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RESEARCH ARTICLE

High-Cycle Fatigue Life Behaviour of Fabricated Glass Fibre-Reinforced Polymer

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ABSTRACT - This study focuses on the fatigue behaviour analysis of glass fibre-reinforced polymer (GFRP) composite specimens under high-cycle fatigue loading conditions. Therefore, property validation is recommended in the material development process upon further investigation of the fabricated GFRP. This study aims to evaluate the behaviour of the fabricated GFRP fatigue specimen when subjected to high-cycle fatigue loads and compare it to existing studies. A GFRP fatigue test sample was fabricated using the hand layup process into a flat rectangular panel, which was then cut into a small dimension of 28×2×0.2 cm fatigue specimen. Fatigue tests were performed on five flat specimens at different constant amplitude loads or stress levels between 40% and 80% of ultimate tensile strength to obtain the stress–life curve for the fabricated GFRP. Results showed that the high-stress levels of 80% contributed to the most reduced fatigue life cycle of GFRP. This result is consistent with previous studies and lies within the published life cycle range, validating the fabricated GFRP. A new parameter called the failure modulus, or M_f, may be used to quantify a particular set of fatigue tests.

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1.0 INTRODUCTION

Fatigue is one of the failures that affect the well-being of structures globally. Since it offers significant improvements in terms of economic and safety aspects, this monitoring is of great interest to the aerospace, civil, and mechanical industries [1]. The lightweight material is preferable in applications such as modern aircraft [2]. Glass fibre-reinforced polymer (GFRP) is one of the composite materials that is preferred in resin-based engineering applications such as aircraft, building, automotive parts and marines. This thermoset composite material comprises a fibreglass resin-based matrix [3]. Composites made with thermoset matrices are strong and have excellent fatigue strength. In composite material structures from various types of layers and laminates, the fracture behaviour is characterised by a variety of damage modes, such as crazing and cracking of the matrix [4], breakage of fibre [5], matrix fibre rupture [6], ply cracking [7], delamination [89], void growth [10] and multidirectional cracking [11]. Delamination in composites commonly exists in layered composites, starting with fibre breaking and ending with the separation of the fibre reinforcement from its matrix constituent. Inter-laminar cracks that form and propagate in composite materials reduce the strength and stiffness of the laminate, which finally leads to failure [12]. The previous study proposed a test procedure to investigate the fatigue behaviour of bare GFRP bars [13]. A thorough investigation of the performance of a GRFP under different loading conditions and applications involves numerous efforts.

Even though GFRP has been applied in many types of engineering structures, including aircraft and marine, there are still limited studies that focus on the fatigue behaviour of GFRP material. Limited information is available on the behaviour of GFRP thus, more studies are needed. Furthermore, validation of the fabricated GRFP properties is vital during the material development process. Fabrication abnormalities can significantly distort GRFP behaviour. Thus, property validation is recommended in the material development process upon further investigation of the fabricated GRFP. The current study aims to address the fatigue life behaviour of the fabricated GFRP, specifically in the high-cycle fatigue (HCF) region, experimentally. The study mainly aims to investigate the fatigue behaviour of the fabricated GFRP under constant amplitude loading with a stress ratio of R = 0.1. It also seeks to determine the effect of stress levels on the fatigue life of the GFRP composite. In this sense, static and fatigue tests were performed at several different stress amplitudes for each specimen. The fatigue test result was then analysed and compared with the existing studies. The resulting properties of the fabricated material and mechanical testing were then compared with previous findings from the literature as validation. The novelty of this study is the failure modulus, M_f parameter, which could serve as a quantitative measure of a particular set of fatigue tests.

2.0 RELATED WORK

Studies on the characterisation of GFRPs have been performed by several researchers [14-16]. Sathishkumar et al. thoroughly discussed the excellent properties of GFRPs, including mechanical, wear, thermal, water absorption and

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vibrational properties [17]. Focusing on the scope of the current work, namely fatigue properties, Singh et al. [15] conducted a study of the fatigue life behaviour of angle-ply GFRP composite laminates. Ferdous et al. [14] focused on the tension–tension fatigue behaviour of GFRP composite laminates. They studied the effect of stress level, stress concentration and frequency of fatigue tests on GFRP composites using experimental, analytical and numerical analysis. Both works discussed the fatigue properties of GRFP specimens despite varying objectives. They concluded that stress levels affect the failure behaviour of the studied GFRP composite.

Stanciu et al. recently conducted a comparative study between two types of hand-layup fabricated GFRP [18]. They presented the experimental results of research conducted on two types of GFRPs, namely those reinforced with fibre fabric and chopped fibre. The study also presented the mechanical behaviour and properties of GFRPs subjected to tensile, compression and tensile–tensile fatigue tests. The study of Stanciu et al. is similar to that of Ferdous et al. [14] in terms of the [0/90] fibre orientation and hand layup fabrication method. Different from the study of Singh et al. [15], which was performed in multiple directions, the current study was conducted on a [0/90] fibre orientation [15]. GRFP behaviour characterisation has been the subject of numerous classic studies. Therefore, understanding the consistency of GRFP specimen properties is crucial. Figure 1 shows the GRFP methodological framework proposed in this study. As illustrated in the process flow, consistency validation is recommended after fabrication. This validation process serves as a screening procedure before further massive work on sample characterisation is conducted.

