

Parametric Analysis of Thermally Induced Stresses in GFRP-Reinforced Concrete

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Abstract. Thermally induced stresses resulting from the mismatch in transverse thermal expansion between Glass Fiber Reinforced Polymer (GFRP) bars and concrete may significantly affect the serviceability and durability of GFRP-reinforced concrete members. This paper presents a comprehensive parametric analytical study on the development of radial tensile stresses at the GFRP bar–concrete interface under a uniform temperature increase of 50 °C. The analysis investigates the influence of key parameters, including concrete compressive strength, GFRP bar diameter, concrete cover thickness, and the transverse coefficient of thermal expansion of the GFRP bars. An established analytical model was employed to evaluate thermally induced stresses in concrete cylindrical specimens reinforced with GFRP bars of 13, 16, and 19 mm diameters.

The results indicate that concrete compressive strength has a limited effect on the magnitude of induced thermal stresses, whereas bar diameter and transverse thermal expansion of GFRP reinforcement are the dominant governing parameters. Larger bar diameters were found to generate significantly higher interfacial tensile stresses, increasing the potential for cracking and bond degradation. Increasing concrete cover thickness effectively reduced thermal stresses and limited their propagation toward the concrete surface. The study provides clear analytical insight into the thermal–mechanical interaction between concrete and GFRP reinforcement and offers practical guidance for the safe and economical design of GFRP-reinforced concrete structures exposed to temperature variations.

Keywords: GFRP bars, thermal stresses, thermal cracking, concrete cover, bond.

1. Introduction

The use of GFRP bars in concrete has increased due to their corrosion resistance and high strength-to-weight ratio. However, the large difference in transverse thermal expansion, quantified by the coefficient of thermal expansion (CTE) between GFRP and concrete generates radial thermal stresses when temperature rises, which can cause splitting of the concrete cover. GFRP exhibits a transverse CTE about 5 to 8 times higher than that of

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concrete (Matthys *et al.* 1996, Challal & Benmokrane 1993). The resulting thermal stresses may exceed the concrete's tensile capacity, reducing bond efficiency (Rahman *et al.* 1995) and potentially producing transverse damage in the cover (Fig. 1) (Abdalla & Elbadry 1997 & EL-Zaroug *et al.* 2007), affecting serviceability and long-term durability (Elbadry & Abdalla 1998). In cases of limited confinement, these stresses may even lead to cover spalling (EL-Zaroug *et al.* 2007, Aiello *et al.* 1999 & Elbadry *et al.* 2000). Accurate analytical prediction of these thermal stresses is therefore essential for structures exposed to significant temperature variations.

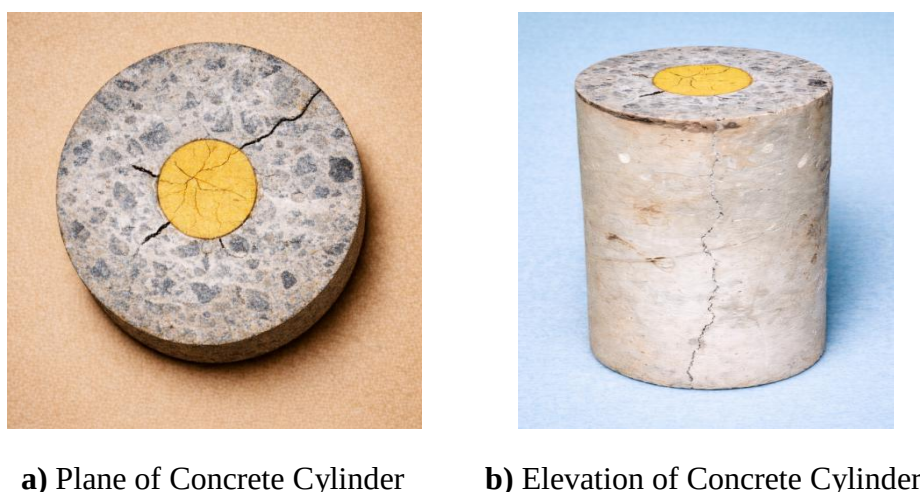


Figure 1 Thermal cracking due to transverse expansion of GFRP

Gentry and Husain (1999) developed an analytical model to quantify tensile stresses in concrete surrounding an FRP bar subjected to a uniform temperature increase of 40°C. Their model treats the FRP bar as transversely isotropic and incorporates the effects of axial strain induced by mechanical loading. However, its applicability is limited to smooth FRP bars and temperature changes not exceeding 40°C.

