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Behavior of FRP bonded to steel under freeze thaw cycles

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Abstract. Fiber reinforced polymers (FRP) materials are increasingly being used for strengthening and repair of steel structures. An issue that concerns engineers in steel members which are retrofitted with FRP is stress experienced due to temperature changes. The changing temperature affects the interface bond between the FRP and Steel. This research focused on the effects of cyclical thermal loadings on the interface properties of FRP bounded to steel members. Over fifty tests were conducted to investigate the thermal effects on bonding between FRP and steel, which were cycled from temperature of -11°C (12°F) to 60°C (140°F) for 21-36 days. This investigation consisted of two test protocols, 1) the tensile test of epoxy resin, tack coat, FRP and FRP-steel plate, 2) tensile test of each FRP compound and FRP with steel after going through thermal cyclic loading. This investigation reveals an extensive reduction in the composite's strength.

Keywords: fiber reinforced materials; CFRP; GFRP; polymers; tack coat; epoxy resin

1. Introduction

Fiber Reinforced Polymers (FRPs), such as Glass-FRP and Carbon-FRP, have excellent mechanical and physical properties that make them excellent candidates for repair and retrofit of steel structures. For instance, tensile strength and modulus of elasticity of FRP can be more than 1,200 MPa and 140 GPa, respectively (Loud and Kliger 2009), and the density of FRP is four to five times less than the density of steel.

In addition, Fiber Reinforced Polymer exhibit highly desirable corrosive resistance properties. Saadatmanesh *et al*. (2010) studied the long-term behavior of different types of FRP laminates containing unidirectional and bidirectional fabrics. The specimens were exposed to nine different environments. These environments were simulated using four different chemical solutions with a pH of 12.5, 10, 7, and 2.5 and substitute seawater. Additional FRP specimens were exposed to ultraviolet (UV) radiation, temperatures of 60 and 50°C (140 and 122°F) with 95% relative humidity (RH), and soil with 25% moisture content and active microorganisms in specially constructed chambers. Uniaxial tension tests were performed on the specimens after 6000, 12,000, and 20,000 hours of exposure as well as on control specimens; and tensile properties were measured for each specimen. The results showed that the carbon and hybrid-carbon laminates exhibited very little loss of mechanical properties under the above condition. On the other hand, the results showed a significant loss of strength and ultimate strain for glass FRP (GFRP) in environments with high pH values.

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Various properties of FRP material have been examined and understood for years. Composite materials (FRPs) have become popular in structural engineering, and as a result there already have been many recent composite material studies (Chen and Das 2009, El-Shihy *et al*. 2010).

Although FRP materials are more expensive than conventional construction materials, their installation requires fewer labor hours and limited equipment. Therefore, FRP products usually result in cost savings in construction projects. A major advantage of FRP is where access is limited, such as hospital floors, occupied buildings, industrial buildings where mechanical equipment and pipes exist, etc. In these situations, the flexibility of the FRP allows it to be passed through narrow openings, without the need to remove the existing attachments to the building. This leads to significant cost and time savings on many projects.

However, the focus of concern is that the bonding between steel members and FRP plates exhibit large differences in the coefficients of thermal expansion. The coefficient of thermal expansion of FRP plates can differ markedly from that of cast-iron or steel. Typical coefficients of thermal expansion for metallic elements range from 10.2×10^{-5}/°C for cast-iron to 12×10^{-6}/°C for mild steel (Rabinovitch 2010). However, the coefficient of thermal of expansion of FRP laminates can be extensively less and may even be negative in some cases (ACI 440, 2002). Thermal loads on the interface of FRP to steel bounded members develop critical longitudinal shear stresses and normal tensile stresses in the adhesive layer near the ends of the FRP plate (Rabinovitch 2007a).

The difference between the two coefficients of thermal expansion will degrade the elastic properties of the adhesive, which is another factor in the mechanisms that are related to thermal loading cycles (Leterrier *et al.* 2010). This effect compounds the effects of the coefficients of thermal expansion mismatch and the debonding failure of the element. (Kelmar *et al*. 2008, Biel and Carlberger 2007, Carlberger *et al*. 2009).

