Effect of Temperature on the Mechanical Behavior of Wrapped Composite Joints

Marcio M. Arouche(✉), Mathieu Koetsier, and Marko Pavlovic

Faculty of Civil Engineering and Geosciences, TU Delft, Delft, The Netherlands
{m.moreiraarouche,m.koetsier,m.pavlovic}@tudelft.nl

Abstract. The wrapped composite joints have been introduced as a new technology to connect steel circular hollow sections of support structures for offshore wind turbines. The design and implementation of this innovation require predicting the effects of environmental conditions on the mechanical performance of the structure. In particular, temperature changes can generate interfacial stresses along the bonded interface between the two dissimilar materials, affecting the performance of the structure. This work aims to investigate the effect of short-term changes of temperature on the mechanical behavior of a wrapped composite joint. Specimens were produced with two steel tubes wrapped by a glass fiber composite laminate. Mechanical tests were performed under fatigue and static loading conditions. Experiments are carried out at room temperature (21 °C) as well as at non-ambient temperature using a climate chamber at –10 °C 50 °C and 70 °C. Results revealed that lower temperatures improve the performance of wrapped composite joints under both fatigue and static loading conditions. This points to a significant contribution of the thermally-induced effects on the performance of the structure due to the different coefficients of thermal expansion of the steel and composite materials. Experimental results obtained from this work can be applied to create numerical models capable of predicting the mechanical behavior of wrapped composite joints in different temperatures.

Keywords: Steel-composite structures · bonded interface · temperature effects · fatigue · fracture

1 Introduction

Composite materials, namely the fiber-reinforced polymers (FRPs), have been widely applied to structural elements due to its high strength-to-weight ratio, design flexibility, and high fatigue resistance [1]. FRP elements are usually combined with different materials, such as metals, to create hybrid structures. In the case of composite structures, adhesive bonding is the most appropriate joining method, compared to bolted joint and riveted joint, due to its efficient load transfer with reduced stress concentrations over a large area [1]. Composite bonded structures have been increasingly applied to strengthen existing steel structures [2, 3].

Recently, the wrapped composite joints has been introduced as an innovative technology to connect steel hollow sections in offshore supporting structures for wind turbines

J. R. Correia et al. (Eds.): CICE 2025, LNCE 777, pp. 1868–1875, 2026.
https://doi.org/10.1007/978-3-032-09399-8_177

[4]. The assembly is created by a glass fibre reinforced polymer (GFRP) laminated around the steel parts with a polymer matrix, resulting in a multi-material bonded structure. The loading transfer occurs through the steel-composite interface. Compared to the traditional welding methods, the composite wrap improves the fatigue life and reduced the weight of the structure. While the wrapped composite joints offer significant improvements compared to the welded joints, they are still subjected to crack propagation wihin the steel-composite interface when subjected to operational conditions.

The mechanical behavior of composite materials and bonded interfaces are affected by short-term changes of temperature [5, 6]. In particular, discrepancy in the coefficients of thermal expansion (CTE) between the steel and composite parts generates interfacial stresses along the bonded area. Thermally-induced stresses may accelerate premature debonding of the FRP, thereby decreasing the performance of the structure [7]. This work aims to investigate the effects of short-term changes of temperature on the mechanical behavior of wrapped composite joints. Specimens were manufactured using two steel tubes wrapped with a glass fiber composite, and experiments were performed under axial fatigue and static tensile loadings. In addition to tests performed in room conditions (21 °C), the performance of the structure is investigated in a range of operational temperatures using a environmental chamber with controlled temperatures of –10 °C. 50 °C and 70 °C.

2 Materials and Methods

2.1 Specimens Manufacture

Wrapped composite joints were manufactured from S355 steel tubes of 500 mm length, external diameter of 102 mm and an thickness of 10 mm. The external surface of the steel tubes are treated with grit blasting and degreased for optimal bond quality. Two steel tubes are aligned on the top surfaces and a non-adhesive insert of 32 μm thickness is placed at the mid-plane to create an artificial pre-crack of 50 mm length (25 mm on each tube). Then, the composite is wrapped around the tubes. A vinyl ester resin is applied to the steel tubes followed by the hand lay-up lamination of glass fiber 0°/90° woven interleaved with chopped strand mat (CSM). The composite wrap is produced with a constant 17 mm thick cross section of 270 mm length (135 mm on each tube) at the center of the wrap and tapered at the sides to a total length of 600 mm (300 mm on each tube). The consolidation of the resin occurred in room conditions of 18 ± 1 °C and 50 ± 3% humidity. No post-curing process was performed. A previous work showed that post-curing the composite material does not affect its performance under delamination fracture, and the measured glass transition temperature of the fully cured composite is 111 °C [8]. Moreover, the measured linear coefficient of thermal expansion of the composite material in the fiber direction is 21.5E-06 m/(m °C), while typical values for the steel materials is 12.0E-06 m/(m °C).

