Tikrit Journal of Engineering Sciences (2025); 32(2): 1967
DOI: http://doi.org/10.25130/tjes.32.2.39

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Influence of High Temperatures on the Mechanical Properties of GFRP Pultruded Sections- Review

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Keywords:

Glass fiber reinforced pultruded (GFRP); Concrete; Hybrid beams; Composite beam; Mathematical model.

Highlights:

- *Section of (GFRP) can be used with high temperatures in a condition that the bonding water is protected from reaching the critical temperature (Tc).*
- *Mathematical and statistical models give results that are close to practical results.*
- *The loss ratio in tension and compression for sections (GFRP) is approximately equal.*

ARTICLE INFO

Article history:

Received	11 Jan.	2024
Received in revised form	19 Jan.	2024
Accepted	16 May	2024
Final Proofreading	02 July	2025
Available online	28 Aug.	2025

Citation: Ali MI, Allawi AA. **Influence of High Temperatures on the Mechanical Properties of GFRP Pultruded Sections- Review**. *Tikrit Journal of Engineering Sciences* 2025; **32**(2): 1967.
http://doi.org/10.25130/tjes.32.2.39

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Abstract: The application of pultruded (GFRP) composite has become increasingly prominent in civil infrastructure projects. This study provides a comprehensive analysis of experimental and numerical studies conducted on the mechanical characteristics of (GFRP) composites across various temperature conditions, encompassing ambient and fire scenarios. The compilation comprises over 100 scholarly articles that examine the mechanical behavior of (GFRP) materials, specifically emphasizing their tensile and compressive strengths, showed the mechanical properties of (GFRP) materials are commonly compromised when exposed to high temperatures that approach or surpass the resin's glass transition temperature (Tg). In contrast, temperatures that are lower than the glass transition temperature (Tg) have the potential to cause minimal degradation. This study provides that at temperatures exceeding 450°C, the tensile strength of (GFRP) bars experiences a significant decline, with a retention rate of less than 20%. Similarly, GFRP laminates or sheets exhibit a substantial loss in strength, ranging from 68% to 94%, when exposed to temperatures exceeding 400°C. Also, the optimal model and the closest results to practical experiments in the case of compression are the models (Mahieux and wang). This review provides an in-depth understanding of the GFRP composite's behavior after being subjected to elevated temperatures. The results presented in this literature review could be used as a base for developing predictive models related to GFRP composite behavior after being subjected to elevated temperatures.

تأثير درجات الحرارة العالية على الخواص الميكانيكية لمقاطع البلاستيك المقوى بألياف الزجاج المبثوقة - مراجعة

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الخلاصة
أصبح استخدام مركبات البوليمر المقولب المقوى بالالياف الزجاجية ((pultruded (GFRP)) بارزًا بشكل متزايد في مشاريع البنية التحتية المدنية. تقدم هذه الدراسة تحليلاً شاملاً للدراسات التجريبية والعددية التي أجريت على الخصائص الميكانيكية لمركبات (GFRP) عبر ظروف درجات الحرارة المختلفة، بما في ذلك ضروف البيئة المحيطة وضرف الحريق. وذلك من خلال تسليط الضوء على أكثر من ١٠٠ مقالة علمية تدرس السلوك الميكانيكي لمواد(GFRP) ، مع التركيز بشكل خاص على قوة الشد والضغط، وأظهرت أن الخواص الميكانيكية لمواد (GFRP) تتعرض للخطر عند تعرضها لدرجات حرارة عالية تقترب أو تتجاوز درجة حرارة التزجيج للراتنج (الايبوكسي).Tg وبينت الدراسة ان درجات الحرارة الأقل من درجة حرارة التزجج Tg لديها القدرة على التسبب في الحد الأدنى من الانهيار. كما بينت الدراسة ان درجات حرارة الاعلى من ٤٥٠ درجة مئوية، تواجه قوة الشد لقضبان (GFRP انخفاضًا كبيرًا، مع معدل قوة متبقية أقل من ٢٠٪. وبالمثل فإن شرائح أو صفائح GFRP تظهر خسارة كبيرة في القوة تتراوح من ٦٨٪ إلى ٩٤٪ عند تعرضها لدرجات حرارة تتجاوز ٤٠٠ درجة مئوية، كما أن النموذج الأمثل والأقرب في النتائج للتجارب العملية في حالة الضغط هو النموذج (Mahieux and wang). توفر هذه المراجعة للبحوث فهمًا متعمقًا لسلوك مركبات GFRP بعد تعرضها لدرجات حرارة مرتفعة حيث يمكن استخدام النتائج المقدمة في مراجعة البحوث كقاعدة لتطوير النماذج التنبؤية المتعلقة بسلوك مركبات GFRP بعد تعرضها لدرجات حرارة مرتفعة.

الكلمات الدالة: الخرسانة المسلحة بألياف زجاجية (GFRP)؛ الخرسانة؛ العوارض الهجينة؛ العوارض المركبة؛ النموذج الرياضي.

1.INTRODUCTION

GFRP has been widely used in practice in the context of repair, rehabilitation, and upgradation of the R/C elements significantly calcium oxide (CaO), and GFRP has become a prefab option for structural needs [1-4]. Furthermore, GFRP has been successfully employed to restore and enhance the performance of pre-existing concrete structures, thereby extending their service life and structural integrity [5–7]. GFRP sheets and ropes have been frequently used to reinforce and retrofit pre-existing concrete structural elements that contain defects or damage [8-10]. Also, GFRP materials have viable issues regarding fire performance properties. GFRP materials significantly reduce their strength and stiffness properties when exposed to mildly elevated temperature [11-13], and such kind of thermal degradation of GFRP materials can be better classified into a few distinct stages as per previous research outcomes [14-17].