Kelmer revealed different and sometimes opposite trends in various experimental protocols. There is an increase in the debonding load during double lap shear tests, as the temperature increases to about 50°C. Then, a notable decrease in the debonding load was observed at a higher temperature. In reverse, Di Tommaso *et al*. (2001) reported, with the increase in temperature, the failure load decreased under four point bending of full scale strengthened beams. Deng *et al*. (2004) analytically studied the response of steel beams reinforced with CFRP plates, and Roberts and Haji-Kazemi (1989) introduced a model that thermal strain was taken into account. Their assumption violates the zero shear condition at the free edge and the equilibrium condition with in the adhesive layer, since it was assumed a linear deformations and uniform shear and vertical normal stresses distributions through the depth of the adhesive layer. Therefore, it affects the assessment of the stress concentrations near irregular points (edges, cracks, or debonded regions, etc.), see Rabinovitch (2004).

This study reveals the effects of cyclical thermal loadings on the interface properties of FRP bounded to steel members. In laboratory, epoxy resin, tack coat and FRP bonded to two steel plates were tested in tensile, since FRPs are most likely used as tensile membranes. After thermal cycling of each FRP compound and FRP-steel composite, they were tested in tension once again to observe the effect of cyclical thermal loading.

2. Materials used in this study

2.1 Fabric

2.1.1 Unidirectional fiber glass

The strength of the Glass Fiber Reinforced Polymer (GFRP) composite comes from the layers of fiber glass. The glass fabric is white and is impregnated in the field using polymer matrix to form a glass fiber reinforced polymer (GFRP). The fabric, which is used in this study, weighs 677 g/m^2 (20 oz/yd^2) and the fibers are in the longitudinal (0°) direction.

2.1.2 Unidirectional carbon fiber

The strength of the Carbon Fiber Reinforced Polymer (CFRP) composite comes from the layers of carbon fiber. This fabric is black and is impregnated in the field using polymer matrix to form a carbon fiber reinforced polymer (CFRP). The fabric, which is used in this study, weighs 779 g/m^2 (23 oz/yd^2) and the fibers are in the longitudinal (0°) direction.

2.2 Polymer matrix

2.2.1 Epoxy resin

A two-component mildly viscous epoxy was used to transmit forces between fiber and the applied loads, since adhesion between individual fibers is limited. The mixing ratio of the epoxy was two parts resin (bisphenal A based) and one part hardener (polyamide) by volume. The epoxy has a pot life of 1 hr at room temperature and is fully cured after two days at 25°C. This epoxy has a longer gel time and much lower viscosity and was used in between the FRP sheets to insure the least amount of entrapped voids.

2.2.2 Tack coat

A two-component viscous epoxy was used for bonding the laminates. The mixing ratio of the epoxy was one part resin (bisphenal A based) and one part hardener (polyethylenepolyamin) by volume. The epoxy has a pot life of 30 min at room temperature and is fully cured after two days at 25°C. This epoxy immediately reaches high-tack consistency and is ideal for over-head applications. The main difference between tack coat and epoxy resin is that in Tack Coat China clay is used.

Fig. 1 Two plastic plates for making resin and tack coat

2.3 Fiber reinforced polymer

2.3.1 Glass fiber reinforced polymer

Unidirectional Glass Fiber Reinforced Polymer (GFRP) sheets with dimensions of 25.4 mm (1.00 in) by 304.8 mm (12 in) and thickness of 0.635mm (0.025 in) were constructed by saturating glass fabric with epoxy resin. A total of eight straight strips were tested and an average tensile strength of 345 MPa (50 ksi), tensile modulus of elasticity of 17,513 MPa (2540 ksi), and Poisson's ratio of 0.25 were computed.

2.3.2 Carbon fiber reinforced polymer

Unidirectional Carbon Fiber Reinforced Polymer (CFRP) sheets with dimensions of 25.4 mm (1.00 in) by 304.8 mm (12 in) and thickness of 0.635mm (0.025 in) were constructed by saturating carbon fabric with epoxy resin. A total of eight straight strips were tested and an average tensile strength of 931 MPa (135 ksi), tensile modulus of elasticity of 60,949 MPa (8840 ksi), and Poisson's ratio of 0.34 were computed.

3. Specimens preparation

The first setup preparation consisted of one sheet of epoxy resin and one sheet of tack coat (15 × 30 × 0.64 cm (6 × 12 × ¼ in)) for tensile test. According to ASTM D638, two plastic plates were used in this process, which the first plate had a rectangular cavity (15 × 30 × 1.9 cm (6 × 12 × ¾ in)) and the second plate was designed to fit inside the cavity of the first plate as shown in Fig. 1.

When the plates were put together, they created a 15 × 30 × 0.64 cm (6 × 12 × ¼ in) gap. The cavity of the first plate was filled with either epoxy resin or tack coat. Then, the second plate was placed on top. Air and resin were squeezed out by pressing the two plates against each other. The sheets remained in the molds for 48 hours in order to cure after which the plastic plates were removed. The epoxy resin (Fig. 2) or tack coat (Fig. 3) were cut into one inch strips using a band saw.

