

CRACKING OF CONCRETE COVER IN FRP REINFORCED CONCRETE ELEMENTS UNDER THERMAL LOADS

M. A. Aiello, F. Focacci, P.C. Huang, A. Nanni

Synopsis: The effects of thermal loads on the structural performance of FRP reinforced concrete elements are analyzed in this paper. The difference in transverse coefficient of thermal expansion (CTE) between FRP and concrete causes the presence of tensile stresses within the concrete and, eventually, the formation of cracks when the temperature increases.

As part of an inter-university experimental program, initial results are presented in the paper. They address the evaluation of temperature variations on concrete elements reinforced with AFRP and GFRP rebars, varying the thickness of the concrete cover and the shape of the cross-section, in absence of transverse reinforcement.

Results obtained confirm the influence of temperature variations on the state of strain and stress within FRP reinforced concrete elements and the necessity of a minimum concrete cover to be provided in order to avoid the formation of through cracks. Comparisons between experimental and theoretical predictions, the latter obtained by means of analytical and numerical models, are presented. The progress of the experimental investigation will provide an opportunity to improve the effectiveness of theoretical models and their use for practical detailing.

Keywords: Coefficient of thermal expansion, Concrete cover, Cracking, FRP, Transverse CTE, Thermal load.

Aiello, M., Focacci, F., Huang, P. C., and Nanni, A., "Cracking of Concrete Cover in FRP Reinforced Concrete Elements under Thermal Loads," Selected Presentation Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp. 233-243.

M. A. Aiello, is a Researcher in Structural Engineering, Department of Materials Science, University of Lecce, Italy. Her main research interests include the structural analysis of the FRP reinforced concrete members, the adhesion systems between polymers and concrete and the analysis of composite laminated structures.

F. Focacci is a Post Doctoral Researcher in the Dipartimento di Costruzione dell' Architettura (DCA), University of Venice. His research deals with the structural behavior of FRP reinforced concrete members, bond between FRP bars and concrete and structural rehabilitation using FRP.

P. C. Huang is a graduate student at the University of Missouri-Rolla studying towards an MS in Civil Engineering. He graduated from Feng Chia University, Taiwan, with a BS in Civil Engineering in 1995. Mr. Huang's areas of interest include structural analysis and design as well as strengthening of existing structures with FRP.

Antonio Nanni, FACI, is the V&M Jones Professor of Civil Engineering and Director of the University Transportation Center (UTC) at the University of Missouri-Rolla. Dr. Nanni is interested in construction materials, their structural performance, and field application. He is an active member in the technical committees of ACI, ASCE, ASTM and TMS.

INTRODUCTION

The increasing success of FRP reinforcement for concrete elements is linked to several advantageous properties such as high-strength, lightness, absence of corrosion, and magnetic permeability. However, the different mechanical behavior of non-metallic reinforcement, with respect to steel, involves some drawbacks: new design problems arise and must be solved; among all, those caused by the lack of thermal compatibility between concrete and FRP reinforcement. Unidirectional composite rods, generally utilized in concrete, present a transverse coefficient of thermal expansion (CTE) 6 to 8 times greater than that of concrete. As a result of temperature variations, stresses within the concrete may cause splitting cracks (1, 2, 3). This results in the degradation of the bond between concrete and reinforcement, affecting the structural response. The occurrence of splitting cracks under thermal loads depends on several factors: type of FRP reinforcement, type of concrete, presence of confining action (transverse reinforcement) and geometrical properties of the cross-section. An experimental program has been initiated in order to investigate the influence of various parameters on the cracking phenomenon and the effects of cracks on the bond performances between concrete and reinforcement. The initial results are presented and discussed in this paper. Evolution of strain within FRP reinforced concrete elements, produced by an increasing temperature, was recorded up to the occurrence of a through crack. Experimental results are compared with theoretical

predictions obtained by utilizing analytical and numerical models. In particular, the critical temperature variation, ΔT_{sp} , corresponding to the occurrence of the through crack, has been evaluated as a function of the concrete cover thickness, c . Curves (ΔT_{sp-c}) have been generated. Experimental results generally fall between analytical and numerical ones. These theoretical predictions present the same trend.

