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Fatigue behavior of laminated glass fiber reinforced polyamide

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Abstract

The fatigue performance of laminated glass fiber reinforced polyamide composites was investigated in this study. Fatigue tests were conducted on both unidirectional and cross-ply specimens at room temperature. The S-N diagram of $[0]_8$ followed a bilinear curve, however, the $[90]_8$ laminates presented a linear S-N diagram. Compared to the same lamination of glass/epoxy, $[0]_8$ and $[90]_8$ glass/polyamide laminates presented a lower fatigue resistance, while $[0_2/90_2]_s$ laminates exhibited a superior fatigue resistance. In addition, stiffness degradation was investigated for the laminates and was compared with that of glass/epoxy with the same lamination. Glass/polyamide composites had lower stiffness reduction compared to glass/epoxy.
During fatigue tests, an infrared (IR) camera was also used to monitor the temperature rise in $[0_2/90_2]_s$ and $[0_4/90_4]_s$ laminates resulting from mechanical cyclic loading, and to capture the temperature profile associated with the failure area in the specimens. The maximum temperature in $[0_4/90_4]_s$ laminates was comparable to that of $[0_2/90_2]_s$ laminates and the final temperature in some of the cross-ply specimens reached 50 °C, which was near the glass transition temperature of the polyamide matrix.

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Keywords: Fatigue; Continous glass/polyamide; IR camera

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1. Introduction

Composite materials have gained much interest in different sections of industry due to a lot of advantages that they exhibit e.g. light weight, high stiffness and strength and damage tolerance. These materials are divided into two main groups namely thermoset and thermoplastic composites. In addition to recyclability, thermoplastic composites are tougher and more damage resistance than thermoset composites, so their application for structures under different static and cyclic fatigue loadings are preferred. In this regard, fatigue loading is more critical since it is expressed to be the reason of 80% of service failures [1].

There are some studies on fatigue behavior of thermoplastic composites but are limited to some high performance and engineering thermoplastic composites e.g. PEEK, PPS and PP-based composites. Some of the main research studies on the fatigue behaviour of these composites are as described here.

Dickson et al. [2] studied the fatigue behavior of cross ply 0/90 and ±45 carbon/PEEK and carbon/epoxy. They found that 0/90 lay-up for both materials had comparable fatigue resistance while ±45 carbon/PEEK laminates had better fatigue resistance than carbon/epoxy laminates. Aymerich and Found [3] studied the fatigue behaviour of notched and unnotched quasi-isotropic carbon/PEEK and carbon/epoxy composites and evaluated fatigue damage mechanisms through X-radiography and C-scan. They concluded that in spite of having different damage mechanisms until failure in the two composites, the unnotched specimens had the same S-N curve. In contrast to these two studies, Heneff-Gardin and Lafarie-Frenot [4] studied the fatigue behaviour of $[0_7/90]_s$ and $[0_3/90/0_4]_s$ carbon/epoxy and carbon/PEEK composites. Carbon/PEEK composites showed shorter fatigue life compared to carbon/epoxy. Gamstedt and Talreja [5] compared the fatigue behaviour of unidirectional AS4 carbon/epoxy and AS4 carbon/PEEK composites and found that carbon/PEEK had lower fatigue life compared to carbon/epoxy. In addition, the damage accumulation and damage progression rate were higher in carbon/PEEK compared to carbon/epoxy.

Apart from PEEK, PPS is another high performance thermoplastic which is used for applications that undergo fatigue loading. Vieille et al. [6] investigated the effect of matrix ductility on reducing the overstress near the hole. They proposed an analytical expression to model the damage accumulation in both composite materials. In another study [7] they examined the fatigue behaviour of glass/epoxy and glass/PPS composites. They found the effect of matrix ductility useful for delaying fatigue initiation and propagation at high temperatures.

Apart from these high performance thermoplastics some engineering thermoplastics such as polypropylene have used for fatigue applications.