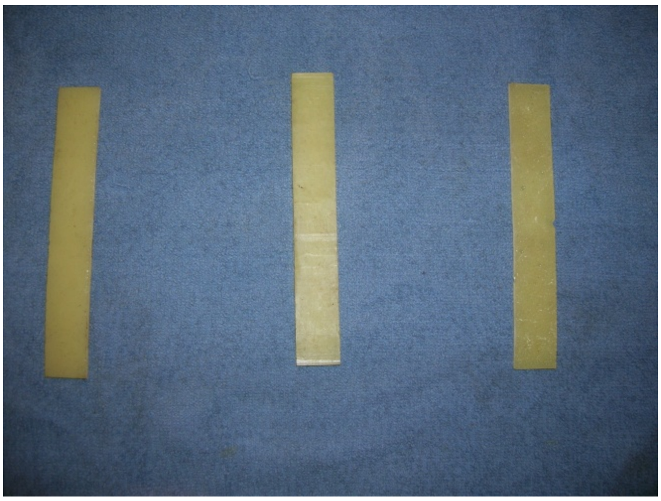

Fig. 2 Epoxy resin specimens

Fig. 3 Tack coat specimens

The second setup was prepared with one layer of carbon fiber which was sandwiched between two layers of fiber glass. The first layer of epoxy saturated fiber glass was placed on a smooth surface, and a sheet of epoxy saturated carbon fiber was then placed on top of the glass fiber. The remaining sheet of saturated fiber glass was placed on top of the carbon fiber (Fig. 4), and then the specimen was allowed to cure for 48 hours.

In the last setup, two sets of two steel bars (30 × 3.8 × 0.64 cm (12 × 1 ½ × ¼ in)) were utilized. The two bars were placed end to end (leaving a slight gap approximately 1.6 mm (1/16 in). In the first set, a layer of epoxy resin was distributed on the top and bottom surfaces, and in the second set, a layer of tack coat distributed on the top and bottom surfaces. Then, a layer of saturated glass fiber (30 cm (12 in) long) was placed on either side of the two steel plates such that they covered the entire width and extended 15 cm (6 in) past either end of the bars overall length. Glass FRP as

Fig. 4 Two layers of glass and one layer of carbon

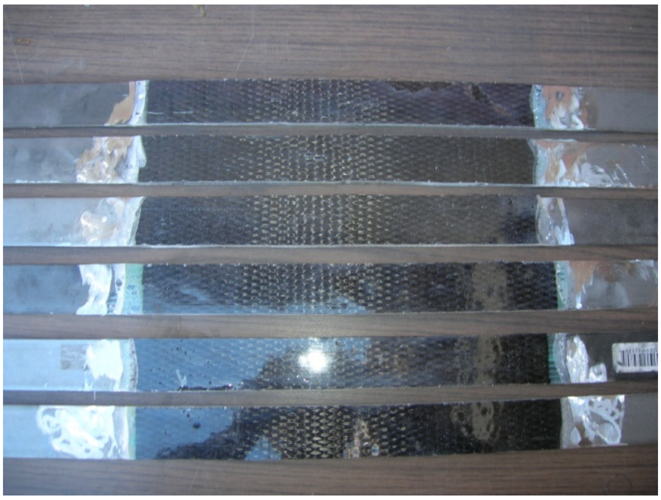

Fig. 5 Two steel plates bonded with FRP

opposed to carbon FRP is primarily used due to the fact that glass FRP does not conduct electrons thereby creating a barrier that retards the process of corrosion. A layer of saturated carbon (same dimension as the fiber glass sheet) was placed on top of each fiber glass sheet. The specimen was allowed to cure for 48 hours (Fig. 5).

4. Results and discussions I

The results section is divided to two test sets as follow: 1) the tensile test of epoxy resin, tack coat, FRP and FRP-steel plate, 2) tensile test of each FRP compound and FRP with steel after going through thermal cyclic loading.

Both test sets investigate the properties such as: maximum stress, corresponding strain, modulus of elasticity, and load per length for epoxy resin, tack coat, two layers of glass-one layer of carbon, and steel-FRP. However, in test set 2 all the specimens were subjected to cyclical thermal loading. All tests set 2 specimens were placed in an oven for 24 hours at temperature of 60°C (140°F). The specimens were then moved to a freezer for 24 hours at a temperature of -11°C (12°F) and again returned to the oven. The cycle of heating and cooling ran for a maximum of 36 days and a minimum of 20 days depending on the specimen. After thermal cycling, the specimens stayed at room temperature for one to two days prior to testing. This range of thermo cyclic is used in this study to simulate steel pipelines repaired with FRP, which experience a very high range of thermo cycling.