EXPERIMENTAL INVESTIGATION

Goals of the experimental investigation to analyze the effects of temperature variations on concrete elements reinforced with a FRP bar are:

1. Determination of the minimum concrete cover thickness to avoid the occurrence of through cracks under thermal loads.
2. Determination of the state of strain and stress within the concrete, caused by temperature variations, as a consequence of the thermal incompatibility between concrete and FRP reinforcement.
3. Determination of the effects of the thermal loads on the local bond-slip relationship between concrete and FRP.

Tests were planned focusing on the following parameters: type of FRP reinforcement, type of the concrete, and role of the confining action. The experimental program is being conducted at the University of Missouri-Rolla, Rolla, USA, and at the University of Lecce, Lecce, Italy.

FRP Reinforcement and Concrete

Three kinds of FRP rebars made of glass, aramid, and carbon fibers (i.e., GFRP, AFRP and CFRP) were used. At present, tests were carried out only on AFRP and GFRP reinforced concrete elements. The AFRP rebars (ARAPREE), supplied by SIREG, Italy, had a nominal diameter of 10 mm and were grain covered to improve the bond with concrete. The GFRP deformed rods (C-BARTM), produced by Marshall Industries Composites, USA, had a nominal diameter of 13 mm. Mechanical properties of the reinforcement were experimentally determined (4, 5) and reported in Table 1. In the table, f_r is the average tensile strength, E_r is the average tensile elastic modulus, α_b is the transverse coefficient of thermal expansion (CTE), and E_{tb} is the transverse Young's modulus. The CTE of AFRP was determined using the rule of mixtures, while the CTE of GFRP was experimentally determined by means of a strain gage placed on the rod's surface, in the transverse direction. The transverse Young's

modulus of the bars, E_{Tb} , was determined by the rule of mixtures based on the percentage of fibers and matrix.

Table 1 Mechanical properties of the FRP reinforcement

ARAPREE				C-BAR™			
f_r (4) (MPa)	E_r (5) (MPa)	α_b ** (°C-1)	E_{tb} ** (MPa)	f_r^* (4) (MPa)	E_r^* (4) (MPa)	α_b *** (°C-1)	E_{tb} ** (MPa)
1507	50100	$60 \cdot 10^{-6}$	3200	568-640	37500-40600	$37 \cdot 10^{-6}$	4000

* Depending on anchorage method, ** Theoretically evaluated, *** Experimentally determined

The mechanical properties of the three kinds of concrete (A, B, C) are reported in Table 2. The average compressive strength, f_c , was evaluated by standard compression tests on prisms 150 mm deep. The average tensile strength, f_{ct} , was determined by splitting tests carried out on 150 mm diameter by 300 mm long cylinders for types A and B. Others mechanical properties (elastic modulus E_c for types A, B, C and tensile strength f_{ct} for type C) were evaluated following EC2 (Eurocode 2) suggestions. The transverse CTE of concrete was assumed equal to $10 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$.

Table 2 Mechanical properties of concrete

Concrete	f_c (MPa)	f_{ct} (MPa)	E_c (MPa)
A	24.40	2.36	24300*
B	55.77	3.71	34000*
C	38.50	2.97*	32300*

* Determined as a function of f_c based on EC2 suggestions.

Specimens Geometry and Test Procedure

Concrete elements were reinforced with a FRP bar without transverse reinforcement. Two shapes of cross section, circular and rectangular, were considered to analyze the influence of the concrete confining action on the structural performance of members under thermal loading. In the first case, the confining action is axis-symmetric, as generally considered in analytical models utilized for studying the thermal stress problem. For rectangular cross sections, the axis-symmetry is removed by placing the bar closer to one of two opposite sides. Details of the specimens geometry are reported in Fig. 1 and Table 3. The specimen's codes indicate the shape (first letter, r: rectangular, c: cylindrical), the

diameter (first number), the concrete cover (second number) and the concrete type (A, B or C). Different specimens with the same dimensions are identified by the last number (1 or 2).

