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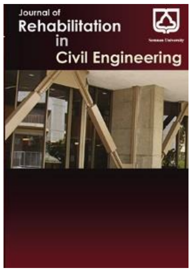

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The Improvement of the Tensile Behavior of CFRP and GFRP Laminates at Elevated Temperatures Using Fire Protection Mortar

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ABSTRACT

In spite of many benefits, FRP materials are susceptible to elevated temperatures. On the other hand, because FRP laminates are different from other FRP materials, data acquired from investigations concerning FRP materials cannot be suggested for FRP laminates. An assessment of the tensile performance of fibers impregnated by epoxy resin as binder is needed. In recent decades, many methods have been presented to protect fiber reinforced polymer (FRP) composites against high temperatures. The application of fire protection mortar is a low-cost and easy technique among all methods. In this investigation, the influence of fire protection mortar on the improvement of the tensile strength of glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) laminates was evaluated. For this object, over 200 FRP laminates with or without fire protection mortar were tested at various elevated temperatures. Investigated temperatures varied from 25°C to 500°C. According to the results obtained from this study, the strength of FRP laminates considerably reduced following the laminates experienced the temperatures higher than 400°C. However, the samples covered with fire protection mortar underwent lower the tensile strength decrements. Eventually, a linear model was presented to estimate the strength of FRP laminates including or excluding protective mortar at elevated temperatures on the basis of linear regressions carried out on test data.

1. Introduction

In current decades, fiber reinforced polymer (FRP) has been considerably applied in different branches of engineering such as civil, mechanical, aerospace engineering, owing to their beneficial characteristics. Useful characteristics of FRP material

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include high strength to weight ratio, corrosion resistance, easy installation, and etc. [1-7]. For instance, glass fiber reinforced polymer (GFRP) bars have been suitably applied as inner reinforcement in concrete elements due to their many excellent mechanical characteristics [7-10]. There are instances for GFRP and carbon fiber reinforced polymer (CFRP) bars as reinforcement in concrete beams, slabs, and wall owing to useful characteristics of FRP materials include high strength to weight ratio, corrosion resistance, easy installation. However, FRP materials used to strengthen structural elements can experience some difficulties, e.g. low strength at elevated temperature and high costs [11-14]. One of the most important issues is evaluating the performance of such materials at elevated temperatures [15-17]. A number of researches have investigated this important factor; however, researches suggesting techniques to enhance the strength of FRP materials at elevated temperatures are very limited. On the other hand, more studies are needed to complete the data applied for FRP materials in harsh environments.

Generally, FRP composites have been consisted of resin matrix and fibers [18-20]. The behavior of matrix and fibers is different when they are exposed to elevated temperatures. FRP materials are often fabricated by glass and carbon fibers less vulnerable compared with resin matrix at elevated temperatures [14, 17-19]. When temperature of FRP reaches glass transition temperature (T_g), the state of the matrix will change from a glassy to rubbery [21,22]. T_g ranges from 50°C to 90°C for the common materials applied in civil engineering [23]. In this temperature, the mechanical properties of FRP laminates decrease owing to the matrix loses the capability to transfer the load between fibers [15]. Decomposition temperature of the matrix (T_d) begins at the temperature equal to 300-400°C [10]. Eventually, at temperatures after T_d, the matrix burns. This burn creates more heat decomposing fibers, and significantly decreasing properties of FRP composites [20]. FRP materials are manufactured as laminates, bars, and profiles for various applications. Among all forms, FRP laminates are more susceptible to high temperatures owing to their low thickness and straight contact to environments [24]. Chowdhury et al. [25] studied the performance of two concrete columns strengthened by FRP wraps. Fire-retardant material applied in this investigation was a layer of cementitious mortar. The finding indicated that the failure of FRP-confined columns with a cementitious layer occurred subsequent to FRP-confined columns without protection. Cao et al. [26] showed that the tensile strength of CFRP sheets significantly reduced at the temperature about 60°C, and remained nearly unchanged at the temperatures between 60°C and 200°C. Wang et al. [19] evaluated characteristics of CFRP plates under high temperatures. On the basis of the study, a considerable decrement in the strength of CFRPs happened at temperatures between 20°C and 150°C, and also 450°C and 706°C. They reported that such reduction is 38% and 40% for 20-150°C and 450-706°C, respectively. They also showed that the decrement of the tensile strength was slight at temperatures between 150°C and 450°C due to slight degradations at this range. In addition, Hawileh et al. [27] assessed performance of CFRPs and GFRPs at various temperatures between 25°C and 300°C. The findings demonstrated that the laminates exposed to 250°C for 45 min, underwent a decrement 35% and 17% in the tensile strength and elastic modulus, respectively. Hawileh et al. [28] also investigated the influences of elevated temperatures on the mechanical properties of CFRP and BFRP laminates. Different models were presented by them to estimate elastic modulus and the strength of such materials under elevated temperatures. Based on investigated research, the mechanical deterioration of CFRPs is more considerable than BFRPs at elevated temperatures.

