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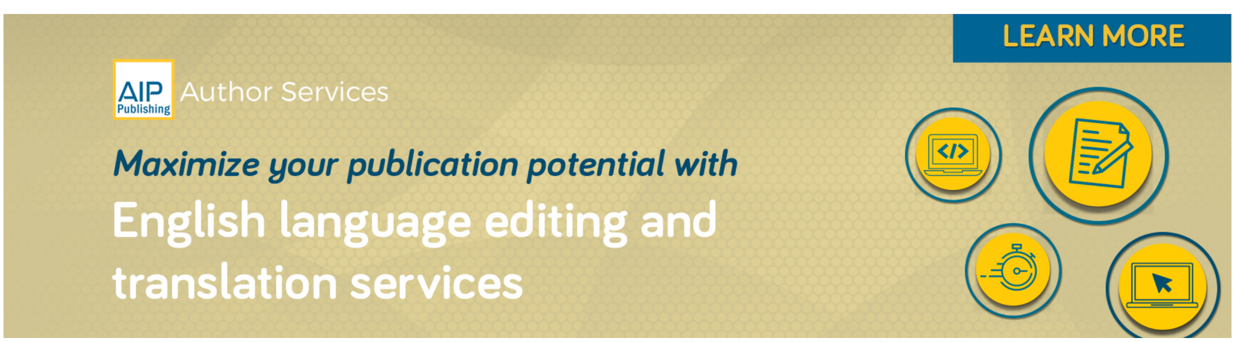

A Numerical Study on One-Way RC Slabs Strengthened with Fibre Reinforced Cementitious Mortar (FRCM)

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Abstract. In this research, a nonlinear 3D finite element (FE) has been developed to investigate the flexural performance of FRCM strengthened one-way reinforced concrete (RC) slabs. The concrete was simulated using a non-metal plasticity concrete model which can capture concrete cracking and crushing. Composite damage mechanics-based model was used to represent the rupture failure in the FRP textile within FRCM composite. In addition, a cohesive zone material (CZM) law is employed to model the bond-slip behaviour for the FRCM-concrete interface and predict potential debonding and slipping failures. The developed model is then validated against experimental results obtained from literature. The validation was performed by comparing the experimental results with the corresponding FE results in terms of ultimate load, deflection at steel yielding and ultimate load, load-deflection curves, and load-strain profiles. The comparison results showed that the FE model can capture the ultimate load recorded in the experiment with a difference of less than 10%. These results are motivating reasons to use the developed model in a further research to provide a comprehensive understanding of FRCM strengthened one-way slabs and conducting a detailed parametric study to characterize the effects of key design parameters.

Keywords: Fibre reinforced cementitious mortar (FRCM), fibre reinforced polymer (FRP); concrete; finite element, one-way slab

INTRODUCTION

Extending the service life and improving the bearing capacity of reinforced concrete (RC) elements have become a major endeavour for local, state, and federal authorities, due to effects of aging, corrosion, and extreme load events such as earthquakes and hurricanes [1]. Fibre reinforced polymer (FRP) composites, typically comprising carbon, glass, or basalt fibres embedded in an organic resin such as epoxy, are one of the most used methods for strengthening of structures [2]. Prominence of FRP in infrastructure retrofit is related to their high-strength to weight ratio, speed of application, corrosion resistance, and negligible change to the member’s size [1]. However, some drawbacks still exist with using FRP in rehabilitation, such as poor fire resistance, susceptibility to UV radiations, low reversibility, and difficulty in application when sites are subject to low temperatures or wet surfaces. These issues, which are mainly caused by using organic resins to bond FRP to concrete, have prompted the development of fibre reinforced cementitious matrix (FRCM). The new system utilizes a two-dimensional FRP grid or textile bonded to the substrate using an inorganic matrix such as cement mortar [3].

Numerous research has shown that FRCM technique can be successfully employed to enhance the bending [2, 4, 5], shear [6, 7], and torsional [8] strengths of RC beams. In addition FRCM composites have been used to improve the performance of RC elements [3, 9] and eccentric axial loads [10, 11]. However, limited attention is paid to investigating the applicability of FRCM technique in strengthening of one-way [12, 13], and two-way slabs [14, 15]. Regarding the two-way slabs, Koutas and Bournas [14] studied various parameters including the number of FRCM layers, the strengthening configuration, the fabric material (carbon or glass fibres), and the role of initial cracking in the slab. In an another study, Kim, et al. [15] investigated the effect of number of FRCM layers. In both studies, it was found that the ultimate flexural capacity of the strengthened slabs was greater than the corresponding value in un-strengthened ones by 115%-206%, depending on the number of FRCM layers and other parameters.

