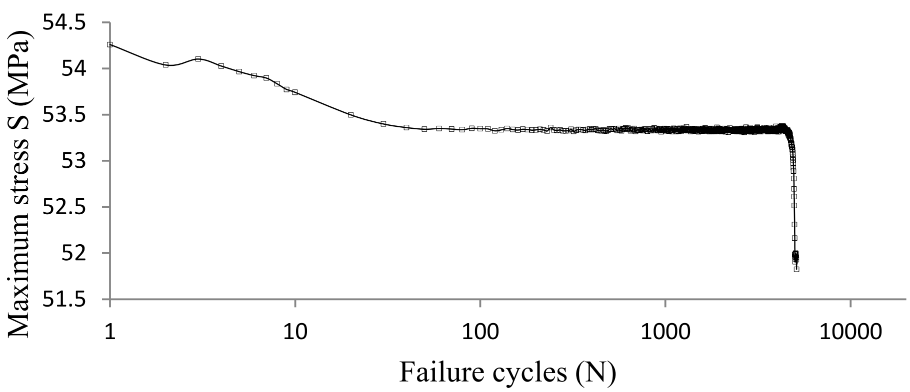

Fig. 17. Stress upon failure cycles of angle-ply 12-layer $[45/-45]_{3s}$ lamination with temperature at 350K and load frequency at 0.7 Hz.

The fatigue test results for maximum stress versus number of failure cycles at 300k with a load frequency of 0.7Hz is presented through a graphical curve in **Fig. 18**. The 16-layer plate experienced fatigue failure after a load cycle of 16,460 as elicited from the graph.

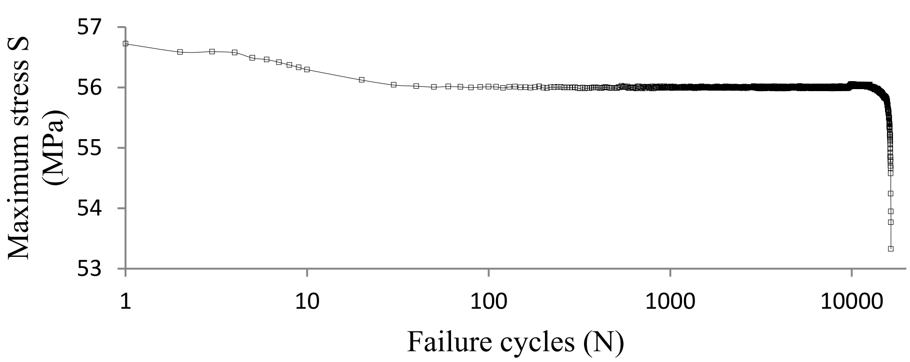

Fig. 18. Stress upon failure cycles of angle-ply 12-layer $[45/-45]_{4s}$ lamination with temperature at 300K and load frequency at 0.7 Hz

In a similar manner **Fig. 19** expresses the curve for stress-failure cycle for a 16-layer $[45/-45]_{4s}$ lamination panel subjected to a temperature of 350K for attest frequency of 0.7 Hz. After 15,960 load cycles, the 16-layer plate operating at 350 K temperature exhibits fatigue failure. A reflection in this case is seen that the influence of temperature on lowering the fatigue life of the composite laminate is minimal (within 2.5%).

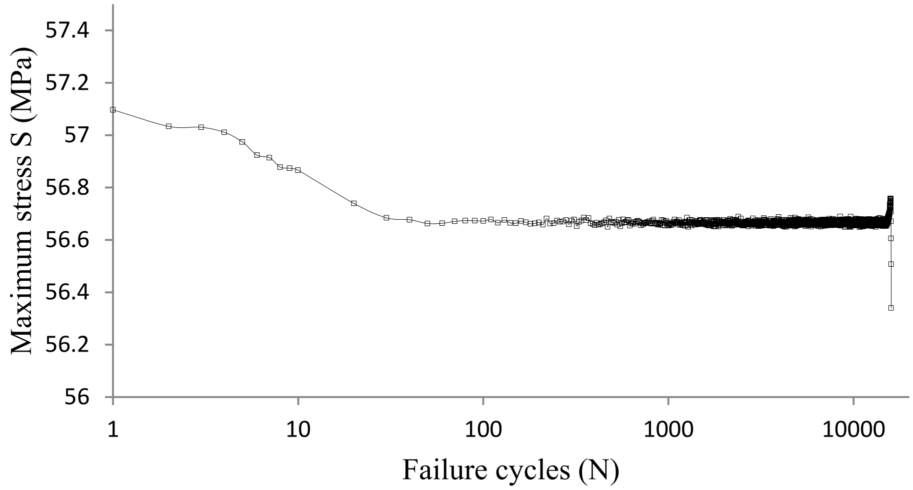

Fig. 19. Stress upon failure cycles of angle-ply 12-layer $[45/-45]_{4s}$ lamination with temperature at 350K and load frequency at 0.7 Hz

4. Conclusions

In this work, a woven fabric glass/epoxy composite plate's tensile-tensile low cycle fatigue behavior is examined for two alternative lamination sequences, cross-ply and angle-ply symmetric for varying numbers of lamination layers that are exposed to temperature stress. Following are some general interpretations that may be drawn from the current study:

- Symmetric cross-ply laminated plate has a substantially higher ultimate tensile strength than a symmetric angle-ply laminated plate.
- Both laminates exhibit a steady decrease in fatigue cycles with increasing levels of fatigue stress.
- Increasing the count for lamination layers for both cross-ply lamination and angle-ply lamination improves the fatigue life of woven fiber laminated composite plates.
- When the temperature rises, the fatigue life of laminate composite panels declines.
- The fatigue life of laminated composite plates is decreased with an increase in loading frequency.
- The fatigue life of the symmetric cross-ply laminated composite plates is superior to that of the symmetric angle-ply plates.

This in-depth investigation of fatigue damage will be helpful in creating and verifying numerical models of fatigue behavior for composite panels of this type. These simulations are valid for the range of material, thermal, and geometrical factors used in the study.

Author Contributions

Madhusmita Biswal: Software, Methodology, Conceptualization, Writing – original draft. **Priyadarshi Das:** Writing – original draft, Methodology, Data curation. **Shishir Kumar Sahu:** Supervision, Visualization, Investigation, Review & Editing, Software.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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