Influence of elevated temperatures on performance of the other FRP composites like bars has been studied by many researches. Hamad et al. [24] investigated influences of elevated temperatures on characteristics of FRP and steel bars. According to the research, CFRP, GFRP, BFRP, and steel bars underwent 54%, 46%, 46%, and 1.7% decrements in the strength, respectively at the temperature 325°C. Ashrafi et al. [10] studied performance of CFRP and GFRP bars having different diameters under high temperatures until 450°C. They reported strength of bars reduced around 50-70% at the temperature 450°C. Also, the authors indicated that the strength reduction of the bars having larger diameters was lower than that of the bars with smaller diameters under high temperatures. In fact, internal sections of the bars with larger diameters were suitably confined and this led to lower ignition.

As stated previously, FRP composites are susceptible to elevated temperatures. To decrease susceptibility of FRP composites, there are many methods. These methods include the application of fire protection covering like mortars or paints, contributing anti-fire additives to resin matrix [29,30]. Khaneghahi et al. [29] studied the influences of fire protection material on strength of FRP composites under elevated temperatures. They indicated materials used can be activated after the temperature 350°C. They reported the material led to 21-31% and 14-26% increment in strength of GFRP and CFRP bars, respectively.

Since FRP laminates are different from other FRP materials, data acquired from investigations concerning FRP materials cannot be suggested for FRP laminates. It is owing to low thickness of FRP laminates, the fabrication method with hand lay-out, and straight contact of FRP laminates to fire conditions. Therefore, an assessment of the tensile performance of fibers impregnated by epoxy resin as binder is needed to fill gap.

In current investigation, performance of FRP laminates were studied at elevated temperatures. To achieve the object, some samples were covered by a type of fire protection mortar to present an appropriate method for decreasing fire susceptibility of FRP laminates at elevated temperatures. Also, linear regressions were used to acquire new models predicting behavior of FRP laminates at elevated temperatures including or excluding fire protection mortar.

2. Experimental investigation

To assess performance of various kinds of fibers impregnated by epoxy resin with or without fire protection mortar, over 200 specimens were provided and examined using direct tension test.

2.1. Materials

2.1.1. Glass and carbon fibers

Two various kinds of fibers including glass fiber having a thickness 0.18 mm and carbon fiber having a thickness 0.17 mm were applied. According to data obtained from manufacturer, density, elastic modulus, and the tensile strength of glass fibers were 2.55

g/cm3, 95 GPa, and 2400 MPa and those of carbon fibers were 1.9 g/cm3, 240 GPa, and 5000 MPa, respectively.

2.1.2. Epoxy resin binder

Sikadur 300 epoxy resin impregnated carbon and glass fibers. Such resin is a two part, epoxy based impregnating resin having glass transition temperature, elastic modulus, and tensile strength 53°C, 3.5 GPa, and 45 MPa, respectively.

2.1.3. Fire protection mortar

In this study, a type of fire protection mortar swelling as subjected to elevated temperature was used. This mortar concludes Portland cement and magnesium as binder and aggregates, respectively. The used mortar avoids heat and oxygen to reach the sample by making a pervious layer on the covered surface. The layer of used mortar had a thickness equal to 0.7 mm. It should be noted that heat-insulation mortar is inactive at temperature under 300°C. Above 300°C, it begins acting and produces an obstacle through expanding and bubble formation improving the performance of FRP sheets. Therefore, FRPs with retarding mortar at low elevated temperatures is similar to FRP without retarding mortar. For this reason, retarding mortar was only used at high elevated temperatures.