Rahman *et al.* (1995) analyzed hoop stresses in concrete by modelling it as a ring encasing the FRP bar. As temperature rises, the larger transverse expansion of the bar produces radial pressure and induces tensile stresses in the concrete.

Bellakehal and Zaidi (2016) investigated the impact of transverse thermal expansion in vertically overlapped FRP bars embedded in prismatic beams. To simplify their analysis, they suggested substituting the overlapping bars with a single equivalent bar when evaluating critical and service temperature thresholds.

Gentry and Husain (1999) also explored thermal compatibility between E-glass/vinylester rebars with smooth and helical configurations in concrete covers of varying thickness. Using nonlinear thermoelastic simulations under a 40°C temperature rise, they showed that smaller bar diameters and improved confinement reduced the likelihood of concrete cracking.

Abdalla (2006) examined the influence of cover thickness using analytical, numerical, and experimental methods. Results showed that numerical predictions were 11–14% lower than analytical estimates, highlighting the role of concrete cover in reducing interface stresses.

El-Zaroug *et al.* (2013) used 2D NLFE modeling to investigate thermal mismatch between concrete and GFRP bars for temperatures ranging from 20°C to 100°C. Results indicated

complex stress patterns driven by differential thermal expansion. They recommended specific cover requirements and smaller bar diameters to reduce cracking up to 60°C.

Zaidi *et al.* (2017) studied the influence of the transverse elastic modulus of FRP bars on thermally induced stresses in concrete cylinders. Higher FRP transverse modulus increased interface stresses, while concrete cover thickness had limited effect on strain responses.

Lardjane *et al.* (2018) used ADINA to simulate the thermal behaviour of GFRP-reinforced concrete slabs under temperatures ranging from –50°C to 60°C. Cracking initiation and splitting patterns were found to depend on cover ratio and concrete tensile strength.

Yi (2022) examined the thermal behavior of concrete cylinders reinforced with FRP bars using theoretical models and 2D nonlinear Abaqus simulations over temperatures from –70°C to 80°C. Results showed elastic behavior up to 20°C temperature change, followed by cracking at higher temperatures.

Saleem and El-Zaroug (2023) conducted DIANA-based NLFE simulations to evaluate thermal loads causing initial cracking and cover splitting in GFRP-reinforced slabs. Their study confirmed that bar spacing, diameter, concrete grade, and cover thickness significantly influence crack initiation and crack patterns.

2. Analytical Model and Parametric Study

A parametric theoretical study was performed to assess the effects of concrete compressive strength f_c , GFRP bar diameter d_b , concrete cover c , and the transverse coefficient of thermal expansion of GFRP bars α_t on the maximum thermally induced stress $\sigma_{t\ max}$ developed at the bar–concrete interface under an imposed temperature increase of $\Delta T=50^\circ\text{C}$.

The thermal stress formulations proposed by Rahman *et al.* (1995) and Masmoudi *et al.* (2005) yield identical expressions. Accordingly, the model developed by Masmoudi *et al.* was adopted in the present analysis for consistency and clarity and is reproduced herein as:

$$\sigma_{t\ max} = \left(\frac{r^2+1}{r^2-1} \right) \frac{(\alpha_t - \alpha_c) \Delta T}{\frac{1}{E_c} \left(\frac{r^2+1}{r^2-1} + \nu_c \right) + \frac{1}{E_t} (1 - \nu_t)} \quad 1$$

where: $\sigma_{t\ max}$: maximum thermally induced tensile stress at the GFRP bar–concrete interface; r : ratio of the external concrete radius to the bar radius in the cylindrical model; α_t and α_c : transverse coefficient of thermal expansion of the GFRP bar and the coefficient of thermal expansion of concrete, respectively; ΔT : applied temperature increase; E_c and ν_c : elastic modulus and Poisson's ratio of concrete; E_t and ν_t : transverse elastic modulus and Poisson's ratio of the GFRP bar, respectively.

