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Flexural Evaluation of RC One-Way Slabs Strengthened with Different Composite Materials

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Abstract

Composite materials are widely used in retrofitting bridge and building construction in order to improve the load-carrying capacity of understrength or deficient structural members. This paper presents experimental research conducted on full-scale one-way reinforced concrete (RC) slabs strengthened using three different composites. The flexure performance of a new innovative composite, fibre-reinforced cementitious matrix (FRCM), is evaluated and compared with that of conventional fibre-reinforced polymers for some specimens under laboratory condition and for other specimens exposed to environmental conditioning before testing. The test results illustrate the impact of the composite materials on enhancing the flexural strength of RC slabs and their durability performance.

Keywords: Fiber-reinforced cementitious matrix (FRCM); carbon-fiber-reinforced polymer grid (CFRP grid); SRP; reinforced concrete slabs; one-way; strengthening; flexural behavior.

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Introduction

There is an increasing need and a great challenge to repair and upgrade transportation infrastructures. There can be several reasons for the need to repair and/or upgrade structures, such as a structural insufficiency due to de-icing-salts, freeze-thaw, or process of deficient concrete. In other cases, a structure may be upgraded to bear larger loads or to comply with new standards. In extreme cases, a structure may have to be repaired due to an accident or errors that were made during the design phase (ACI 440, 2008; ACI 549, 2013). Fibre reinforced polymers (FRP) are currently in use for repairing or strengthening RC structural members. Experimental works have addressed the outstanding mechanical properties of the FRP in terms of high strength-to-weight ratio and corrosion resistance. However, some drawbacks of epoxy curing agent such as low impact resistance, poor thermal compatibility with the base concrete, poor fire resistance, and low reversibility have limited its use (Loreto et al. 2013; Babaeidarabad et al. 2014). As a result, new composite materials that consisted of continuous dry-fabric with cement-based matrix were developed. The fibre reinforced cementitious matrix (FRCM) composite is the new innovative composite material. It has superior physical-durability properties that come over the FRP composites (Aljazaeri and Myers 2017a; Aljazaeri and Myers 2017b; Aljazaeri et al. 2019). For instant; the FRCM composite is not influenced by outdoor temperature, has high fire resistance and it does not produce toxic fumes under fire action as the epoxy curing agent does, Loreto et al. 2013; ACI 549, 2013; Babaeidarabad et al. 2014. In this experimental study, a unique evaluation for expanding the use of the FRCM composite in strengthening one-way slabs are presented in comparison with two known composites. The first composite is the carbon fibre reinforced polymer grid (CFRP-grid) and the second composite is the steel reinforced polymer (SRP). The aim of this study was two-fold; the first aim was to study the flexure behaviour of one-way RC slabs before and after strengthening. The second aim was to evaluate the durability performance of the composites on the flexural behaviour of the strengthened RC slabs exposed to environmental conditioning.

Materials and Methods

A total of 14 RC slabs were fabricated using ready-mix concrete in two batches. The details for the longitudinal and transverse sections through the slabs with reinforcements are shown in Fig. 1. The average 28-day compressive strength of two batches was 38 MPa (5,512 psi) based on ASTM C39 (2014) at the date of testing. The average concrete modulus of elasticity was 30,330 MPa (4,400 ksi) based on ASTM C469 (2014). The average yield strength of three rebar's was 482 MPa (70 ksi).