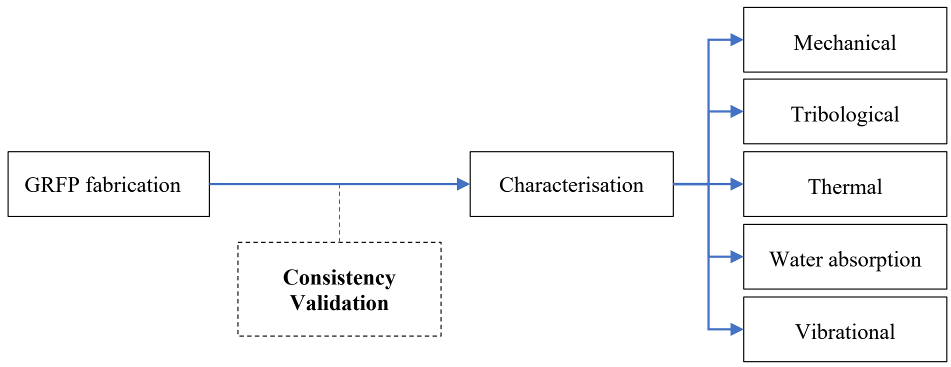

Figure 1. GRFP methodological framework proposed in this study

Various parameters that affect fatigue damage in composites include orientation of reinforcement in weft and warp directions, matrix interface, interface strength and fibre surface defects [19]. The life of a component is also affected by the energy dissipation during cyclic loading. The existence of damages such as fibre breakage, fibre bridging and friction of the matrix and fibre interface occasionally caused energy dissipation [20]. Kumar et al. [22] found that different manufacturing processes for 0° and (0/±45) laminate fabrication also resulted in different static and dynamic behaviours of the composite [21] and correlated them with machining parameters. Progressive material property degradation, structural decomposition and stiffness decrement may occur due to delamination, which causes the final failure of the structures. Therefore, comprehensive research or study is required to investigate the damage behaviour of delamination in laminated composites with different ply angles, which is an essential consideration for the analysis and design of composite structures. Delamination is a matrix-dominated failure mode and mainly occurs in resin-rich interlaminar regions [23].

High-cycle fatigue starts at 10^2 to 10^4 cycles, where fatigue lives are divided into low-cycle fatigue (LCF) for 10^0 to 10^2 cycles and HCF for 10^3 cycles and above. LCF is indicated by its high-stress amplitude and low frequency. Thus, LCF may not take more time compared to HCF. In this region, stress results in elastic and plastic strains [24]. Compared to HCF failure, materials failed in LCF due to plastic deformation after fewer cycles. HCF is a failure that happens because of minor elastic strains under numerous cycles. The stress emerges from the mean and alternating stresses [25]. For HCF, a large number of loading cycles must be completed before fatigue failure due to elastic deformation occurs. Similar to the material's yield strength, the stresses of HCF are lower than those of LCF. Unlike LCF, HCF does not commonly show macroscopic plastic deformation. Elastic strains are dominant in HCF, and plastic strains are dominant in LCF. Because HCF is regulated by elastic deformation, stress is a more practical metric to employ as the failure criterion than strain. The stress–life curve is typically used to characterise the HCF life, where a cyclic stress's amplitude is shown as a function of the logarithmic scale of the number of cycles before failure. The fatigue cycles that result in fatigue damage, initiation, and propagation to final failure can be combined to characterise HCF using the empirical stress-life approach to total fatigue life. The HCF technique is appropriate for parts that are normally intended to be unrestrained, undergo low amplitude loads within the material's elastic limit, and be used repeatedly [26]. This approach leads to the idea of an endurance limit which defines the stress intensity, below which the material is predicted to have an unlimited fatigue life without the presence of pre-existing flaws.

3.0 METHODOLOGY

3.1 Composite Fabrication

The GFRP composite fatigue sample has been produced in the form of a flat rectangular panel sized 60×60×0.2 cm using a hand layup process, as shown in Figure 2. During the hand layup process, four glass fibre mats were layered alternately with five layers of epoxy resin to form a composite panel, as shown in Figure 3. The layers of fibre mat and epoxy resin were pressed together using a roller; therefore, all resins uniformly penetrated the fabrics to ensure improved layer-to-layer bonding [27]. The layup schematics are unidirectional (UD) with longitudinal fibre orientation, and the stacking sequences of the glass fibre mat were [0/90]°. All tests were conducted in an ambient environment. The schematic of the [0/90]° orientation of the woven mat can be found elsewhere [28]. Rectangular plates with the different layup schemes mentioned were produced for each of the material combinations using four plies of the UD fabric per plate. The stacking sequences of the epoxy resin as the matrix and the fibreglass mat as the reinforcement are also shown in Figure 3. The GFRP flat panel was then cut into a small dimension of 280×20×2 mm flat specimens according to ASTMD3479 [29], as shown in Figure 4.