A parametric analysis was performed on cylindrical concrete specimens reinforced with GFRP bars of 13, 16, and 19 mm diameters (Fig. 2), accounting for variations in concrete compressive strength, bar diameter, concrete cover and transverse thermal expansion coefficient and subjected to a uniform temperature increase of 50 °C.

3. Results and Discussion

3.1 Influence of f_c on $\sigma_{t\ max}$

Figure 3 presents the maximum radial tensile stress $\sigma_{t\ max}$ at the GFRP bar–concrete interface as a function of concrete cover thickness (20–60 mm). Three concrete compressive strengths

$f_c = 30, 40$ and 50 MPa were considered for each specimen type. An assumed uniform temperature increase of $\Delta T=50^\circ\text{C}$ was adopted in all analyses. The transverse coefficients of thermal expansion were experimentally determined as $23 \times 10^{-6}/^\circ\text{C}$, $25 \times 10^{-6}/^\circ\text{C}$ and $27 \times 10^{-6}/^\circ\text{C}$ for bar diameters of 13, 16, and 19 mm, respectively.

The results indicate that increasing f_c has a limited effect on the magnitude of $\sigma_{t \max}$ for all models. This behavior is attributed to the corresponding increase in the concrete elastic modulus E_c with higher f_c (Eq. 1), which mitigates stress amplification. In addition, $\sigma_{t \max}$ decreases with increasing concrete cover thickness. For cover thicknesses exceeding 45 mm, the influence of f_c on $\sigma_{t \max}$ becomes negligible.

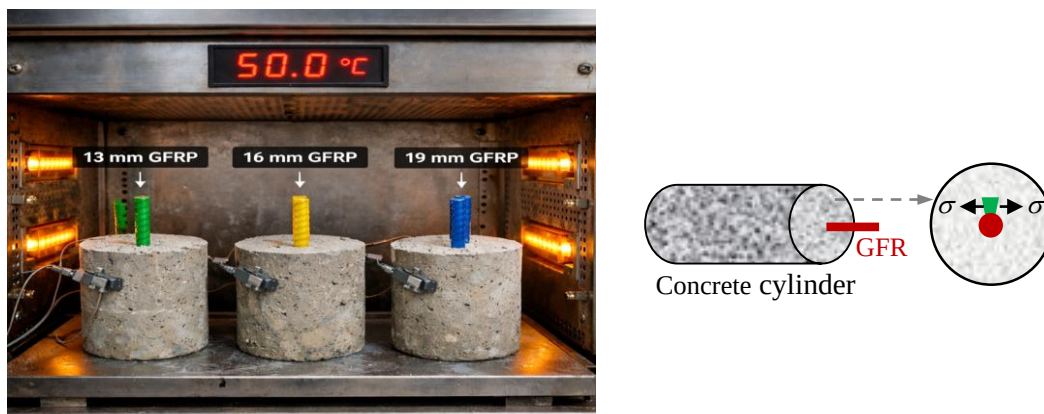


Figure 2 GFRP-reinforced concrete cylinders under thermal loading

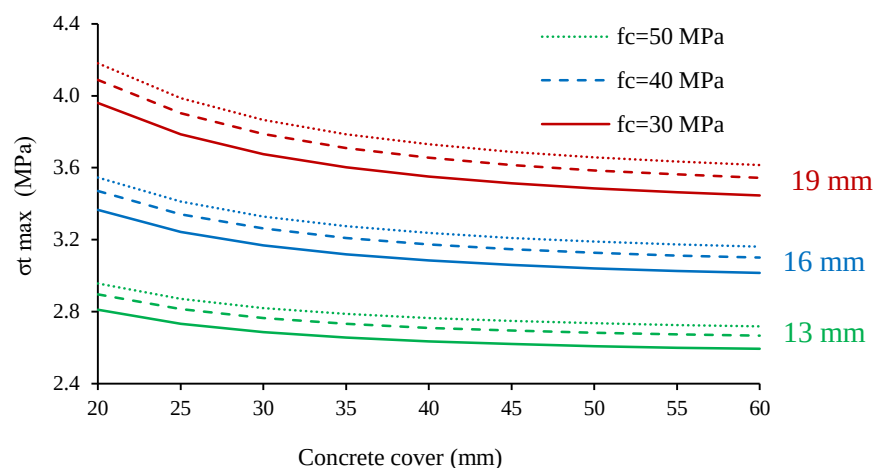


Figure 3 $\sigma_{t \max}$ at GFRP bar–concrete interface for different values of Concrete compressive f_c