2.2. Samples

Over 200 samples were provided and examined in this investigation. To ensure the accuracy of the test results, three similar samples were examined. The samples were classified into four classifications of carbon and glass laminates with or without fire protection mortar labeled as CM, GM, CW, and GW. The first letter represents the type of fiber (i.e. carbon or glass) and the ‘M’ and ‘W’ letters show whether the sample is covered with mortar or not.

2.3. Test apparatus and process

According to ASTM D3039/D3039M (Standard Test Method for Tensile Properties of Polymer Composite Materials) [31], the tensile strength test was carried out by a machine having a capacity of 200 KN. To assess the post-fire performance of samples at elevated temperatures 25, 100, 200, 250, 300, 400, and 500°C, the samples were kept in a furnace with maximum heat temperature 600°C for 20 min. After cooling and reaching ambient temperature for 24h, they were tested. The test machine and the furnace used in this study were shown in Fig. 1. At high elevated temperature such as 400°C and 500°C, the tensile strength significantly decreased and an increase in time exposure led to a considerable reduction in strength such a way that tensile strength reached zero after 20 min. Therefore, due to providing similar condition for all specimens, exposure time 20 min was selected. The samples were tested in a displacement control device with a loading rate 2.0 mm/min to acquire the displacements after maximum load.

3. Test results and discussion

The test results including the load-displacement curves, tensile strength, strength retention of samples, and failure modes have been presented in this section.

3.1. GFRP laminates (GW and GP)

The results of tensile behavior of GFRP laminates are reported in Table 1. It is usually observed that an increment in the temperature resulted in a decrease in the tensile strength.

(a)

(b)

Fig. 1. (a) Test setup of tensile strength, (b) furnace.

The load-displacement curves of GFRP laminates at various temperatures are shown in Fig. 2. As shown in this figure, a nearly linear behavior was seen in the curves before the maximum load. After that, a significant strength loss and failure occurred. Fig. 3a and b presents maximum tensile strength and tensile strength retention versus different temperatures, respectively.

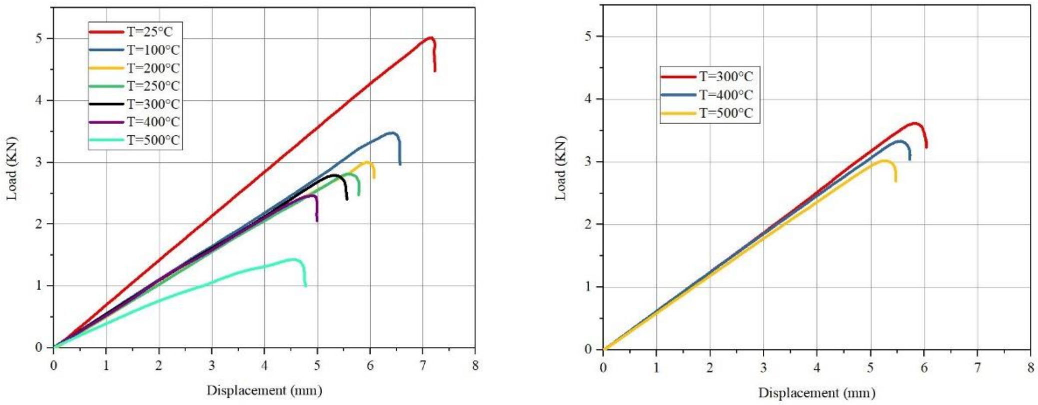
To describe the strength retention versus temperature behavior, the curves are grouped into three temperature ranges including 25-200, 200-400, and 400-500°C. In the range 25-200, when the temperature reached glass transition temperature (T_g) of epoxy resin (i.e. 53°C), resin binder softened and changed from a glassy to rubbery situation. Therefore, resin is no longer able to transfer the load to fibers; thus, the tensile strength considerably decreases. In the range of 200-400°C higher than T_g and lower than decomposition temperature (T_d), strength of glass laminates slightly reduced compared with the range 25-200°C. It can be attributed the fact that glass fibers bear the greater part of the exerted load and withstand the temperature range. In the temperature range 400-500°C, the temperature of the samples approximates to decomposition temperature (T_d) of resin binder. Therefore, resin binder begins to change into gas, and it is unable to transfer the load to fiber; and thus the load bearing capacity significantly reduces. As shown in Fig. 3, tensile strength of GFRP laminates was enhanced using a layer of fire protection mortar. This increment ranges from 30% at the temperature 300°C to 110% at the temperature 500°C. Generally, heat-insulation mortar is inactive at temperature under 300°C. Above 300°C, it begins acting and produces an obstacle by expanding and bubble formation improving the performance of FRP sheets (such as toughness and elastic modulus) at elevated temperatures compared with sheets without heat-insulation mortar. In fact, these bubbles avoid oxygen from reaching the matrix.