2.2 Testing Methods

Mechanical tests were performed on the wrapped composite joints using testing machine coupled with a 2.5 MN load cell. The test set up is shown in Fig. 1. The steel tubes are clamped on both sides of the testing rig. The loading protocol comprises first initiating and growing a delamination crack from the non-adhesive insert to a predetermined crack length using axial fatigue tensile loadings. Force controlled cycles are set from a minimum (F_{min}) of 33 kN to a maximum (F_{max}) of 330 kN, at the frequency of 2 Hz. In the fatigue loading, F_{max} is chosen in order to have a stepwise crack growth rate, and F_{min} is set as 10% of F_{max}. Then, the tensile static loading is applied to the specimens at the constant machine crackhead displacement rate of 0.5 mm/min. Until complete failure of the wrapped composite joint.

A thin layer of white matt paint was coated and a random black speckle pattern was applied to measure the full field displacements of the specimen surface during the tests using digital image correlation (DIC). A DIC system with 2 cameras of 12 MPx and a blue LED light source is positioned to take photos synchronized with load measurements during the fatigue tests at minimum and maximum force every 1000 cycles, and in the quasi-static tests every 5 s. In addition, an optical fiber system (Luna ODISI 6000) was applied to monitor the crack growth during the tests. The optical fibers measure the longitudinal strain development in the composite wrap. Strain measurements are collected during both cyclic and static loading phases at an interval of 500 to 1000 cycles and at regular intervals during static loading ranging from 0.2 to 1 Hz, gradually increasing towards critical failure.

Room temperature tests were performed in laboratory controlled conditions of 21 °C. In order to condition the specimens to different testing temperatures, a climate chamber was built around the specimen, as shown in Fig. 1. Air mixing fans are placed to ensure stability of air conditions over time. Thermocouples are placed on the specimens to ensure the low temperature (LT) of –10 °C, medium temperature (MT) of 50 °C and high temperature (HT) of 70 °C. The specimens were maintained in the set temperature for 12 h prior to the tests to ensure a homogeneous temperature field. A test matrix is shown in Table 1. The measured linear coefficient of thermal expansion of the composite material in the fiber direction is 21.5E-06 m/(m °C), while typical values for the steel materials is 12.0E-06 m/(m °C).

Fig. 1. Mechanical test set up of the wrapped composite joints.

Table 1. Test matrix

Test Series	Testing Temperature (°C)	Number of specimens
LT	–10	2
RT	21	2
MT	50	2
HT	70	1

3 Results and Discussion

Figure 2 shows the stiffness degradation curves of the fatigue tests on wrapped composite joints. Higher temperatures cause higher crack growth rates that results in the higher stiffness degradation rates. The fatigue crack growth is presented and Fig. 3, measured from the longitudinal strains measured in the composite material using optical fibers.

Inconsistencies in crack length measurements at early cycles should be disregarded. Tests in low temperature (–10 °C) required over 200.000 cycles to reach the same crack length of 90 mm as the room temperature tests (21 °C) required around 60.000 cycles. Specimens tested in medium temperature (50 °C) tests required around 30.000 cycles while the specimen tested in high temperature (70 °C) needed only 10.000 cycles to reach the same level. This indicates that the dissimilar thermal expansion of the materials increased the contribution of friction between the composite and steel parts to the resistance to crack growth when tested in lower temperatures.

Figure 4 shows the load-displacement curves of static tests performed after the fatigue tests. All specimens presented a linear elastic behavior up to around 400 kN followed by non-linearity until the peak force is reached. Peak forces showed to be slightly higher in lower testing temperature. Displacements remained applied to one specimen of each testing series in order to verify the residual strength of the structure after ultimate failure. The results show a steady load reaction resulted from friction between the debonded wrap from the steel tube. This pullout force is significant in all tested temperatures due to stresses resulted from the shrinkage of the composite material during curing process. Moreover, the pullout force is higher in lower temperatures, which indicates a contribution of the dissimilar thermal expansion of the materials on the friction forces.

A representative fracture surface of the wrapped composite joint is displayed in Fig. 5. Composite material can be observed bonded to the steel tube after the insert region (on the left side). This mean that a delamination failure resulted from crack propagation within the composite material. The delamination occurred within the first ply of composite laminate adjacent to the steel-composite interface. Moreover, the failure mode resulted from fatigue loading is similar to the failure caused by static loading.