Regarding the strengthening of one-way slabs, limited research has been performed until today. Loreto, et al. [13] tested several RC slabs strengthened with FRCM technique and evaluated key parameters, namely concrete compressive strength and number of FRCM layers. Recently, Aljazaeri and Myers [12] performed experimental tests on FRCM strengthened one-way slabs to investigate the effects of number of FRCM layers and the effect of environmental conditioning on the strengthened slabs. Generally, the experimental results showed that the FRCM technique has a superior performance. However, general conclusion regarding the efficacy of FRCM cannot be made until more tests or numerical simulations become available and all parameters affecting the behaviour of strengthened members, such as length of FRCM layer, FRCM configuration, steel reinforcement ratio and slab dimensions, are evaluated. Also, a simple design tool to characterize the capacity of one-way slabs strengthened with FRCM is needed.

In this study, a rigorous FE model is developed for FRCM-strengthened one-way RC slabs and validated by comparing with test results from literature. The model will be used in a further research to provide a comprehensive understanding of FRCM strengthened one-way slabs and conducting a detailed parametric study to characterize the effects of key design parameters. Based on that the main aim of this research is to validate a FE model against an experimental work from literature to be used later in a further research.

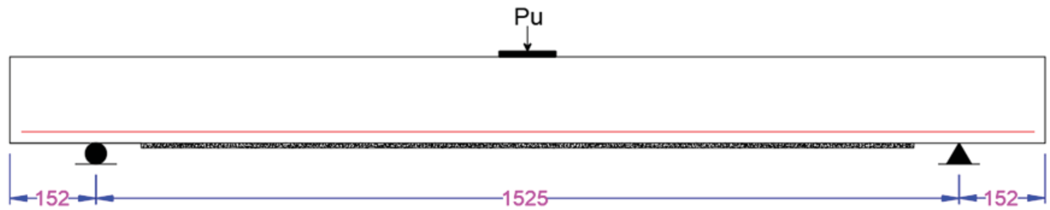
Experimental Investigation

To ensure the accuracy of the developed FE model, a validation process is carried out using the experimental study conducted by Loreto, et al. [13]. The test matrix in [13] included testing a control (un-strengthened) slab, a slab strengthened with one FRCM layer, and a slab strengthened with 4 FRCM layers. For each slab, three identical repetitions were tested for accuracy and statistical confidence. The total length of each slab was 1829 mm, with a clear span of 1524 mm. The cross section of tested slabs was (152 × 305 mm) as shown in Fig. 1 (a, b). The slabs were tested with a three-point bending configuration as shown in Fig. 1. Three linear variable differential transducers (LVDTs) were included to measure the net deflection at the mid-span section. In addition, six strain gauges were bonded to internal tension-steel, FRCM-layer in tension and concrete surface in compression, and measured strains at various load levels.

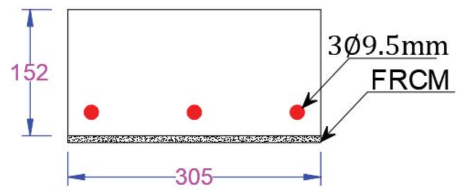
The main steel reinforcement consisted of three bars of 9.5 mm diameter with a yield stress of 414 MPa. The compressive strength of concrete was 40 MPa, determined from several cylinder tests. The FRCM system used in the experimental program consisted of dry-fibre fabric of polyparaphenylene benzobisoxazole (PBO) fibres embedded in a cementitious matrix containing Portland cement binder and polymers. The PBO fabric was made of two orthogonal strands in warp and weft directions, having a nominal thickness of 0.046 and 0.011 mm, respectively. Tensile coupons were tested to obtain the tensile response of the FRCM composite. The modulus of elasticity of un-cracked specimens and the ultimate tensile strength were 1,546 GPa and 1,058 MPa respectively.