Bureau and Denault [8] investigated the fatigue behavior of continuous glass fiber/polypropylene composites. They found a linear relationship between Basquin's fatigue strength and flexural strength and Basquin's fatigue sensitivity and interlaminar shear strength. In another study [9] they investigated the effect of environmental temperature on the fatigue resistance of these composites and compared the fatigue resistance with glass/polyester composites. They observed higher fatigue resistance for glass/polypropylene in all temperatures.

Van den Oevert and Peijs [10] investigated the fatigue behaviour of unidirectional glass/PP composites and glass/MA-PP. They concluded that blending MA with PP improved the adhesion between fiber and matrix thus improving fatigue resistant of the composite. Gamstedt et al. [11] studied the fatigue behaviour of unidirectional glass/PP and glass/MA-PP composites. They observed more debonding until failure for glass/PP than glass/MA-PP composites due to the weaker interface between fiber and matrix in glass/PP and also the fatigue life was increased by one decade for that of glass/MA-PP, but the sensitivities of the S-N curves were the same.

Ferreira et al. [12] investigated the fatigue behavior of woven glass/PP composites with different lay-ups. They studied the damage parameter based on stiffness degradation and observed a linear relationship between this parameter and temperature rise in different loading conditions.

Apart from polypropylene, polyamides are known to have outstanding mechanical properties in addition to being relatively inexpensive. If they are used as matrix material with fibers such as carbon and glass, the final thermoplastic composite may have good mechanical properties in terms of stiffness and strength [13] and also fatigue resistance [14]. However, there should be more research studies to prove this claim and to use (carbon or glass)/polyamide composites in loadbearing applications instead of more conventional thermoset composites such as (carbon or glass)/epoxy [15,16]. However, the reported studies on fatigue behaviour of continuous glass polyamide composites are limited to those presented subsequently.

Cinquin et al. [17] investigated the flexural fatigue behavior of unidirectional glass/polyamide composites in parts of his studies which was limited to displacement control fatigue tests on longitudinal specimens. Rasool [18] characterized the fatigue behavior of woven thermoplastic glass/polyamide and glass/PPS experimentally through S-N curves and DIC monitoring of local and global strain fields during fatigue and related it to the stiffness degradation of the material. Malpot et al. [19,20] studied the effect of moisture on the static and fatigue behavior of woven glass/polyamide composites and proposed an enhanced model to predict the fatigue life of the composite at any angle and moisture content.

To the best knowledge of the authors there are few studies in the literature that assess the fatigue behavior of multidirectional glass/polyamide composites. It is important since glass/polyamide composites as mentioned may be a suitable substitute for glass/epoxy composites in structural applications such as wind turbine blades. In these applications, laminates with different laminations are used to satisfy the required stiffness and strength in different directions. Meanwhile, fatigue resistance is a major concern in these applications so in order to have a confidential design, fatigue behavior should be obtained in different directions and also in laminates with different lay-ups and compared with those of glass/epoxy. Therefore, the goal of this study is to assess the fatigue behaviour of a glass/polyamide lamina and cross-ply laminate. More studies should be performed on other laminations such as quasi-isotropic laminates to have a thorough understanding of the fatigue behavior of these composite materials.

2. Experimental

2.1. Process and materials

E-glass/polyamide prepregs were prepared from Jonam Composites Ltd. and were used to fabricate glass/polyamide laminates with different laminations including, $[90]_8$, $[0_2/90_2]_s$ and $[0_4/90_4]_s$ laminates via compression moulding. For the process, consolidation pressure of 0.9 bar and the maximum temperature of 240 °C was used.

2.2. Fatigue tests

Fatigue tests were performed based on ASTM D3479 (2002). Straight-sided and dog bone specimens were cut from 110 mm by 110 mm panels by using a diamond blade saw and water-jet machining with geometry and dimensions mentioned in Fig. 1 and Table 1, respectively. Aluminum alloy end tabs (15 mm by 20 mm) were bonded to both ends of the specimen to prevent the effect of gripping pressure on the sample. A 50 kN MTS 810 was used for the testing of $[0]_8$ and $[0_4/90_4]_s$ and the remaining specimens were tested by a 25 kN Instron 8874. Both apparatus were equipped with an extensometer for measuring the tensile strain. The frequency and the load ratio of the tests were set at 10 Hz and 0.1 respectively.

