International Journal of Engineering & Technology, 7 (4.19) (2018) 629-635

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Shear Strengthening of RC Beams with FRCM Technique

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Abstract

Nowadays, utilizationof Fibre Reinforced Polymer (FRP) in rehabilitation and strengthening of Reinforced Concrete (RC) beams is commonly used with a proper type of epoxy. Fabric Reinforced Cementitious Material (FRCM) presentsan alternative technique instead of the traditional epoxy. This paper investigates the shear performance of RC beamsusing FRCM strengthening.
Finite Element method was adopted in modelingthe FRCM strengtheningfor RC beams in shear using ANSYS software with nonlinear and 3D analysis. In the beginning, the FE model was verified through comparing with the tests in the literature in terms of load-mid span deflection response, ultimate load, strain readings of reinforcement at mid-spanand the mode of failure. It was found that the FE model was capable to capture the behavior of FRCM strengthened RC beams with a high level of accuracy. This validated model has been employed later in studying some of parameters which have a potential effecton efficiency of this technique such as concrete compressive strength, number of fiber layers, and the arrangement of the fiber. Generally, it was found that the concrete compressive with high strength has significant impact in increase the efficiencyof FRCM strengthening system.

Keywords: *RC beams; fabric reinforced cementitious mortar; finite element.*

1. Introduction

Unexpected increase in loads and exposure to environmental conditions for long periods leads to deterioration of structural elements. In order to increase the length of service of concrete structures to longer service periods, the civil engineering community proposed several research involving various strengthening systems such as fiber reinforced polymer (FRP) technique[1-3],ferrocement, Textile Reinforced Mortar (TRM), TextileReinforced Concrete (TRC), the Mineral Based Composites (MBC), the Fiber Reinforced Concrete (FRC) and the Fiber Reinforced Cementitious Mortar (FRCM)[4].The FRCM techniquecomprises of fabric meshes with dry fiber strandsdistributed along two perpendicular directions bonded to concrete surfaces with cement based mortar.In the previous period, FRCM technology has contributed to the rehabilitation of many different concrete element[5].
In 1990, Curbach and Jesse [6]conducted the first study to the FRCM technique in strengthening concrete elements, after which the technique was used extensively. The FRCM technique has reduced the problems encountered when using the FRP system. The study showed that the mortar-based cement as bindingagentin FRCM systems ismore compatible with the concrete substrate compared to epoxy resins used in externally bonded FRPs. In addition, there was no failure in binding mortar at relatively high temperatures which can make the FRCM system is competitive to usein high temperature applications.Furthermore, FRCM systemcan accommodate a recycled cementwhich helpin providing a sustainable product with low environmental impact[7]. Several studies have been conducted to investigate theefficiency of the FRCM technique instrengtheningof RC columns[8], RC beams in flexure[9], torsional members[10] and RC beams in shear[11]. Overall, the outcomes of these studies showed significant improvements in load capacity and deformation characteristics of strengthening RC members compared to unstrengthening elements.
Some studies [11-13]investigated the shear contribution of FRCM technique in strengthening RC beams. Generally, it found that the FRCM technique is very powerful in strengthening the RC beams in shear. However, there were some parameters did not investigated such as concrete compressive strength, number of layers, and the configurations of the FRCM system.
The current work aims to create a database for FRCMstrengthening in shear and provide a numerical model FE to predict the behavior of strengthened RC members. The FE results were compared with laboratory results conducted byAzam, et al. [11]. Several variables were conducted in the current research in order to provide a comprehensive understanding of the effects of those variables on the performance of this process. Thus, it can provide a useful design guideline of FRCM systems in practicefor shear applications.