Finite Element Modelling

The RC slab tested by Loreto, et al. [13] were numerically modelled using the commercial finite element software ANSYS 17.2. Appropriate element types and material constitutive relations were chosen from the software's extensive library to accurately represent the different parts of the RC slab, and the interaction between FRCM overlay and concrete's bottom face. Nonlinear features were implemented to enable simulating the failure modes that were observed in the experiments such as crushing and cracking of concrete, de-bonding or slippage of FRCM, and yielding of steel reinforcement.



(a) Longitudinal view



(b) Cross section

FIGURE 1. Details of tested specimens.

Eight-node SOLID65 brick element with three degrees of freedom for each node is used to model the concrete part. This element has an ability to represent cracking and crushing. The steel plates that are located at loading and support points were modelled using SOLID185 element, which is also defined by 8-nodes having 3-degrees of freedom at each node. Two-node truss element (Link180) with three degrees of freedom for each node was used to represent the steel-reinforcement. The FRCM-jacket was modelled by four-node shell element (SHELL181), having six-degrees of freedom for each node, three of which are translational and the remaining three are rotational. The interface between FRCM layer and concrete is simulated by a contact-target pair of elements, using CONTA173 (for contact surface) and TARGE170 element (for target surface). The interface's slipping and debonding behaviour which can be defined by introducing a cohesive zone material (CZM) for CONTA173 element, is discussed separately in next sections. CONTA173 is defined by four nodes with a specific number for degrees of freedom which can be set by users based on the interface behaviour. The degrees of freedom for this element type could be translations (X, Y and Z), temperature, voltage or combined between them. However, in this research it is set to translations only based on the simulated case in this research. Force and displacement confergence criteria were used with tolerance values of 0.025 and 0.01 respectively.

The uniaxial stress-strain curve developed by Kent and Park (K&P) [16] and widely used in numerical analysis of concrete structures was used to represent the compressive behaviour of concrete part. The model consists of two parts: a nonlinear ascending curve, defined by the concrete stress (f_c) and corresponding strain (ε_c), up to the compressive strength of concrete (f_c'); and a second descending line that continuous from f_c' until concrete crushes at an assumed stress of $0.2\,f_c'$. In addition to above stress-strain relation, the concrete model requires defining the open (β_o) and closed (β_c) shear transfer coefficients that are used to represent the transfer of shear forces across crack faces during loading and unloading stages, respectively. Values of 0.2 and 0.8 were used for β_o and β_c, respectively [17]. The concrete's elastic modulus (E_c) was determined from the American Concrete Institute [18] theoretical equation of ($E_c = 4700\sqrt{f_c'}$) [18]; while the Poisson's ratio was taken as 0.2 [1].

The behaviour of concrete in tension is assumed to be linear elastic prior to cracking at a maximum tensile stress of ($f_t = 0.625\sqrt{f_c'}$) [18]. Immediately after cracking, the stress is assumed to drop to a stress of $0.6f_c'$, and then continues in a linear descending fashion till reaching a stress of zero at an accompanying strain 6 times that at cracking. Further information about the concrete model can be found in the authors previous work [1, 19].

Steel reinforcement was modelled as elastic-plastic bilinear material. Besides the yield strength which is taken from Loreto et al [13] tests and reported in previous sections, the model requires defining the steel elastic modulus (E_s) and Poison's ratio (v_s). Typical values of 200 GPa and 0.3, were used for E_s and v_s, respectively [11].

The mortar was emitted when modelling the FRCM composite by shell elements because it does not contribute significantly to the FRCM's tensile force after cracking. Thus, the shell element was idealized by only the orthogonal plies representing the warp and weft directions of PBO fabric. The fabric was modelled as an orthotropic linear elastic material, utilizing the material properties reported in [13] and those from literature [10-11] for the elastic and shear moduli, and Poisons ratios. The rupture failure in the fibers was explicitly considered in this study using the composite damage model (CDM) available in ANSYS along with a failure criterion based on maximum stresses. From the several modes available for the FRP composite in CDM (e.g. shear, compression), only the tensile failure was activated using the values reported in [13] for the fibers tensile strength.