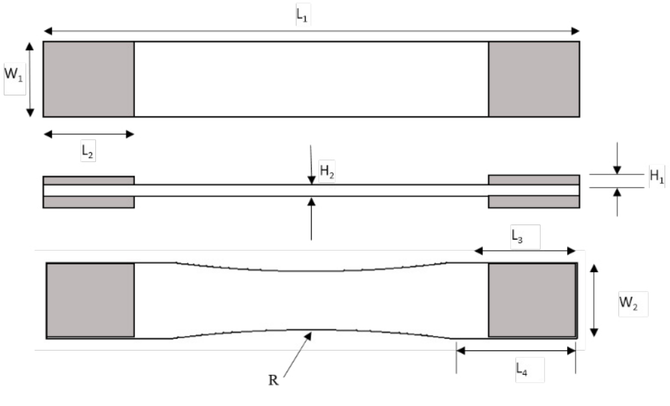


Fig. 1. Geometry of the specimens used for fatigue tests.

Table 1. Dimensions of the specimens used for fatigue tests.

lamination	L_1	L_2	H_1	H_2	W_1
$[0]_8$	110	20	10	1.4±0.1	15±0.1
$[90]_8$	110	20	10	1.4±0.1	15±0.1
lamination	L_3	L_4	W_2	R	
$[0_2/90_2]_s$	20	25	20	165	
$[0_4/90_4]_s$	20	25	20	165	

$[0]_8$ Laminates. The stress versus number of cycles (S-N) curve for $[0]_8$ laminates is presented in Fig. 2. As observed in the figure, the diagram is bilinear and there is a knee point in the stress level equal to 60 percent of ultimate tensile strength (UTS). This behavior has been mentioned in previous studies for unidirectional glass fiber-reinforced epoxy under rectangular cyclic loading [21]. The region before the knee point is called the low-cycle fatigue region. In this region large strains are induced by stresses which are close to the ultimate strength of the composite material. When these strains become higher than the failure strain of glass fibers, weak glass fibers start to break then the composite fails in a similar manner seen in static failure.

The S-N curve of glass/polyamide has been compared with that of glass/epoxy from Ref. [22]. The sensitivity of the two S-N curves is different. Glass/epoxy is more fatigue resistant than glass/polyamide, particularity at low stress levels. It can be mentioned that the knee point for the two composites is nearly at the same stress level i.e. 60 % of the UTS.

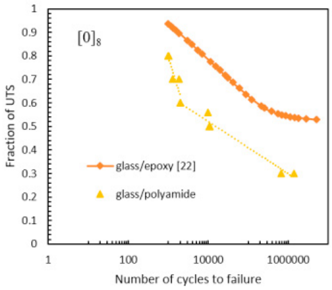


Fig. 2. S-N diagram for fatigue testing of $[0]_8$ glass/polyamide laminates.

$[90]_8$ Laminates. The stress versus number of cycles (S-N) curve for $[90]_8$ laminates is shown in Fig. 3. The S-N curve is compared with that of glass/epoxy in the figure. The fatigue resistance of glass/polyamide is much lower than that of glass/epoxy particularly at low stress levels. The S-N curve intercepts are the same, while the fatigue sensitivity of glass/epoxy is 0.61 times of that of glass/polyamide.