- The softening temperature (Ts) has no substantial alteration in mechanical properties [18, 19].
- The glass transition temperature (Tg) rubbery state is typically noticed to be within the range of 65 to 120 °C, i.e., it does not uniformly establish a definitive differentiation between Tg and Tm [10, 20].
- The critical temperature (Tc) is when the reinforcement material's strength decreases by 50% [21, 22], as shown in Fig. 1.
- The melting temperature (Tm): A temperature larger than Tc, reaching a residual value denoted as $P_{residual}$ [21-23].
- Resin decomposition temperature (Td): When subjected to high temperatures ranging from 300 to 500 °C, degradation of their inherent structure, smoke, ash, and toxic volatile substances [24-27].

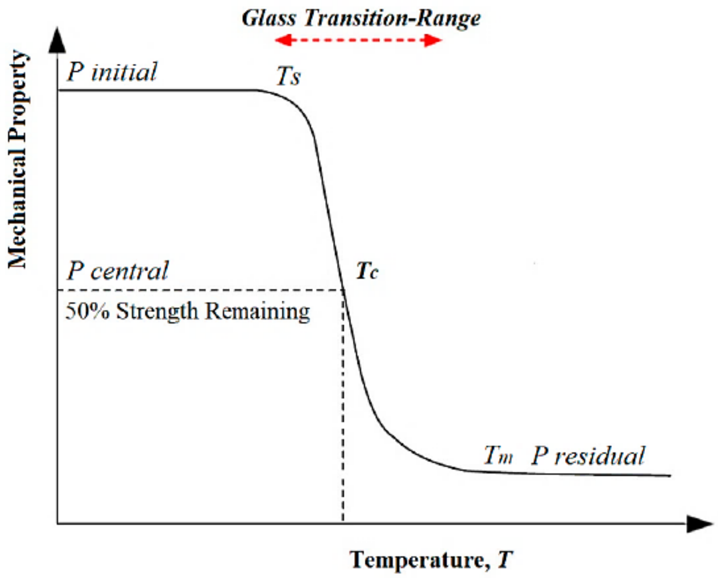


Fig. 1 The Temperature Vs. GFRP Mechanical Properties [21, 22].

Determining the glass transition temperature (Tg) of the resin matrix can be achieved by utilizing either dynamic mechanical thermal analysis (DMTA) techniques or differential thermal analysis (DSC) [9, 28-32]. Recently, (GFRP) composites across configurations have been increasingly used, such as I-shaped profiles, channels, tubes, reinforcing bars, sheets, strips, grids, and tendons [33-40]. The behavior of (GFRP) materials demonstrates variations when subjected to direct exposure to open flames during fire incidents, in contrast to scenarios where GFRP is incorporated within concrete structures [23, 41]. This review's primary goal is to comprehensively analyze the behavior of (GFRP) composites under high temperatures. This analysis will be based on examining more than 100 experimental and theoretical studies. The primary aim is to furnish dependable and fundamental information for the discipline [42, 43]. This study investigates the mechanisms of damage and mechanical behavior of (GFRP) bars, laminates, and sheets under elevated temperatures. Also, suggestions for future activities are provided, and the conclusion is formulated [14, 44-46]. The voluminous data collection provides a comprehensive understanding of the subject and a solid basis for further investigation.

2.DEGRADATION MECHANISM

This section reviews studies on various GFRP thermal properties, including (Ts, Tg, Tc, and Td), and how they affect mechanical properties (tensile and compressive strength) [3, 4, 47-52]. According to the literature, distinct failure processes will occur when laminates, bars, and pultruded GFRP are exposed to various high-temperature ranges. The degradation mechanisms of all forms of GFRP under high temperatures can be categorized into four groups [53-55]:

- At the softening temperature Ts (in this case, below the glass transition temperature Tg), the surface of the resin matrix will primarily keep its unconditioned sample characteristics. At these temperatures, some microcracks in the resin matrix will be visible [56, 57], Fig. 2.
- The resin softens, revealing the positions of the fibers, and causes the individual fibers to fracture at the temperature near the resin Tg (above Ts and below Tm) [58]. This fracture will affect the resin matrix, lessen the tensile of GFRP, and result in the loss of some epoxy, Fig. 3.
- The plane of the resin matrix nearly grows smooth when exposed to the melting temperature Tm (above Tg and below T_d). Fibers are more noticeable since the resin softens (major fiber/resin debonding). The mechanical properties will decrease to a residual value of less than 50% of the maximal force) as the temperature rises until it reaches the resin decomposition temperature (T_d) [59].
- When resin decomposition temperature Td is achieved, the resin matrix encasing the fibers will almost entirely disintegrate, exposing the fiber clearly (the fiber/resin debonding) and significantly reducing the tensile properties of GFRP. Much resin will not be left because it has achieved its self-ignition temperature [60-62]. It is crucial to remember that these extreme temperature ranges have an insignificant impact on fiber characteristics, Fig. 4.

