FRP Bars Spacing Effect on Numerical Thermal Deformations in Concrete Beams under High Temperatures

A. Zaidi, F. Khelifi, R. Masmoudi, M. Bouhicha

***Abstract*—**In order to eradicate the degradation of reinforced concrete structures due to the steel corrosion, professionals in constructions suggest using fiber reinforced polymers (FRP) for their excellent properties. Nevertheless, high temperatures may affect the bond between FRP bar and concrete, and consequently the serviceability of FRP-reinforced concrete structures. This paper presents a nonlinear numerical investigation using ADINA software to investigate the effect of the spacing between glass FRP (GFRP) bars embedded in concrete on circumferential thermal deformations and the distribution of radial thermal cracks in reinforced concrete beams submitted to high temperature variations up to 60 °C for asymmetrical problems. The thermal deformations predicted from nonlinear finite elements model, at the FRP bar/concrete interface and at the external surface of concrete cover, were established as a function of the ratio of concrete cover thickness to FRP bar diameter (c/d_b) and the ratio of spacing between FRP bars in concrete to FRP bar diameter (e/d_b). Numerical results show that the circumferential thermal deformations at the external surface of concrete cover are linear until cracking thermal load varied from 32 to 55 °C corresponding to the ratio of e/d_b varied from 1.3 to 2.3, respectively. However, for ratios e/d_b >2.3 and c/d_b >1.6, the thermal deformations at the external surface of concrete cover exhibit linear behavior without any cracks observed on the specified surface. The numerical results are compared to those obtained from analytical models validated by experimental tests.

***Keywords*—**Concrete beam, FRP bars, spacing effect, thermal deformation.

I. Introduction

In the last decade, concrete structures reinforced with steel bars subjected to aggressive environmental conditions have been deteriorated because of the corrosion of steel bars induced mainly by the carbonation or chlorides in the presence of humidity and temperatures. As a consequence, the ultimate capacity and the durability of concrete structures could be reduced. For this reason, FRP have been introduced in civil engineering constructions such as bridges and parking. FRP bars present high properties as tensile strength and corrosion resistance. Nevertheless, the thermal incompatibility between FRP bars and concrete may cause splitting cracks within concrete under high temperatures, and eventually, the degradation of the bond at the interface of FRP bar/concrete. Extensive research works have been carried out on thermal behavior of concrete structures reinforced with FRP bars [1]-[5]. However, certain parameters were not sufficiently investigated using finite elements modeling such as the spacing between FRP bars in concrete structures. This paper examines the nonlinear finite elements modeling (ADINA software) of FRP bars spacing effect on transverse thermal deformations in prismatic rectangular concrete beams reinforced with GFRP bars submitted to high temperature increases (ΔT) up to 60 °C. This investigation permits to analyze circumferential thermal deformations within concrete at the FRP bar/concrete interface and at the external surface of concrete cover varying the ratio of spacing between FRP bars in concrete to FRP bar diameter (e/d_b) and the ratio of concrete cover thickness to FRP bar diameter (c/d_b). Comparisons between transverse thermal deformations predicted from nonlinear numerical model and those obtained from linear analytical model and Zaidi's model are presented.

II. Numerical Simulation of Thermal Deformations

A. Model Description

The nonlinear numerical simulation of FRP bars spacing effect on transverse thermal deformations of reinforced concrete beams was investigated using finite element ADINA software. The beams of 380 mm length had a ratio of spacing between FRP bars to FRP bar diameter e/d_b varied between 1.3 and 3.3 and a ratio of concrete cover thickness to FRP bar diameter c/d_b varied from 1.0 to 3.2. Concrete beams reinforced each one with 2 GFRP bars are presented in Fig. 1 and Table I. As the cross section of concrete reinforced with two GFRP bars is symmetric with respect to z axis, the numerical simulation was carried out only for the half of the cross section. Triangular elements with six nodes were used for the meshing of the both materials: concrete and GFRP bars as shown in Fig. 2. The thermal load ΔT has been increased with increment of 5 °C from 0 up to 60 °C.