As can be seen in Fig. 4, different failures of GFRP laminates without fire protection mortar occurred in this study. In a type of failure happening at the temperatures 25 and 100°C, resin can transfer the load to fibers because the failure zone is at 90 degrees to the applied load. The second kind of failure happened at temperatures ranging from

200°C to 400°C. At such temperature range, brittleness of resin binder increases. In addition, the color of fiber and resin changed into brown and black, respectively. In the failure happening at the temperatures 400 and 500°C, resin burned. Also, three various failure kinds were observed in specimens protected by mortar. At temperature 300°C, the first failure type happened, where fire protection mortar is unable to expand significantly. At the temperature 400°C, the mortar significantly expanded and avoided heat to reach resin and fibers. Hence, increments in tensile strength of laminates were considerable. At the temperature 500°C, the mortar significantly expanded and this increased the thickness of the thermal obstacle. Therefore, the laminates with fire protection mortar had no ignition at 500°C.

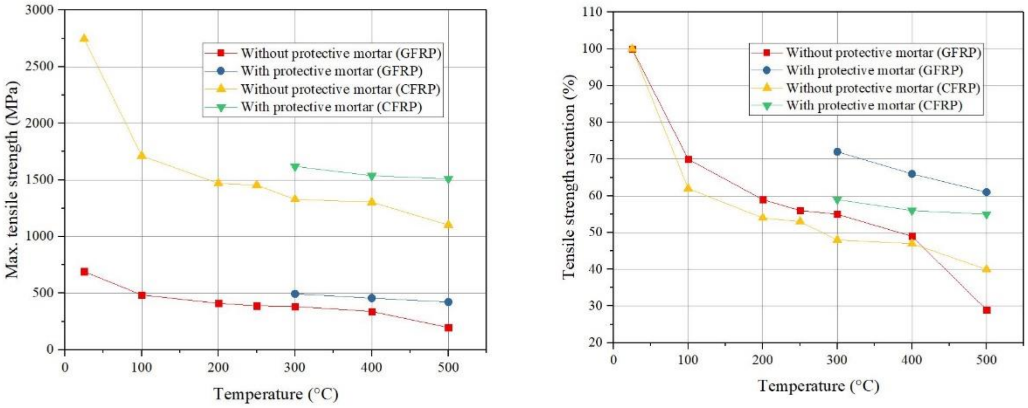
Table 1. The results of tensile strength for GFRP laminates

Temperature (°C)	Without protective mortar				With protective mortar			
	σ_{max} (MPa)	CoV (%)	Strength retention (%)	Failure type	σ_{max} (MPa)	CoV (%)	Strength retention (%)	Failure type
25	691.3	3.9	100	First	-	-	-	-
100	484.5	4.8	70	First	-	-	-	-
200	410.8	6.3	59	Second	-	-	-	-
250	388.7	3.7	56	Second	-	-	-	-
300	382.9	5.2	55	Second	494.3	4.6	72	First
400	339.1	1.8	49	Third	456.3	3.3	66	Second
500	197.3	5.0	29	Third	421.7	4.5	61	Third



(a) (b)