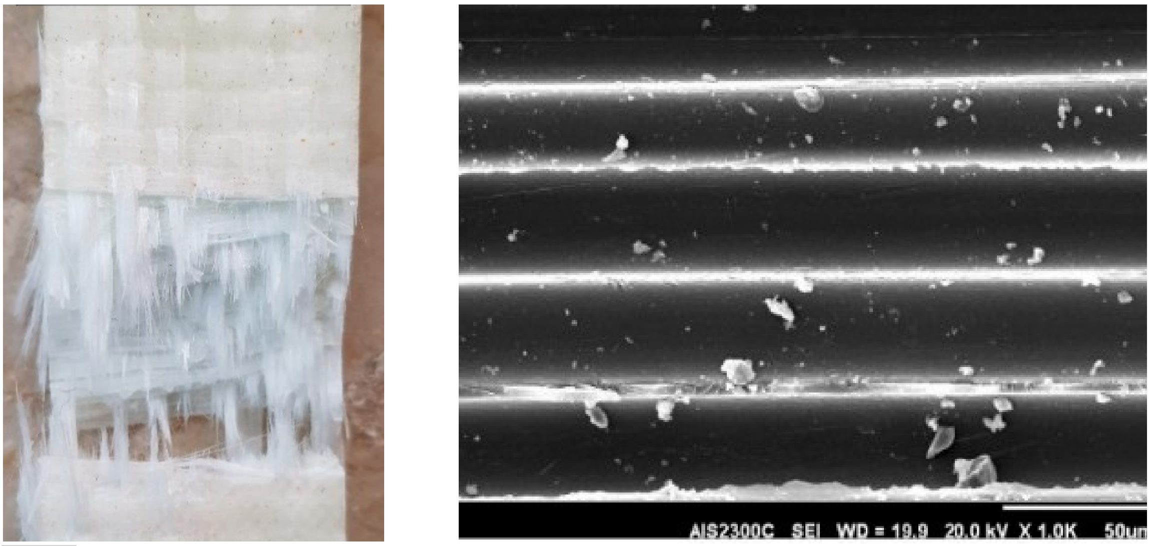


Fig. 2 The GFRP Laminates After Exposure to Ts Temperature and Images of the SEM Test.

Fig. 3 The GFRP Laminates at Exposure to Tg Temperature and Images of the SEM Test.

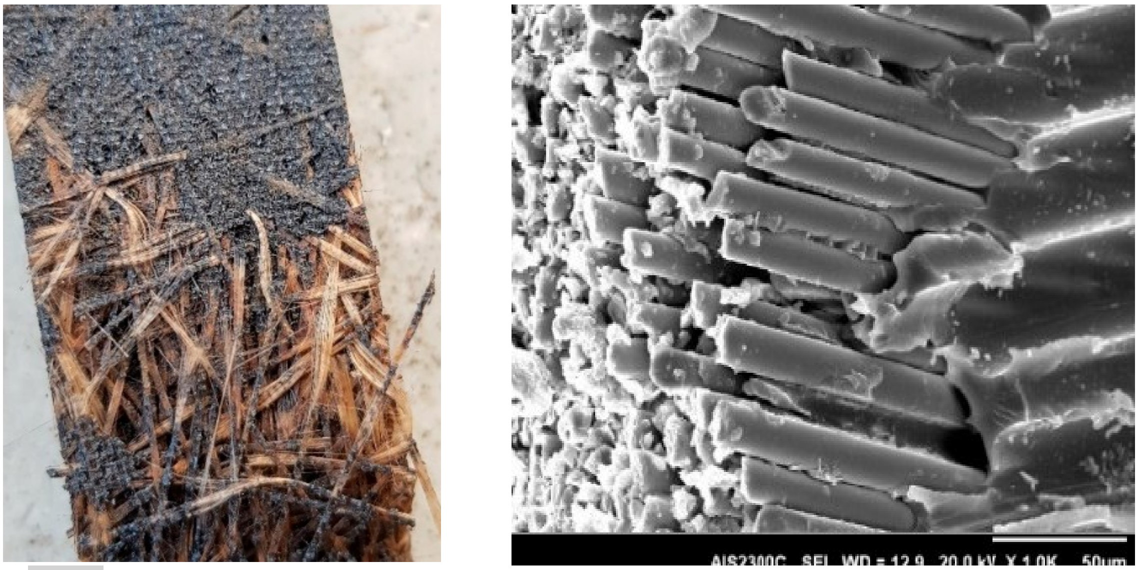


Fig. 4 The GFRP Laminates After Exposure to Td Temperature and Images of the SEM Test.

3.MECHANICAL PROPERTIES

3.1.Tensile Strength

Many studies have investigated the mechanical tensile properties of various kinds of (GFRP) materials at high temperatures. A quantity of (GFRP) materials is investigated numerically and experimentally by employing a large number of adverse materials, carbon and glass fibers, and various thicknesses of laminate/sheet, resins and orientations, and high temperatures illustrated in previous studies [63-66]. Regression models are proposed by researchers to forecast the mechanical properties of (GFRP) materials at high temperatures using test results [35, 67, 68]. Table 1 illustrates a comparative examination of the steady-state results of different studies. The analysis primarily centers on the critical temperature (Tc), i.e., the temperature at which a 50% decrease in strength is observed. Additionally, Table 1. highlights the corresponding retention of elastic modulus at the critical temperature and the mechanical characteristics demonstrated at excessive temperatures, precisely the highest temperature employed in every study. Moreover, the relationship between the tensile strength of Glass Fibre fiber-reinforced polymer bars and GFRP laminates with the critical temperature (Tc) is depicted in Fig. 5. Furthermore, Fig. 6 provides a comprehensive depiction of the different magnitudes of tensile strength observed in the studies being examined, specifically concerning Tc.