Table 3 Tested specimens

Specimen	Bar Diameter d (cm)	Concrete cover c (cm)	Spec. Length L (cm)	Concrete	FRP type
r_d1_1.2_A	1	1.19	100	A	AFRP
r_d1_1.3_A	1	1.25	100	A	AFRP
r_d1_1.7_A	1	1.67	100	A	AFRP
r_d1_2.2_A	1	2.15	100	A	AFRP
r_d1_2.3_A	1	2.28	100	A	AFRP
r_d1_1.0_B	1	1	100	B	AFRP
r_d1_2.0_B	1	2	100	B	AFRP
c_d1.3_1.9_C_1	1.3	1.9	45.7	C	GFRP
c_d1.3_1.9_C_2	1.3	1.9	45.7	C	GFRP

All tested specimens were subjected to a thermal loading by utilizing an oven. Holes were drilled in the concrete to place thermo-couples for detecting the temperature inside the specimen. The oven's temperature was increased in steps of 5 to 10°C once the temperature in the concrete had stabilized. Strain measurements were obtained with strain gages placed as shown in Fig. 1.

RESULTS AND DISCUSSION

Theoretical Predictions

Theoretical predictions were obtained by using two different approaches, an analytical and a numerical model, both based on the following assumptions:

1. absence of transverse reinforcement
2. absence of boundary restraints or further loading conditions besides that of thermal type
3. elastic linear behavior of both the concrete and the FRP bar

For the analytical model, concrete is a thick-walled pipe surrounding the FRP rod. Analytical relationships are determined by taking into account different states of stress within the concrete. Two stages are considered. The first corresponds to un-cracked concrete up to the temperature variation, ΔT_{cr} , producing the first radial crack inside the concrete at the bar/concrete surface. The second corresponds to the partially cracked concrete: cracks expand to the outer surface,

reaching it at $\Delta T = \Delta T_{sp}$ (cover spalling). The model allows to determine the thermal loads ΔT_{cr} and ΔT_{sp} for given geometrical and thermal properties as:

$$\Delta T_{cr} = \left[\frac{f_{ct}}{E_c} + \frac{\gamma^2 - 1}{\gamma^2 + 1} \left(\frac{v_c f_{ct}}{E_c} + \frac{f_{ct}}{E_{Tb}} \right) \right] \frac{1}{\alpha_b - \alpha_c} \quad (1)$$

$$\Delta T_{sp} = \left\{ \frac{0.3 f_{ct} \gamma}{E_c} [\ln(0.48\gamma) + 1.6 + v_c] + \frac{0.3 f_{ct} \gamma}{E_{Tb}} \right\} \frac{1}{\alpha_b - \alpha_c} \quad (2)$$

where:

$$\gamma = \frac{2c + d}{d} \quad (3)$$

and v_c is the concrete Poisson's ratio.

The numerical analysis is performed on a concrete structural member of rectangular cross section reinforced with a FRP bar. The confining action of concrete depends on bar location and is controlled by the thinner cover. The investigation is performed by adopting a FEM discretization with triangular elements as explained in (5).

Comparison between Experimental and Theoretical Results

In all tested specimens a longitudinal crack developed in the concrete cover and the corresponding temperature was recorded. Figure 2 represents the experimental GFRP transverse strain as a function of temperature variation, ΔT . The CTE's determined for the two specimens are $42 \cdot 10^{-6}$ and $37 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$, respectively. The average value, $\alpha_b = 39 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1}$, was adopted in the models.

In Figs. 3 and 4 the temperature variation producing the spalling of the concrete cover, ΔT_{sp} , is reported versus the ratio c/d (concrete cover thickness/bar diameter). The experimental results indicated by discrete points refer to the AFRP reinforced concrete specimens with rectangular cross section. Theoretical predictions obtained by both the analytical and the numerical model are shown as continuous curves.

The figures show that both analytical and numerical predictions present an almost linear trend and experimental results fall between the theoretical curves for c/d values larger than 1.5. The analytical prediction appears more conservative. This may be due to the assumption that thickness of the concrete surrounding the bar is constant and equal to the smallest concrete cover.

Aiello, M., Focacci, F., Huang, P. C., and Nanni, A., "Cracking of Concrete Cover in FRP Reinforced Concrete Elements under Thermal Loads," Selected Presentation Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp. 233-243.