4.1 Epoxy resin (ER)

In this part, five specimens of resin (approximately, 25.4 mm wide and 3.3 mm thick) were tested in tension according to ASTM D638 with displacement rate of 5.1 mm/min (0.2 in/min) as shown in Fig. 6. Data was collected every 0.1 second. The average and standard deviation of the properties such as maximum stress, corresponding strain, modulus of elasticity and load per width of five specimens are given in Table 1.

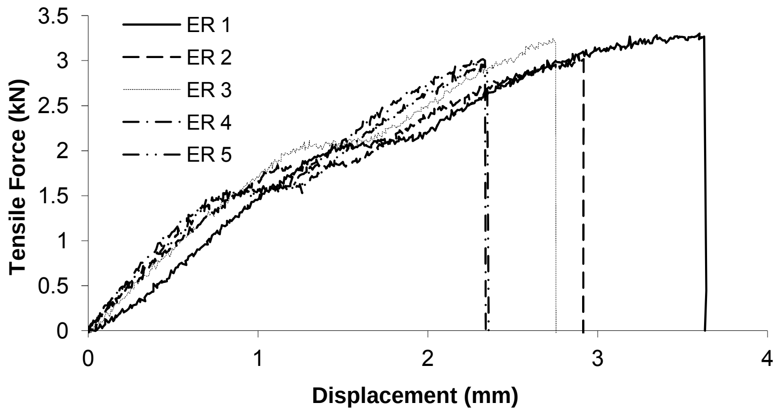

Fig. 6 Relationship of tensile force and displacement for epoxy resin

Table 1 Epoxy resin

(a) Average			(b) Standard deviation		
Stress	38.15	MPa	Stress	1.16	MPa
Strain	0.028	mm/mm	Strain	0.0024	mm/mm
Load/W	130.11	N/mm	Load/W	3.93	N/mm
E	1662.88	MPa	E	180.72	MPa

4.2 Tack coat (TC)

In this section, five specimens of tack coat (approximately, 25.4 mm wide and 3.3 mm thick) were tested in tension (Fig. 7). The setup and testing procedure was identical to the resin testing procedure. Table 2 shows the average and standard deviation of the material properties.

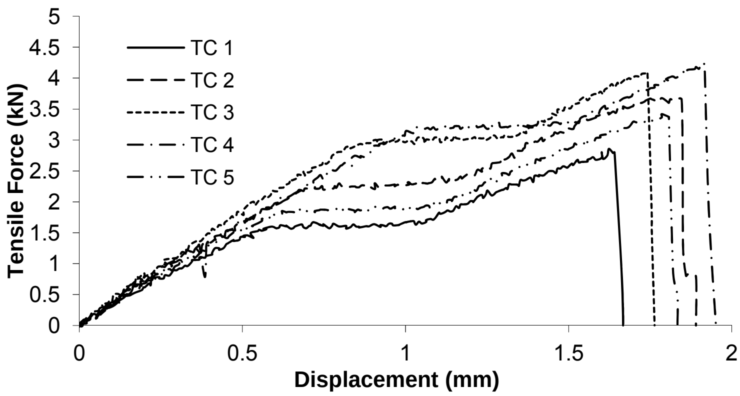

Fig. 7 Relationship of tensile force and displacement for tack coat

Table 2 Tack coat

(a) Average			(b) Standard deviation		
Stress	31.34	MPa	Stress	2.6	MPa
Strain	0.011	mm/mm	Strain	0.0027	mm/mm
Load/W	159.23	N/mm	Load/W	18.05	N/mm
E	3090.29	MPa	E	659.24	MPa

4.3 Two layers of fiber glass and one layer of carbon fiber (IIGIC)

For the next part, eight specimens were constructed using two layers of fiber glass and one layer of carbon fiber. Each specimen has a width of 12.7 mm (0.5 in). The displacement rate was set at 1.27 mm/min (0.05 in/min) according to ASTM D3039 standard (Fig. 8). Table 3 shows the average and standard deviation for properties such as maximum stress, corresponding strain, modulus of elasticity and load per unit width of the eight specimens.