Fig. 2. The load-displacement curves of GFRP laminates at various temperatures: (a) without protective mortar, (b) with protective mortar



(a) (b)

Fig. 3. (a) Maximum tensile strength of GFRP and CFRP laminates versus temperatures, (b) Tensile strength retention of GFRP and CFRP laminates versus temperatures

Fig. 4. Different failure modes of GFRP laminates at elevated temperatures

3.2. CFRP laminates (CW and CP)

The results of tensile strength of CFRP laminates are reported in Table 2. Also, the load versus displacement curves of CFRP laminates at various elevated temperatures are illustrated in Fig. 5. Identical to GFRP laminates, CFRP laminates indicated a nearly linear behavior before the maximum load. After the peak point, a significant strength loss happened. Fig. 3a and b presents maximum tensile strength and tensile strength retention versus different temperatures for carbon laminates, respectively. The curves are grouped into three temperature ranges including 25-200, 200-400, and 400-500°C to assess the tensile performance of CFRP laminates. In the range 25-200, when the temperature reached T_g, a considerable reduction occurred in tensile strength and resin cannot transfer the load to fibers. In the range of 200-400°C higher than T_g and lower than T_d, decrease in the strength of CFRP laminates was slight compared with the range 25-200 because the fibers withstand the exposed temperatures. In the range 400-500°C, decrement of tensile strength accelerated due to resin decomposition and deterioration of fibers.

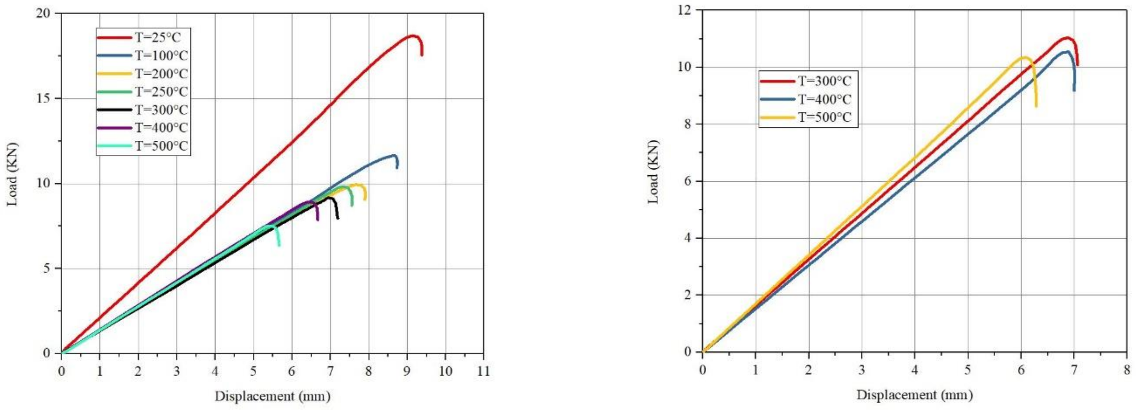
Identical to GFRP laminates, tensile strength of CFRP laminates covered with fire protection mortar was higher than that of CFRPs without mortar. It is well known that carbon fibers are more impervious to heating and elevated temperatures compared with glass fibers. Also, at temperatures above 400°C given as decomposition temperature, resin matrix begins to decompose and the fibers have main role in load-bearing capacity. This leads to lower strength reduction for CFRP sheets compared with GFRP sheets at such temperatures. Therefore, the effect of retarding mortar in compensation of tensile strength reduction for GFRP sheets are higher than that of CFRP sheets. The results obtained from this study showed that strength increment because of using fire protection mortar ranges from 23% at the temperature 300°C to 38% at the temperature 500°C.

Various failure modes of CFRP laminates are seen in this investigation. In the first type happening at the temperatures 25 and 100°C, the failure manner of the samples is brittle. In the temperatures 100 and 200°C, the color of resin converted to brown and the deterioration beginning in the previous failure type escalated. In another failure type at the temperature range 200-400°C, resin cannot maintain continuity of carbon fibers. Hence, the laminates were divided into separated strips at the failure zone. At the temperatures 400°C and 500°C occurred the last type of failure, where resin binder burned and began to create gas.