The mechanical properties of GFRP bars used in this investigation are presented in Table II. The average values of the coefficient of thermal expansion (CTE) in transverse and longitudinal directions for the five GFRP bar diameters were α_t=33x10^{-6}/°C and α_l = 8.9 x10^{-6}/°C, respectively. All GFRP bars properties were determined experimentally by Zaidi and

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Masmoudi [2]. The concrete used had average values of the compressive strength and the tensile strength of 40 MPa and 4.1 MPa, respectively, determined experimentally by Zaidi and Masmoudi [2]. The modulus of elasticity E_c=28 GPa, the Poisson's ratio ν_c=0.17, and the CTE α_c=11.6x10^{-6} /°C.

TABLE I
GFRP BARS-REINFORCED CONCRETE BEAMS PROPERTIES

N° beams	Beam width b_1(mm)	Beam height h(mm)	Bar diameter d_b (mm)	Concrete cover c_1 (mm)	Concrete cover c_2 (mm)	Spacing between bars e (mm)	c_1/d_b	c_2/d_b	e/d_b
P.#10.20/30[a]	76	100	9.5	20	30	31	2.1	3.2	3.3
P.#13.20/25	76	100	12.7	20	25	29.6	1.6	2.0	2.3
P.#16.20/20	76	100	15.9	20	20	28.2	1.3	1.3	1.8
P.#19.20/35	100	125	19.1	20	35	31.8	1.0	1.8	1.7
P.#25.30/35	100	150	25.4	30	35	34.2	1.2	1.4	1.3

[a] P = Prismatic beam; #10 = nominal size of the bar; 20 = concrete cover thickness in mm of the first bar and 30 = concrete cover thickness in mm of the second bar

TABLE II
GFRP BARS MECHANICAL PROPERTIES

Bar designation	Bar diameter, d_b(mm)	Ultimate tensile strength, f_{tu} (MPa)	Longitudinal elasticity E_l (GPa)	Ultimate tensile strain (%)	Longitudinal Poisson 's ratio ν_{lt}	Transverse modulus of elasticity, E_t (GPa)	Transverse Poisson's ratio ν_{tt}
N°.10	9.5	627±22	42±1	1.8±0.2			
N°.13	12.7	617±16	42±1	1.4±0.2			
N°.16	15.9	535±9	42±1	1.5±0.2	0.28± 0.02	7.1	0.38
N°.19	19.1	600±15	40±1	1.4±0.2			
N°.25	25.4	N/A	N/A	N/A			

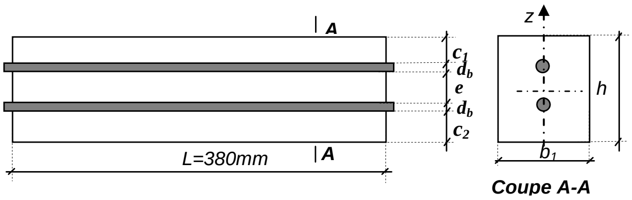


Fig. 1 Concrete beam reinforced with 2 GFRP bars modeled

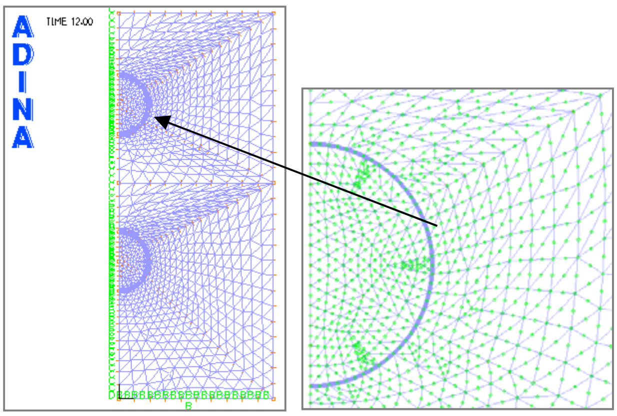


Fig. 2 Meshing of GFRP bars and concrete of prismatic beam

B. Thermal Deformations

Figs. 3 and 4 present circumferential thermal deformation curves as a function of temperature variation ΔT at the interface of FRP bar/concrete and also at the external surface of concrete cover, respectively, for concrete beams reinforced with two GFRP bars having a ratio of spacing between FRP bars to FRP bar diameter (e/d_b) varying between 1.3 and 3.3.