2. Experimental description of test conducted by Azam et al. [10]

Six full-scale beams were prepared and tested under two point loads until failure [11]. The experimental study consists of three reference beams, one without shear reinforcement and two with different ratios of shear reinforcement, and threeFRCM strengthened beams. All beams had the same cross section 400mm×250mm with2700mm of length. The longitudinal reinforcement consisted of six bars 25 mmin diameterthat were positioned at the tension zone while three bars were positioned at the compression zone of beam section as shown in **Fig**. Reinforcement with 6mm of diameter was used for shear and was distributed as listed in

Table 1.The concrete of beams was 61MPa of compressive strength. Theyield strength was494MPa and 365MPa for longitudinal and transverse steelrespectively.The ultimate strength of carbon fiber used in FRCM system (without mortar) 325kN/m and 250kN/m for the vertical and horizontal directions respectively. The modulus of elasticity, bond strength and tensile strength of the mortar properties were 21GPa, 10MPa and 3.5MPa respectivelyas listed in the manufacturer leaflet.

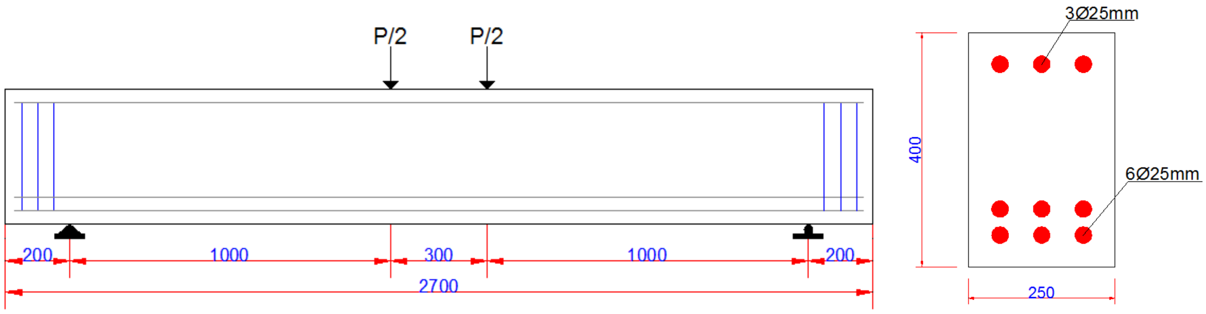


Fig. 1: Beam geometry, boundary conditions and reinforcement details.

Table 1: Details of tested samples

Beam label	Longitudinal reinforcement		Shear reinforcement	
	Tension steel	Compression steel	Steel	FRCM
S0-N	6Φ25 mm	3Φ25 mm	None	None
S250-N	6Φ25 mm	3Φ25 mm	Φ6@250mm	None
S150-N	6Φ25 mm	3Φ25 mm	Φ6@150mm	None
S0-CM	6Φ25 mm	3Φ25 mm	None	CFRCM
S250-CM	6Φ25 mm	3Φ25 mm	Φ6@250mm	CFRCM
S150-CM	6Φ25 mm	3Φ25 mm	Φ6@150mm	CFRCM

3. Finite Element Models

SOLID65 element with 8 nodes was used for concrete and cement mortar modeling. This element has the ability of crushing under compression and cracking under tension so it is suitable for concrete and cement mortar representation[10]. SOLID65 has three degrees of freedom at each node. The three-dimensional LINK188 component is used to represent flexural and shear reinforcement. This element has the ability to represent the distortion that occurs in the steel. In the modeling of carbon fabric, SHELL181 was used that is suitable for modeling the thin/moderate thick shell structures[10]. It has four-node element with six degrees of freedom at each node.