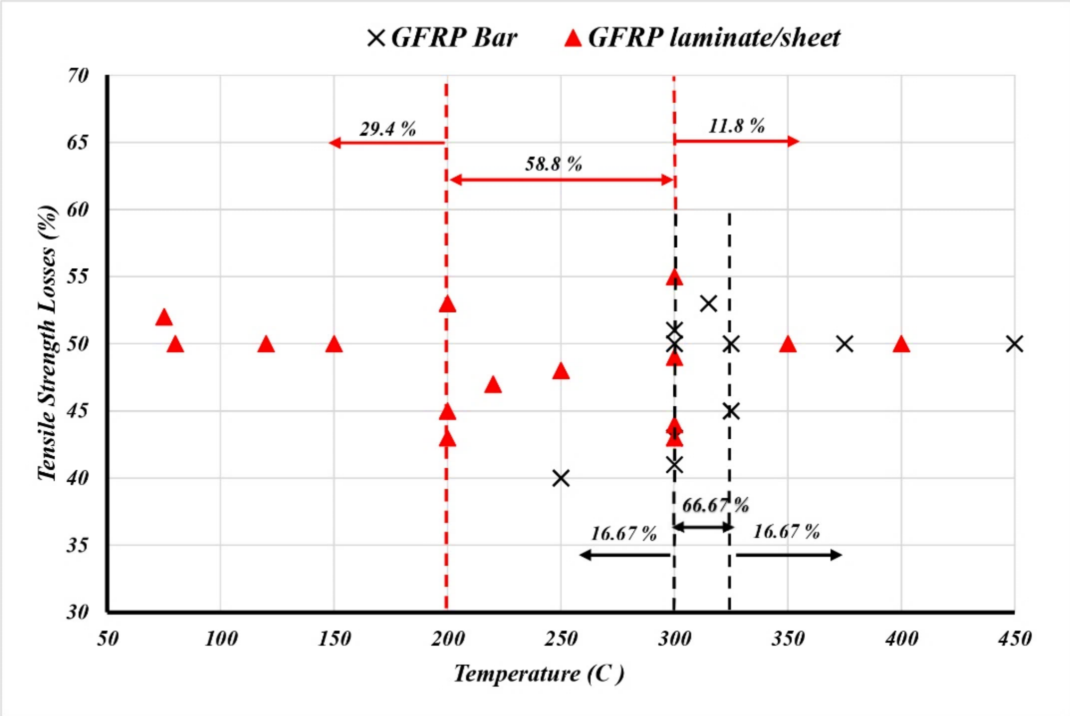


Fig. 5 GFRP (Bars and Laminates/ Pultruded) Loses Tensile Strength Vs. Tc, Given in the Literature.

Table 1 Tensile Characteristics of All Kinds of GFRP (Bars, Laminates, and Pultruded) Placed at High Temperatures.

Study	GFRP Type	Fibres Orientation	Resin Type	Specimen Dimensions (mm)	Tg (c)	Tc (c)	Strength losses at Tc	Modulus losses at Tc	Temperatures T test (c)	Strength losses at T test	Modulus losses at T test	Td (c)	Strength losses at Td	Modulus losses at Td
[69]	pultruded	Unidirectional	Polyester	200×20×4	---	200	53	---	----	---	----	----	---	---
[70]	pultruded	Unidirectional	Polyester	200×20×8	----	220	47	---	---	---	---	----	---	---
[71]	pultruded	Unidirectional	Polyester	200×25×8	---	120	50	---	---	---	----	220	80	---
[72]	Bar	Unidirectional	Vinyl ester	D. 10	--	250	40	---	350	---	60	400	60	---
			PPS	D. 10	--	250	40	---	350	---	0 %	---	---	---
[73]	Bar	Unidirectional	Epoxy	D. 10	---	---	---	---	450	65	---	---	---	---
[69, 74]	Bar	Unidirectional	Polyester	D. 9.5	---	325	50	10	----	---	---	500	84	---
[75]	Bar	Unidirectional	Vinyl ester	12.7	113	315	53	---	---	---	---	----	---	---
[76]	Bar	Unidirectional	Polyester	D. 10	---	325	45	21	---	---	----	375	91	48
[77]	Bar	Unidirectional	Vinyl ester	D. 17	----	---	---	---	---	---	---	400	17	18
[78]	Bar	Unidirectional	Vinyl ester	D. 16	110	300	51	25	157	41	----	518	78	25
									193	47	----			
									327	53	----			
									425	65	----			
[79]	Bar	Unidirectional	Vinyl ester	D. 12	---	300	41	0	100	9	----	----	---	---
[41]	Bar	Unidirectional	Vinyl ester	D. 8	----	325	45	43	250	27	28	500	67	---
[63]	Bar	Unidirectional	Epoxy	D. 4	110	300	50	---	---	---	----	450	71	---
				D. 10	110	450	50	---	---	---	----	450	50	---
[80]	Bar	Unidirectional	Epoxy	D. 10	95	300	43	---	----	---	----	----	---	---
[81]	Bar	Unidirectional	Epoxy	D. 9	---	375	50	25	---	---	---	500	90	93
[82]	laminate	Unidirectional	Epoxy	600×20×2	70	300	44	---	---	---	---	550	82	---
		Woven	Epoxy	600×20×2	70	300	49	---	---	---	---	400	92	---
		Chopped strand mat	Epoxy	600×20×2	70	80	50	---	---	---	---	250	87	---
[5]	laminate	Unidirectional	Epoxy	300×20×2	70	300	55	18	300	55	18	-----	---	---
		Woven	Epoxy	300×20×2	70	200	45	13	300	65	32	----	---	---
		Chopped strand mat	Epoxy	300×20×2	70	120	50	11	300	94	76	----	---	---
[83]	laminate	Woven	Epoxy	300×30	60	400	50	---	---	---	----	600	87	---
[84]	laminate	Unidirectional	Polypro pylene	300×15×12	----	150	50	---	---	---	----	300	75	---
[85]	laminate	Unidirectional	Epoxy	250×40×0.35	----	300	43	30	----	---	----	----	---	---
[86]	laminate	Unidirectional	Epoxy	250×40×1.3	78	350	50	---	---	---	---	400	80	---
[87]	laminate	Unidirectional	Epoxy	600×25×2.5	100	250	48	---	----	---	----	500	83	---
[58]	laminate	Unidirectional	Epoxy	250×15×1.27	167	200	43	20	----	----	----	----	---	---
[69]	laminate	Unidirectional	Polyester	200×20×4	----	200	53	---	----	----	----	----	---	---
[21]	laminate	Unidirectional	Epoxy	735×38×2.6	75	75	52	23	200	54	19	----	---	----