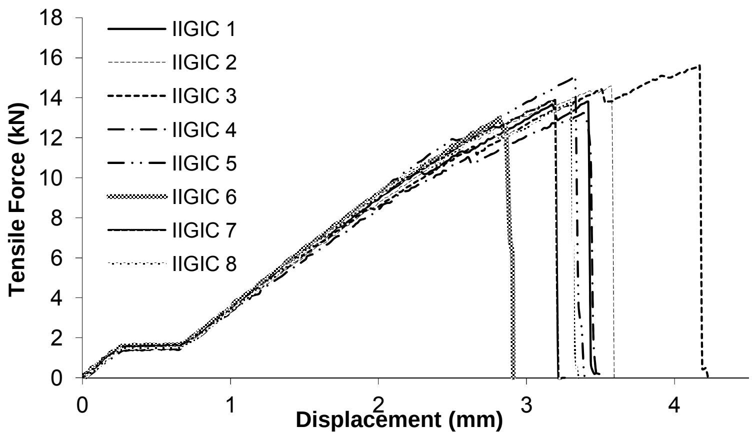

Fig. 8 Relationship of tensile force and displacement for IIGIC

Table 3 Two layers of GFRP and one layer CFRP

(a) Average			(b) Standard deviation		
Stress	479.99	MPa	Stress	24.19	MPa
Strain	0.0166	mm/mm	Strain	0.0015	mm/mm
Load/W	1152	N/mm	Load/W	81	N/mm
E	30.06	MPa	E	2.81	MPa

4.4 Steel plates bonded by FRP with epoxy resin (SFRP-ER)

Four specimens of FRP and steel, which were bonded with epoxy resin, were tested in tension as shown in Fig. 9. The average and standard deviation of maximum tensile load were 21.25 kN

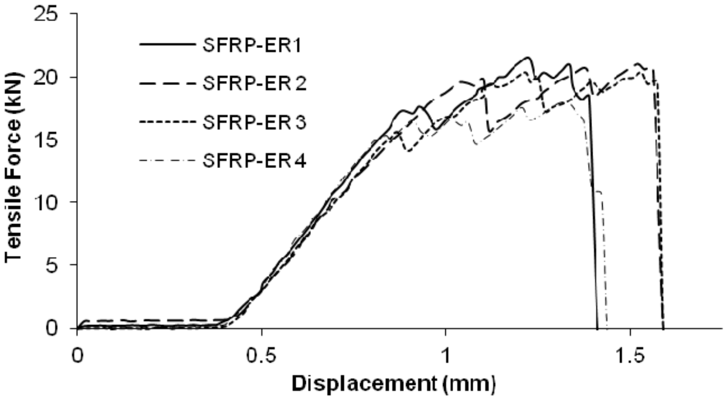

Fig. 9 Relationship of tensile force and displacement for SFRP-ER

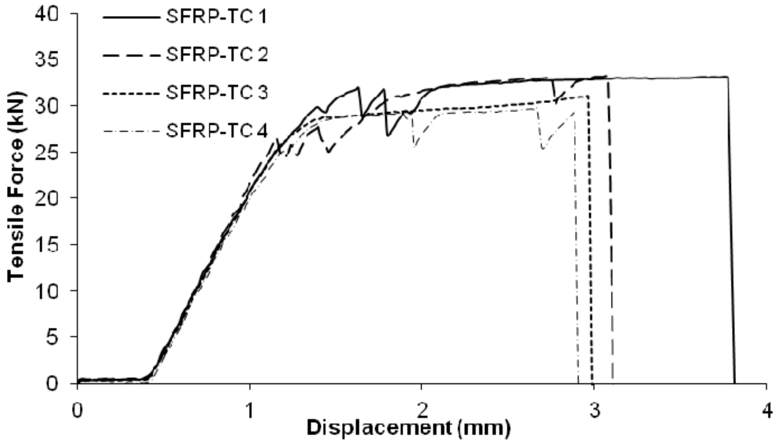

Fig. 10 Relationship of tensile force and displacement for SFRP-TC

(4778 lbf) and 1.71 kN (384 lbf), respectively. The specimens failed at an average of 1.42 mm (0.056 inch) deformation with standard deviation of 0.147 mm (0.0058 inch). The failure was between the layers of FRP and steel.

4.5 Steel plates bonded by FRP with tack coat (SFRP-TC)

Four specimens of steel and FRP bonded with tack coat were tested in tension. The average and standard deviation of the maximum load were 32.81 kN (7376 lbf) and 1.6 kN (360 lbf), respectively as shown in Fig. 10. The average and standard deviation of the maximum deformation were 3.12 mm (0.123 in) and 0.51 mm (0.02 in), respectively. In these tests, all the modes of the failures were the same as steel and FRP bonded with epoxy resin.

