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EFFECT OF TEMPERATURE ON THE MODE II FATIGUE DELAMINATION OF A GLASS FIBER REINFORCED POLYMER (GFRP)

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Abstract

A new technology of composite wrapped joints emerges as a promising solution for improving the long-term performance of connections between circular hollow sections (CHS). The use of composite materials is shown to improve the fatigue life of structures. However, a major challenge to the implementation of this technology is to ensure the long-term performance of the composite materials subjected to the operational conditions. This work aims to evaluate the effects of temperature changes on the fatigue delamination of a glass fiber reinforced polymer (GFRP) for application in offshore structures. Specimens were manufactured by hand lay-up and series of experiments are performed to access delamination fatigue crack growth behavior in a range of operational temperatures: -10, 21 and 70 °C. Displacement controlled end-notched flexure (ENF) tests were applied to measure the fatigue behavior together with a digital image correlation (DIC) system to monitor the displacements during the tests. Results show that the delamination fatigue performance of the composite material is not significantly affected by the range of tested temperatures. The fracture behavior also remained unchanged. Standard ENF test method has limited range of crack growth to evaluate the fatigue behavior of composite laminates.

1. Introduction

Composite materials, e.g. fiber-reinforced polymers (FRPs), are increasingly popular in structural applications due to their high strength-to-weight ratio, design flexibility, and fatigue resistance. In the construction sector, an innovative joining technique for steel hollow sections has been introduced using wrapped composite joints instead of traditional welded joints [1]. The loadings in jacket structures are transmitted through a wrapped glass fibre reinforced polymer (GFRP) with a large bonded area. The stress concentration can be significantly relieved, improving fatigue resistance. The elastic stiffness, static resistance, and fatigue behaviour are equivalent to or larger than those of their welded alternative for the properly designed composite wrap. However, the mechanical behavior of the composite material under operational conditions still needs to be clarified for the implementation of the technology.

The performance of composite structures is significantly influenced by environmental factors [2]. Short-term changes of temperature can have a significant impact on the mechanical properties of the material. In particular, the mode II delamination crack growth is the most relevant for the design of composite wrapped joints. Understanding the effects of temperature on the mode II delamination fracture and fatigue of the material is crucial for the design and structural integrity of the joints during operational life.

In this work, the effects of temperature changes on the fatigue delamination of a glass fiber reinforced polymer (GFRP) is investigated. Specimens were manufactured by hand lay-up and series of experiments are performed to access delamination fatigue crack growth behavior in a range of operational temperatures. The reference temperature of 21 °C, a low temperature of -10 °C and a high temperature condition of 70 °C are tested.

2. Materials and Manufacturing

Glass fiber reinforced polymer (GFRP) plates were manufactured. A vinyl ester resin was applied to the hand lay-up lamination of glass fiber bi-directional woven interleaved to layers of glass fiber chopped strand mat (CSM), as shown in Figure 1. A non-adhesive insert of 32 µm thickness was placed at the mid-plane to create an artificial pre-crack. The laminated plate cured in air conditions of 18±1 °C and 50±5% humidity. Then, the composite plate was cut to 0/90 coupon specimens using water jet. Finally, part of the specimens was post cured in an oven at 120 °C for 7 h. The testing specimens have a nominal length of 230 mm, and an average width (w) and thickness (2h) of 19.68±0.14 mm and 7.68±0.21 mm, respectively, measured from the average of 3 different sections using a digital caliper.

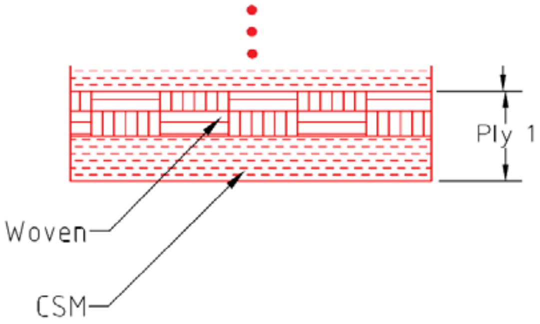

Figure 1. Scheme of the composite lay-up.