3.1. Material Modelling

3.1.1. Concrete

Kent and Park [14]suggested a nonlinear stress-strain model, used to represent compressive behavior of concreteup to the ultimate strength ($f_c^{\prime}$) as shown in Figa. The mathematical formulaof the model can be expressed as:

$$f_c = f_c^{\prime}\left[2\left(\frac{\varepsilon}{\varepsilon_0}\right) - \left(\frac{\varepsilon}{\varepsilon_0}\right)^2\right] \quad (1)$$

$$\varepsilon_0 = \frac{2f_c^{\prime}}{E_c} \quad (2)$$

Where, f_c is the nominal compressive stress of concrete.The ACI 318 [15], determines the following equation (3) for computing the concrete elastic modulusE_c.

$$E_c = 4700\sqrt{f_c^{\prime}} \quad (3)$$

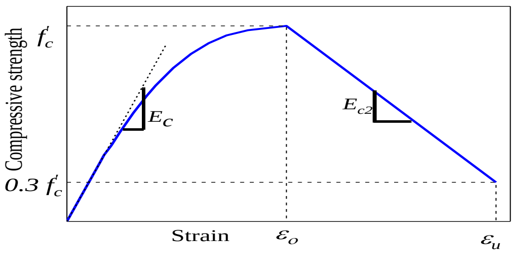
Compressive stresses in the concrete when they reach $f_c^{\prime}$, after which the concrete behavior imposes a partially confined material due to the lateral resistance that comesfrom the steel stirrups and/or FRCM.Chansawat, et al. [16]suggested the post-peak behaviour for concrete beams reinforced in shear by steel stirrups and/or FRCM. The slope of the descending line (E_{c2}), see Figa, can be determined as in equation (4). The concrete stress at the termination point is $0.3f_c^{\prime}$.

$$E \quad (4)$$

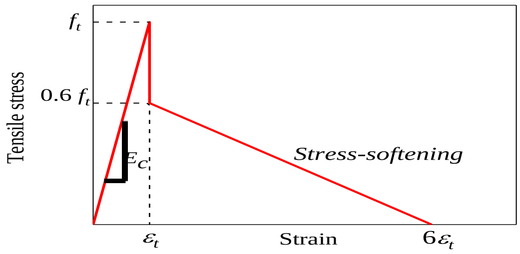
The tensile stress-strain behaviour of the concrete before onset of crackingcan be expressed as in equation (5) to calculate the tensile stress [15].

$$f_t \quad (5)$$

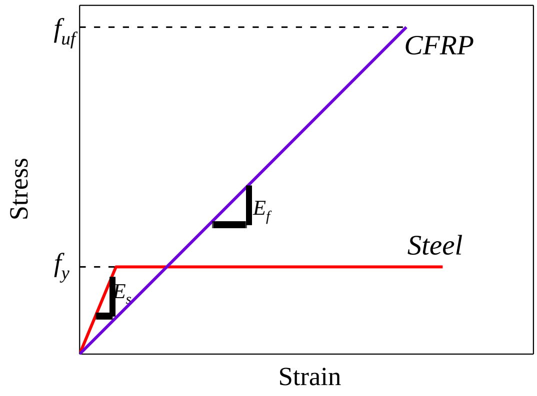
At a strain of $6\varepsilon_t$, the linear descending curve was used to represented tension-softening effects, see Fig b. The Poison's ratio and shear transfer of concrete were assumed 0.2 and 0.3 respectively in the analysis.



(a) Concrete in compression



(b) Concrete in tension



(c) Steel and CFRP reinforcement

Fig. 2: Constitutive material models

3.1.2. Steel Reinforcement

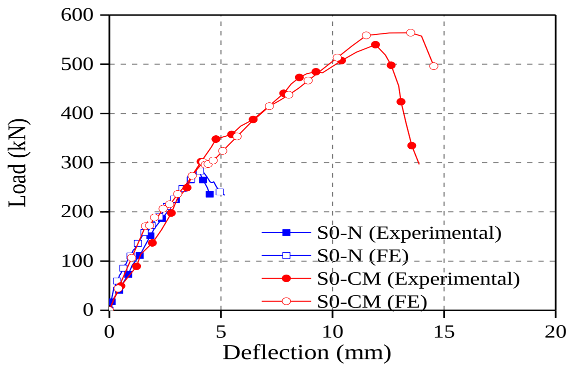
The steel material of the flexural and shear reinforcement was assumedto be elastic-perfect plastic behaviour as shown in Figc with200GPa of modulus of elasticity (Es) and 0.3 as a Poisson's ratio (ν). The yield strength values were 494 and 365 MPa for longitudinal and transverse steel, respectively.