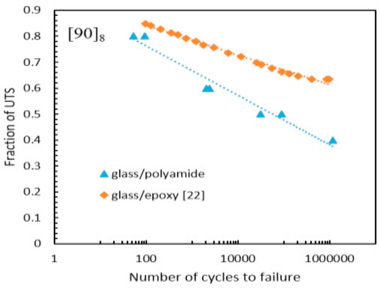
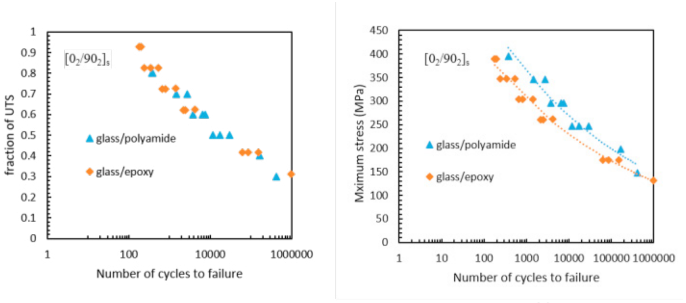


Fig. 3. S-N diagram for fatigue testing of $[90]_8$ glass/polyamide laminates.

$[0_2/90_2]_s$ Laminates. The fatigue behaviour of $[0_2/90_2]_s$ is compared for glass/epoxy and glass/polyamide in Fig. 4. As seen in the figure, the fatigue resistance of glass/polyamide is higher than that of glass/epoxy which is in contrast with the comparison performed for the two materials for $[0]_8$ and $[90]_8$ laminates. It was observed in [23] that increasing the toughness of the epoxy matrix for cross-ply glass/epoxy would increase the fatigue life by decreasing the damage extent and it was shown in [24] that the mode I toughness of glass/polyamide is higher than that of glass/epoxy. Therefore, based on these two studies the higher fatigue resistance of cross-ply glass/polyamide in comparison to cross-ply glass/epoxy is explained.



a) b)

Fig. 4. S-N diagram for fatigue testing of $[0_2/90_2]_s$ glass/polyamide laminates.

The fatigue behaviour of $[0_2/90_2]_s$ glass/polyamide is compared with $[0_4/90_4]_s$ glass/polyamide in Fig. 5. As seen in the figure, the $[0_4/90_4]_s$ laminates have lower fatigue life than $[0_2/90_2]_s$ laminates. This behaviour can be explained by earlier transverse crack initiation in $[0_4/90_4]_s$ laminates compared to $[0_2/90_2]_s$ because of higher thickness of 90 degree plies as has been mentioned in Ref. [25, 26].

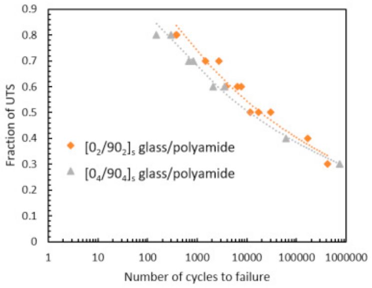


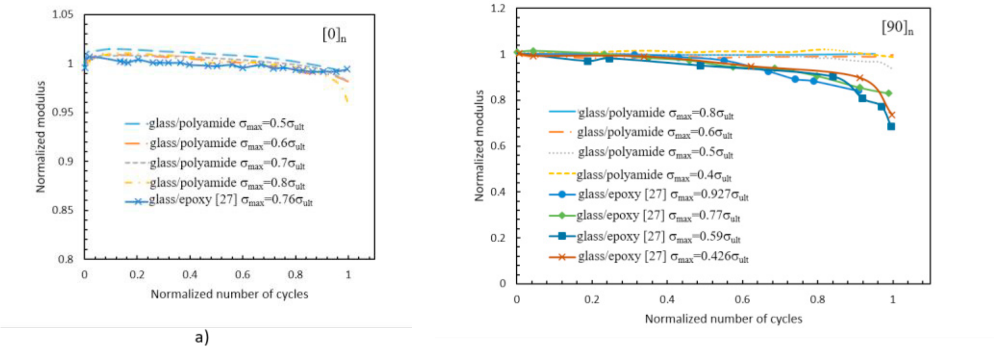
Fig. 5. S-N diagram for fatigue testing of $[0_2/90_2]_s$ and $[0_4/90_4]_s$ glass/polyamide laminates.