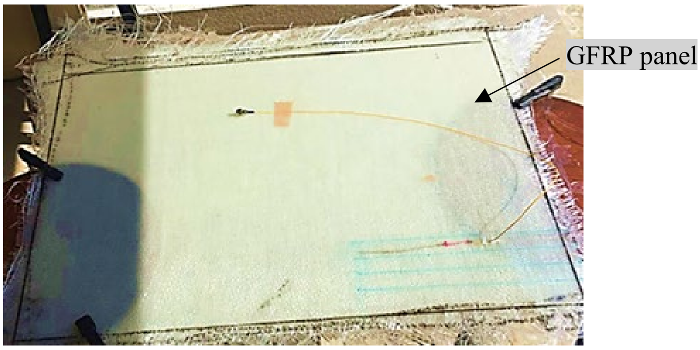

Figure 2. Fabricated GFRP panel and the fatigue test sample

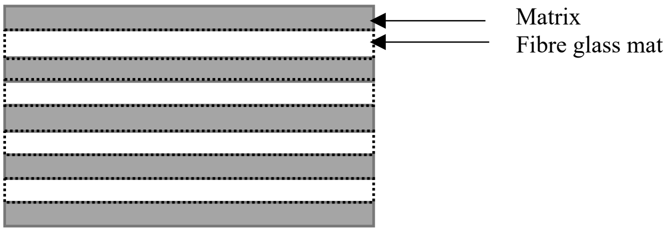

Figure 3. Schematic of GFRP composite that was fabricated from a combination of four layers of fibre mat and five layers of epoxy resin

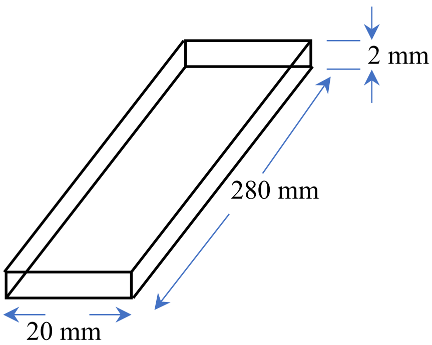

Figure 4. Fabricated GFRP fatigue test sample

3.2 Static Test

Before starting the fatigue test, the tensile properties of the specimen were evaluated to determine the load corresponding to the ultimate strength of the GFRP material. Uniaxial tensile static tests were performed to determine the material properties of the fabricated GFRP, especially tensile strength and Young's modulus. The ultimate or tensile strength is required as a basis for the maximum loading (100%) of a fatigue test. The Instron 8872 universal testing machine with a maximum load of 100 kN was utilised during the fatigue test, as shown in Figure 5.

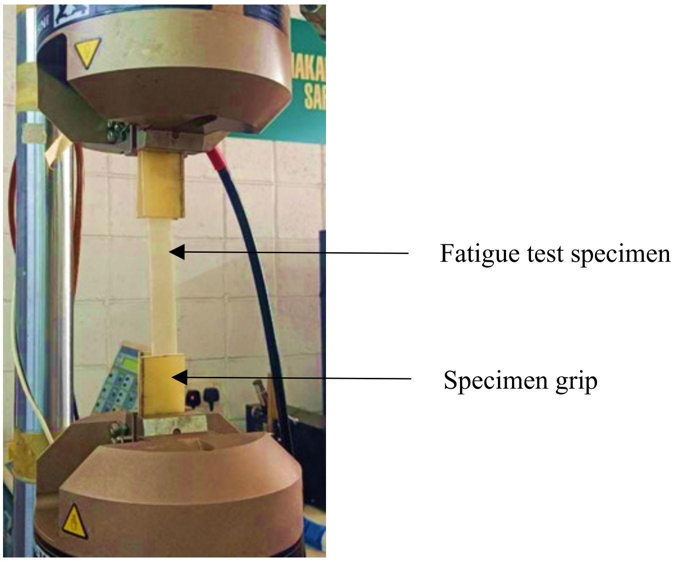

Figure 5. Tensile test setup of GFRP flat specimen

3.3 Fatigue Test

Each sample was tested using a constant amplitude cyclic load, which was applied around a mean load that was increased incrementally from 1 kN to 3.56 kN in steps of 0.44 kN for each specimen. The cyclic load amplitude started at 1.78 kN or equal to 44.50 MPa for 40% of the ultimate strength specimen, as in Table 1, at a frequency of 2 Hz. All tests were performed using a universal testing system with a 100 kN uniaxial testing machine fitted with hydraulic grips. The specimen was inserted into the machine and gripped at each end with roughly 50 mm. Additional composite grips were added at both ends; thus, the load was well-distributed and would not cause failure due to stress concentration at the grips. Therefore, further observation and evaluation of the test specimen focused on fatigue failure. The load cell and the displacement sensors, respectively, provided the load and displacement measurements. The test was conducted by selecting five loading amplitudes ranging from 40% to 80% of ultimate strength. A different load was introduced for each of the following fatigue specimens after the GFRP specimen break.