4. Validation of FE Model

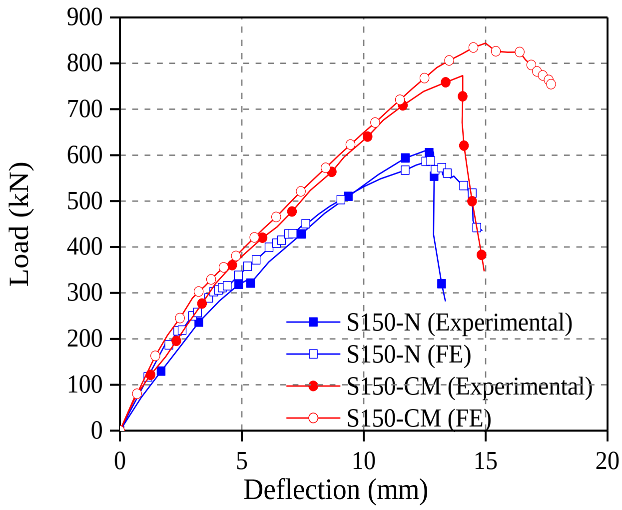
The results of the numerical model were compared with the available practical results to verify the precision of the FE model. The results included the load-deflection curve, the maximum load, and the failure pattern. To ensure accurate results in the FE model, the authors used different types of mesh size. It was found 25 mm mesh size provided divergence less than 1% compared to the finer mesh sizes.

Figpresents the load-deflection relationships for both the experimental and numerical results. The results revealed that the numerical model can capture the tests behaviour with a high level of accuracy. In addition,

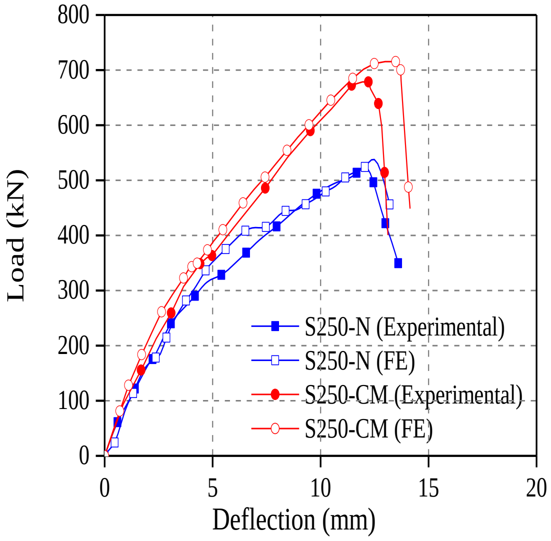
Table 2 summarises a comparison between the ultimate load obtained from the experimental and numerical model. It can be concluded from this table that the numerical model was able to predict the ultimate load with 9.5% maximum divergence. It can also be seen from this table that the error in predicted deflection at ultimate load was 6.4% in maximum. Similarly, the predictions of the strain in the longitudinal reinforcement at mid-span at the ultimate load were also in good agreement when compared to the corresponding data obtained from experimental results.



(a) S0



(b) S150



(c) S250

Fig. 3: Comparison of load-deflection curves obtained from the FE model and experimental results

Table 2: Summary of the FE and experimental key results

Beam label	Ultimate load (kN)			Deflection at ultimate load (mm)			Strain in longitudinal reinforcement at mid-span at failure (με)		
	Exp.	FE	%	Exp.	FE	%	Exp.	FE	%
S0-N	287.5	283.9	1.3	4.0	4.1	-2.5	1073	1018	5.1
S250-N	520.3	537.6	-3.3	12.1	12.5	-3.3	1870	1905	-1.9
S150-N	613.9	588.0	4.2	12.7	12.8	-0.8	2595	2672	-3.0
S0-CM	538.3	564.0	-4.8	12.3	12.5	-1.6	2227	2185	1.9
S250-CM	678.7	715.4	-5.4	12.4	13.0	-4.8	2874	2572	10.5
S150-CM	771.0	843.9	-9.5	14.0	14.9	-6.4	3021	2784	7.8

