Parametric Optimization of RC Beams Strengthened with FRCM Using FE Modelling and Response Surface Methodology

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Abstract

This study focuses on the numerical and statistical analyses to predict the mid-span moment capacity of RC beams strengthened with fabric reinforcement cementitious mortar (FRCM) laminate. A finite element model (FEM) has been built to simulate twelve RC beams strengthened with two types of FRCM, namely Polyparaphenylene benzobisoxazole (PBO) FRCM and Carbon (C) FRCM. The FE models were verified based on experimental work available in the literature. The finite element models have shown a good agreement with experimental results in terms of maximum load-carrying capacity, load-deflection curves, and concrete strain values. The numerical simulation was followed by a parametric study on 42 models using face centred response surface methodology (RSM). Combining FEM and RSM, a novel mathematical model has been proposed to predict the mid-span moment capacity of the RC beams strengthened with FRCM. The results of the proposed model have shown optimal predictability with R^2 equal to 90.34%. In addition, the proposed model agreed with the ACI design procedures and the existing literature.

Keywords: FEM; Nonlinear modelling; FRCM; Strengthening; Response surface method

1 Introduction

Textile reinforced mortar, also known as fabric reinforced cementitious matrix (FRCM), is a material that consists of fabric grids made of fibers such as carbon, glass, and PBO Polyparaphenylene benzobisoxazole (PBO) embedded in mortar (Awani et al., 2017). These fabric grids are mounted on a concrete surface and their grid geometry allows the penetration of mortar, creating an interlocking between the matrix and the host surface. The use of FRCM in strengthening reinforced concrete (RC) structures has many advantages, including higher durability and greater bond efficiency (Al-Lami et al, 2020; Ebead & Wakjira, 2018; Elghazy et al., 2018; Wakjira & Ebead, 2019; Wei et al., 2022; Younis et al., 2017). There is a significant amount of literature on the experimental use of FRCM in various structural applications, such as flexural strengthening, shear strengthening, and durability, and these studies have shown improvements in ultimate load-carrying capacity and durability (Aljazaeri & Myers, 2017; Azam & Soudki, 2014; Babaeidarabad et al., 2014; Ebead et al., 2017; El-Sherif et al., 2020; Elghazy et al., 2018; Kadhim et al., 2022; Pino et al., 2016; Wakjira & Ebead, 2018).

However, there has been less research on numerical studies of FRCM, and the numerical models that have been developed have primarily been used to verify experimental data. This is in contrast to traditional finite element (FE) models, which are often used to predict the behavior of a system before it is built or tested. In this context, the authors of the paper are proposing the use of response surface methodology (RSM) to update the FE model of an FRCM-strengthened RC beam and improve its predictive accuracy. RSM is a statistical approach that can be used to model the relationships between multiple input variables and an output variable, and it can be used to optimize the performance of a system by identifying the optimal values of the input variables.

The proposed RSM-based FE model is then validated using experimental data and compared to a traditional FE model. The results show that the proposed RSM-based FE model has improved predictive accuracy and can be used to accurately predict the behavior of FRCM-strengthened RC beams. This means that the model can be used to design FRCM-strengthened RC beams without the need for physical testing, potentially saving time and resources. Overall, the use of RSM to update the FE model of FRCM-strengthened RC beams represents an important step forward in the use of numerical modeling to predict the behavior of these structures. A graphical representation of the process followed in the presented study is shown in Figure 1.

