

Experimental Investigation of Transverse Coefficient of Thermal Expansion of GFRP Rods under Heating

Omer ELzaroug¹ Mossa Elzaroug², John Forth³, J YE⁴

¹Department of Civil Engineering, Omar El-Mukhtar University

²Department of Materials Science and Engineering, Omar El-Mukhtar University

³School of Civil Engineering, University of Leeds

⁴Department of Engineering, Lancaster University

omerelzaroug@yahoo.com

Abstract. Glass fiber-reinforced polymer (GFRP) reinforcement is increasingly used in reinforced concrete structures due to its corrosion resistance and high strength-to-weight ratio. Unlike steel, GFRP bars exhibit anisotropic thermal expansion. The transverse coefficient of thermal expansion (CTE) of GFRP rods can be significantly greater than that of concrete, which generates radial pressure at the bar–concrete interface and circumferential tensile stresses in the concrete cover during temperature rise. These stresses may initiate splitting cracks even in the absence of mechanical loading. This study experimentally determines the transverse CTE of commercially produced GFRP rods with nominal diameters of 13, 16, and 19 mm using bonded strain gauges and controlled heating from 18°C to 65°C. The measured transverse CTE values were $23.14 \times 10^{-6}/^{\circ}\text{C}$, $25.19 \times 10^{-6}/^{\circ}\text{C}$, and $26.66 \times 10^{-6}/^{\circ}\text{C}$ for 13, 16, and 19 mm rods, respectively. The results show slight nonlinearity in strain–temperature response and demonstrate a diameter-dependent variation, likely related to manufacturing factors such as fiber volume fraction and surface wrapping. The findings provide essential input for analytical prediction and numerical simulation of thermal-induced cracking in GFRP-reinforced concrete members.

Keywords: GFRP rods, transverse thermal expansion, thermal cracking, concrete cover splitting, bond.

1. Introduction

Temperature variations in reinforced concrete structures may produce significant internal stresses due to thermal incompatibility between reinforcement and surrounding concrete. In conventional steel-reinforced concrete, this effect is generally limited because steel and concrete have comparable coefficients of thermal expansion. However, the use of fiber-reinforced polymer (FRP) reinforcement, particularly glass FRP (GFRP), introduces a different thermal mechanism due to the anisotropic (orthotropic) nature of FRP materials.

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GFRP bars exhibit distinct thermal expansion properties in the longitudinal and transverse directions. The longitudinal thermal response is governed mainly by the aligned glass fibers, resulting in a relatively moderate longitudinal coefficient of thermal expansion. In contrast, the transverse thermal response is primarily controlled by the polymer resin matrix, producing much larger transverse deformation. As a consequence, the transverse coefficient of thermal expansion (α_T) of GFRP bars may be significantly higher than that of concrete, typically reported as 5 to 8 times greater [1, 2]. This mismatch becomes critical under heating conditions.

When temperature increases, GFRP bars tend to expand transversely more than the surrounding concrete. Since the bar is restrained by bond and confinement, this expansion generates radial pressure at the GFRP–concrete interface, which in turn induces circumferential (hoop) tensile stresses within the concrete cover. If these tensile stresses exceed the tensile capacity of concrete, splitting cracks may initiate around the reinforcement, even in the absence of external mechanical loads [3]. Thermal cracking of this type (Fig. 1) has been reported in previous studies [4, 5] and may significantly reduce the integrity of the FRP–concrete bond, leading to degradation in structural performance, serviceability, and long-term durability [6].

The severity of this phenomenon is strongly influenced by concrete confinement and cover thickness. In severe cases, inadequate cover may lead to progressive cracking and eventual spalling of the concrete cover [5, 7 & 8]. Current design guidance also acknowledges this risk: ACI 440.1R-15 [9] reports an average transverse CTE for GFRP bars of approximately $22 \times 10^{-6}/^{\circ}\text{C}$, and suggests that a cover-to-bar diameter ratio (c/d_b) exceeding about 1.6 can significantly reduce the likelihood of thermal-induced splitting cracks.



a) Plane of Concrete Cylinder



b) Elevation of Concrete Cylinder

Figure 1 Thermal cracking due to transverse expansion of GFRP [5].