As stated previously, the concrete-FRCM interface was modelled by contact-target elements and idealized constitutively by a CZM model. The analytical bond-slip relation by Zou, et al. [20] was implemented within the CZM model to simulate potential slipping and debonding of FRCM layer. The model in Zou, et al. [20] is characterized by three parts, a linear increasing one until the maximum shear (bond) strength (τ_m) is reached at a slip (s_m), then a nonlinear decreasing one, and final part representing a constant shear stress associated with friction (matrix-fiber interlocking). Eq.s 1 and 2 can be used to determine the numerical values for τ_m and $s_{m,}$ respectively;

$$\tau_m = \frac{A^2 B E_f t_f}{4} + \tau_f \tag{1}$$

$$s_m = 0.693/B \tag{2}$$

where A and B are empirical parameters found by Zou, et al. [20] to be 0.0104 and 2.32 mm^{-1} respectively; E_f and t_f are the elastic modulus and thickness of FRP textile; τ_f is shear stress due to friction and interlocking and is equal to 0.08-0.12 MPa based on recommendations of Carloni, et al. [21].

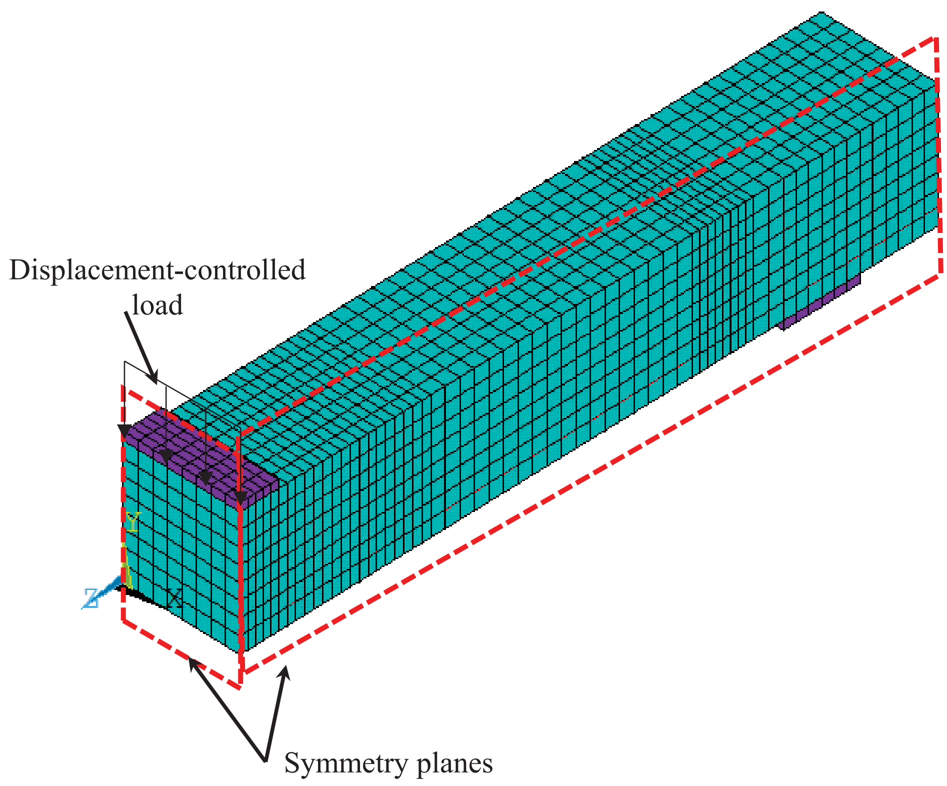


FIGURE 2. Quarter-size FE model of one-way slab.

RESULTS AND DISCUSSION

To verify the FE model predictions, the experimental results were compared with the corresponding FE results in terms of ultimate load, deflection value at yielding and ultimate load, load-deflection responses, and load-strain curves for steel and FRCM materials. Table 1 summarizes the comparison of the key results including ultimate load (P_u) and deflection at yielding (δ_y) and ultimate load (δ_u). The comparison shows that the maximum divergence between the experimental and FE results was less than 10% for the ultimate load (P_u), while it ranges between 4% and 25% for the deflection values (δ_y and δ_u). However, these differences are considered normal and might be attributed to numerical limitations (e. g., fixity of beams, materials idealization) and typical experimental uncertainties, such as a difference between reported and actual boundary conditions or material and geometric properties.

It should be noted that the experimental values of the key results represent the average of three repetitions.