Moreover, it is feasible to derive the subsequent inferences from the data provided in Table 1, Fig. 5, and Fig. 6.

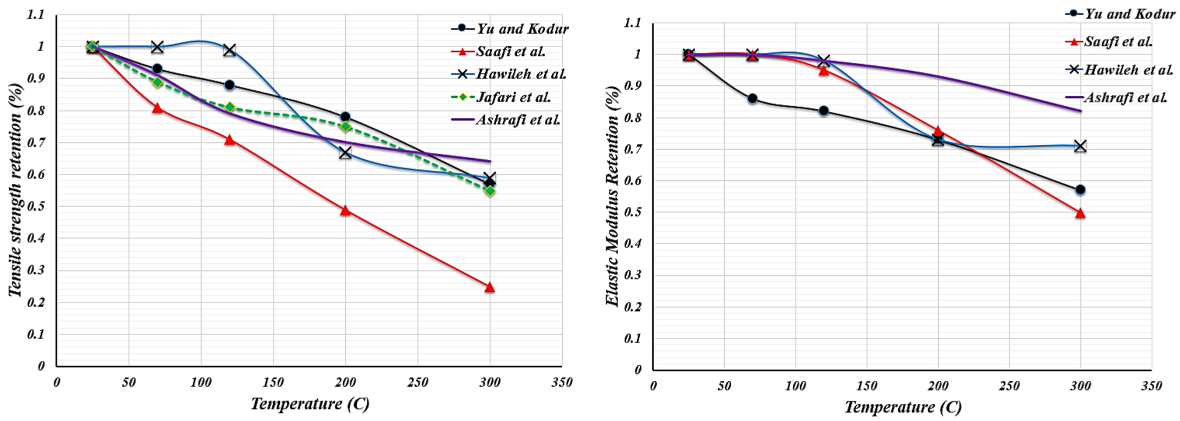
- The data obtained from laminates subjected to elevated temperatures exhibit a higher degree of dispersion than GFRP bars, which can be attributed to the use of distinct fabrication techniques in constructing GFRP sheets and laminates.
- Irrespective of the specific composition of the materials, the critical temperature (Tc) typically falls within the range of 300 to 325 degrees Celsius for (GFRP) bars and between 200 to 300 degrees Celsius for GFRP laminates.
- The thermal conductivity (Tc) of the laminates is far less than that of the (GFRP) bars due to the higher (fiber/resin) ratio present in the bars in comparison to the laminates.
- At temperatures exceeding 450°C, the tensile strength of (GFRP) bars experiences a significant decline, with a retention rate of less than 20%. Similarly, GFRP laminates or sheets exhibit a substantial loss in strength, ranging from 68% to 94%, when exposed to temperatures exceeding 400°C.
- At temperatures below 450°C, (GFRP) exhibits a certain degree of load-bearing capacity.
- Elevated temperatures have a considerably lower impact on the tensile elastic modulus than tensile strength.

3.2. Tensile Strength Predicting Models

The tensile properties of (GFRP) composites are important when designing high-temperature composite structures [85, 88-90]. Based on actual test data, many researchers have developed theoretical models to predict the material's tensile properties at high temperatures. Some researchers believe that temperature alone controls GFRP composites' tensile properties [91]. Several researchers modeled experimental results [82, 92-94]. Composite thickness and radiation time were also examined by several researchers [5, 82, 95]. Researchers suggest numerical models in Table 2. To conduct a comparative analysis of the identified models, Fig. 7 displays the predicted outcomes of several models about the tensile behavior of composites containing continuous fibers when exposed to high temperatures reaching upwards of 300 C. As expected, multiple trends are observed due to various parameters, such as test protocols, fiber kind, cross-section configuration, and material property [30]. However, it can be generally inferred that the influence of increased temperatures on the elastic modulus of (FRP) composites is relatively less significant when compared to its impact on tensile strength.

3.3. Compressive Strength

GFRP profiles exhibit greater susceptibility to compression than tension when exposed to higher temperatures. Furthermore, empirical evidence demonstrates that when subjecting the lower flange of the profiles to elevated temperatures exceeding the resin's (Td), maintaining this condition for an extended duration, the profile exhibits exceptional resistance to tensile failure [64, 96, 97]. Failure is more likely to occur at lower temperatures when subjected to compression force. This failure predominantly manifests on the web, where the load is applied at the top flange at the midpoint of the structure [98]. The research has also examined the compressive characteristics of (GFRP) laminates under elevated temperatures [95, 99-101].



(a) Tensile Strength. **(b)** Tensile Elastic Modulus.

Fig. 7 Temperature Compared with Predicting Model Retention.

Table 4 presents a comparative analysis of the steady-state compression and compressive elastic modulus test outcomes obtained from pultruded GFRP profiles and GFRP laminates at Tc and compressive strength at high temperatures. The compressive strength versus Tc data for the Pultrude GFRP profile, as given in the literature, are depicted in Fig. 8.