Several experimental and analytical investigations have addressed thermal compatibility of FRP reinforcement and concrete, focusing on cracking and cover splitting mechanisms. Masmoudi *et al.* [10] experimentally studied GFRP bars embedded in concrete cylinders and reported transverse CTE values around $33 \times 10^{-6}/^{\circ}\text{C}$ on average for the tested bars, showing that cover-to-diameter ratio significantly affects cracking behavior. Zaidi and Masmoudi [11] further investigated thermal effects on FRP-reinforced concrete slabs under

temperature ranges approximately -30°C to $+80^{\circ}\text{C}$ and reported cover failure at elevated temperatures when confinement is inadequate.

Galati *et al.* [12] reported thermal effects on bond performance and referenced typical transverse CTE values near $29 \times 10^{-6}/^{\circ}\text{C}$ for GFRP bars. ACI 440 [9] documents that FRP bars are anisotropic and that transverse expansion is generally dominated by resin, leading to higher transverse CTE than concrete. Ellis *et al.* [13] reviewed experimental evidence related to GFRP bars at elevated temperatures and summarized that transverse thermal expansion of GFRP is typically much higher than concrete (reported transverse CTE around $21 - 23 \times 10^{-6}/^{\circ}\text{C}$) and can contribute to thermal incompatibility and bond degradation. Qian *et al.* [14] experimentally studied the high-temperature effects on GFRP rebars embedded in concrete with different cover thicknesses. Their results showed that cover concrete delays heating and influences thermal damage development in the rebar during heating

El-Zaroug *et al.* [15] developed nonlinear numerical simulations to predict thermally induced transverse cracking in GFRP-reinforced concrete and showed that thermal mismatch generates interface pressure and hoop tensile stresses leading to cover cracking. El-Zaroug *et al.* [16] experimentally and numerically investigated the effect of bundled GFRP bars on thermal cracking behavior and reported that reinforcement configuration and confinement significantly influence crack initiation and propagation under temperature rise. Saleem and El-Zaroug [17] used DIANA finite element analysis to predict thermal loads causing first cracking and concrete cover splitting in GFRP-reinforced slabs (ΔT up to 80°C), showing that cover thickness, bar diameter, and concrete strength govern cracking onset, while bar spacing mainly controls crack patterns.

While the above studies provide essential information, measured transverse CTE values vary considerably ($\approx 22 - 33 \times 10^{-6}/^{\circ}\text{C}$) depending on bar type, manufacturer, fiber volume fraction, and surface wrap. Therefore, direct experimental determination of α_T for the exact GFRP reinforcement used in structural application is critical for accurate analytical and nonlinear numerical prediction of thermal cracking.