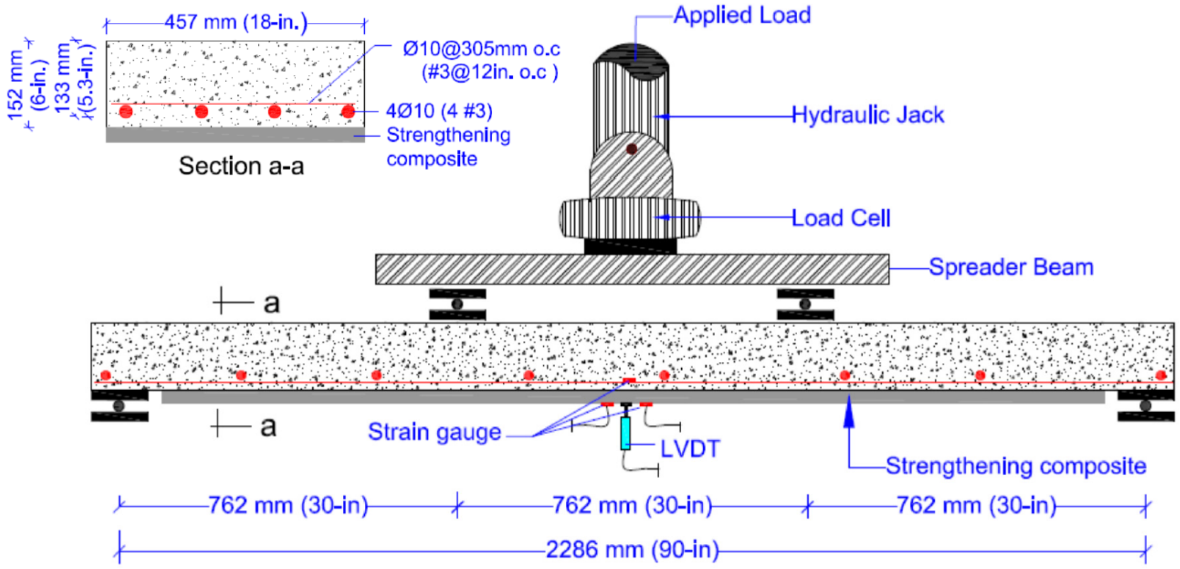

Fig. 1. Cross-section, reinforcement details and test set-up

Three composite materials were used in this study. Their reinforcement meshes are shown in Fig. 2. The first composite was the polyparaphenylene benzobisoxazole (PBO) fabric with a cement based curing agent. The second composite was the carbon fibre grid with a polymer curing agent (Sikadur 30). The third composite was the low density steel wires mesh (3x2-4-12) and epoxy adhesive (Sikadur 330). The test matrix was divided into three groups based on the type of composite material, as presented in Table 1. One RC slab served as a control slab. The other thirteen slabs were strengthened with different composite reinforcement ratios. Prior to strengthening, surface preparation was undertaken using the sand blasting method to ICRI specifications. The strengthening composite width (W_f), the axial stiffness, and the reinforcement ratio of the composites (ρ_f) were also presented in Table 1. After curing all RC slabs for 28 days, the slabs were precracked to 65% of their ultimate design capacities based on ACI 440 (2008) and ACI 549 (2013). Then, the hand-layup procedure was used to apply the strengthening composites. Three of the strengthened slabs were placed inside the environmental chamber for 72 exposure days after curing period. The exposure cycles included 50 cycles of freezing and thawing, 150 cycles of high temperature, and 150 cycles of high relative humidity. It was based on collected data from the National Weather Service and Worldwide Weather Station for Missouri weather in the United States from 1980 to 2013. Aljazaeri and Myers (2018) may be referenced for more details regarding the exposure details. The flexural test was performed monotonically at a displacement control rate of 1.3 mm/min. (0.05 in./min.), as specified in Fig. 1.

(a) (b) (c)

Fig. 2. Composite reinforcement meshes: (a) PBO mesh; (b) CFRP grid; (c) steel wire

Table 1. Test matrix for strengthening configuration and composite properties

Composite type	Specimen ID	n	Exposure conditions	W_f, mm	Stiffness kN/m*10^3	A_f mm^2/mm	A_f, total mm^2	ρ_f %
Control	C-0		Laboratory					
FRCM	G1-L-1	1	Laboratory	457	54	0.123	56	0.092
	G1-L-2	2	Laboratory	457	108	0.123	112	0.184
	G1-L-3	3	Laboratory	457	162	0.123	169	0.277
	G1-E-1	1	Environmental	457	54	0.123	56	0.092
CFRP	G2-L-1	1	Laboratory	457	81	0.150	69	0.112
	G2-L-2	2	Laboratory	457	162	0.150	137	0.225
	G2-L-3	3	Laboratory	457	243	0.150	206	0.337
	G2-E-1	1	Environmental	457	81	0.150	69	0.112
SRP	G3-L-1	1	Laboratory	305	19	0.100	31	0.050
	G3-L-2	2	Laboratory	305	39	0.100	61	0.100
	G3-L-3	3	Laboratory	305	58	0.100	92	0.150
	G1-E-1	1	Environmental	305	78	0.100	122	0.200
	G3-L-Lap*	2	Laboratory	305	39	0.100	61	0.100

* indicates that the multiple SRP layers were overlapped in this case rather than centrally stacked.