4.6 Comparison between steel plate, SFRP-ER, and SFRP-TC

In this section, the results of steel bonded by FRP with tack coat, steel bonded by FRP with

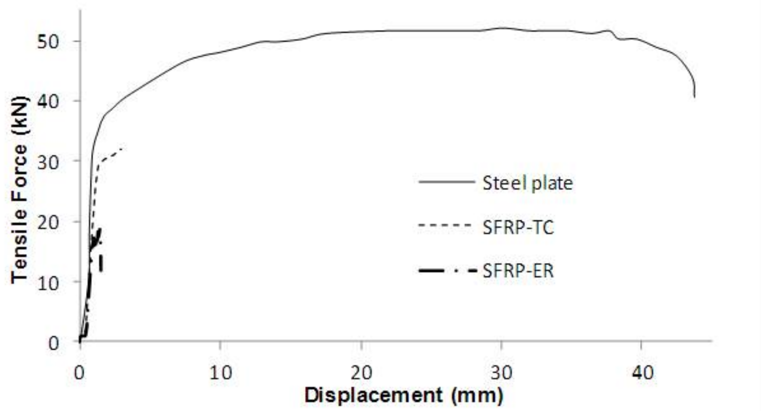

Fig. 11 Comparison of tensile force vs. displacement between steel plate, SFRP-ER, and SFRP-TC

epoxy, and the steel plate (the same steel plate used for making SFRP-ER or SFRP-TC specimens) are compared. Fig. 11 shows the tensile force (kN) versus displacement (mm) of the three specimens. According to Fig. 11, the maximum tensile force for steel plate, steel bonded by FRP with tack coat, and steel bonded by FRP with epoxy resin are approximately 52, 32, and 18 kN, respectively.

Based on this result, the steel plate which is repaired by FRP using tack coat has 72 % tensile force of steel plate, and the steel plate which is repaired by FRP using epoxy resin has 55 % tensile force of steel plate. Therefore, fixing a damaged steel plate using FRP is practical. The next step is to investigate the effects of cyclical thermal loading on the interface properties of FRP bounded to steel members.

5 Results and discussions II

5.1 Epoxy resin-cyclical thermal loading (ER-CTL)

Three specimens of epoxy resin were tested in tension after the specimens were subjected to cyclical thermal loading. The specimens were cycled from temperature of -11°C (12°F) to 60°C (140°F) for 21 days and then stayed for one day at room temperature (20°C) before testing. Table 4 shows the average and standard deviation (maximum stress, corresponding strain, modulus of elasticity, and load per length) for the three specimens, and Fig. 12 shows load and displacement relationships of the three specimens.

Table 4 Epoxy resin (cyclical thermal loading)

(a) Average			(b) Standard deviation		
Stress	26.55	MPa	Stress	4.04	MPa
Strain	0.011	mm/mm	Strain	0.0018	mm/mm
Load/W	108.46	N/mm	Load/W	16.85	N/mm
E	2401.63	MPa	E	166.39	MPa

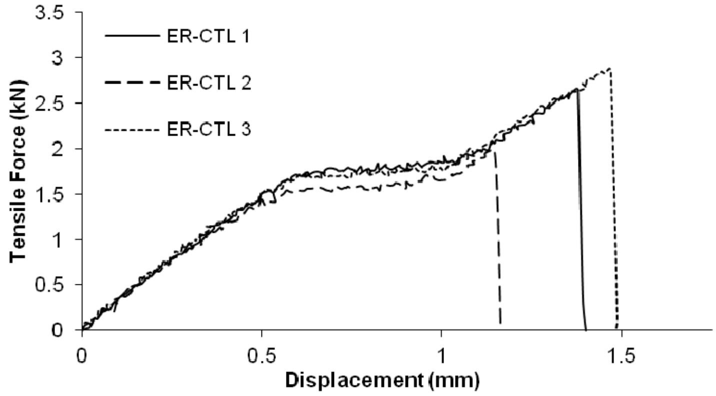

Fig. 12 Relationship of tensile force and displacement for epoxy resin (cyclical thermal loading)