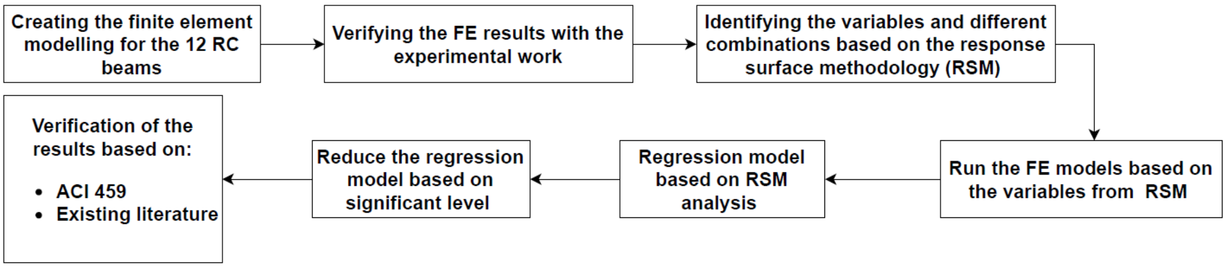


Fig. 1: Flow chart of the proposed methodology

2 Summary of the Prevous Experimental Study done by (Ebead et al., 2017)

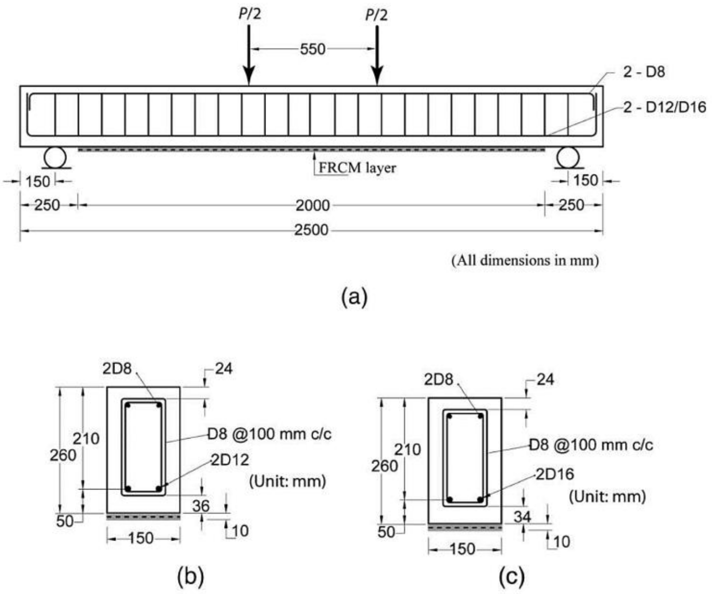
2.1 Experimental Dataset

A total of twelve RC beams were strengthened in flexural form using two types of FRCM (PBO-FRCM and C-FRCM) based on a previous study (Ebead et al., 2017). The experimental dataset of the RC beams was chosen according to the following criteria: (a) experiment-based tensile constitutive relations for (PBO-FRCM and C-FRCM) were used allowing for an accurate FE model; (b) The beam details such as reinforcement, and material properties, surface preparation for the strengthening and dimensions were accurately known; and (c) concrete strains, load-deflection curves, and failure modes were clearly presented.

In the experimental work, the RC beams were tested under four points pending load. All beams had a rectangular cross-section of 150 mm × 260 mm and a length of 2500 mm with a clear span of 2000 mm. Reinforcement consisted of two steel bottom and top bars. The bottom bar size was varied between 12 mm and 16 mm to consider the reinforcement ratio as a study parameter, namely ρ_s(D12) =0.72% and ρ_s(D16) =1.27%. 8-mm diameter stirrups spaced at 100 mm were used, the schematic drawing for the RC beam is shown in Figure 2.

2.2 FE analysis

A total of twelve 3D models were built using the finite element software ABAQUS 6.14 (Smith, 2009).A 30 mm mesh size has been used after doing a mesh sensitivity study. The reference beams in the experimental work were simulated as a benchmark for the FE models as illustrated in Figure 3, followed by adjusting the FE models based on parameters investigated in the experimental work. To increase the reliability of the FE model a mesh sensitivity study was conducted and therefore a mesh size of 30 mm was selected and applied for all the simulated beams.



(a)

(b) (c)

Fig. 2: Experimental beam details (Ebead et al., 2017).