Test Results and Discussion

All of the strengthened slabs exhibited a flexural strength higher than the flexural strength of the control slab. The experimental ultimate loads were compared with the theoretical ultimate loads based on ACI 440 (2008) and ACI 549 (2013). The ultimate loads of the FRCM and CFRP strengthened slabs were around 50% higher than the theoretical ultimate loads. However, the ultimate loads of the SRP strengthened slabs were around 20% higher than the theoretical ultimate loads. Fig. 3 shows the load-displacement responses for the control slab and strengthened slabs with one, two, and three layers of the FRCM, CFRP-grid, and SRP composites, respectively. The slabs' displacement ductility index was determined to ensure adequate displacement ductility was retained after the strengthening composites reached their ultimate loads, Loreto et al. 2013; Babaeidarabad et al. 2014. The control slab had a displacement ductility index of 7.25. The FRCM strengthened slabs had displacement ductility indexes that ranged between 3.5 and 6.25. The CFRP strengthened slabs had displacement ductility indexes that ranged between 1.5 and 2.65. While the SRP strengthened slabs had a displacement ductility indexes that ranged between 3.5 and 5.8. It is clear that the FRCM and SRP composites provided higher displacement ductility with respect the CFRP composite. Different failure modes were observed for the strengthened slabs, which were influenced by the composite material type and composite's reinforcement ratio. A slippage of the FRCM composite was observed for strengthened slabs with one FRCM layer. Debonding failure mode was observed in strengthened slabs with two or three FRCM layers. All strengthened slabs with a CFRP-grid had a rupture failure mode. The slabs that were strengthened with one layer of the SRP composite had also a rupture failure mode, while the strengthened slabs with two or three SRP layers had a debonding failure mode. The ultimate load enhancement was unproportioned as the composite's reinforcement ratio increased due to a premature debonding of the composite materials out of concrete substrate. The strengthened slab with two overlapped layers of SRP composite had the same flexural behaviour as the strengthened slab with two central layers of SRP composite.

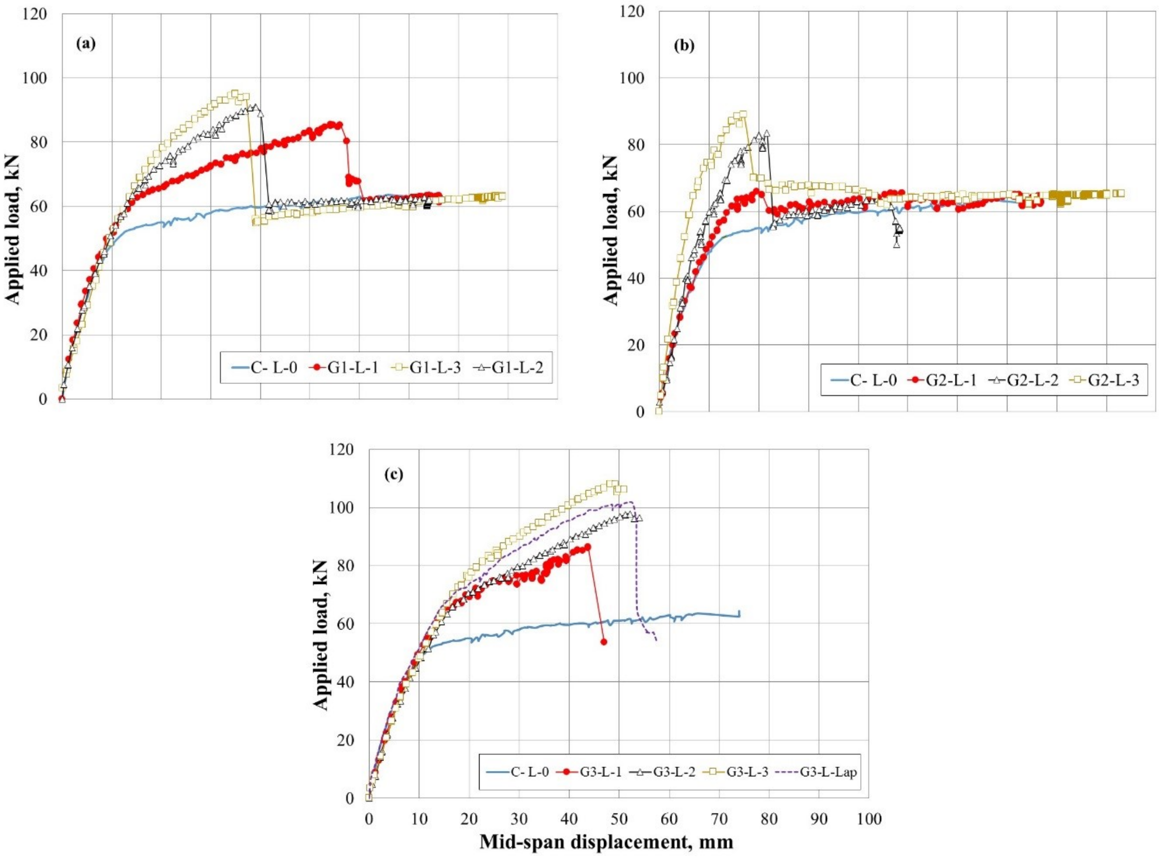

Fig. 3. Load-mid span displacement responses: (a) FRCM composite (b) CFRP composite, and (c) SRP composite

The displacement ductility of the strengthened slabs declined as the composite' reinforcement ratio increased. The SRP composite revealed improved flexural behaviour due to the high tensile strength of the steel wires and the effectiveness of its bonding agent. The strengthened slabs with the FRCM composite had lower ultimate loads compared to the SRP composite due to the premature debonding failure mode in case of using two or three FRCM layers. The CFRP-grid had a lower influence on the flexural behaviour of the strengthened slabs in spite of its higher axial stiffness and reinforcement ratio properties.