In Figs 5 and 6 the experimental and theoretical relationships between concrete strain as a function of temperature variation ΔT are given. The strain is measured at the surface of the cylindrical specimen in the direction perpendicular to its axis (Figure 1). There is a reasonable match between predicted and experimental values up to the point when concrete cracks. At this time, the experimental strain has a sudden jump due to the "concentration" of strain at the location of the crack. The model can only represent the average strain as the result of smeared cracks. The model's results strongly depend on the transverse FRP Young's modulus, and on concrete Young's modulus, tensile strength and CTE. Calibration of these parameters is necessary.

CONCLUSIONS

On the basis of the results obtained, the following conclusions can be drawn.

- Measurement of the transverse CTE of GFEP bars confirms the thermal incompatibility between FRP and concrete. Concrete cover cracking under thermal loads, as evidenced in all tested specimens, can be explained.
- Analytical and numerical models allow to determine the minimum required cover to avoid the cracking phenomenon.
- Experimental work is needed to calibrate critical parameters.

ACKNOWLEDGEMENTS

Partial funding for the collaborative work was made available through the UMR - University Transportation Center.

REFERENCES

1. De Sitter, W.R., and Tolman, F. (1995). "Uni-directional fibre pretensioned concrete elements." *Non metallic (FRP) reinforcement for concrete structures*. L. Taerwe, ed., E & FN Spon, London, England, pp. 49 - 56.
2. Den Uijl, J.A. (1995). "Bond and fatigue properties of Arapree." *Non metallic (FRP) reinforcement for concrete structures*. L. Taerwe, ed., E & FN Spon, London, England, pp. 146 - 153.
3. Matthys, S., De Schutter, G., and Taerwe, L. (1996). "Influence of transverse thermal expansion of FRP reinforcement on the critical concrete cover."

Aiello, M., Focacci, F., Huang, P .C., and Nanni, A., "Cracking of Concrete Cover in FRP Reinforced Concrete Elements under Thermal Loads," Selected Presentation Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp. 233-243.

Proc., 2nd Int. Conf. on Advanced Composite Materials in Bridges and Structures. M. El-Badry, ed., Canadian Society for Civil Engineering, Montreal, Quebec, pp. 665 - 672.

4. Nanni, A., Rizkalla, S., Bakis, C.E., Conrad, J.O., Abdelrahman, A.A. "Characterization of GFRP Ribbed Rod Used For Reinforced Concrete Construction", ICE-98, January 1998, Nashville, TN, 16A/1-6.
5. Aiello, M.A. (1998). "Comportamento statico di elementi strutturali in conglomerato armato con barre in FRP (Fiber Reinforced Plastics)", *PhD Thesis*. Lecce, Italy.
6. Aiello, M.A. (1999). "Concrete Cover Failure in FRP Reinforced Beams under Thermal Loading." *Journal of Composites for Construction*, ASCE Vol. 3, no. 1, pp. 46-52.

Fig. 1 Specimens geometry. a) Rectangular cross-section; b) Circular cross-section