3.2 Influence of α_t on $\sigma_{t \max}$

The influence of the transverse coefficient of thermal expansion α_t on the maximum radial tensile stress $\sigma_{t \max}$, as shown in Figure 4, was examined using three GFRP bar diameters (13, 16 and 19 mm) with corresponding α_t values of $23 \times 10^{-6}/^\circ\text{C}$, $25 \times 10^{-6}/^\circ\text{C}$ and $27 \times 10^{-6}/^\circ\text{C}$, respectively. A constant concrete compressive strength of 50 MPa and a uniform temperature increase of $\Delta T=50^\circ\text{C}$ were adopted in all analyses.

Despite the relatively small differences in α_t among the studied bar diameters, a significant increase in $\sigma_{t \max}$ was observed for larger bars. This behavior promotes earlier initiation of transverse cracking and accelerates bond degradation at the GFRP–concrete interface under thermal loading. The findings confirm that α_t is a key parameter governing thermally induced interfacial stresses and damage mechanisms in GFRP-reinforced concrete members.

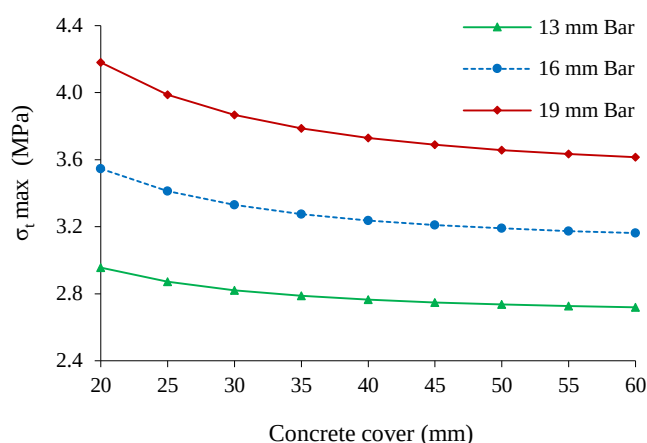


Figure 4 $\sigma_{t \max}$ at GFRP bar–concrete interface for different values of α_t

3.3 Influence of Bar Size on $\sigma_{t \max}$

The influence of GFRP bar size on the maximum radial tensile stress $\sigma_{t \max}$ is illustrated in Figure 5, which presents $\sigma_{t \max}$ as a function of concrete cover thickness. A constant concrete compressive strength of 50 MPa and a constant transverse coefficient of thermal expansion α_t ($25 \times 10^{-6}/^\circ\text{C}$) were adopted for all models to isolate the effect of bar diameter.

The results shown in Figure 5 indicate that increasing the bar diameter from 13 mm to 19 mm leads to an increase in $\sigma_{t \max}$. At the bar–concrete interface, the predicted $\sigma_{t \max}$ for the 19 mm bar is approximately 4% and 8% higher than those for the 16 mm and 13 mm bars, respectively, confirming that bar size directly influences the magnitude of radial tensile stresses.

Additional analyses conducted for different temperature increases ($\Delta T = 20, 30, 40$, and 60°C) showed that these percentage differences remain essentially unchanged, indicating a consistent bar-size effect across the examined thermal range. As observed previously, $\sigma_{t \max}$ decreases with increasing concrete cover thickness, highlighting the mitigating role of concrete cover.

3.4 Distribution of σ_t within Concrete Cover

The distribution of radial tensile stress σ_t within the concrete cover was examined using a single set of parameters for all bar diameters: concrete compressive strength $f_c = 50$ MPa, concrete cover thickness of 30 mm, transverse coefficient of thermal expansion $\alpha_t = 25 \times 10^{-6}/^\circ\text{C}$, and a uniform temperature increase of $\Delta T = 50^\circ\text{C}$.