Durability Performance

The previous experimental studies that involved the influence of different composite materials on strengthening RC one-way slabs were focused only on the mechanical performance (flexure or shear) of the strengthening composites. In particular, little work to date has related to the effect of severe environmental conditioning on the flexural performance of full-scale structural members. This study provided information on the validation of the reduction factors that have been used in the ACI 440 (2008) and ACI 549 (2013) design standards. A comparison between the unexposed and exposed slabs to environmental regime cycles is presented in Fig. 4. The flexural strength of exposed slabs was generally equal to the flexural strength of the unexposed slabs although a very slight decrease was noted between the exposed and unexposed FRCM specimens. While the exposed slabs had a different displacement ductility behaviour in comparison with the unexposed slabs based on the composite material type. The FRCM exposed slab had a 13% increase in its displacement ductility with respect to the unexposed slabs. The displacement ductility improvement in the FRCM strengthened slab was due to the effect of high temperature and relative humidity cycles on curing the FRCM composite. Oppositely, the CFRP-grid and SRP exposed slabs had lower displacement ductility with respect to the unexposed ones. The high temperature cycles indicated the bond degradation in the epoxy curing agent which lowered the ductility performance of CFRP-grid and SRP exposed slabs.

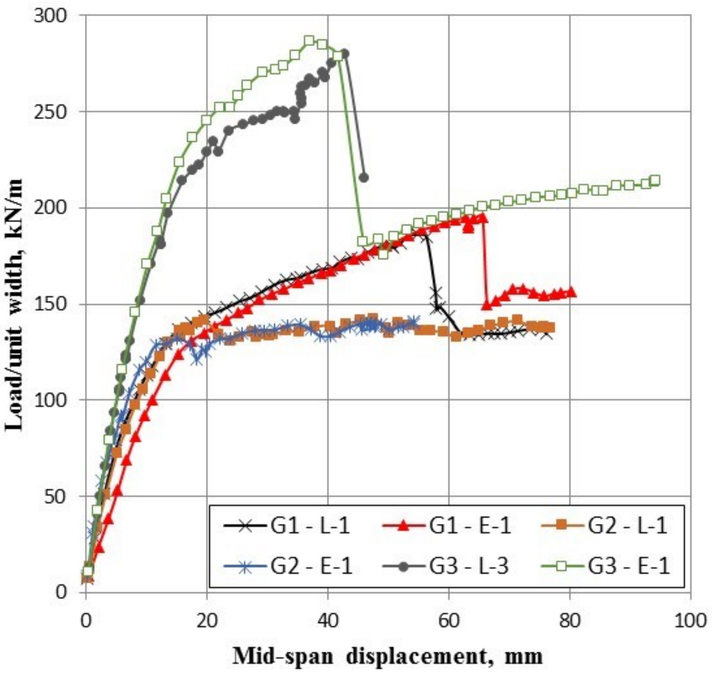

Fig. 4. Effect of environmental regime cycles on strengthened RC slabs

Conclusions

Based on the results of the experimental investigation presented in this paper, the following conclusions can be drawn:

- The flexural strength of RC one-way slabs improved by strengthening with FRCM, CFRP-grid, and SRP composites. The increase in ultimate loads were approximately 1.3 to 2 times that of the unstrengthen slab.
- Impregnation of the PBO-fabric with cementitious mortar for strengthening one-way RC slabs exhibited coinciding flexure enhancement with the SRP composite.
- Increasing the number of strengthening composite layers does not correspondingly increase the flexural strength due to the premature debonding failure mode.
- No delamination or debonding of the strengthening composites appeared in the exposed slabs due to environmental conditioning. Except for the FRCM system, the exposed strengthened slabs had the same flexural strength as the unexposed slabs. Additionally, the displacement ductility was partially influenced by the type of bonding agent.
- ACI 440 (2008) and ACI 549 (2013) predicted the ultimate flexural capacities of the externally bonded RC one-way slabs conservatively.
- No delamination or debonding of the strengthening composites appeared in the exposed slabs due to environmental conditioning.
- The exposed strengthened slabs largely had the same flexural strength that was determined for the unexposed slabs. However, the displacement ductility of the strengthened slabs was partially influenced based on the type of bonding agent.

Acknowledgements

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