Table 2 Details of Mathematical Models for Predicting the Tensile Properties of All Types of GFRP After Exposure to High Temperatures.

Study	Dependent	Independent	Model	Sample	Define Sample	Value Sample	Eq.
[91]	Tensile Strength	Temperature	$P(T)=\frac{P_u+P_R}{2}-\frac{P_u-P_R}{2}\operatorname{erf}\left(k(T-T')\right)$	$P(T)$ P_u P_R	specific property Unrelaxed property at low Temp. Relaxed property at high Temp.	% kN kN	Eq. (1)
			$P(T)=\frac{P_u+P_R}{2}-\frac{P_u-P_R}{2}\tanh\left(k(T-T')\right)$	k T T'	distribution constant Target value Tg	---- C C	Eq. (2)
[94]	Tensile Strength	Temperature	$R(T)=0.56-0.44\tanh\left(0.0052(T-305)\right)$	$R(T)$ $R(E)$	specific property tensile specific property modulus	% %	Eq. (3)
	Elastic Modulus		$R(E)=0.51-0.49\tanh\left(0.0035(T-340)\right)$	T ----	Target value -----	C ---	Eq. (4)
[93]	Tensile Strength	Temperature	$R(T)=1-0.0025T \quad 0\le T\le 400°C$	$R(T)$	specific property tensile	%	Eq. (5)
	Elastic Modulus	Temperature	$R(E)=\begin{cases}1 & 0\le T\le 100°C\\ 1.25-0.0025T & 100°C\le T\le 300°C\\ 2-0.005T & 300°C\le T\le 400°C\end{cases}$	$R(E)$ T	specific property modulus Target value	% C	Eq. (6)
[92]	Tensile Strength	Temperature	$R(T)=0.795-0.205\tan\ h\left(0.075(T-190.58)\right)$	$R(T)$ $R(E)$	specific property tensile specific property modulus	% %	Eq. (7)
	Elastic Modulus	Temperature	$R(E)=0.86-0.140\tanh\left(0.035(T-163.24)\right)$	T ----	Target value -----	C ---	Eq. (8)
[82]	Tensile Strength	Temperature Thicknesses	$R(T)=\begin{cases}1 & 24°C\le T\le 45°C\\ a\left(\frac{1}{T^3}\right)+b\left((\log(t))^{0.333}\right)+c & 45°C\le T\le 500°C\end{cases}$	$R(T)$ t T a b c	specific property tensile Thickness of the laminate Target value Constant Constant Constant	% mm K Table 3 Table 3 Table 3	Eq. (9)
[5]	Tensile Strength	Temperature Thicknesses	$R(T)=a\left(\frac{1}{T^3}\right)+b\left(\frac{1}{\left(\log\left(\frac{t_1}{6}\right)\right)^{0.5}}\right)-c\left(\frac{1}{(\log(t_2))^{0.5}}\right)+d$	$R(T)$ $R(E)$ T $t2$ $t1$	specific property tensile specific property modulus Target value Thickness of the laminate exposure time	% % C mm min	Eq. (10)
	Elastic Modulus	Time	$R(E)=-a(T)^4+b\left(\frac{1}{\left(\log\left(\frac{t_1}{6}\right)\right)^{0.5}}\right)-c\left(\frac{1}{(\log(t_2))^{0.5}}\right)+d$	a b c d	Constant Constant Constant Constant	Table 3 Table 3 Table 3 Table 3	Eq. (11)

Table 3 The Constant Value for Mathematical Models is Mentioned in Table 2 Studies.

Study	[82]			
Direction fiber	**Temperature**	**A**	**b**	**c**
Unidirectional	>45, <250	9.365 ×10^6	0.158	0.526
	>250	9.591×10^7	0.198	-0.136
Woven	>45, <250	1.238 ×10^7	0.182	0.408
	>250	1.281× 10^8	0.137	-0.354
Random	>45, <300	3.049×10^7	0.115	-0.250

Study	[5]				
Direction fiber	**Temperature**	**a**	**b**	**c**	**d**
Unidirectional	Eq. (10)	1.395×10^7	0.116	0.039	0.454
	Eq. (11)	1.964×10^{-12}	0.028	0.024	1.025
Woven	Eq. (10)	1.609×10^7	0.138	0.029	0.281
	Eq. (11)	3.624×10^{-12}	0.050	0.064	1.076
Random	Eq. (10)	2.077×10^7	0.128	0.257	0.455
	Eq. (11)	7.636×10^{-12}	0.083	0.071	1.082