Table 1. Load applied on each of the fatigue test specimen

Level of ultimate strength load (%)	Stress (MPa)
40	44.50
50	55.50
60	66.75
70	77.75
80	89.00

The stress cycle is characterised by the stress range $\Delta S = S_{max} - S_{min}$ as the difference between maximum S_{max} and minimum S_{min} stress levels [30]. The stress ratio is defined as $R = S_{min}/S_{max}$. A material's S-N curve plots the amplitudes of alternating stress cycles versus the number of cycles necessary to cause failure at a given stress ratio R. The ratio of the minimum cyclic stress to the maximum cyclic stress is known as the stress ratio R. $R = -1$ represents a fully reversed loading while $R = 0$ when the loading is applied, then removed (but not in reverse). The direction of the cyclic load applied on the glass fibre mat is shown in Figure 6. Different stress ratios such as cyclic tension, compression, shear, torsion and other loading conditions result in different fatigue properties of materials. Thus, choosing the closest cyclic load state that best represents the actual load experienced by the materials is crucial to determining their fatigue properties [31].

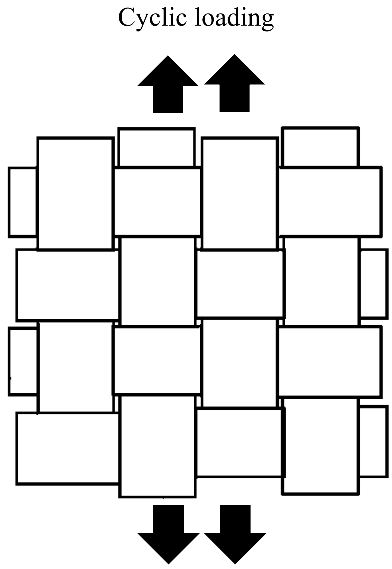

Figure 6. Cyclic loading applied to the glass fibre mat

4.0 RESULTS AND DISCUSSION

4.1 Tensile Properties

This experiment investigates the performance of the tensile strength of the fabricated GFRP compared to the other existing studies [14-15]. Table 2 lists the tensile properties of the fabricated GRFP. The tensile strength of the fabricated GFRP is 110 MPa and can withstand a maximum load of 4431 N. This material strength is compatible with Ferdous et al. [14], and similarly, the fabricated GFRP in the current study experienced the same tension–tension loading. Although the type of matrix naturally affects material qualities, the orientation, length, tangle state, structure of the fibre mat, moulding condition, and impregnation features of the matrix and reinforcement all affect material characteristics. The tensile stress profile is shown in Figure 7, and the elastic part of the fabricated GFRP is demonstrated. The specimen shows linear behaviour up to failure immediately after reaching the plastic region. The failure started with fibre splitting or delamination of the reinforcement from the matrix and ended with a rupture of the specimen due to tensile rupture of the reinforcement. When the matrix around the intact fibres was loaded above the resistance limit, the resin layer resulted [32-34]. When delamination occurs where the fibres are split from the matrix, the bond strength that holds them together weakens and yields successively. This event causes the failure to occur abruptly and the breakage of the composite [35]. The study of fatigue in brittle materials such as composites has attracted increased attention amongst researchers because of the immense potential and applications of composites as structural materials with high temperature, lightweight, high strength, and resistance to corrosion.

Table 2. Tensile properties of the fabricated GFRP

Tensile properties	Value
Tensile strength (MPa)	110
Maximum load (N)	4431

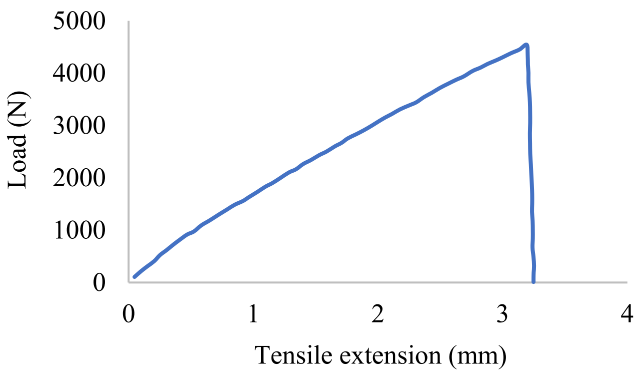

Figure 7. Load-extension curve of fabricated GFRP under tensile test

4.2 Stress–Life Curve of Fabricated GFRP

The ultimate tensile strength resulting from the tensile test is used to determine the life cycle of the fabricated GFRP specimen. This test was conducted by assigning five specimens a 40%, 50%, 60%, 70% and 80% load from the ultimate tensile strength. The fractured specimen due to fatigue failure is shown in Figure 8. This figure reveals that the GFRP specimen experienced fibre breakage. The fibre was separated from its matrix and induced composite breakage due to excessive breakage from the cyclic load withstood by the specimen. Delamination forms if the loads on the composite plies exceed the interlaminar fracture toughness of the composite, resulting in layer separation, interlaminar cracks and material discontinuities [36]. Delamination is one of the most prevalent and serious structural flaws in fiber-reinforced composite materials because it drastically diminishes inter-laminar strength and frequently causes failure to begin prematurely [37].