From Fig. 3, it can be seen that the thermal strain curves are linear and almost similar until ΔT around 30 °C. Beyond this ΔT value, a significant increase of thermal deformation is observed due to the development of circular crowns of concrete cracks in which the radial cracks reach or are too close to the midpoint between GFRP bars as shown in Fig. 5. The same remarks could be noted for Fig. 4, the circumferential thermal deformations at the external surface of concrete cover are linear until cracking thermal load varied from 32 to 55 °C corresponding to the ratio of e/d_b varied from 1.3 to 2.3, respectively. However, for ratios e/d_b >2.3 and c/d_b>1.6, the strain curve is linear up to 60 °C because cracks do not reach the external surface of concrete cover. It can be concluded that a ratio e/d_b>2.3 reduces radial cracks depth within concrete and avoid splitting cracks to reach the external surface of concrete cover.

III. ANALYTICAL MODEL

The analytical model developed for prismatic concrete beam reinforced with FRP bars has been inspired from that established for a concrete cylinder reinforced with FRP bars [1], [3], [4].

The transverse thermal incompatibility between FRP bars and concrete generates a radial pressure P at the interface of FRP bars/concrete of a concrete beam reinforced with two FRP bars under thermal loads. Each bar is studied separately so as to define the radial pressure at the interface of each reinforcing bar.

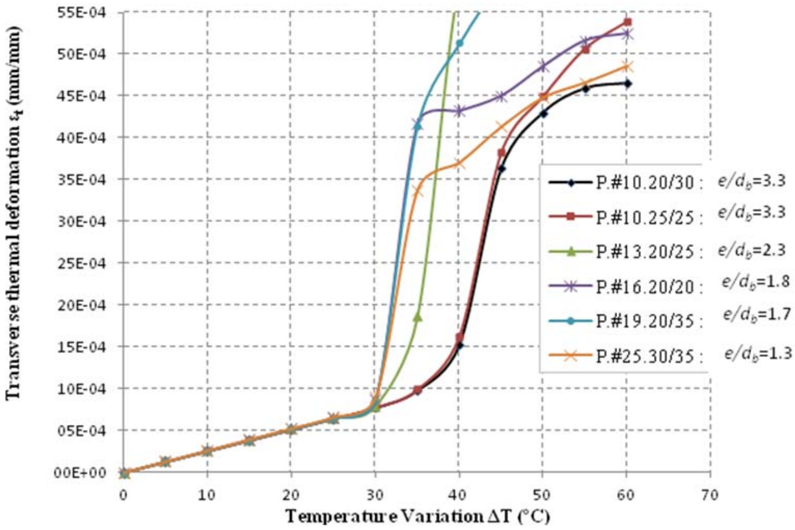


Fig. 3 Transverse thermal deformation at FRP bar/concrete interface of concrete beam reinforced with two FRP bars having different ratio e/d_b

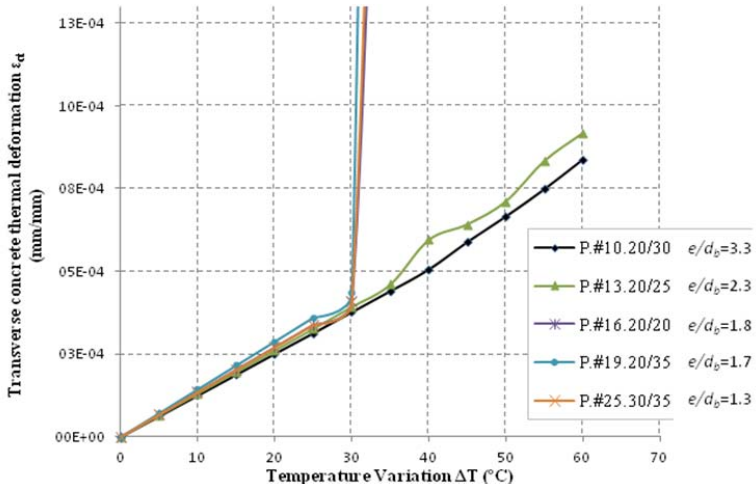
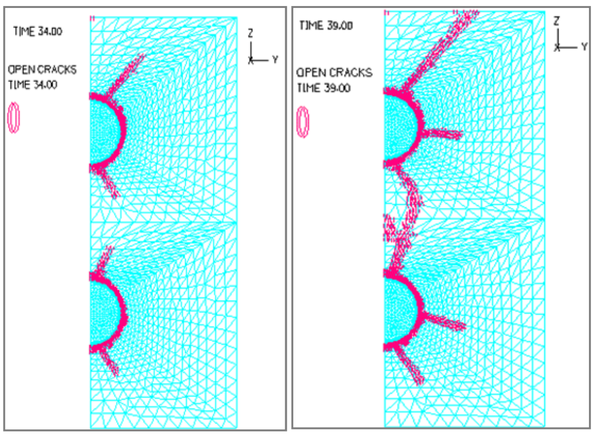