2.3 Material Models

The concrete damage plasticity (CDP) model has been used for concrete while an elastic perfectly plastic model has been used for the steel rebar and the FRCM shell.

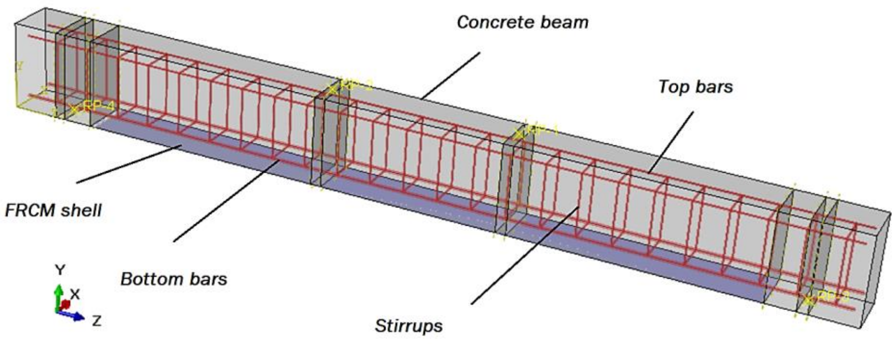


Fig. 3: Numerical beam 3D view

2.4 Boundary conditions and interactions

The overall assembly of the applied boundary conditions is shown in Figure 4. Constraints were applied to the reference points (RP) that have been assigned to the indicated regions and constrained with tie constrains. For RP4 and RP3, only transitional restrain in the y-direction has been assigned to provide the roller restrain effect used in experiment. The out-of-plane movement was restrained by locking the z-transition along the end faces. The load has been applied to points RP1 and RP2 as incremental displacement in the negative y-direction.

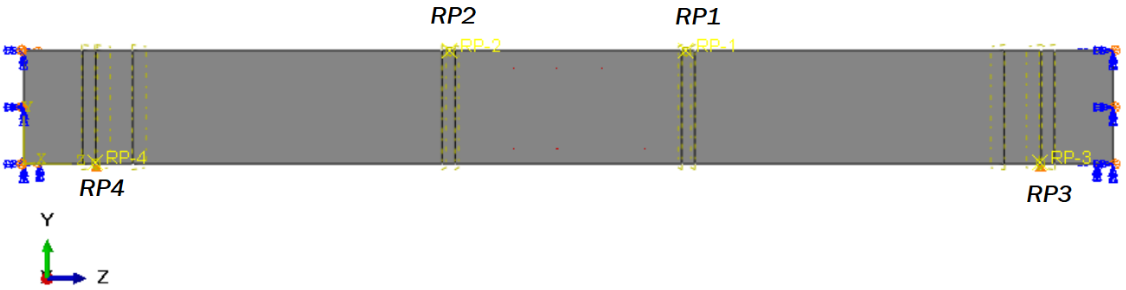


Fig. 4: Boundary conditions applied to the numerical model

3 Methodology

3.1 RSM analysis

Response surface methodology (RSM) analysis has been used to develop a mathematical equation that can be used to predict the mid-span moment capacity.

A face-cantered design (FCD) approach is adopted here. The selected parameter and levels of each are shown in Table 1.

Table 1: Variables level for RSM analysis

Variables	Description	Low	Mid	High
R (%)	1000ρ	7.18	9.94	12.7
Fc (MPa)	$\frac{F_c'}{10}$	3	4.85	6.7
Kf (MPa)	$10 \times K_f$	2.3	7.8	13.3
D (mm)	$\frac{d}{100}$	26	31	36
L (mm)	$\frac{L}{100}$	22	26	30

3.2 FE analysis

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4 Results and Discussion

4.1 Load-deflection responses

The comparison of the load-deflection curves of the experimental and the FE analysis is shown in Figure 5. It can be observed the well-predicted load-deflection curves and maximum load capacity resulted from the FE analysis in all FE models.