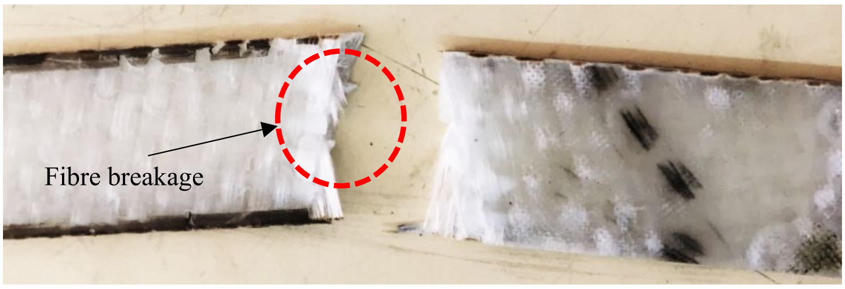

Figure 8. Fatigue failure on fabricated GFRP specimen at 60% stress level

The following stress-life (S–N) curve in Figure 9 shows the fatigue life of the fabricated GFRP in this study. This curve is a semi-log plot of stress amplitude in percentage (%) versus the number of cycles (*N*) for the fabricated GFRP. The S–N curve of the fabricated GFRP follows a general trend in which the number of cycles increases with decreasing stress amplitude. This trend is expected because it is commonly experienced by composite laminates due to their constant amplitude loadings. The stress level (%) that was applied to each specimen is oppositely proportional to the number of cycles to failure (N). Therefore, high stress applied to the fatigue test specimen shortens the number of cycles to failure. The value of $R^2 = 0.8038$ showed that the applied stress on each fatigue specimen moves relatively oppositely to the number of cycles to failure (N). The figure reveals that the number of cycles is less than 1000 at 70% to 90% tensile stress amplitude. The number of cycles that the composite could withstand increased to 10,000 and 100,000 cycles when the stress amplitude was reduced to 50% and 60% and the stress amplitude reached 40% ultimate load, respectively.

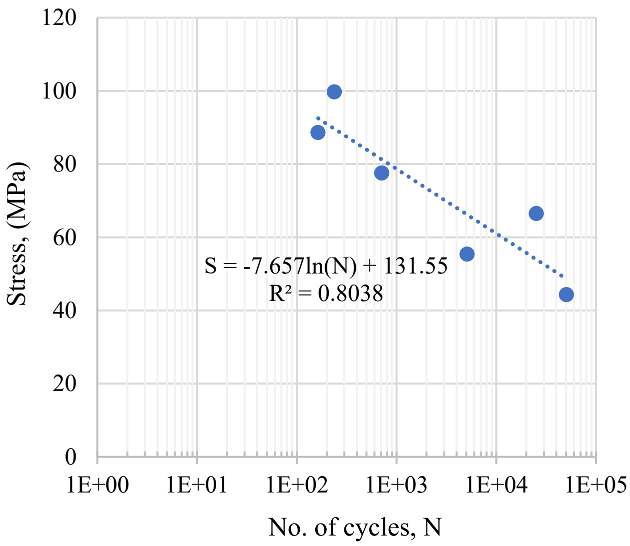

Figure 9. S–N curve of the fabricated GFRP

Table 3. Similarities and differences between this study and previous studies

Materials	Reinforcement type	Fibre orientation	Reference
GRFP	Fibre mat	[0/90]°	Ferdous et al. [14]
GRFP	Woven mat	[0/90]°	Singh et al. [15]
GRFP	Fibre mat	[0/90]°	This study
Kenaf		-	Suriati et al. [41]
PPFC	Coir fibre	-	Bettini et al. [42]

Figure 10 shows a comparison of the resulting S–N curve of the fabricated GFRP with that from the studies of Ferdous et al. [14], Singh et al. [15], who studied GFRP material and Suriati et al. [41] and Bettini et al. [42]. All five S–N curves were formed from the fatigue tests of different studies of GFRP, Kenaf and polypropylene coir fibre composites (PPFC). Notably, in [16], the number of fatigue cycles to failures is greater in the [0/90]° orientation from [14] compared to the current study and that of Singh et al. [15]. Thus, the fatigue limit from [14] is higher than that of the two other studies. The figure reveals that although [14] has the highest number of fatigue cycles before failure, the number of fatigue cycles to failure for the current study is still comparable to [14] and higher than that of Singh et al. [15]. Comparing the three S-N curves of GFRP in the figure, cycles to failure for the current study and [14] approached 10^6 cycles, whilst [15] only approached 10^3 cycles. If all five curves are compared, this study lies in the range of 10^3 to 10^6 number of cycles to failure. This range is close to Ferdous et al. [14] and Singh et al. [15], who studied a similar material, which is GFRP. The stress value for this study was also in the range of 30 to 60 MPa. The stress range of the other two studies was between 20 MPa and 30 MPa for Suriati et al. [41] and 50 to 95 MPa for Bettini et al. [42]. These results show that the trend of this study is consistent with Ferdous et al. [14] and Singh et al. [15] and in the different range with other types of composites in previous works [41] and [42].