2.3. *Stiffness degradation*

Fig. 6 presents the normalized modulus as a function of the number of cycles for $[0]_8$, $[90]_8$ and $[0_2/90_2]_s$ laminates. As seen in Fig. 6(a) the stiffness degradation is very low in $[0]_8$ laminates since after week fibre failures, the remaining unbroken fibres will tolerate the load and the stiffness of the whole laminate does not decrease. The stiffness degradation of glass/polyamide has also been compared with that of glass/epoxy for $\sigma_{max} = 0.76\sigma_{ult}$ in Fig. 6(a). The stiffness degradation for $\sigma_{max} = 0.7\sigma_{ult}$ and $\sigma_{max} = 0.8\sigma_{ult}$ in glass/polyamide are less than the stiffness degradation for $\sigma_{max} = 0.76\sigma_{ult}$ in glass/epoxy which confirms that glass/polyamide degrades less compared to glass/epoxy. Based on the curve and Ref. [27] the stiffness degradation for $[0]_n$ glass/epoxy is 1-2 % which is lower than the stiffness degradation of glass/polyamide for most of its life.

Stiffness degradation versus the number of cycles for $[90]_8$ is presented in Fig. 6(b). For most of the stress levels, the stiffness degradation is less than 2 % which is negligible and can be explained by the high fracture toughness of the polyamide matrix which has been observed for unidirectional glass/PA12 in Ref. [24] and was explained by the high ductility of the polyamide matrix. This high toughness decreases the initiation and propagation of matrix cracks in mode I and as a result decreases the stiffness degradation of the $[90]_8$ laminate.

Stiffness degradation for $[90]_8$ glass/polyamide has compared with that of glass/epoxy in Fig. 6(b). As seen in the figure the maximum stiffness degradation for glass/epoxy is 30 % which is much higher than maximum stiffness degradation for glass/polyamide which is 6 %. This again confirms the higher fatigue toughness of glass/polyamide.



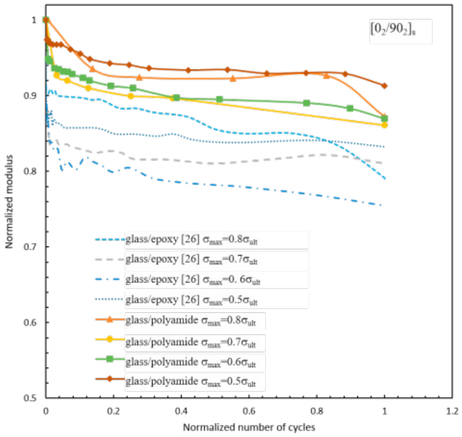
a)

b)

Fig. 6. Normalized modulus degradation versus normalized number of cycles for a) $[0]_8$ b) $[90]_8$.

The diagram of normalized stiffness degradation versus the number of cycles for $[0_2/90_2]_s$ is shown in Fig. 7. The diagram was obtained using interrupted quasi-static tensile tests at predefined numbers of cycles using digital image correlation (DIC). As seen in the figure, the stiffness degradation curve has three stages which correspond to transverse matrix cracking in region I, longitudinal matrix splitting in region II and fiber failure in region III.

The curves have also been compared with those of glass/epoxy with the same lamination from Ref. [23]. As seen in the figure, the stiffness degradation for glass/epoxy is higher than the stiffness degradation for glass/polyamide for all stress levels. This demonstrates the higher fatigue resistance of $[0_2/90_2]_s$ glass/polyamide compared to $[0_2/90_2]_s$ glass/epoxy as was shown in Fig. 4(b).