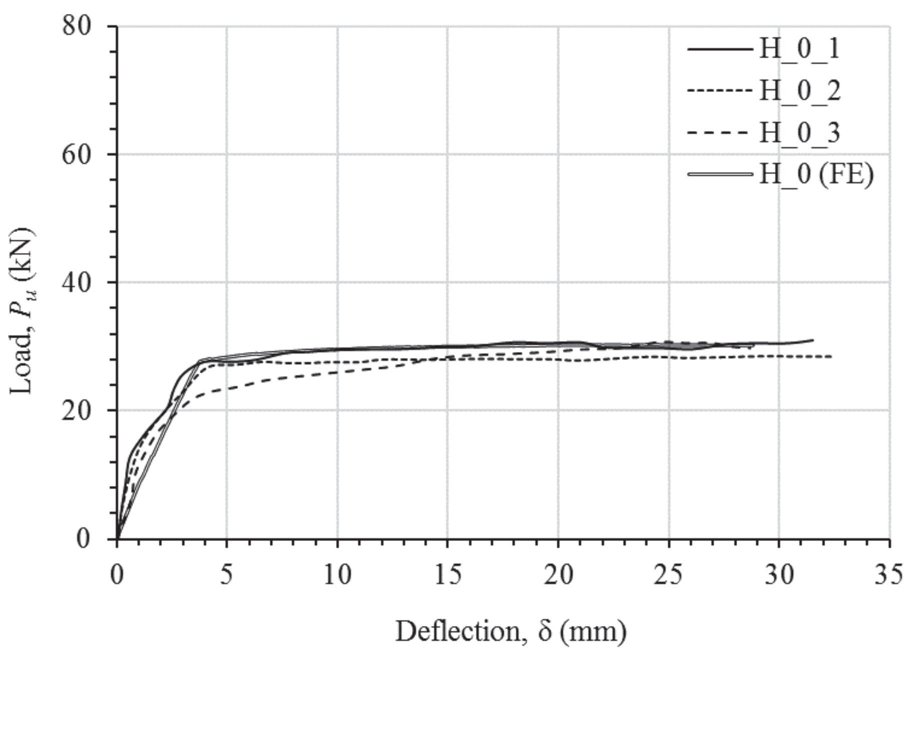
TABLE 1. Comparison between experimental and FE key results

Specimen ID	Ultimate load, P_u (kN)			Deflection at yielding, δ_y (mm)			Deflection at ultimate, δ_u (mm)		
	Exp.*	FE	Exp./FE	Exp.*	FE	Exp./FE	Exp.*	FE	Exp./FE
H-0	31.01	30.29	1.02	2.46	3.27	0.75	30.71	28.84	1.06
H-1	42.00	46.67	0.90	4.32	4.51	0.96	21.81	27.22	0.80
H-4	65.76	68.61	0.96	5.42	4.51	1.20	16.79	18.33	0.92
* All experimental values represent the average value of three repetitions									

Fig. 3 illustrates load vs deflection curves for all simulated slabs. It can be seen from this figure that the FE model is able to capture the experimental load-deflection curves with an acceptable level of correlation. The load-deflection curves consist of an elastic part which ends at yielding of the steel reinforcement. After that and for the control slabs, the beam shows a minor increase in load until crushing of concrete in compression and termination of tests. For the strengthened slabs, a noticeable increase in load occurred after steel yielding due to the contribution from FRCM composite. It can also be seen that both ultimate load and slope of load-deflection curves for strengthened slabs are significantly affected by the fabric amount (1 ply or 4 plies).

Regarding the load-strain curves in tests slabs, Fig. 4 shows the load-strain in steel reinforcement (P- ε_s) at the mid-span section. It is clear from this figure that the FE curve is in good agreement with the corresponding experimental one. The agreement in results is also noticed for the load-strain in FRCM layer (P- ε_f), at mid-span section also. The above results reflect the ability of the FE model to capture the strains of various slab components and at multiple load levels, increasing the reliability of the developed FE model.

The observations for the FE results showed that the model was also able to predict the various failure modes observed in physical tests including yielding in steel, concrete crushing and slippage in FRCM system.