This study is close to Ferdous et al. [14] because the fatigue limit is ~30 MPa. By contrast, for Singh et al. [15], the percentage of stress in this range is substantially higher than in the two studies. The rate of increment in the number of cycles to fatigue failure, known as failure modulus M_f, is linear with the reduction of tensile stress. The results of the correlational analysis prove that the M_f of this study, which is −4.37, is close to that of Ferdous et al. [14] and Suriati et al. [41] with −5.62 and -5.55, respectively. The fatigue limit and failure modulus similarities between the findings of this study and Ferdous et al. [14] might be affected by the similar type of reinforcement, which was fibre mat [0/90]°. Notably, the M_f parameter could serve as an additional quantitative measure of a particular set of fatigue tests. In addition to sample consistency validation, this parameter is useful for sample classification. Thus, subsequent characterisation is comparable and reliable. The subsequent growth of these cracks and delamination eventually leads to the final failure or fracture of materials [38]. In addition to [14,15,18], these studies [39-40] also conducted static and cyclic tests on GFRP specimens, but the fibre was varied with chopped fibre type and fibre mat.

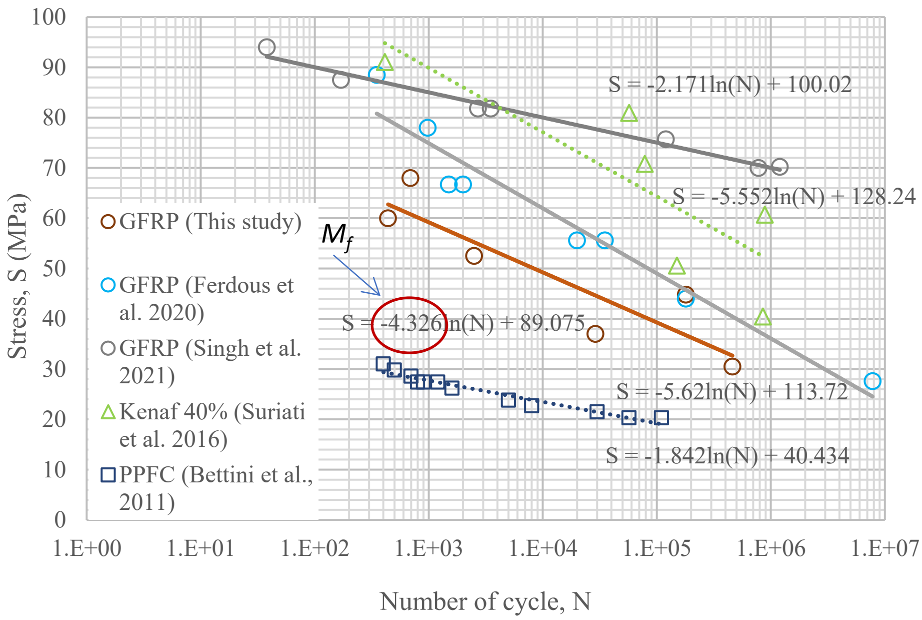

Figure 10. Comparison of the S–N curve of fabricated GFRP in this study to Ferdous et al. [14], Singh et al. [15], Suriati et al. [41] and Bettini et al. [42]

5.0 CONCLUSIONS

This paper provides an insight into the study of the fatigue behaviour of GFRP. The fatigued GFRP specimens have been fabricated in this study and, static and cyclic uniaxial tests were conducted. The experimental results reveal that the fabricated GFRP specimens have not failed up to 1,000,000 cycles when the stress levels range between 20% and 30% of the ultimate tensile strength. Compared with the existing studies, the fatigue life of GFRP is generally beyond 1,000,000. Observations showed that matrix cracks initiate and propagate during fatigue cycling, initiating disintegration and delamination. The presented finding suggested that the fatigue behaviour of GFRP, which was fabricated by a hand layup process, mainly depended on the procedure of the fabrication process. Additionally, other criteria, such as the direction of the fibre mat, stress amplitudes. The results of this investigation show that a parameter called failure modulus M_f was introduced as a measure of property validity or classification. An implication of the suggested validation procedure lies in the possibility of highly effective further sample characterisation. The quantitative measure provides strong empirical confirmation that different sets of test specimens are comparable.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

[1] L. Friedrich, A. Colpo, A. Maggi, T. Becker, G. Lacidogna, and I. Iturrioz, "Damage process in glass fiber reinforced polymer specimens using acoustic emission technique with low frequency acquisition," *Composite Structures,* vol. 256, p. 113105, 2021.