% = ((Exp. - FE)/Exp.) ×100%

In term of failure mode, Figshows the comparison between the failure modes obtained from experimental and FE results for beams S250-N and S250-CM. This figure demonstrates that the FE model was able to capture the failure mode (shear failure) in reasonable agreement. For instance the average angle of the main failure crack was 48° as reported in the experimental work for beam S250-CM. The corresponding angle was about 43.3° as obtained from the FE simulation.

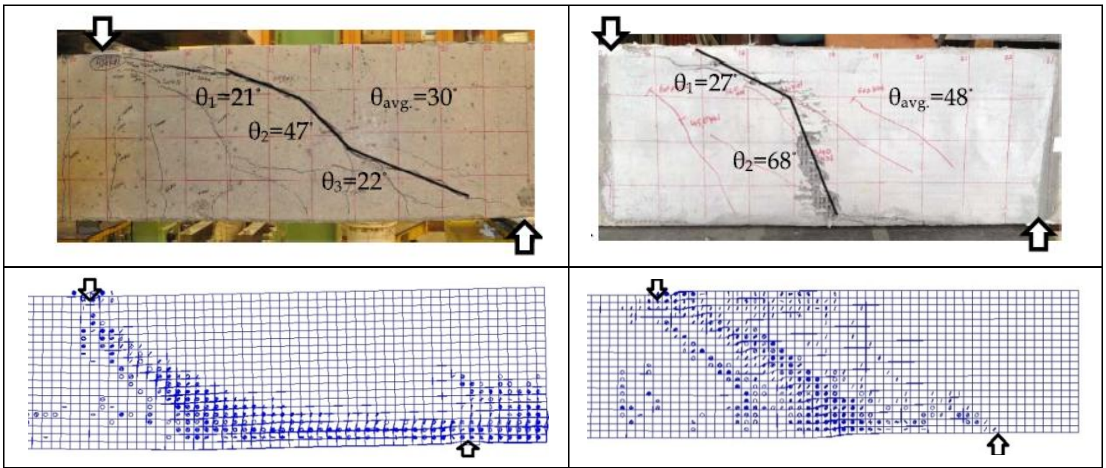


Fig. 4: Failure modes for beams S250-N and S250-CM

It can be concluded from this section that the FE model is able to capture the entire behaviour of FRCM strengthened RC beams in shear. This conclusion is drawn based on the excellent agreement obtained from comparison the FE model with the corresponding experimental data.

5. Parametric Study

5.1. Concrete Compressive Strength

The concrete compressive strength in the current research varied from (20 to 60) MPa. Beams S250-N and S250-CM were used in this and all other parameters.
It is clear from
Figthat the ultimate load of the analysed beams was increased as a result of the increase in the concrete compressive strength of the RC beam. However, the percentage of the increase of ultimate load was various based on the value of the concrete compressive strength of RC beam. It can also be seen from
Figthat the increase in concrete compressive strength led to a significant improvement in the contribution of FRCM technique.

The main reason for this variation is that with the lower concrete compressive strength the separation more likely occurred in the concrete cover which causes in some cases full separation to the strengthening system.