Fig. 4 Transverse concrete thermal deformation at external surface of concrete cover of concrete beam reinforced with two FRP bars having different ratio e/d_b



(a) ΔT = 34 °C (b) ΔT = 39 °C

Fig. 5 Cracks developed within concrete (beam P.#16.20/20 having e/d_b = 1.8)

$$P_i = \frac{(\alpha_t - \alpha_c)\Delta T}{\frac{1}{E_c}\left(\frac{r_i^2+1}{r_i^2-1}+\nu_c\right)+\frac{1}{E_t}(1-\nu_{tt})} \qquad for \quad i=1\ ,\ 2 \tag{1}$$

where $r_i=b_i/a$, $b_i=c_i+a$, a: radius of FRP bar, c_i: thickness of concrete cover for each FRP bar, α_c: CTE of concrete α_t: transverse CTE of FRP bar, E_c: modulus of elasticity of concrete, E_t: modulus of elasticity of FRP bar in transverse direction, ν_c: Poisson's ratio of concrete, ν_{tt}: Poisson's ratio of FRP bar in transverse direction.

The transverse thermal strains in concrete (ε_{ct}) and in FRP bar (ε_{ft}), at the interface of FRP bar/concrete, due to the radial pressure P and the temperature variation ΔT, are given by the following equations:

$$\varepsilon_{ct}(a) = \frac{P}{E_c}\left(\frac{r^2+1}{r^2-1}+\nu_c\right)+\alpha_c\,\Delta T \tag{2}$$

$$\varepsilon_{ft}(a) = \alpha_t \, \Delta T - \frac{(1-\nu_{tt})}{E_t} P \tag{3}$$

The transverse thermal strain of concrete $\varepsilon_{ct}(b)$, at the external surface of concrete cover of prismatic concrete beams, due to the radial pressure P and the temperature variation ΔT, is given by:

$$\varepsilon_{ct}(b) = \frac{2P}{E_c(r^2-1)} + \alpha_c \Delta T \tag{4}$$

Zaidi [3] proposed an analytical model which has been validated by experimental results, permits to determine the transverse thermal strains in FRP bar $\varepsilon_{ft}(a)$ at the interface of FRP bar/concrete of prismatic concrete beam reinforced with GFRP bar.

$$\varepsilon_{ft} = \alpha_t \, \Delta T - \frac{(1-\nu_{tt})}{E_t} P \quad \text{for } \Delta T \le +20\ °\text{C}$$

$$\varepsilon_{ft} = 0.80 \alpha_t \, \Delta T \quad \text{for} \quad \Delta T > +20\ °\text{C} \tag{5}$$

IV. Comparison between Numerical and Analytical Results

Figs. 6 and 7 show comparisons between theoretical results predicted from the linear analytical model, Zaidi's model, and the numerical model in terms of transversal thermal deformations at the interface of FRP bar/concrete of prismatic concrete beams reinforced with two FRP bars. From these figures, it can be observed that the transverse thermal deformation curves obtained by the Zaidi's model are in good agreement with those predicted from the numerical model for temperature variations less than 30 °C, the same remark can be noted for analytical curves predicted from the linear analytical model for temperature variations less than 20 °C. For ΔT>30 °C, the numerical results are larger because of the presence of the circular crown of tensile cracks that are deeper than those obtained from Zaidi's model. However, the linear analytical model based on the theory of elasticity ignores completely the presence of these cracks.