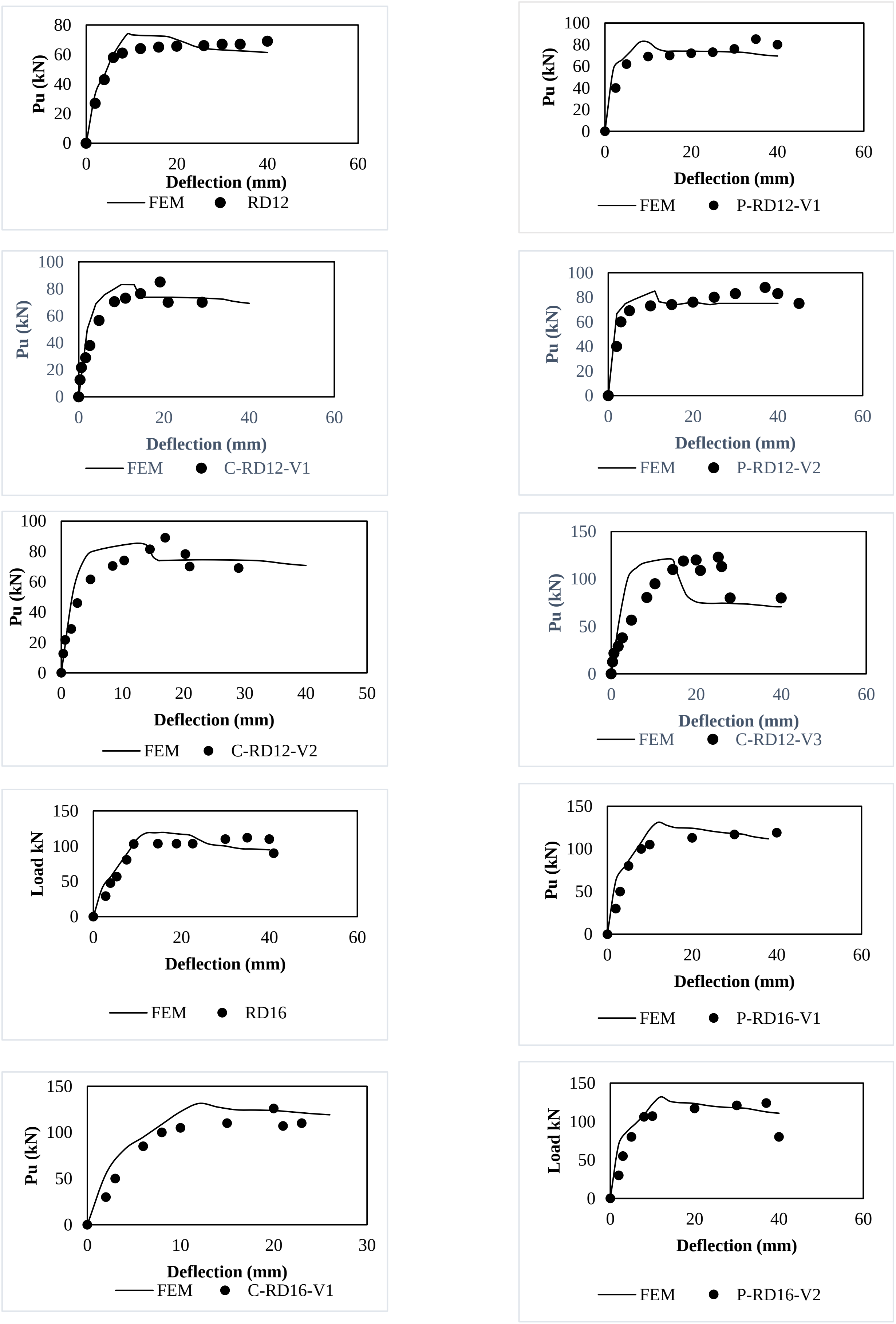

Fig. 5: Maximum load capacity curves for 10 numerical beams

4.2 RSM results

A total of 42 numerical models have been built to conduct the required statistical combinations and runs. A response surface regression in Eq. (1) has been generated with a significant level of 0.05.

$$Mu = 106.4 - 11.64R - 20.71Fc - 7.05K_f - 2.62D - 0.64L + 0.541R \times D + 0.453Fc \times K_f + 0.69Fc \times D + 0.275K_f \times L \qquad (1)$$

It can be observed that there are no second-order effects in the study parameters. However, four interactions between R, D, F_c', K_f and L have a significant effect.