3. Experimental procedures

3.1. Test Set Up

A thin layer of white matt paint was coated and a random black speckle pattern was applied to the measurement surface of the specimen. A high resolution camera (50.6 MPx) and a blue LED light source were positioned to the measurement surface to acquire the full field displacements by DIC. Photos were taken every 200 cycles at the minimum and maximum displacements, synchronized with load measurements from the testing machine. For the image processing, surface points were recognized by a small neighborhood of a square with a side length of 19 pixels and a step size of 11 pixels set in the DIC software.

Displacement controlled fatigue ENF tests were performed. Table 1 shows the test matrix. The first test (01-RT) was used to verify the most appropriate displacement level. Then, the maximum displacement, δ_{max}, was set to have an initial force of 70% of the critical force obtained from quasi-static tests. The minimum displacement, δ_{min}, was set to have $\delta_{max}/\delta_{min}$ equals 0.1. Table 1 also includes the mode II critical SERR, G_{IIc}, and the flexural modulus of the material, E_f, obtained from static tests of specimens cut from the same plate and tested in different temperatures.

Specimens were tested at the room temperature (RT) of 21±1 °C, and a climate chamber was used with the test set up for conditioning specimens in the low temperature (LT) of -10±1 °C and the high temperature (HT) of 70±1 °C. Two air mixing fans improved stability of air conditions over time and the specimens were maintained in a constant condition for 7 hours prior to the tests to ensure a homogeneous temperature field in the material. Series of 3 specimens were tested in each configuration.

Table 1. Test matrix.

Specimen	Temperature (°C)	Maximum Displacement (mm)	G_{IIc} (N/mm^2)	E_f (GPa)
01-RT	21	1.48 - 2.20 - 2.64	3.833	9.09
02-RT	21	2.05		
03- RT	21	2.31		
04-HT	70	3.28	7.664	7.92
05-HT	70	3.13		
06-HT	70	3.09		
07-LT	-10	2.70	3.837	12.50
08-LT	-10	2.67		
09-LT	-10	3.01		

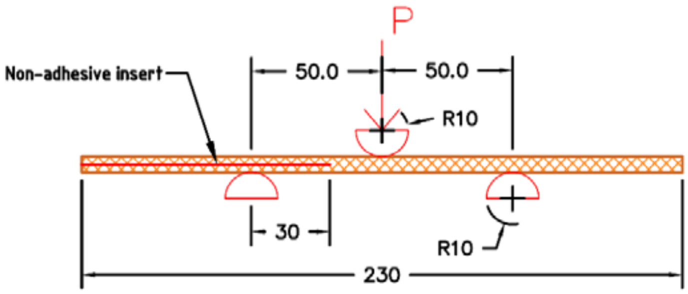

Figure 2. ENF test set up.

3.2. Calculation of the strain energy release rate

The delamination fracture toughness is described by the Resistance curves, or R-curves, that relates the strain energy release rate (SERR) with the crack length. The SERR, or G, from the crack growth of a tested specimen can be analytically derived from Irwin-Kies Equation (1):

$$G = \frac{P^2}{2B}\frac{dC}{da} \tag{1}$$

where P is the applied load, B is the specimen width, C is the specimen compliance, or the ratio of the load point displacement to the applied load ($C = \delta/P$), and a is the crack length. The compliance based beam method (CBBM) [3] relates Timoshenko beam theory and the specimen compliance to obtain the fracture energy.