Two various failure types happened in CFRP laminates covered with mortar. In the first type, the activation of the mortar was not provided suitably. Also, covered CFRP laminates were divided into separated strips at the failure zone. In another type of failure happened at the temperature range from 400 to 500°C, the mortar expanded appropriately and created a thermal obstacle.

Table 2. The results of tensile strength for CFRP laminates

Temperature (°C)	Without protective mortar				With protective mortar			
	σ_{max} (MPa)	CoV (%)	Strength retention (%)	Failure type	σ_{max} (MPa)	CoV (%)	Strength retention (%)	Failure type
25	2745.6	2.8	100	First	-	-	-	-
100	1712.8	4.4	62	First-Second	-	-	-	-
200	1469.9	2.9	54	Second-Third	-	-	-	-
250	1454.5	3.8	53	Third	-	-	-	-
300	1328.3	5.1	48	Third	1619.9	4.6	59	First
400	1303.9	4.0	47	Fourth	1537.5	3.8	56	Second
500	1102.6	3.3	40	Fourth	1510.1	2.0	55	Second



(a) (b)

Fig. 5. The load-displacement curves of CFRP laminates at various temperatures: (a) without protective mortar, (b) with protective mortar

4. Test results and discussion

Different studies have been carried out to present appropriate expression to estimate the strength of various FRP composites at elevated temperatures. In one of the researches, Gibson et al. [32] presented a model to estimate the mechanical characteristics of FRP composites at elevated temperatures. The model can be expressed by Eq. (1):

$$P(T)=\left(\frac{P_L+P_H}{2}-\frac{P_L-P_H}{2}\tanh\left(k\left(T-T'\right)\right)\right)R^n \qquad (1)$$

where P(t) is given mechanical characteristics of FRP composites such as elastic modulus and tensile strength at the temperature T, P_L and P_H are values of the given characteristic at low and high temperatures, respectively, k is a factor showing the extent of distribution, T' is the glass transition temperature, and R_n is considered for matrix decomposition. Then, several researches were performed to amend the model reported by Gibson et al. using experimental investigations on composites. Hawileh et al. [27] carried out a research leading to a suggested model (Eq. (2)) for estimating strength of carbon sheets.

$$f_c(T)=0.594-0.405\tanh\left(0.017\left(T-117.74\right)\right) \qquad (2)$$

Two various models were presented by Nadjai et al. [33] to estimate strength of composites at elevated temperatures as expressed in Eqs. (3) and (4).

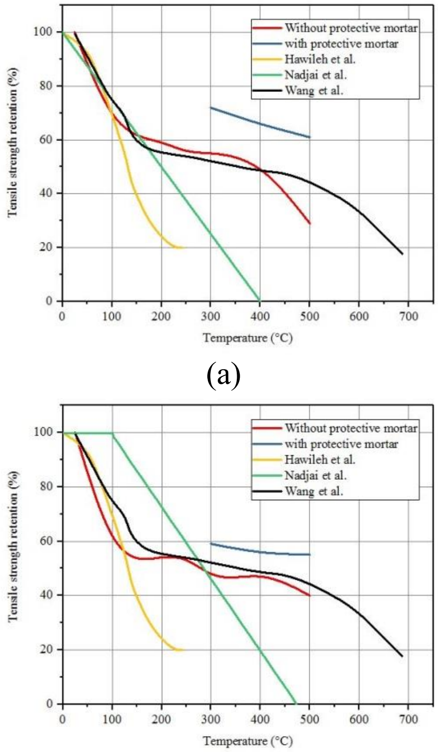
$$\frac{f_{u,t}}{f_u}=\begin{cases}1-0.0025T, & 0\le T<400\\ 0, & 400\le T\end{cases} \qquad (3)$$

$$\frac{f_{u,t}}{f_u}=\begin{cases}1, & 0\le T<100\\ 1.267-0.00267T, & 100\le T<475\\ 0, & 475\le T\end{cases} \qquad (4)$$

where $f_{u,t}$ and f_u present strength of FRP composites at the given and normal temperatures, respectively. Also, a model recommended by Wang et al. [19] to predict strength of carbon sheets at various temperatures until 706°C is presented in Eq. (5).