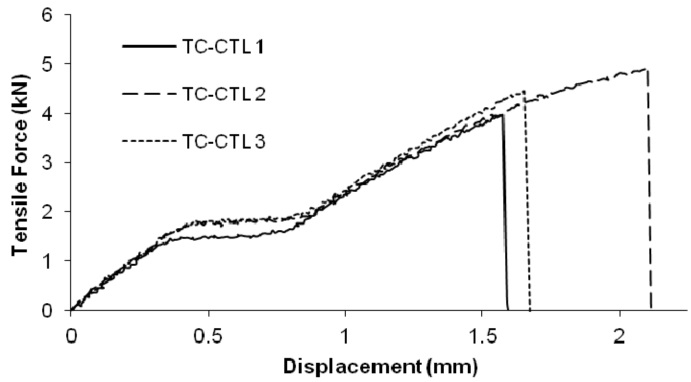

Fig. 13 Relationship of tensile force and displacement for tack coat (cyclical thermal loading)

Table 5 Tack coat (cyclical thermal loading)

(a) Average			(b) Standard deviation		
Stress	37.68	MPa	Stress	5.49	MPa
Strain	0.016	mm/mm	Strain	0.0035	mm/mm
Load/W	188.22	N/mm	Load/W	20.07	N/mm
E	2687.68	MPa	E	106.68	MPa

5.2 Tack coat- cyclical thermal loading (TC-CTL)

Three specimens of tack coat were tested after being subjected to thermal cycling for 21 days. Temperature was changed from -11°C (12°F) to 60°C (140°F) every 24 hours. After 21 days, the specimens were stabilized at room temperature for 24 hours before testing. Table 5 shows the average and standard deviation (maximum stress, corresponding strain, modulus of elasticity, and load per unit length) for the three specimens, and Fig. 13 shows load and displacement relationships of the three specimens.

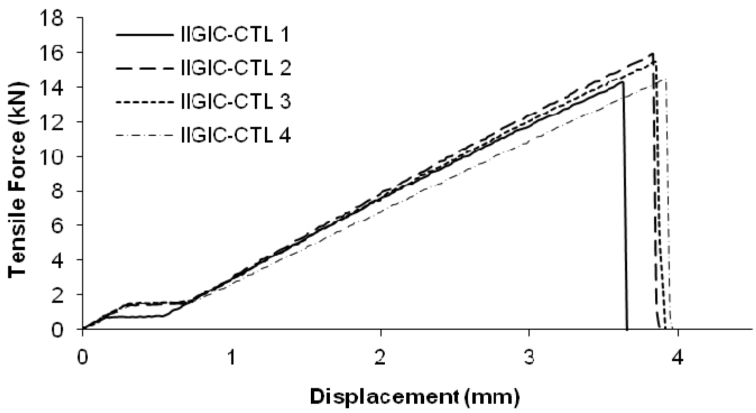

Fig. 14 Relationship of tensile force and displacement for IIGIC (cyclical thermal loading)

Table 6 Two layers of GFRP and one layer CFRP (cyclical thermal loading)

(a) Average			(b) Standard deviation		
Stress	433.62	MPa	Stress	16.5	MPa
Strain	0.016	mm/mm	Strain	0.0017	mm/mm
Load/W	1115.18	N/mm	Load/W	46.1	N/mm
E	27.21	MPa	E	1.16	MPa

5.3 Two layers of fiber glass and one layer of carbon fiber-cyclical thermal loading (IIGIC-CTL)

In this test, four specimens of one layer of carbon fiber and two layers of fiber glass were tested after the specimens were subjected to cyclical thermal loading as shown in Fig. 14. The specimens were cycled from -11°C (12°F) to 60°C (140°F) for 36 days. The specimens were stabilized at room temperature for 24 hours before testing. Table 6 shows the average and standard deviation of the properties such as maximum stress, corresponding strain, modulus of elasticity, and load per unit length of the four specimens.

5.4 Steel plates bonded by FRP with epoxy resin-cyclical thermal loading (SFRP-ER-CTL)

Five specimens of steel and FRP bonded with epoxy resin were tested in tensile after being subjected to thermal cycling for 30 days, where temperature was varied from -11°C (12°F) to 60°C (140°F) every 24 hours. The specimens were stabilized at room temperature for 24 hours before testing. The average and standard deviation of maximum stress for five specimens were 1.71 kN (385 lbf) and 0.15 kN (33 lbf), respectively. The average and standard deviation of maximum deformation of these five specimens was 0.762 mm (0.03 in) and 0.051 mm (0.002 in). Fig. 15 shows the load-displacement relationship, and the mode of failure, which is similar to Steel and FRP bonded with epoxy resin without thermal cycling. The failure of the specimen was at the bond between steel and FRP.