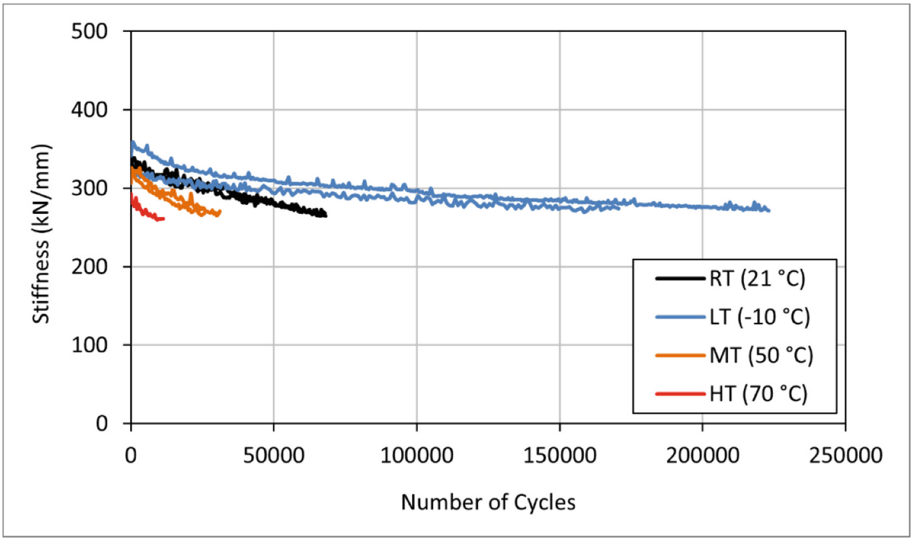

Fig. 2. Tensile fatigue load behavior of wrapped composite joints tested in different temperatures.

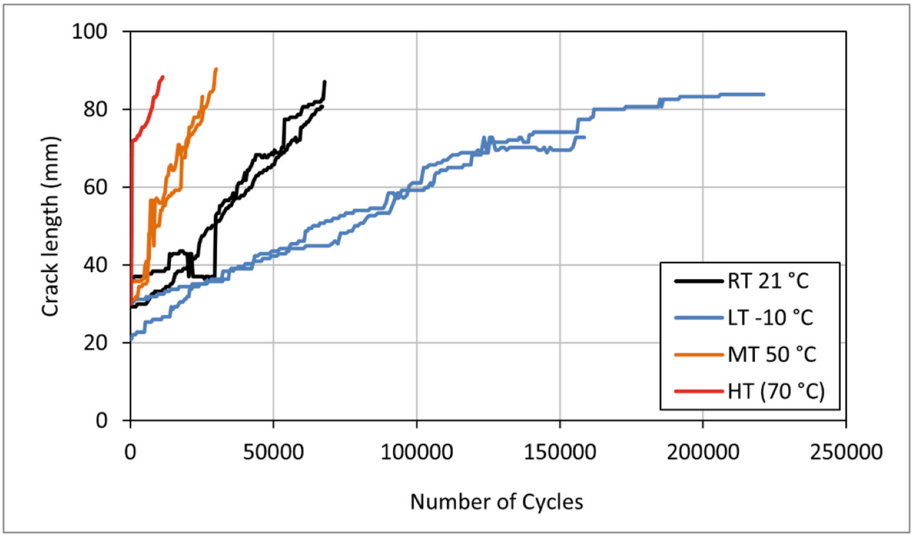

Fig. 3. Fatigue crack length measurements.

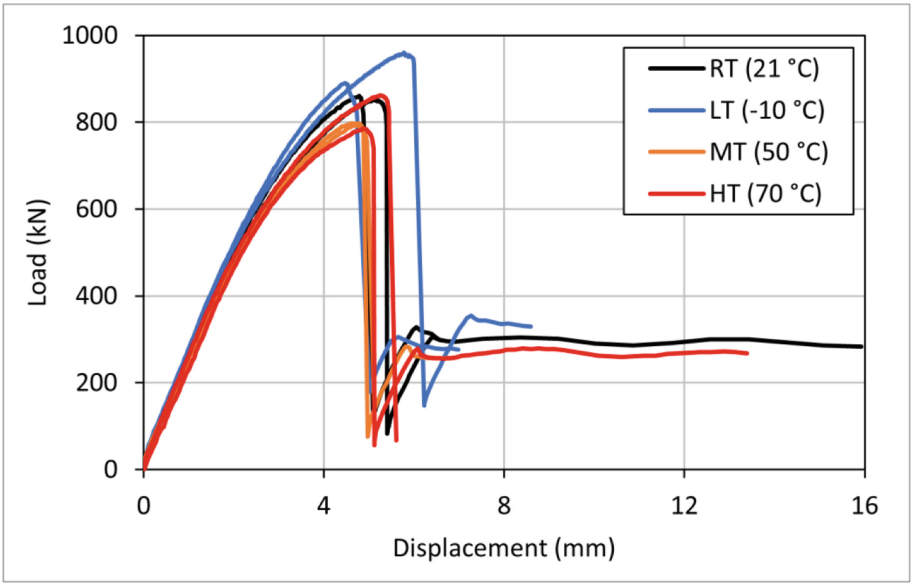

Fig. 4. Tensile static load behavior of wrapped composite joints tested in different temperatures.