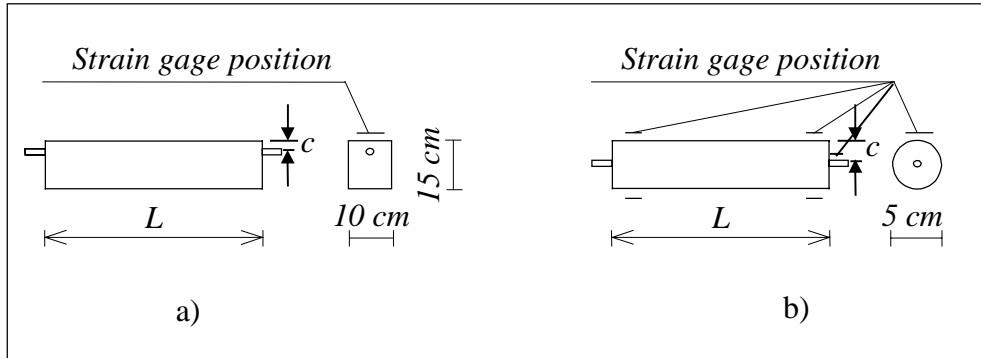


Fig 2 Experimental CTE of GFRP

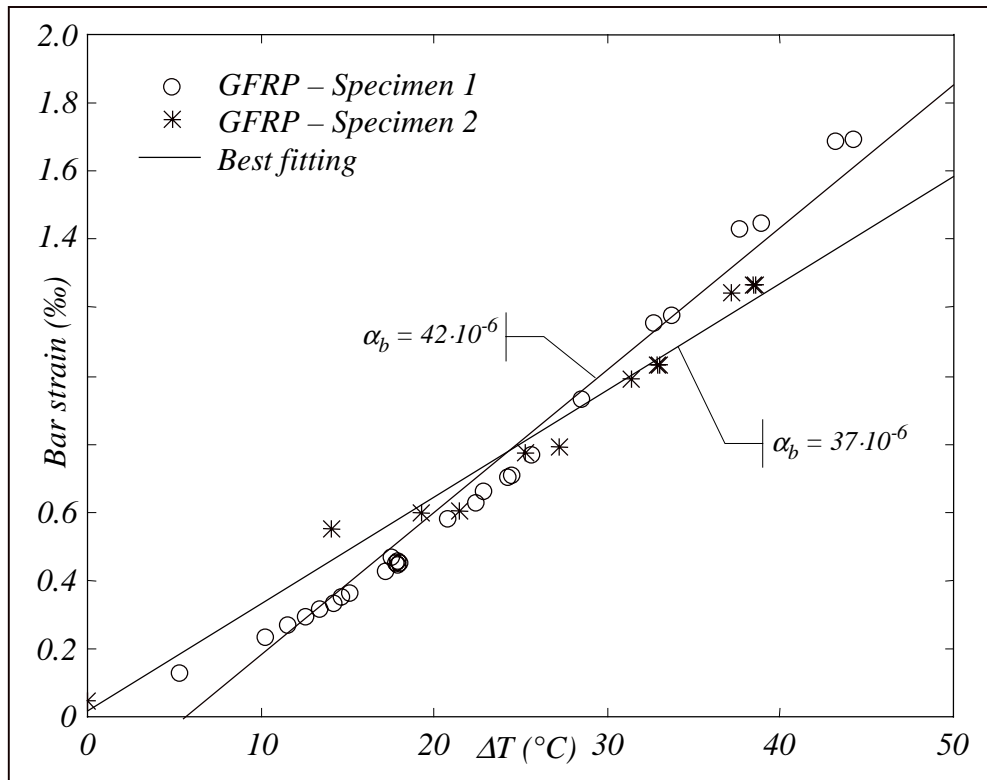


Fig. 3 Experimental and theoretical results (AFRP reinforcement, concrete type A, rectangular cross section)

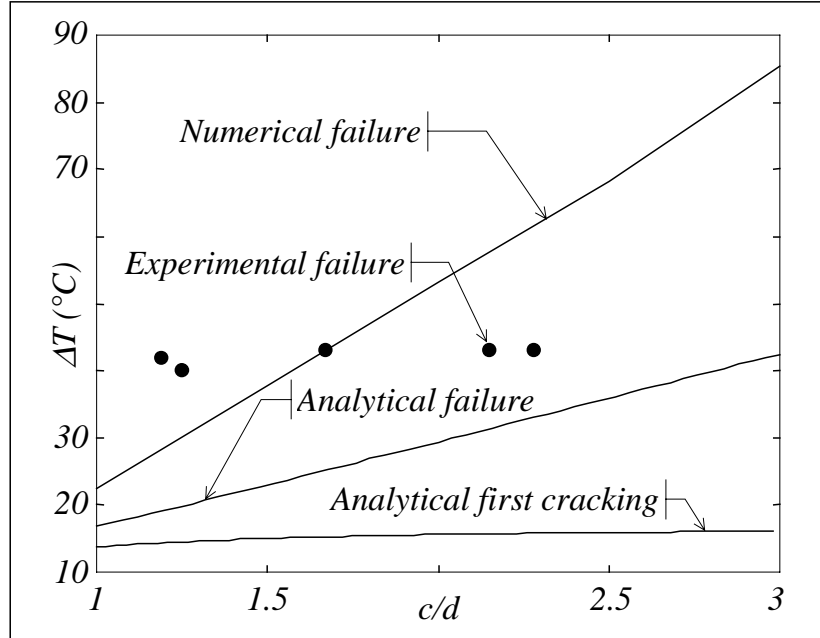


Fig. 4 Experimental and theoretical results (AFRP reinforcement, concrete type B, rectangular cross section)