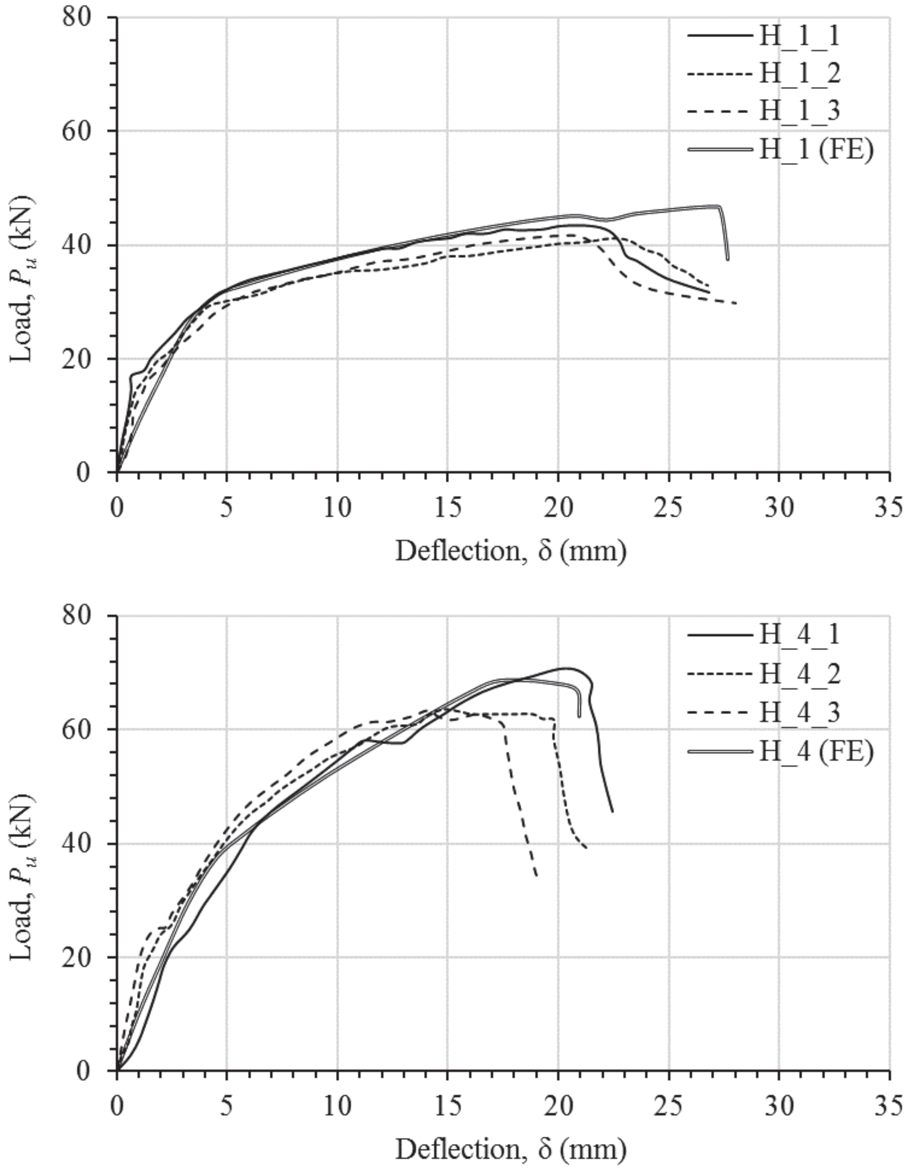


FIGURE 3. Load vs. deflection (P- δ) curves, test and FE prediction.