2. Experimental Program

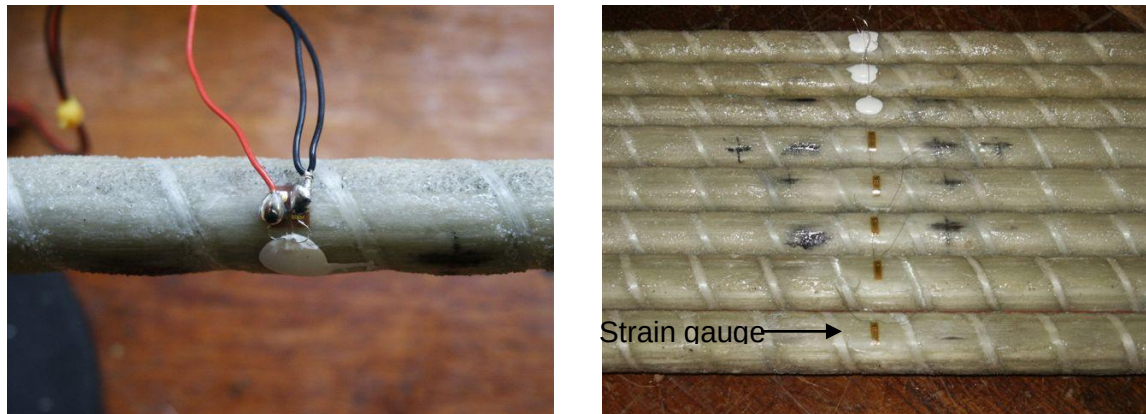
2.1 Materials and Specimens

Commercial GFRP rods were supplied in three nominal diameters: 13, 16, and 19 mm. Three specimens were prepared for each diameter (nine specimens total) and cut to 300 mm length to fit the oven. Type E-glass GFRP bars were used (Fig. 2 [17]), consisting of continuous E-glass fibers (70% by volume) embedded in a vinyl-ester resin matrix with a sand-coated wrapped surface. The thermal resistance of GFRP is governed by the resin; therefore, its properties may degrade near the glass transition temperature (115°C) [17].

2.2 Strain Gauge Installation

A transverse strain gauge (Tokyo Sokki Kenkyujo Co., Ltd.; type BFLA-2-3[18]), gauge length 2 mm) was bonded to the bar surface midway between two spiral wraps (Fig. 2). Surface preparation included progressive sanding (#100, #150, #1000, #1200) followed by cleaning with isopropyl alcohol until contamination-free. The gauge and wires were

protected using epoxy coating (Araldite A). A three-wire connection system was adopted to minimize lead-wire resistance effects and improve strain measurement accuracy.



a) Three-wire system connection

b) Strain gauge transversely attached on GFRP

Figure 2 Strain gauges arrangement

2.3 Thermal Cycling Procedure

Specimens were placed in an oven and subjected to controlled heating from ambient temperature ($\sim 18^{\circ}\text{C}$) to 65°C , maintained for a total duration of 6 hours (Fig. 3). Temperature was increased gradually at increments of $3 - 5^{\circ}\text{C}$, and each increment was held constant for approximately 30 minutes to ensure uniform temperature through the cross-section. A surface thermocouple monitored temperature. Strain and temperature data were recorded using a data-logging system at 30-minute intervals.



Figure 3 GFRP specimens placed in an oven

3. Result Analysis and Discussion

The transverse coefficient of thermal expansion (CTE) was experimentally determined for GFRP bars with nominal diameters of 13, 16, and 19 mm. Specimens were subjected to controlled heating between room temperature (18°C) and 65°C . The maximum temperature of 65°C was recommended by the manufacturer. This temperature is sufficiently lower than

the glass transition temperature of the resin (115°C), thus avoiding inaccurate measurements associated with matrix softening at higher temperatures.

The temperature was increased in increments, and each increment was maintained for 30 min to ensure uniform temperature distribution through the bar cross-section before strain readings were recorded. The transverse thermal strain was related to temperature change and was calculated as:

$$\alpha_T = \varepsilon_T / \Delta T \quad (1)$$

where ε_T is the measured transverse thermal strain, α_T is the transverse coefficient of thermal expansion of GFRP, and ΔT is the temperature increase.

Figure 4 shows the average experimentally measured transverse strain as a function of temperature rise (ΔT) for the three bar diameters. The strain–temperature relationships were nearly linear but not perfectly proportional, with correlation coefficients in the range $R = 0.988$ – 0.992 . Similar slight nonlinearity was noted by the manufacturer [17]. This behavior is attributed to the helical surface wrap, which provides partial confinement against transverse expansion and enhances mechanical interlock with concrete.

The transverse CTE values were determined from the slopes of the experimental strain–temperature relationships (Fig. 4). The calculated coefficients for the tested bar diameters are summarized in Table 1.