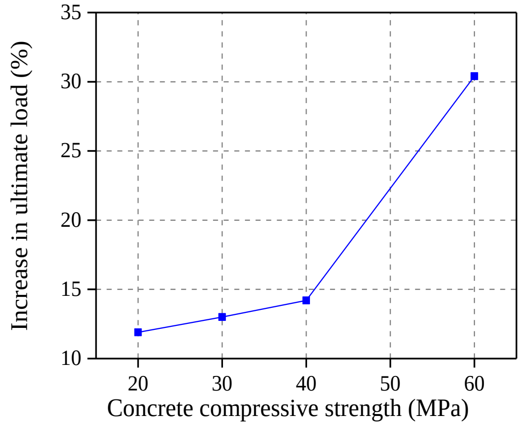


Fig. 5: The increase in the beams' ultimate load against concrete compressive strength

5.2. Number of Fabric Layers

In order to investigate the number of fibre layers, two more configurations are suggested comprising 2 and 4 layers. Beam S250-CM is employed to undertake the effect of this parameter. It is assumed all other properties of the beam are kept constant and the change is only made on the number of the fibre layers.

The simulation results illustrates that the increasing in the number of fibre layers leads to improve the contribution of the FRCM strengthening technique in shear. It can be noticed from Figthat the ultimate load is increased with the higher number of fibre layers and this increase was usually linear. In other words, the increase in the ultimate load as a result of doubled the number of fibre layers from 1 to 2 and from 2 to 4 is about 2.5% and 4.9% for RC beams strengthened with two and four fibre layers respectively compared to the beam strengthened with one fibre layer. It can also be seen from this figure that the increase in the fibre layers causes a reduction in the beam ductility. This reason for this is related to the fact that the increase in the fibre layers caused an increase in the beam stiffness due to the higher fibre modulus of elasticity (230 GPa in this study) compared to concrete (about 37 GPa).

Another important observation is the changing in the fibre layers does not change the failure mode for the simulated samples when all the simulated samples failed in shear. This is related to the fact that the theoretical flexural capacity of this beam – which was strengthened with 6Φ25 mm in tension zone and 3Φ25 mm in compression zone – was 811 kN. Thus, it is not expected to have a different failure mode since the ultimate load does not reach the theoretical flexural capacity of the beam.

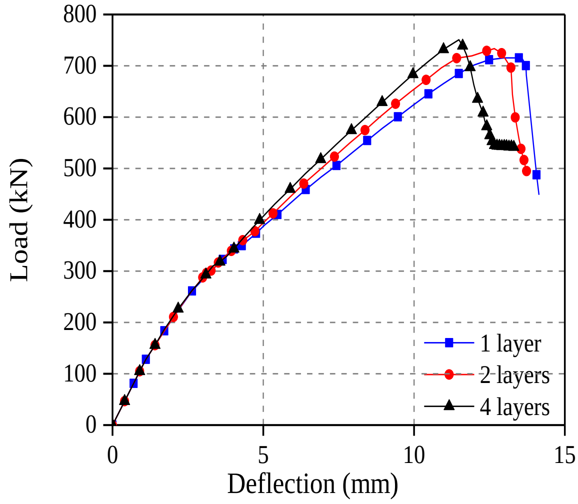
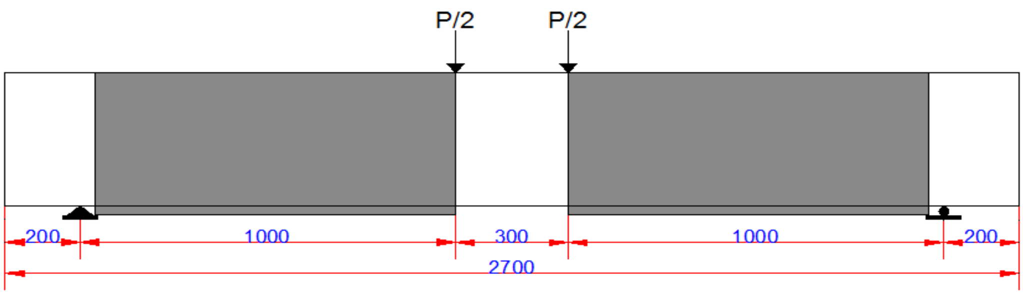