For a ENF test set up, the specimen compliance becomes Equation (2):

$$C = \frac{3a^3 + 2L^3}{8E_f Bh^3} + \frac{3L}{10G_{13}Bh} \tag{2}$$

where L is the half span of the ENF test. Combining Equations (1) and (2), the mode II fracture toughness, G_{II}, can be obtained:

$$G_{II} = \frac{9P^2a^2}{16B^2h^3E_f} \tag{3}$$

The flexural modulus, E_f, can be estimated experimentally, for each ENF test specimen, using the initial compliance C_0 and the initial crack length a_0, as shown in Equations (4) and (5):

$$E_{f(ENF)} = \frac{3a_0^3 + 2L^3}{8Bh^3C_{0\mathrm{corr}}} \tag{4}$$

Where:

$$C_{0\mathrm{corr}} = C_0 - \frac{3L}{10G_{13}Bh} \tag{5}$$

Finally, the CBBM suggests that the crack length, a, can be estimated from the specimen compliance as an equivalent crack length, a_e, obtained directly from Equation (6):

$$a_e = \left[\frac{1}{3}\left(\left(C - \frac{3L}{10G_{13}Bh}\right)8E_fBh^3 - 2L^3\right)\right]^{1/3} \tag{6}$$

This method allows accounting for the variation in the bending modulus of the material of each specimen and due to the effect of temperature.

4. Results and Discussion

The mode II SERR was calculated by the CBBM using Equation (4). In the case of the fatigue ENF tests performed in this work, the displacements were measured with DIC as the difference between the vertical displacement of the load point and the average vertical displacement of the support points. The initial compliance was the measured minimum compliance in the points of maximum displacement. A nominal value of 3.5 GPa was used for G_{13}.

The variation of the SERR with the mode II fatigue cycles is presented in Figure 3 for the different temperautres. The range of SERR in fatigue over the critical SERR ($\Delta G_{II}/G_{IIc}$) remained below 0.4, which is typical of the ENF test set up [4]. Tests in room and low temperatures showed similar results, such as in the G_{IIc} from static tests (see Table 1). A more significant decrease of ΔG_{II} is noticed in high temperatures.

Figure 4 shows the Paris curves of ENF tests in different temperatures. It is observed that high temperature conditions resulted in a slightly better performance of the mode II interlaminar fracture under cyclic loadings. This can be measured by the slope of the Paris curves, represented by the m-parameter in Table 2 where results of high temperature shows relatively smaller *m* parameter than others.

The experimental flexural modulus (E_f) was obtained from the fatigue tests using the initial compliance at the maximum force. Differently from the results of static tests (see Table 1), the fatigue tests was not able to measure a clear change of the E_f with temperature.

Representative fracture surfaces are shown in Figure 5. All tests resulted in the same failure mode. The crack growth occurred between the woven, on the upper side, and the chopped strand mat, on the lower side of the specimens.

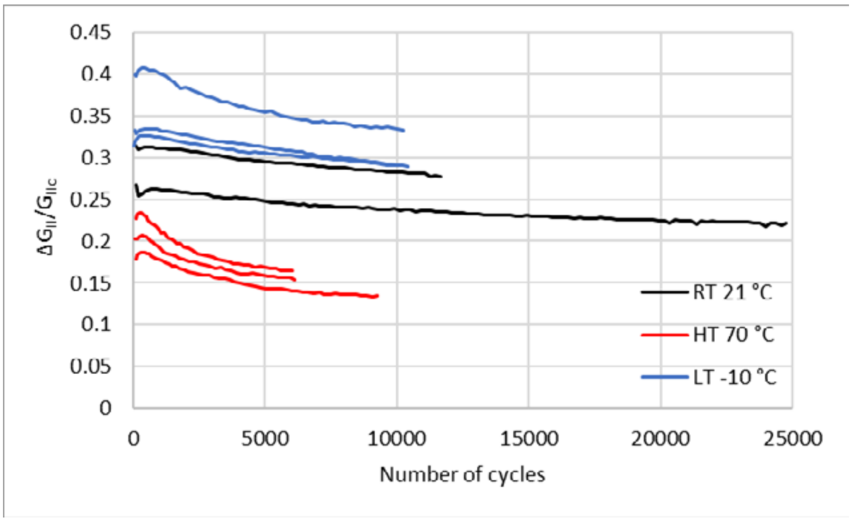

Figure 3. Variation of the SERR with the mode II fatigue cycles in different temperatures.