Table 1 Transverse coefficient of thermal expansion for tested GFRP bars

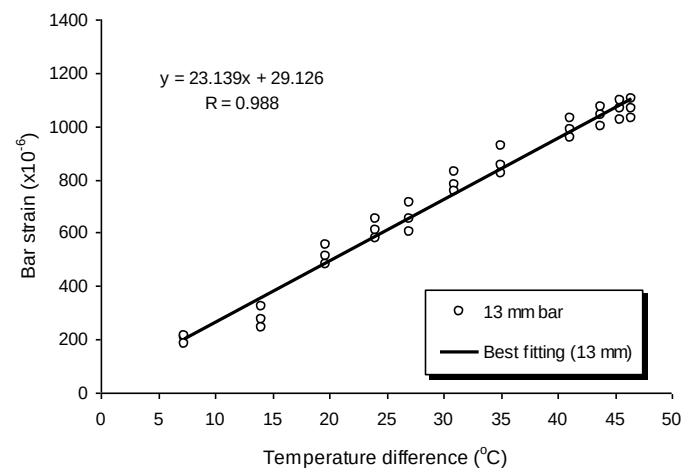
Bar diameter (mm)	$\alpha_T (\times 10^{-6}/^{\circ}\text{C})$
13	23.14
16	25.19
19	26.66

The observed variation between bar diameters may be related to manufacturing differences, such as small changes in glass-to-resin ratios and resin processing additives. This interpretation agrees with ACI 440, which states that the coefficient of thermal expansion of FRP bars differs in the longitudinal and transverse directions depending on fiber type, resin type, and fiber volume fraction.

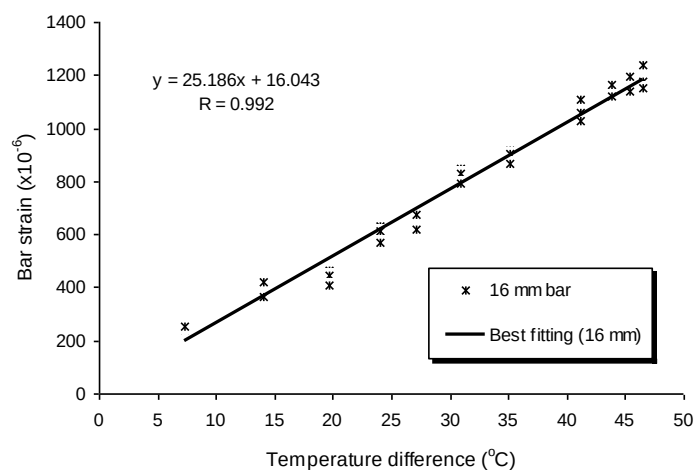
The differences among α_T values were sufficiently clear to justify using separate transverse CTE values for each bar size in subsequent analytical predictions and nonlinear finite element analysis. To further support this approach, regression analysis was also performed on combined thermal strain data from all three bar sizes (Fig. 5), yielding a lower correlation coefficient than individual regression fits, confirming that each diameter exhibits distinct thermal expansion characteristics.

Transverse thermal incompatibility between GFRP reinforcement and concrete ($\alpha_{T,\text{GFRP}} > \alpha_{c,\text{concrete}}$) generates radial pressure at the bar–concrete interface and induces circumferential (hoop) tensile stresses in the concrete cover. When these stresses exceed the tensile capacity of concrete, splitting cracks may develop even in the absence of mechanical loading. This cracking mechanism becomes more critical when the concrete cover is insufficient, which is consistent with the findings of Elzaroug *et al.* [14] and the ACI

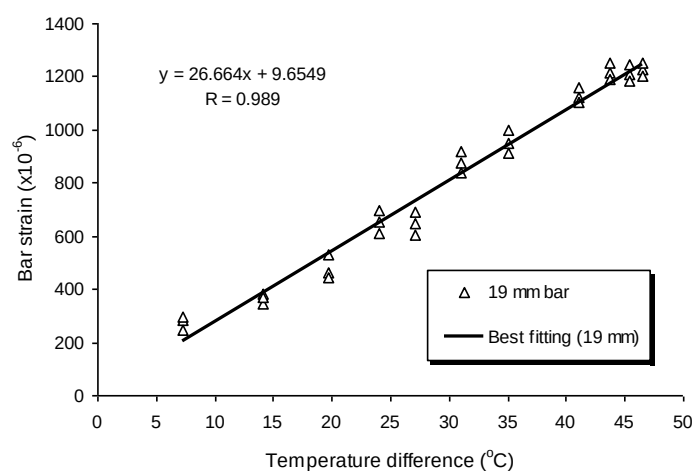
440.1R15 [9] guidance recommending cover-to-bar diameter ratios of approximately $c/d_b \geq 1.6$ to mitigate thermal-induced cracking at elevated temperatures.