$$\frac{f_{u,t}}{f_u}=\begin{cases}1-\dfrac{(T-22)^{0.9}}{200}, & 22\le T<150\\ 0.59-\dfrac{(T-150)^{0.7}}{490}, & 150\le T<420\\ 0.48-\dfrac{(T-420)^{1.8}}{76000}, & 420\le T<706\end{cases} \qquad (5)$$

The results obtained from this investigation and aforementioned models were compared in Fig. 6. As shown in Fig. 6(a), the models are able to estimate tensile strength retention of GFRP laminates without fire protection mortar until 100°C acceptably. On the other hand, after 100°C, the equations reported by Nadjai et al. [33] and Hawileh et al. [27] underestimate tensile strength of FRP laminates. The model presented by Wang et al. [19] has suitable precision for temperatures until 400°C; however, after 400°C, it is unable to appropriately predict behavior of FRP. As can be seen in Fig. 6(b), the model recommended by Wang et al. [19] for CFRP laminates without fire protection mortar is more precise. Furthermore, all models are unable to precisely estimate tensile strength retention of FRP laminates covered with fire protection mortar. In the following section, a probabilistic model estimating strength of FRP laminates including or excluding fire protection mortar at elevated temperatures is suggested.



(a)

(b)

Fig. 6. Comparison of the test results with reported models: (a) GFRP laminates, (b) CFRP laminates

5. Probabilistic model for FRP laminates at elevated temperatures

A probabilistic model predicting ultimate tensile strength of FRP laminates at elevated temperatures is suggested in this section. The model presented uses linear regression process established by Box and Tiao [34]. The form of the suggested model is presented in Eq. (6).

$$\frac{f_{u,t}}{f_u} = \mu_1 \cdot f_1(z) + \mu_2 \cdot f_2(z) + \cdots + \mu_n \cdot f_n(z) + \eta \tag{6}$$

where $f_{u,t}$ is strength at a given temperature T, f_u is strength at ambient temperature, f_n is nth function, μ_n is nth model factor, z is independent parameter and η is model error.

To detect a suitable function, many functions were selected on the basis of test results. In next step, the precision of the functions was evaluated by linear regression defined on Rt software [35]. The form of the model acquired from replacing appropriate functions in Eq. (6) is presented in Eq. (7). It should be noted that temperature of test in this equation is in Kelvin unit (K).

$$\frac{f_{u,t}}{f_u} = \mu_1 + \mu_2 \cdot \frac{1}{\ln(T)} + \eta \tag{7}$$

As the main form expressed in Eq. (7) contains two factors (μ_1 and μ_2), after using a reduction process, one of two models was selected to estimate tensile strength retention of FRP laminates as proposed in Eq. (8).