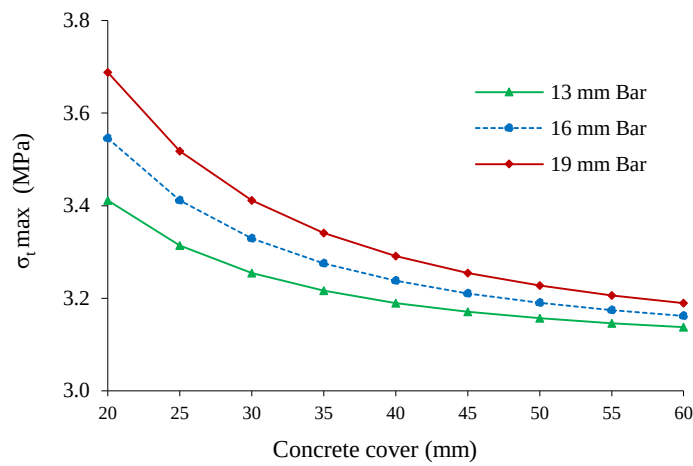


Figure 5 Variation of $\sigma_{t \max}$ with bar size for different concrete cover thicknesses

The variation of σ_t through the concrete cover for GFRP bar diameters of 13, 16, and 19 mm is shown in Figure 6. As illustrated, the maximum radial tensile stress occurs at the GFRP bar–concrete interface (point a). From this location, σ_t decreases progressively with increasing distance from the bar, reaching minimum values at the external surface of the concrete cylinder (point b).

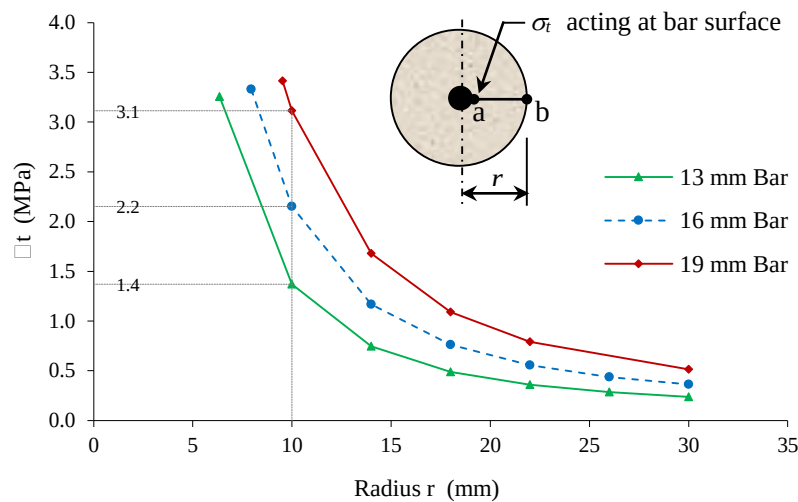


Figure 6 Variation of σ_t within concrete cover for different GFRP bar diameters

Figure 6 also shows that the model reinforced with a 19 mm GFRP bar develops the highest σ_t values throughout the concrete cover. At the bar–concrete interface and at the external surface, σ_t reaches approximately 3.41 MPa and 0.51 MPa, respectively. At a distance of 10 mm from the bar center, the 19 mm bar model similarly exhibits higher σ_t values compared with the 13 mm and 16 mm bar models. This behavior is attributed to the larger transverse thermal deformation associated with the 19 mm bar, which induces higher radial stresses in the surrounding concrete.

Overall, σ_t decreases with increasing distance from the GFRP bar toward the outer concrete surface, while larger bar diameters result in higher stress levels throughout the concrete cover.

4. Conclusion

This study investigated thermally induced radial tensile stresses at the GFRP bar–concrete interface through a parametric analytical approach. The results show that concrete compressive strength has a limited influence on the maximum thermal stresses, whereas bar diameter and the transverse coefficient of thermal expansion of GFRP reinforcement are the dominant parameters. Larger bar diameters were found to generate significantly higher interfacial stresses, increasing the risk of cracking and bond degradation under temperature variations.

Increasing concrete cover effectively reduces thermal stresses and limits their propagation toward the concrete surface. The findings provide practical guidance for the design of GFRP-reinforced concrete members exposed to thermal effects and highlight the economic advantage of using smaller bar diameters with adequate concrete cover to improve serviceability and durability while minimizing material demand.

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