a) 13 mm GFRP bar



b) 16 mm GFRP bar



c) 19 mm GFRP bar

Figure 4 Experimental transverse strain response for 13, 16, and 19 mm GFRP bars

The measured transverse CTE values ($\alpha_T \approx 23\text{--}27 \times 10^{-6}/^\circ\text{C}$) fall within the typical range reported for GFRP reinforcement in design guidance. For instance, ACI 440.1R15 reports transverse CTE values for GFRP bars generally in the range of $21\text{--}23 \times 10^{-6}/^\circ\text{C}$, with a transverse-to-longitudinal expansion ratio of approximately 4.

Nevertheless, higher transverse CTE values have been reported in experimental investigations. Masmoudi *et al.* [10] measured values approaching $33 \times 10^{-6}/^\circ\text{C}$, indicating that transverse thermal expansion may vary significantly among GFRP products. Such variation highlights the strong influence of bar composition and manufacturing parameters on α_T , and confirms the importance of experimentally determining the transverse CTE for the specific GFRP reinforcement used in each project.

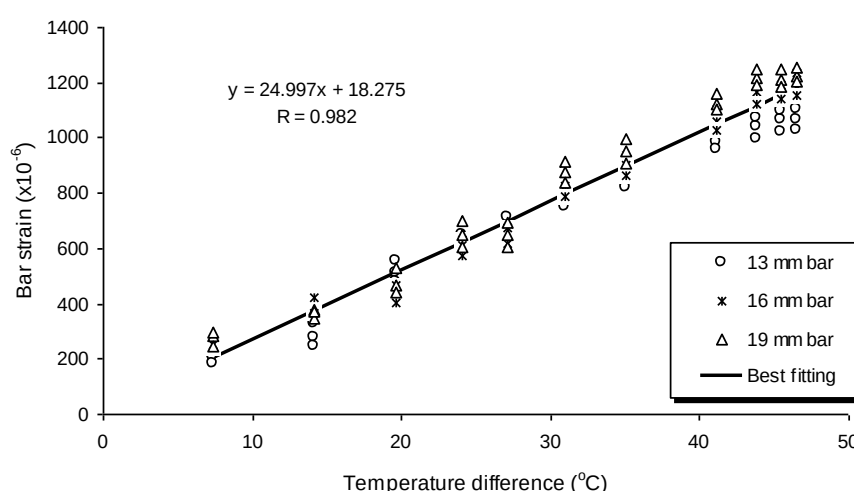


Figure 5 Combined thermal strain data for all tested GFRP bars

4. Conclusion

This study experimentally determined the transverse coefficient of thermal expansion (α_T) of commercially produced GFRP rods. The main conclusions are:

1. The transverse strain–temperature response was near-linear, with slight nonlinearity attributed to surface wrapping and manufacturing effects.
2. The measured transverse CTE values were $23.14 \times 10^{-6}/^\circ\text{C}$ (13 mm), $25.19 \times 10^{-6}/^\circ\text{C}$ (16 mm), and 26.66×10^{-6} .
3. α_T increased with bar diameter, indicating manufacturing-related influence.
4. The results generally agree with ACI 440 ranges but differ from some reported values ($33 \times 10^{-6}/^\circ\text{C}$), confirming the need for direct testing.
5. The measured α_T values provide key input for analytical and nonlinear finite element modeling of thermal-induced cracking in GFRP-reinforced concrete.

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