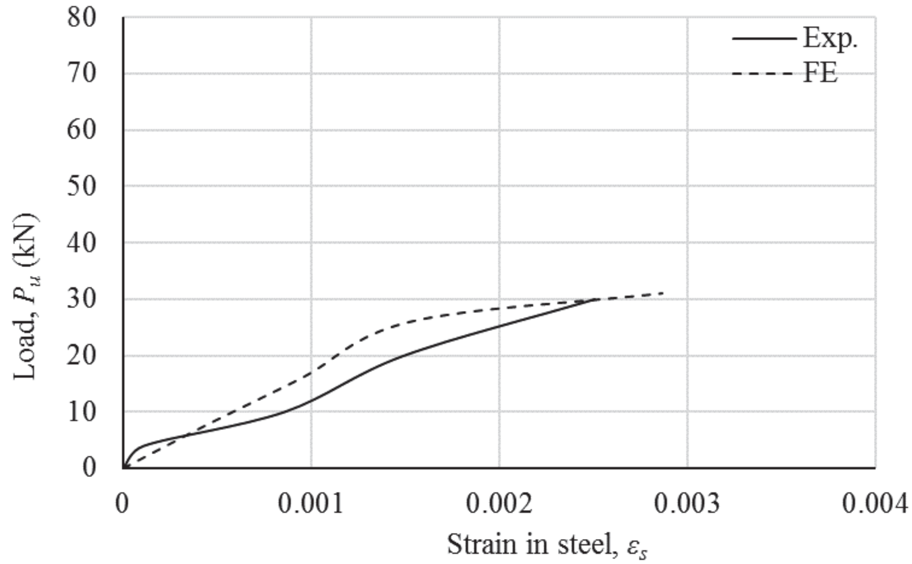


FIGURE 4. Load vs. strain (P- ε_s) curves for beam H-1.

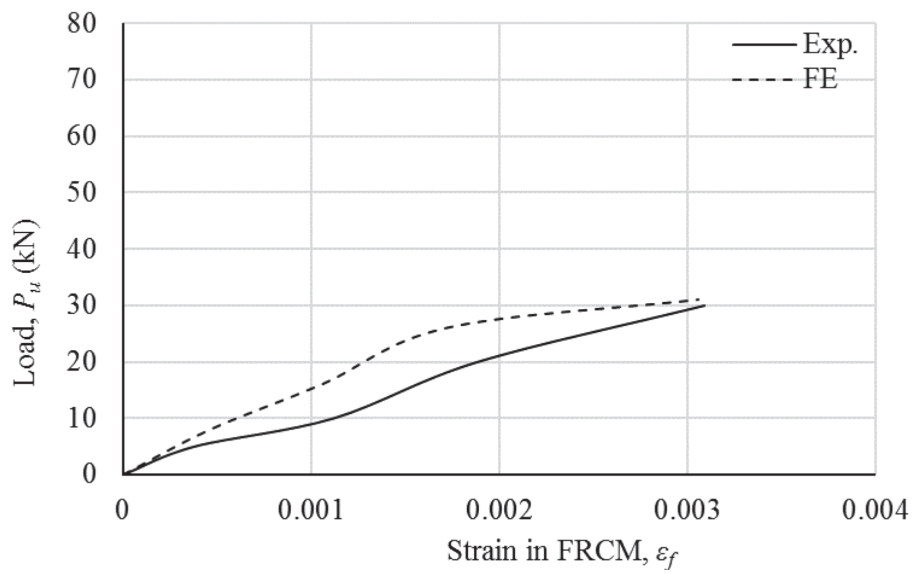


FIGURE 5. Load vs. strain (P- ε_f) curves for beam H-1.

CONCLUSIONS

Fibre reinforced cementitious mortar (FRCM), comprising fibre reinforced polymer (FRP) textiles embedded in an inorganic matrix, is an innovative retrofit technique recently developed to overcome several drawbacks related to the use of organic resins in FRP material. Although numerous studies were conducted on reinforced concrete (RC) beams and columns strengthened with FRCM system under axial, shear, flexural and torsional load, very few evaluated one-way and two-way RC slabs. In this study, a rigorous three-dimensional (3D) finite element (FE) model is developed to study the behaviour of FRCM-strengthened one-way RC slabs in flexure. The objective of this phase of the ongoing study is to verify that the modelling procedures, material, and interfacial relations selected for the slab models can reproduce the physical tests with an acceptable accuracy. Based on the results of the study, the following conclusions can be drawn:

- The model was verified by comparing with experimental tests from literature, yielding excellent predictions for different behavioural results, such as: ultimate load (P_u), deflection at yielding and ultimate load (δ_y and δ_u), load-deflection responses, and load-strain curves for steel and FRCM materials.
- The difference between model and experimental results for P_u was less than 10%, while it ranged between 4% and 25% for δ_y and δ_u. The model was also able to predict the various failure modes observed in physical tests.
- The validated model will be used in an extensive parametric study to evaluate the effects of several key parameters and aid in developing a simple design equation for the FRCM strengthened slabs.

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