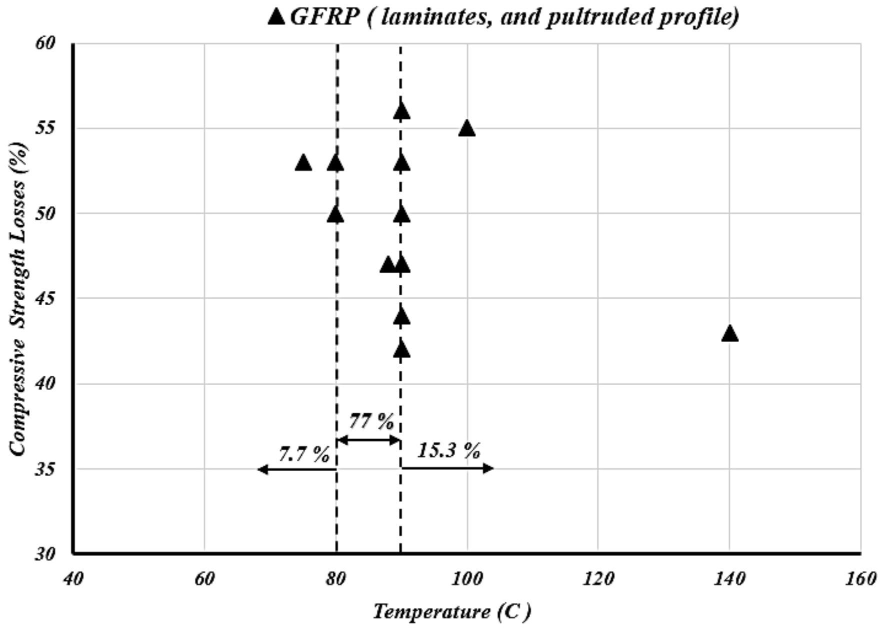


Fig. 8 All Types of GFRP Losses and Compressive Strength Versus Tc are Given in the Literature.

Based on the findings presented in Table 4 and Fig. 8, it is possible to draw the following conclusions:

- The GFRP profiles and GFRP laminates for compressive strength reach the Tc significantly earlier than tensile properties (60-140 °C).
- The strength of GFRP (laminates and pultruded profile), when exposed to higher temperatures, materials exhibit a significantly higher failure rate in compression than in tension.
- Near reaching Td, the GFRP almost loses all of its compressive and reduces compressive strength between 2% and 67% at temperatures less than T_d.
- The compressive elastic modulus exhibits a lower susceptibility to temperature elevation than the compressive strength, as observed in other mechanical properties.

3.4. Compressive Strength Predicting Models

In previous studies, different models were proposed to simulate/predict the compressive characteristics of (GFRP) materials under high-temperature conditions. The models under consideration consist of two main types: (i) empirical mathematical formulations that involve curve-fitting techniques applied to the experimental data [70, 84, 100, 102, 103] and (ii) semi-empirical approaches [26, 70]. The accuracy of these models in describing the temperature-induced changes in the compressive behavior of pultruded GFRP material has been assessed. Table 5 shows some numerical models proposed by the researchers. To conduct a comparative analysis of the proposed models, Fig. 9 illustrates the anticipated outcomes generated by a selection of the models presented with the compressive behavior of composites featuring continuous fibers after exposure to high temperatures reaching up to 200 C. Various trends are observed as anticipated due to several parameters, including test protocols, fiber kind, material characteristics, and cross-section configuration. Also, the main conclusion is that all models are predicting and convergent except for the model of compressive suggested by Bai and Keller, named Rule of mixtures Eq. (16) gives an incompatibility compared to the remaining models [104], in contrast to the second model of the same researcher called Inverse Rule of mixtures Eq. (17) showed similar values to the rest of the proposed models.

Table 4 Compressive Properties of All Types of GFRP (Laminates and Profile Pultruded) Exposed to High Temperatures.

Study	Type GFRP	Type test	Fibers Orientation	Resin Type	Specimen Dimensions (in mm)	Tg (c)	Tc (c)	Strength losses at Tc	Modulus losses at Tc	Td (c)	Strength losses at Td	Modulus losses at Td
[105]	laminate	Sheet	Unidirectional	Polyester	400×48×12	155	140	43	---	180	60	---
[84]	laminate	Sheet	Woven	Polypropylene	125×105×12	----	80	50	---	140	93	---
[106]	laminate	Sheet	Woven	Viny lester	100×100×9	120	100	55	---	180	93	---
[107]	Column	Pultruded	Unidirectional	Polyester	I-section (4.3 mm)	95	90	47	---	400	98	---
					C-section (5 mm)			47	---	400	98	---
					Box (3 mm)			50	---	400	95	---
					Angle (6 mm)			53	---	400	93	---
[108]	Column	Pultruded	Unidirectional	Polyester	C-Sec.(500×5)mm	---	90	44	22	120	60	35
[103]	Column	Pultruded	Unidirectional	Polyester	C-Sec.(30×4)mm	---	75	53	---	250	92	---
[109]	Column	Pultruded	Unidirectional	Polyester	C-Sec.(400×5)mm	---	90	42	30	250	92	70
[69]	Column	Pultruded	Unidirectional	Polyester	Box (74×3)mm	---	88	47	---	175	94	---
[70]	Column	Pultruded	Unidirectional	Polyester	I-Sec.(50×6)mm	136	90	56	---	250	95	---
[71]	Column	Pultruded	Unidirectional	Polyester	Tube (300×3)mm	110	80	53	---	220	90	---

Table 5 Details of Mathematical Models of Predicting the Compressive Properties of All Types of GFRP When Exposed to High Temperatures.