[2] M.W. Joosten, C.G. Davila, and Q. Yang, "Predicting fatigue damage in composites subjected to general loading conditions," *Composites Part A*, vol. 156*,* p. 106862, 2022.

[3] M.F. Akbar, G.N. Jawad, L.R. Danoon, and R. Sloan, "Delamination detection in glass-fibre reinforced polymer (GFRP) using microwave time domain reflectometry," In 2018 15th European Radar Conference (EuRAD), Madrid, Spain, pp. 253-256, 2018.

[4] M.J. Mohammad Fikry, S. Ogihara, and V. Vinogradov, "The effect of matrix cracking on mechanical properties in FRP laminates," *Mechanics of Advanced Materials and Modern Processes*, vol. 4, No. 3, pp.1-16, 2018.

[5] Y. Ma, L. Wu, L. Yu, E. A. Elbadry, W. Yang, *et al.*, "Effect of fiber breakage position on the mechanical performance of unidirectional carbon fiber/epoxy composites," *Reviews on Advanced Materials Science*, vol. 60, pp. 352–364, 2021.

[6] L. Li, "Stress-rupture of fiber-reinforced ceramic-matrix composites with stochastic loading at intermediate temperatures. Part I: Theoretical analysis," *Reviews on Advanced Materials Science*, vol. 60, pp. 352–364, 2021.

[7] H. Ahmadi, M. Hajikazemi, W. V. Paepegem, "A computational study about the effects of ply cracking and delamination on the stiffness reduction of damaged lamina and laminate," *International Journal of Damage Mechanics*, vol. 31, no. 3, pp. 325-347, 2022.

[8] M. Baraheni, A. Tabatabaeian, S. Amini, and A. R. Ghasemi, "Parametric analysis of delamination in GFRP composite profiles by performing rotary ultrasonic drilling approach: Experimental and statistical study, "*Composites Part B: Engineering*, vol. 172, pp. 612-620, 2019.

[9] K.S. Prasad, G. Chaitanya, "Analysis of delamination in drilling of GFRP composites using Taguchi Technique," *Materials Today: Proceedings*, vol. 18, no. 7, pp. 3252-3261, 2019.

[10] M. Mehdikhani, L. Gorbatikh, I. Verpoest, and S. V. Lomov, "Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance," vol. 53, no. 12, pp. 1579-1669, 2019.

[11] H. Mao and S. Mahadevan, "Fatigue damage modeling of composite materials," *Composite Structures*, vol. 58, pp. 405–410, 2002.

[12] C.S. Grimmer, and C.K.H. Dharan, "Enhancement of delamination fatigue resistance in carbon nanotube reinforced glass fiber/polymer composites," *Composites Science and Technology*, vol. 70, pp. 901–908, 2010.

[13] T. D'Antino, M.A. Pisani, C. Poggi," Fatigue tensile testing of glass fiber-reinforced polymer reinforcing bars," *Construction and Building Materials*, vol. 346, p. 12839, 2022.

[14] W. Ferdous, A. Manalo, J. Peauril, C. Salih, K.R. Reddy, P. Yu, P. Schubel, T. Heyer," Testing and modelling the fatigue behaviour of GFRP composites – Effect of stress level, stress concentration and frequency," *Engineering Science and Technology, an International Journal*, vol. 23, pp. 1223–1232, 2020.

[15] K.K. Singh, Md. T. A. Ansari, and M.S. Azam," Fatigue life and damage evolution in woven GFRP angle ply laminates," *International Journal of Fatigue*, vol. 142, p. 105964, 2021.

[16] R.H. Jimit, K.A. Zakaria, O. Bapokutty, M.B. Ali, and A. Rivai, "Fatigue life behaviour of fiber glass reinforced composites subjected to underloading," In Special Issue ICE-SEAM 2017, pp.2300-2310.

[17] T.P Sathishkumar, S. Satheeshkumar, and J. Naveen, "Glass fiber-reinforced polymer composites – a review," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 13, pp. 1258–1275, 2014.

[18] M.D. Stanciu, H. T. Drăghicescu, and I.C. Rosca, "Mechanical properties of GFRPs exposed to tensile, compression and tensile–Tensile cyclic tests," *Polymers*, vol. 13, p. 898. 2021.

[19] M.T.A. Ansari, K.K. Singh and M.S. Azam, "Fatigue damage analysis of fiber-reinforced polymer composites - A review," *Journal of Reinforced Plastics and Composites*, vol. 37, no. 9, pp. 636–654, 2018.

[20] R. Chandra, S.P. Singh and K. Gupta, "Damping studies in fiber-reinforced composites – a review," *Composites Structures*, vol. 46, no. 1, pp. 41–51, 1999.