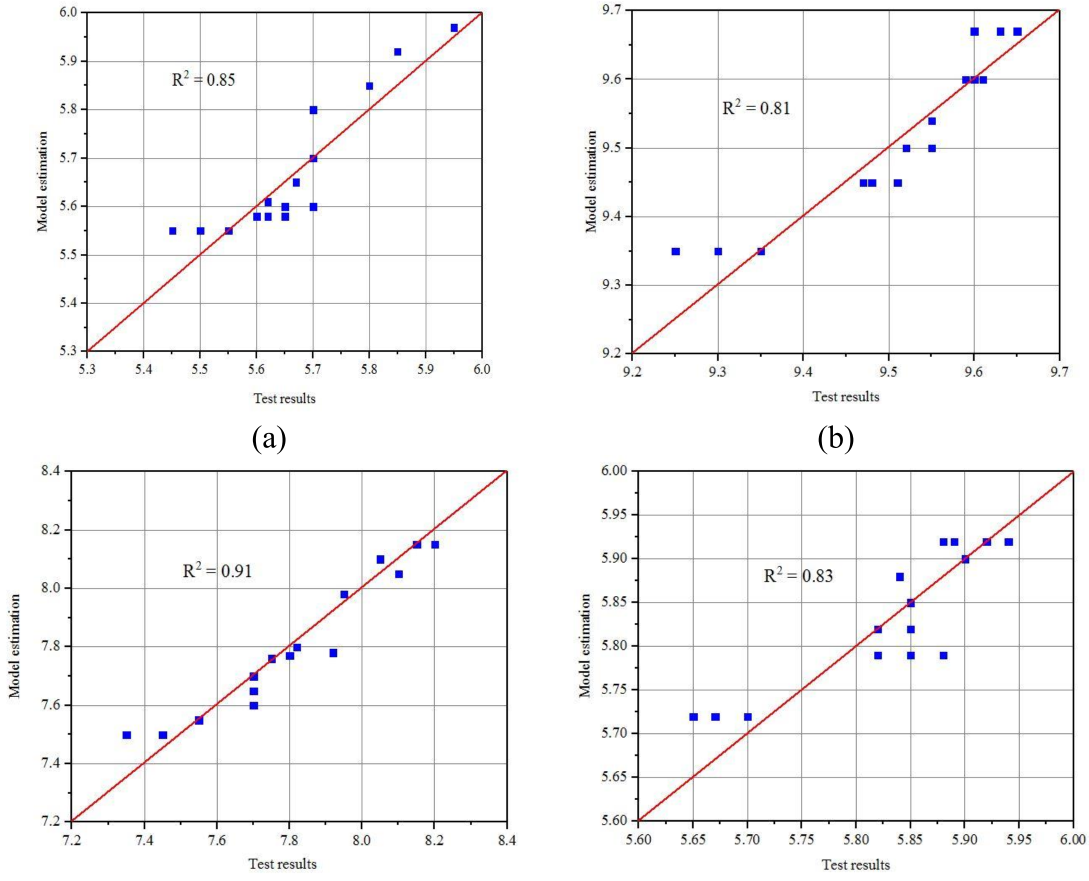
$$\frac{f_{u,t}}{f_u} = \alpha + \mu_2 \left(\beta + \frac{1}{\ln(T)} \right) + \eta \tag{8}$$

where α and β are the coefficients acquired from reduction process. These coefficients are reported in Table 3 for each condition.

To assess appropriateness of the presented model, model prediction versus experimental observation curves are shown in Fig. 7 (a-d). As can be seen in this figure, data are situated roughly about 45° line a criterion for suitable model estimation. It should be noted that the model may be modified by further results to improve precision of the model.

Table 3. Coefficients of model for laminates with or without protective mortar

Coefficients	GFRP without protective mortar	GFRP with protective mortar	CFRP without protective mortar	CFRP with protective mortar
α	-4.91	-7.83	-6.88	-5.45
β	0.28	0.17	0.12	0.19



(a) (b)

(c) (d)

Fig. 7. Comparison of the test results with model estimation: (a) GFRP laminates without protective mortar, (b) GFRP laminates with protective mortar, (c) CFRP laminates without protective mortar, (d) CFRP laminates with protective mortar

6. Conclusion

This investigation evaluated the improvement possibility of behavior of CFRP and GFRP laminates at elevated temperatures using fire protection mortar. Also, linear regression was carried out to modify the existing models for estimating tensile strength of FRP laminates at elevated temperatures. Therefore, the following conclusions can be drawn:

1- At temperature range 25-200°C, CFRP and GFRP laminates underwent considerable decrement in tensile strength owing to resin softening at temperatures near to T_g.

2- At temperature range 200-400°C, strength decrement in FRP laminates was slight as fibers are able to bear a significant percentage of the exerted load.

3- At temperatures higher than 400°C, owing to resin decomposition and deterioration of glass and carbon fibers, decrement of tensile strength accelerated.

4- By covering FRP laminates with fire protection mortar, tensile strength improved compared with similar uncovered samples at a given temperature. This increment ranges from 30% to 110% for GFRP laminates and from 23% to 38% for CFRP laminates.

5- At the temperatures 25 and 100°C, the failure zone is at 90 degrees to the applied load and the specimens experienced no considerable changes in color.

6- Model prediction versus experimental observation curves indicated appropriateness of the presented model in this investigation for FRP laminates with and without fire protection mortar.

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