4.3 RSM model verification

The generated equation has been compared with the results obtained in several experimental works from literature as shown in Table 2.

Table 2: RSM comparison with experimental work

Reference work	Considered sample	Mu - Experiment (kN-m)	Mu-predicted (kN-m)	Absolute varince (kN-m)	Percentage (%) variance
(Hashemi & Al-Mahaidi, 2010)	MSF	46.3	45	1.3	3%
(Ombres, 2011)	S1-T1-P1-1	39.2	36.6	2.6	7%
(Haustein et al., 2012)	sample 2	79	55	24	30%
(Babaeidarabad et al., 2014)	L-4	24.2	37	12.8	53%
(Jung et al., 2015)	B2	33.1	39	5.9	18%
(Akbari Hadad et al., 2020)	FB-6k-4P	50.8	49	1.8	4%

Furthermore, a comparison with the moment value obtained from following ACI code procedures has been generated and plotted against the results obtained from the RSM equation and the FE models as shown in Figure 7.

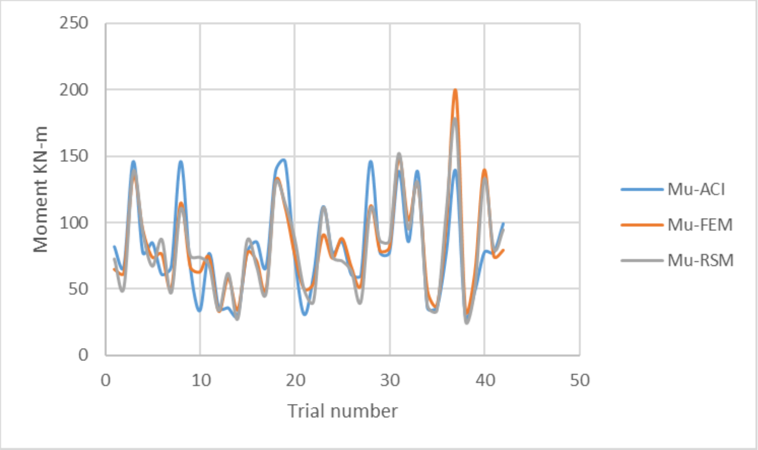

Fig. 7: Moment results comparison

Both comparisons showed a good agreement with the results obtained from the FE procedures and the RSM. However, the moment values from ACI design codes are overestimated (safer) in the cases where the maximum moment is above 100 kN-m. This can be attributed to the assumption of full bond between concrete and FRCM layers by the ACI equations that ignores the debonding and slippage of FRCM.

5 Conclusions

In this study, numerical and statistical analyses of 12 RC concrete beams strengthened with different types and layers of FRCM laminate has been carried out. The non-linear finite element simulations used concrete damage plasticity constitutive model for concrete. The study parameters included FRCM stiffness, number of laminates, reinforcement ratio, beam depth and clear span. The following conclusions can be drawn:

1. The proposed equation to predict the mid-span moment of RC beams strengthened with FRCM is of high accuracy and has been validated using available experimental data in the literature and using code provisions and guidelines.
2. The response surface methodology along with the finite element modeling can be used to optimize parameters and conduct virtual experimentation with high accuracy.
3. The proposed equation has best accuracy for the cases where the loading scheme and test setup matches the one in this study. However, further investigation is needed to generalize the equation for other cases.

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