[21] Z. Bergant, A. Savin, and J. Grum, "Effects of manufacturing technology on static, multi-frequency dynamic mechanical analysis and fracture energy of cross-ply and quasi-isotropic carbon/epoxy laminates," *Polymers & Polymer Composites*, vol. 26, no. 5–6, pp. 358–370, 2018.

[22] A.L. Kumar and M. Prakash, "The effect of fiber orientation on mechanical properties and machinability of GFRP composites by end milling using cutting force analysis," *Polymers & Polymer Composites*, vol. 29, pp. S178–S187, 2021.

[23] E.S. Greenhalgh, *Delamination-dominated failures in polymer composites. In: Failure analysis and fractography of polymer composites*, Sawston, UK: Woodhead Publishing, vol. 4, pp. 164–237, 2009.

[24] H. Farhat, *Typical service-induced damages, operation, maintenance, and repair of land-based gas turbines.* Netherlands : Elsevier, 2021.

[25] Q. Xin, "Durability and reliability in diesel engine system design," *Diesel Engine System Design*, vol.2013, pp. 113-202, 2011,

[26] F.M. Shuaeib, K.Y. Benyounis, M.S.J. Hashmi, "Material behavior and performance in environments of extreme pressure and temperatures," in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2017, pp.1-30.

[27] D.K. Rajak, D.D. Pagar, P.L. Menezes, and E. Linul, "Fiber-reinforced polymer composites: manufacturing, properties, and applications," *Polymers*, vol. 11, pp. 1667, 2019.

[28] H. Gonabadi, A. Oila, A. Yadav, and S. Bull, "Fatigue damage analysis of GFRP composites using digital image correlation," *Journal of Ocean Engineering and Marine Energy* vol. 7, pp. 25–40, 2021.

[29] ASTM, "ASTM D3479 Tension-tension fatigue of polymer matrix composite materials," 2019.

[30] J. Militky, and S. Ibrahim, "Effect of textile processing on fatigue," in *Fatigue Failure of Textile Fibres,* M. Miraftab, Ed. Cambridge: Woodhead Publishing, 2009, pp. 133-168.
[31] A.P. Mouritz, Ed. "Fatigue of aerospace materials," in *Introduction to Aerospace Materials*, Cambridge: Woodhead Publishing, 2012, pp. 469-497.
[32] J. German, "The influence of intralaminar damage on mechanical properties of composite laminates," *Engineering Transactions*, vol. 52, no. 4, pp. 271–296, 2004.
[33] M. Urbanski, "Compressive strength of modified FRP hybrid bars," *Materials*, vol. 13, p. 1898, 2020.
[34] R.P. Behera, P. Rawat, K.K. Singh, S.K. Ha, A. Gaurav, and S.K. Tiwari, "Fracture analysis and mechanical properties of three phased glass/epoxy laminates reinforced with multiwalled carbon nanotubes," *Journal of Science: Advanced Materials and Devices*, vol. 4, pp. 299–309, 2019.
[35] M.D. Stanciu, H. T. Drăghicescu and I. C. Rosca, "Mechanical properties of GFRPs exposed to tensile, compression and tensile–tensile cyclic tests," *Polymer*s, vol. 13, pp. 898, 2021.
[36] S. Gaugel, P. Sripathy, A. Haeger, D. Meinhard, T. Bernthaler, *et al.*, "A comparative study on tool wear and laminate damage in drilling of carbon-fiber reinforced polymers (CFRP)," *Composite Structures*, vol. 155, pp. 173-183, 2016.
[37] J. Montesano, Z. Fawaz, and H. Bougherara "Use of infrared thermography to investigate the fatigue behavior of a carbon fiber reinforced polymer composite," *Composite Structures*, vol. 97, pp. 76-83, 2013.
[38] N. Jagannathan, A. R. Anilchandra, and C. M. Manjunatha, "A study on the fatigue performance of a glass fiber-epoxy polymer nanocomposite under random loads," *Nanocomposites*, vol. 1, no. 3, pp. 138-144, 2015.
[39] C. Ganesan, and P.S. Joanna, "Fatigue life and residual strength prediction of GFRP composites: An experimental and theoretical approach," *Latin American Journal of Solids and Structures,* vol. 15, no. 7, pp.1-16, 2018.
[40] J.W. Kim, "Tensile strength of glass fiber-reinforced plastic by fiber orientation and fiber content variations," *International Journal of Modern Physics: Conference Series.* vol. 6, pp. 640-645, 2012.
[41] M.J. Suriani, Aidy Ali, A. Khalina, S.M. Sapuan, and Haftirman, "Fatigue life estimation of kenaf reinforced composite materials by nondestructive techniques," *Universal Journal of Materials Science*, vol. 4, no. 4, pp. 8896, 2016.
[42] S.H.P. Bettini, M.C. Antunes, and R. Magnabosco, "Investigation on the effect of a compatibilizer on the fatigue behavior of PP/coit fiber composite," *Polymer Engineering Science*, vol. 51, no. 11, pp. 2184-2190, 2011.