Study	Dependent	Independent	Model	Sample	Define Sample	Value Sample	Equation
[91]	Compressive Strength	Temperature	$P(T) = P_u - \frac{P_u - P_r}{2} \times \left(1 + \tanh\left[k'(T - T_{g,\,mech})\right]\right)$	$P(T)$	Specific property compressive	%	Eq. (12)
				P_u	Property at low Temp.	kN	
				P_r	The property after Tg.	kN	
				k'	Normal distribution fitting curve	----	
				T	Target value	C	
				$T_{g,\,mech}$	Fitting Tg experimental data.	C	
[102]	Compressive Strength	Temperature	$P(T) = P_r + (P_u - P_r) \times \exp\left[-(T/T_0)^m\right]$	P_u	Property at low Temp.	kN	Eq. (13)
				P_r	The property after Tg.	kN	
				T	Target value	K	
				T_0	Relaxation Temp. (fitted Exper.)	K	
				m	Weibull exponent (fitted Exper.)	-----	
[108]	Compressive Strength	Temperature	$P(T) = P_u \times \left[A - (T - B)^n / C\right]$	P_u	Property at low Temp.	kN	Eq. (14)
				T	Target value	C	
				n	Parameters from a fitting curve	Table 6	
				A, B, C	Parameters from a fitting curve	Table 6	
[109]	Compressive Strength	Temperature	$P(T) = P_r + (P_u - P_r) \times \left(1 - e^{Be^{C \times T}}\right)$	P_u	Property at low Temp.	kN	Eq. (15)
				P_r	The property after Tg.	kN	
				T	Target value	C	
				Be, C	Parameters from a fitting curve	Table 6	
[105]	Compressive Strength	Temperature	$P(T) = P_g \times \left[1 - \alpha_g(T)\right] + P_1 \times \alpha_g(T) \times \left[1 - \alpha_d(T)\right] + P_d \times \alpha_g(T) \times \alpha_d(T)$	P_g	Materials properties (glassy)	kN	Eq. (16)
				P_l	Materials properties (leathery)	kN	
				P_d	Materials Prop. (decomposed)	kN	
			$\frac{1}{P(T)} = \frac{1 - \alpha_g(T)}{P_g} + \frac{\alpha_g(T) \times \left[1 - \alpha_d(T)\right]}{P_1} + \frac{\alpha_g(T) \times \alpha_d(T)}{P_d}$	T	Target value	C	Eq. (17)
				α_g, α_d	(between 0 and 1) from TGA test	----	

Table 6 Constant Value for Mathematical Models Mentioned in Some Studies in Table 5.

Study		[108]		Eq. (14)
Temperature	A	B	C	n
22<T<150	1.00	22	200	0.9
150<T<420	0.59	150	490	0.7
420<T<706	0.48	420	76,000	1.8
Study		[109]		Eq. (15)
Parameter	B	C		
Compressive	-5.4468	-0.0328		
Shear	-250.91	-0.05706		
Tensile	-166.89	-0.0541		

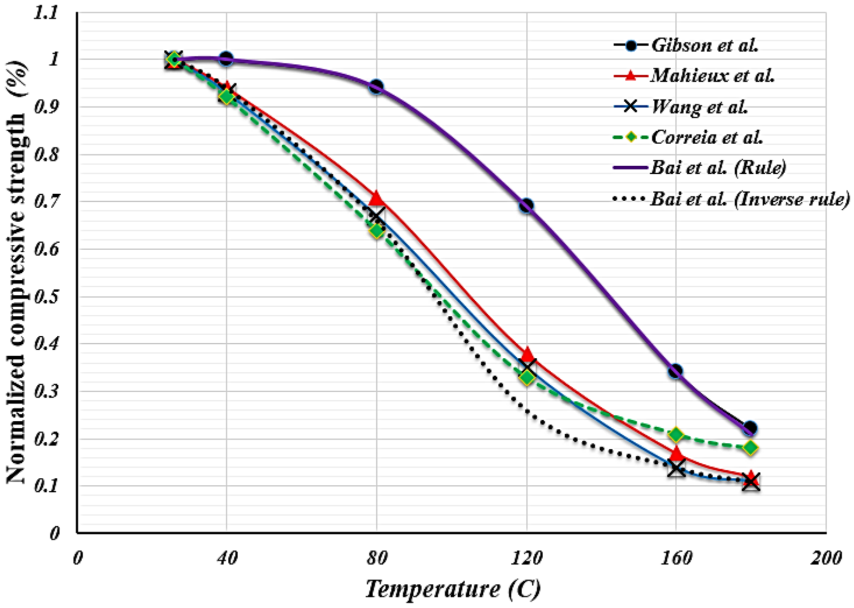


Fig. 9 Temperature Compared with Predicting Models in Compressive Strength Retention.

4.CONCLUSIONS

This paper provides a comprehensive overview of the mechanical properties of GFRP composites, explicitly focusing on reinforced bars, laminates or sheets, and pultruded materials under high temperatures. Depending on the gets derived from the research, it is possible to draw the following primary observations:

- During put to temperatures exceeding the (Tg), the resin matrix will undergo limited effects, potentially resulting in micro-cracks. Furthermore, the outer layer of the resin matrix will maintain its rough texture, resembling the sample that has not undergone conditioning. In the present context, diminished strength or modified characteristics are absent in composites made of (GFRP).
- After (GFRP) composites attain their (Tg) temperature, the resin transitions from a rigid, glassy state to a more flexible, rubbery state. In the present context, it is observed that (GFRP) materials exhibit a phenomenon of softening and creeping, leading to a substantial decrease in strength (tensile and compressive) and modulus properties.
- The GFRP materials experience thermal degradation (Td), during which their organic matrix decomposes. The process of decomposition results in the release of heat, soot, smoke, and toxic volatile substances. Contact with a broad spectrum of high temperatures, mainly ranging (300 – 500) °C, reached the perturbation of chemical interactions, fragmentation of modular chains within the resin, and end of bonds between the fibers. The ignition and burning of the composite material occur at high temperatures.
- Critical temperature (Tc) typically ranges from 300 to 330 °C for (GFRP) bars, 200 to 300 °C for laminates subjected to tension, and 75 to 90 °C for pultruded GFRP profiles experiencing compression.
- GFRP composites exhibit lower compressive strength and thermal resistance than their tensile strength and resistance when subjected to loading and exposure temperatures.
- The impact of high temperatures on the elastic modulus of GFRP composites is less significant than the corresponding strength values. The primary reason for this phenomenon is the strong correlation between the (GFRP) composites (elastic modulus value) and the modulus of elastic fibers rather than the resin.

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