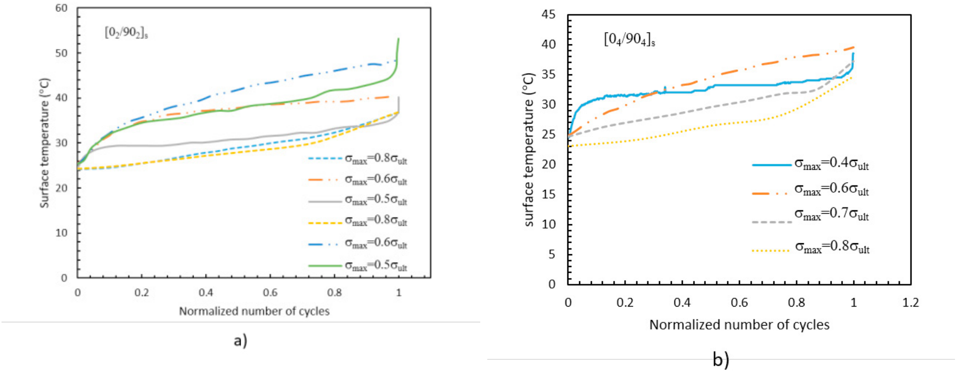
c)

Fig. 7. Normalized modulus degradation versus normalized number of cycles for $[0_2/90_2]_s$ laminates.

2.4. Temperature rise during fatigue tests

The surface temperature of the specimens was measured during fatigue tests using a FLIR T400 IR camera. Fig. 8 presents the maximum surface temperature as a function of the number of cycles for $[0_2/90_2]_s$ and $[0_4/90_4]_s$ laminates. Fig. 8 shows that as the maximum stress level decreases from 0.8 to 0.4, the specimen surface temperature versus time tends to change trend from positive accelerating to negative accelerating and with further decrease of the stress level this curve is a combination of three stages namely negative accelerating, linear increase and positive accelerating which corresponds to three stages of fatigue damage in cross-ply composite materials [28].

As seen in the figure the maximum surface temperature in $[0_4/90_4]_s$ does not exceed the maximum surface temperature in $[0_2/90_2]_s$ laminates. This can be explained by the lower time to final failure in $[0_4/90_4]_s$ laminates as was explained in Section 2.2. In this case the material does not have enough time to reach surface temperature greater than 40 °C which is lower than the maximum temperature obtained in $[0_2/90_s]_s$ laminates (i.e. 53 °C).



a)

b)

Fig. 8. Temperature rise versus normalized number of cycles for a) $[0_2/90_2]_s$ b) $[0_4/90_4]_s$ glass/polyamide laminates.

3. Conclusion

$[0]_8$, $[90]_8$, $[0_2/90_2]_s$ and $[0_4/90_4]_s$ glass/polyamide composite laminates were fabricated using a hot-press machine. The load-controlled tension-tension fatigue tests were conducted at different stress levels corresponding to low and high-cycle fatigue lives. The S-N curves were obtained for each laminate configuration and were compared to those of glass/epoxy. By comparing the S-N curves for $[0]_8$ laminates, it was concluded that both laminates had bilinear trends where the knee point occurred at approximately 0.58 of the UTS, and also the glass/epoxy composite was more fatigue resistant than the glass/polyamide composite. Furthermore, a comparison of S-N curve diagrams for $[90]_8$ laminates showed that both curves had linear trend, and the S-N curve sensitivity for glass/epoxy was 0.61 times of that of the glass/polyamide composite. In contrast to the behavior of unidirectional laminates, $[0_2/90_2]_s$ glass/polyamide laminates had a superior fatigue resistance compared to the glass/epoxy composite. This behavior was explained by the higher toughness of glass/polyamide laminates which decreases the stiffness degradation caused by the transverse matrix cracking. Temperature was monitored by an IR camera at different stress levels for both $[0_2/90_2]_s$ and $[0_4/90_4]_s$ laminates. Although the thickness of $[0_4/90_4]_s$ is double the thickness of $[0_2/90_2]_s$ laminates, the maximum temperature obtained was comparable for both laminate configurations. To explain this behavior, it should be mentioned that as the thickness was doubled, the fatigue life was decreased and the temperature did not rise above the maximum temperature for $[0_2/90_2]_s$ for the same stress levels.

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