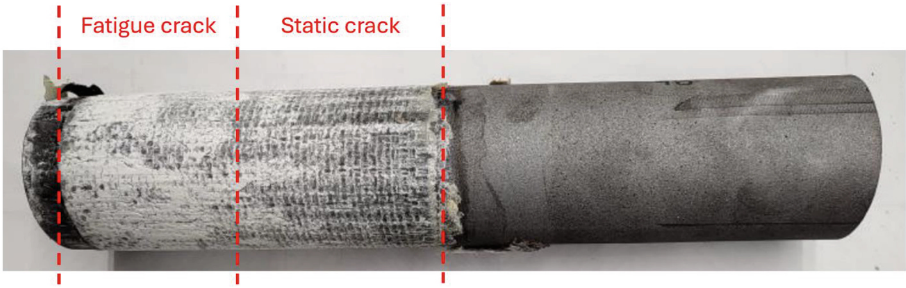

Fig. 5. Representative fracture surface of a wrapped composite joint (crack growth direction from the left to the right side).

4 Conclusions

This work investigated the effects of short-term changes of temperature on the mechanical behavior of wrapped composite joints. Fatigue and static tests were performed under axial tensile loadings. Tests were performed in room conditions (21 °C) and in controlled temperatures of –10 °C. 50 °C and 70 °C using a environmental chamber build around the test set up. This allows evaluating the performance of the structure in a range of operational temperatures.

Lower temperatures showed to improve the performance of wrapped composite joints under both fatigue and static loading conditions. Several effects seem to affect the mechanical behavior of the wrapped composite joints in different temperatures, such as the shrinkage of the composite material during curing of the wrap, the thermal expansion of steel and composite parts, the friction coefficient between cracked surfaces, the changes of composite material properties and delamination fracture toughness with temperature.

The next steps of this research involve the development of a finite element models capable to predict the mechanical behavior of wrapped composite joints in different operational conditions of temperature. Thee results will contribute to the design of more reliable and durable structures.

Acknowledgments. The authors would like to express their gratitude to RVO for the financial support with Topsector Energie subsidie van het Ministerie van Economische Zaken through WrapNode-I and WrapNode-II projects, and Tree Composites B.V. for the production of specimens.

References

1. Budhe, S., Banea, M.D., de Barros, S., Da Silva, L.F.M.: An updated review of adhesively bonded joints in composite materials. Int. J. Adhes. Adhes. **72**, 30–42 (2017)
2. da Costa Mattos, H.S., Reis, J.M.L., Paim, L.M., da Silva, M.L., Lopes Junior, R., Perrut, V.A.: Failure analysis of corroded pipelines reinforced with composite repair systems. Eng. Fail. Anal. **59**, 223–236 (2016)

3. Arouche, M.M., Teixeira de Freitas, S., de Barros, S.: On the influence of glass fiber mat on the mixed-mode fracture of composite-to-metal bonded joints. Compos. Struct. **256**, 113109 (2021)
4. Feng, W., Pavlovic, M.: Fatigue behaviour of non-welded wrapped composite joints for steel hollow sections in axial load experiments. Eng. Struct. **249**, 113369 (2021)
5. Arouche, M.M. Pavlovic, M.: Effect of offshore environmental conditions on the mechanical behavior of glass fiber reinforced polymers (GFRPs). In: 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE), Rio de Janeiro, Brazil (2023)
6. Fernandes, R.L., de Moura, M.F.S.F., Moreira, R.D.F.: Effect of temperature on pure modes I and II fracture behavior of composite bonded joints. Compos. B Eng. **96**, 35–44 (2016)
7. Yoshitake, I., Tsuda, H., Itose, J., Hisabe, N.: Effect of discrepancy in thermal expansion coefficients of CFRP and steel under cold temperature. Constr. Build. Mater. **59**, 17–24 (2014)
8. Arouche, M.M., Pavlovic, M.: Experimental and numerical analysis of the effect of temperature on the mode I and mode II delamination of glass fiber woven composites. Compos. B Eng. **293**, 112131 (2025)