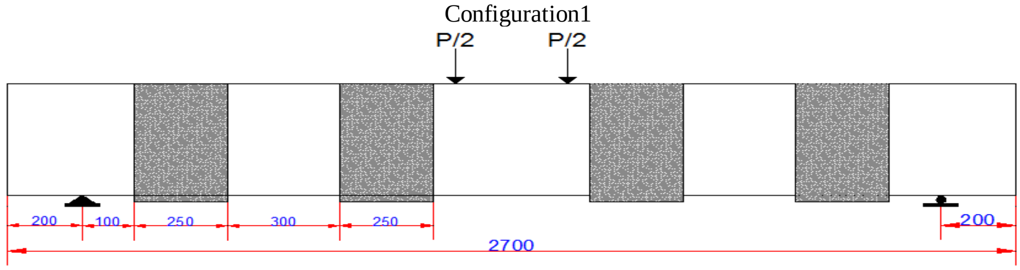
Fig. 6: Effects of the number of fabric layers on load deflection curve

5.3. FRCM Configuration

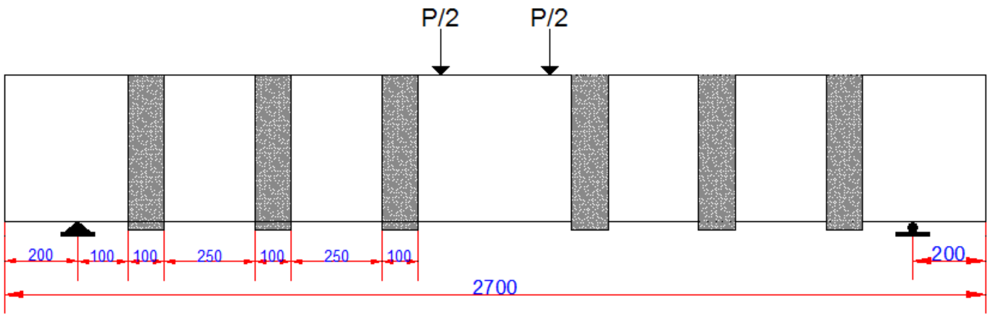
In all beams investigated in the present research the distribution of fibre was identical as mentioned in Section 2. In order to find the optimum fibre distribution, several fibre arrangements was examined in this subsection as shown inFig. This distribution was undertaken by keeping the amount (volume) of fibre as a constant and the change was only made on dimensions of the fibres. In addition, in the simulated experimental work the FRCM system was wrapped around three sides of RC beams as a U-shape. However, the fibres in the bottom face of RC beams do not have a significant effect on the shear resistance. Thus, one of the parameters examined in this subsection is comparing the response of RC beams strengthened with fibre located on the beams' sides only with that having fibre wrapped around three sides of the beam (U-shape).



Configuration1



Configuration 2



Configuration 3

Fig. 7: RC beam strengthened with different FRCM configurations

The simulation results demonstrated that bonding fabric as in "Configuration 1" leads to have the best performance compared to the other configurations as shown in Fig. This partly caused as a result of the extensive cracks that appears in the cementitious material for samples using configurations 2 and 3 which is more likely occurred in the case of thicker fabric layer [17]. Another reason was that the amount of fibres was kept constant but the bond material (cementitious material) was reduced as a result of adopting configurations 2 and 3. This material had a slight contribution in the overall response of the strengthened beams. However, the maximum difference between the ultimate loads was less than 13% compared to configuration 1. Moving to the effect of bond fibres in the bottom face of beams, it was found that the beams strengthened with FRCM located only on the beams' sides (Case 2) had ultimate strengths less than the corresponding beams with fibres wrapped around three sides (U-shape) (Case 1) as shown in Fig. This difference was usually about 1% for most configurations. However, applying fibres as in case 2 leads to using 30% less bonding material (cementitious material) than that used in case 1. In addition, using fibres as in case 2 does not increase the crack in the bonding material significantly since the bond length was quite sufficient (beam depth = 400 mm). Thus, one of the important findings of this research is that using fibres in beam's sides is better than using fibres as U-shape.