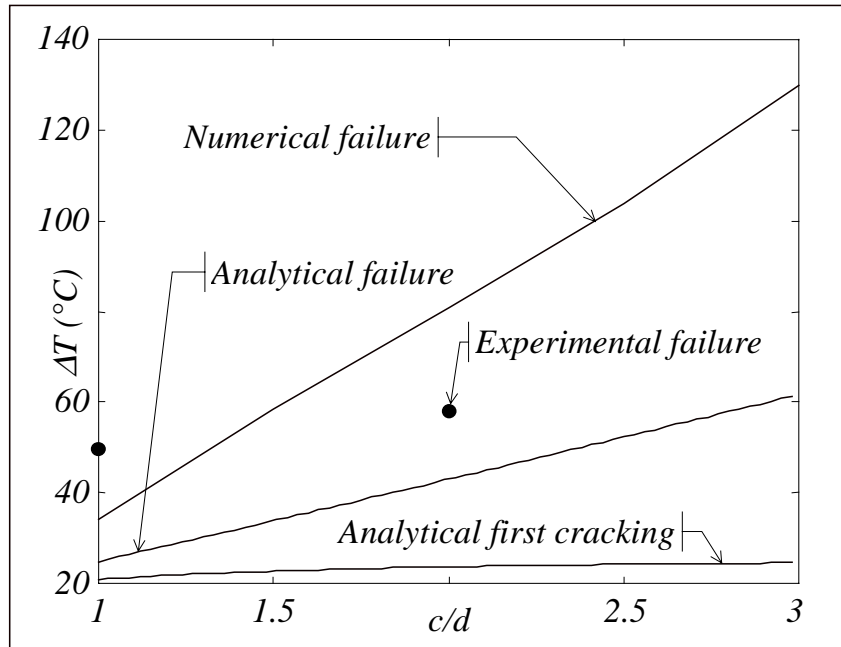


Fig. 5 Comparison between experimental and theoretical results, GFRP specimen 1

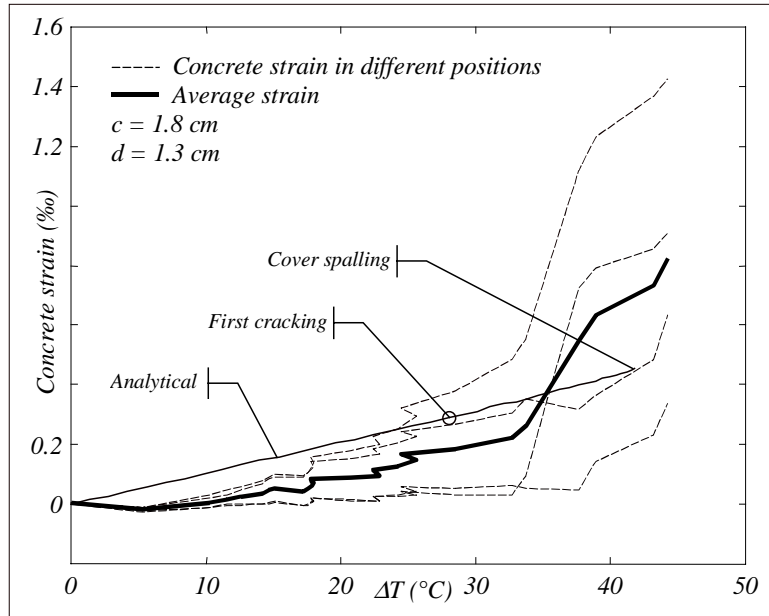


Fig. 6 Comparison between experimental and theoretical results, GFRP specimen 2