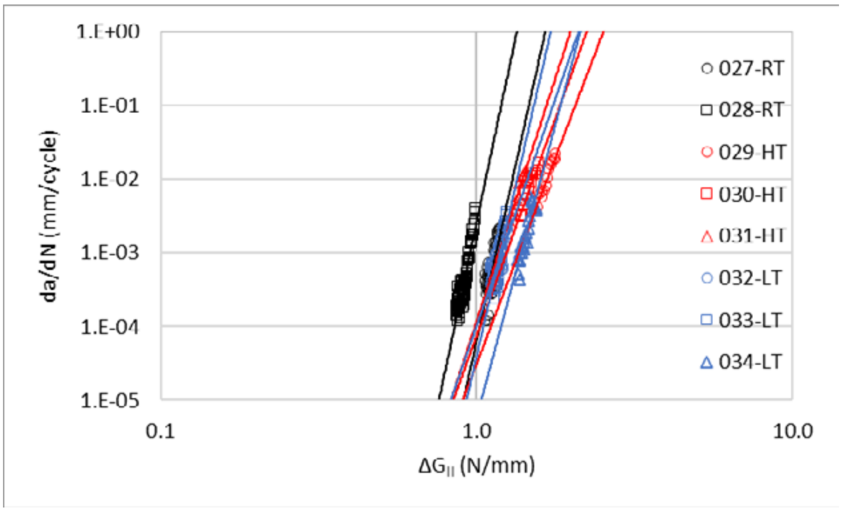

Figure 4. Paris curves from fatigue ENF tests in terms of (a) ΔG_{II} and (b) $\Delta G_{II}/G_{IIc}$.

Table 2. Experimental parameters from fatigue Paris curves.

Specimen	Temperature (°C)	E_f (GPa)	C	m	R
026-RT	21	12.2	-	-	-
027-RT	21	11.9	6.0E-05	19.297	0.845
028- RT	21	10.8	2.6E-03	20.295	0.927
029-HT	70	10.4	3.0E-05	11.227	0.933
030-HT	70	10.3	8.0E-05	11.832	0.942

031-HT	70	9.6	1.0E-04	13.228	0.928
032-LT	-10	10.7	1.0E-04	12.353	0.701
033-LT	-10	11.7	4.0E-05	18.747	0.910
034-LT	-10	10.6	6.0E-06	15.964	0.675

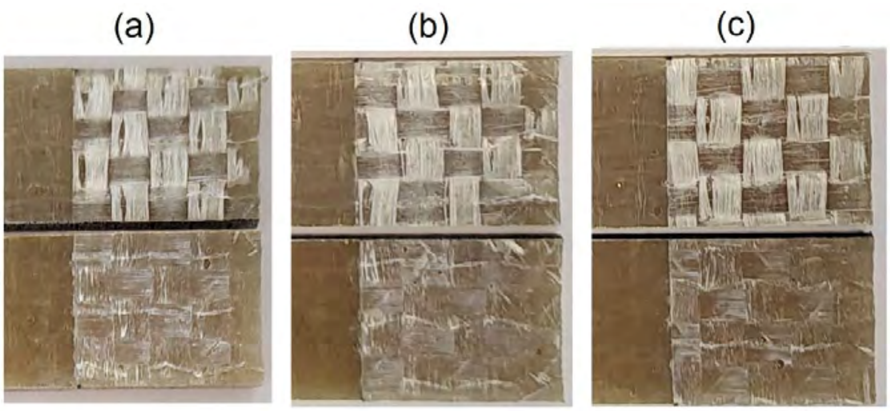

Figure 5. representative fracture surfaces of specimens tested in different temperatures.

5. Conclusions

The effects of temperature changes on the fatigue delamination of a GFRP was investigated. Displacement controlled ENF tests were applied to measure the fatigue performance in room conditions (21 °C), and using a chamber at -10 and 70 °C. A DIC system to monitor the displacements during the tests.

Changes of temperature did not significantly affect the delamination fatigue performance of the composite material. In addition, no change in the fracture surfaces was observed with temperature.

The standard ENF test method has limited range of crack growth to evaluate the fatigue behavior of composite laminates.

Acknowledgments

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