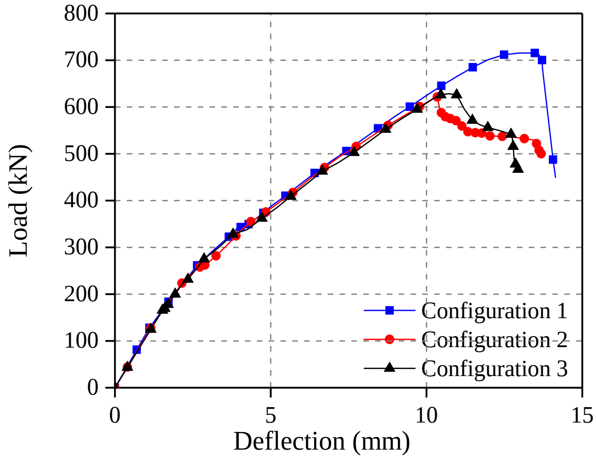


Fig. 8: Load-deflection curves for different FRCM configurations

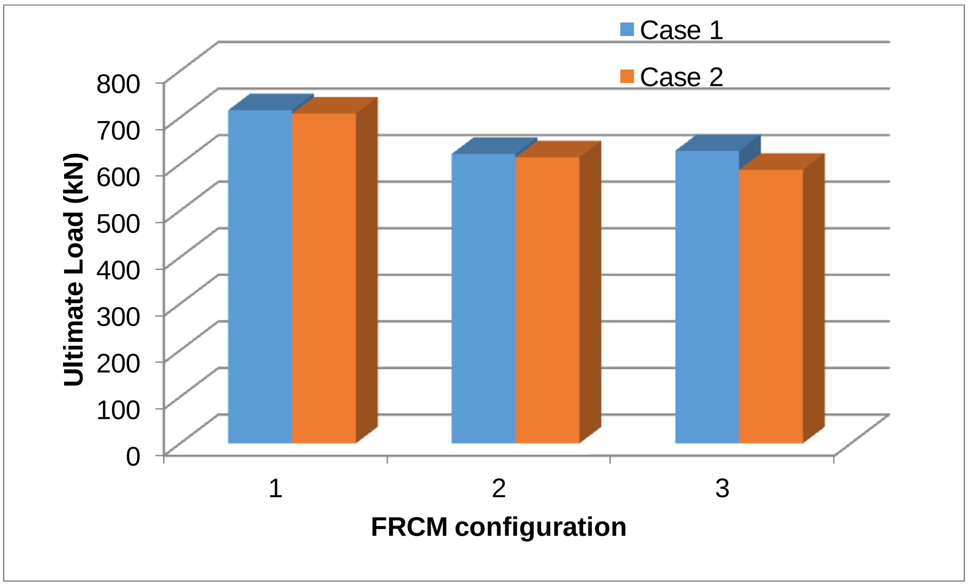


Fig. 9: Ultimate load against various FRCM configurations

6. Conclusion

In the current paper, the shear response of FRCM strengthened RC beams was investigated. 3D nonlinear FE model was proposed to simulate this strengthening system. The results of the proposed FE model was then validated against corresponding experimental data obtained from previous research. From the obtained simulation results the following conclusions can be drawn:

- The comparison between the FE and experimental results demonstrated that the FE model was able to represent the shear behaviour of FRCM strengthened RC beams with high level of accuracy. The comparison included load-deflection curves, ultimate load, strain in the longitudinal reinforcement and failure mode.

- It was found that when the concrete compressive strength was increased the contribution of the FRCM strengthening system was also significantly increased.
- The increasing in the number of fabric layers caused a noticeable increase in the beams ultimate load but without changing in the failure mode.
- Using various fabric arrangements had a significant effect on the contribution of the strengthening technique. Thus, choosing the right configuration is important to use the strengthening system effectively.

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