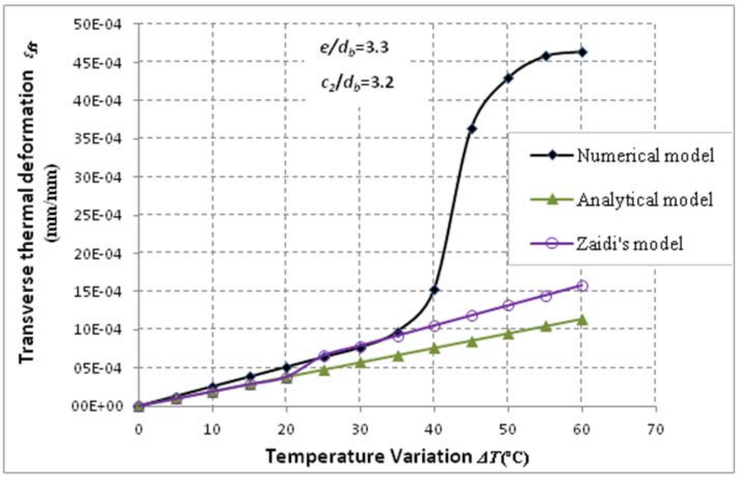


Fig. 6 Transverse thermal deformation at FRP bar/concrete interface of concrete beam reinforced with two FRP bars P.#10.20/30 having ratios e/d_b=3.3 and c_2/d_b=3.2

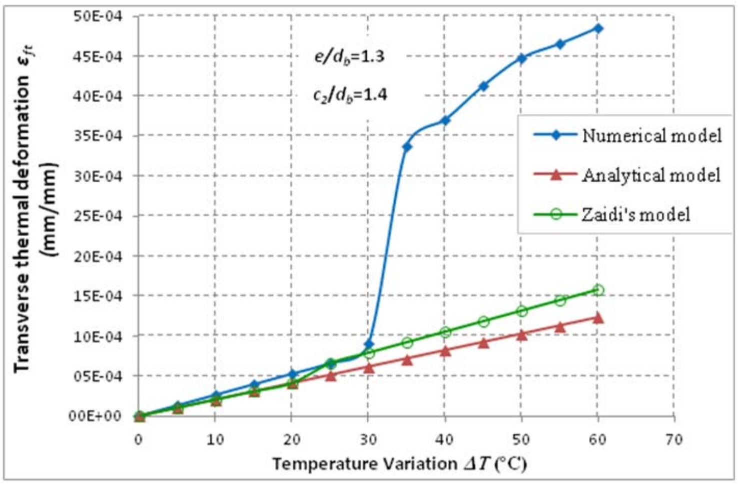


Fig. 7 Transverse thermal deformation at FRP bar/concrete interface of concrete beam reinforced with two FRP bars P.#25.30/35 having ratios e/d_b=1.3 and c_2/d_b=1.4

V. Conclusions

The nonlinear numerical analysis of the effect of the spacing between GFRP bars embedded in concrete on transverse thermal deformations in reinforced concrete beams submitted to high temperature variations, permits to draw the following conclusions:

- Circular crowns of concrete cracks were developed within concrete at temperature variations around 30 °C for concrete beams reinforced with two GFRP bars having a ratio of spacing between FRP bars to FRP bar diameter (e/d_b) varying between 1.3 and 3.3.
- The transverse thermal deformation curves are linear and almost similar until ΔT around 30 °C corresponding to the ratio of e/d_b varied from 1.3 to 2.3. An important increase of thermal deformations is observed due to the development of circular crowns of concrete cracks for concrete beams reinforced with two GFRP under temperature variations up to 60 °C.
- A ratio e/d_b>2.3 reduces radial cracks depth within concrete and avoid splitting cracks to reach the external surface of concrete cover for concrete beams reinforced with two GFRP under temperature variations up to 60 °C.

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