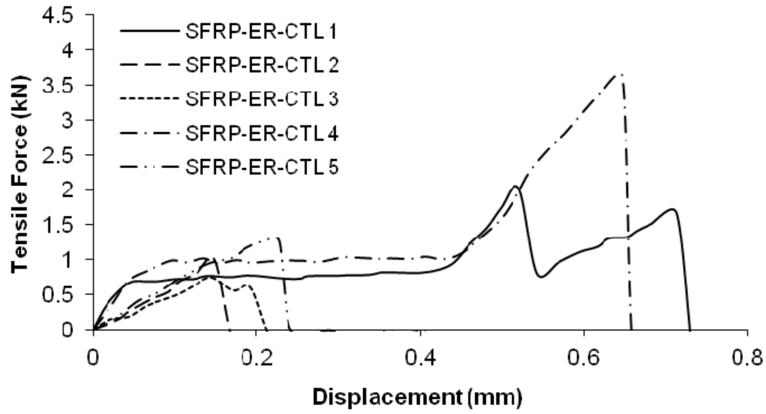

Fig. 15 Relationship of tensile force and displacement for SFRP-ER (cyclical thermal loading)

5.5 Steel plates bonded by FRP with tack coat- cyclical thermal loading (SFRP-TC-CTL)

Five specimens of steel and FRP bonded with tack coat were tested in tensile after experiencing thermal cycling for 30 days, where temperature was changed from -11°C (12°F) to 60°C (140°F) every 24 hours. The specimens were stabilized at room temperature for 24 hours before testing. The average and standard deviation of maximum stress of the specimens were 6.85 kN (1539 lbs) and 2.22 kN (500 lbs), respectively. The average and standard deviation of maximum deformation of five specimens were 0.762 mm (0.03 in) and 0.0762 mm (0.003 in). Fig. 16 shows the tensile force verses displacement relationship and the mode of failure, which was similar to steel and FRP bonded with tack coat that did not experience thermal cycling. The failure of the specimen occurred at the bonding region between steel and FRP.

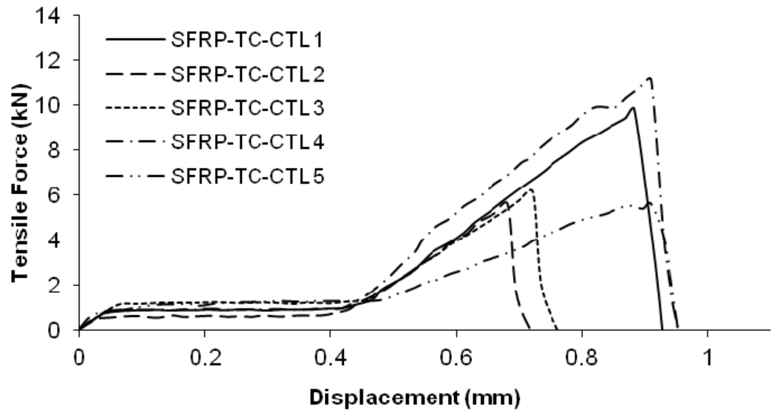

Fig. 16 Relationship of tensile force and displacement for SFRP-TC (cyclical thermal loading)

5. Conclusions

For all of the test specimens, at the very beginning of their stress-strain curve, the strain increased while stress remained constant. This phenomenon can be attributed to slippage between the specimen and the grip, and/or slack in fibers created during construction. This slack can be removed if the fibers are stretched and held in place while the sheet is constructed. However, since this phenomenon occurs at early stages of loading, it can be speculated that this has no effect on the overall behavior of the composites.

Experiments conducted to investigate the effects of cyclical thermal loading on FRP-Steel composites demonstrated a tremendous decrease in strength as compared to specimens that were kept at room temperature. The strength of Epoxy Resin, two layers of fiber glass and one layer of carbon fiber, steel bonded by FRP with epoxy resin and steel bonded by FRP with tack coat, after experiencing thermal cycling, were decreased 30.4%, 9.66 %, 91.95 %, and 79.12%, respectively. This can be attributed to the fact that the difference in thermal expansion rates of steel and FRP causes damage at micro-level to bonding between steel and FRP. However, the strength of tack coat increased 16.8 %, after experiencing thermal cycling.

In the field, most of the members that are retrofitted by FRP are usually under stress, and it is usually installed at different temperatures. However, in this experimental study, none of the members are pre-stressed, and all the members are made and tested at room temperature. Therefore, this investigation did not simulate exactly the field conditions. However, it is not necessary to do so, since there was a decisive reduction in tensile strength of the composite under thermal cycling. It is recommended not to use tack coat or epoxy resin for members that are exposed to cyclic changes in temperature. Due to the slippage related failures as demonstrated in this investigation a recommendation would be to construct the FRP-steel interface with physical barriers to longitudinal and lateral movement.

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