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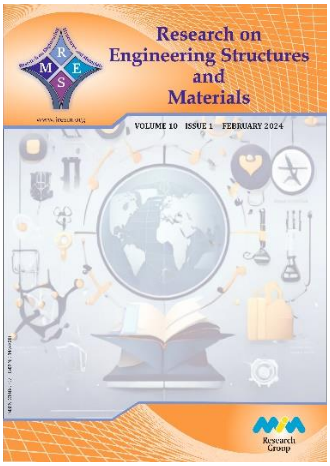

A state of art of review on strengthening of concrete structures using fabric reinforced cementitious matrix

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Review Article

A state of art of review on strengthening of concrete structures using fabric reinforced cementitious matrix

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Abstract

Renovation, refurbishment, restoration, and retrofitting of existing structures have grown more challenging issues for the construction profession. Construction buildings are susceptible to damage at the time of the earthquake and need strengthening to enhance their strength, stiffness, and ductility. Fabric-reinforced cementitious matrix (FRCM) techniques have been recently introduced to the construction sector as a feasible solution for fiber-reinforced polymers (FRP) in strengthening application. FRCM composed of high strength fabric grids with cement-based material serve as a binder for FRCM matrices. The binder employed for FRCM composed of cement-based mortar along with polymers are added to improve the bond strength properties. The cementitious matrix utilized in FRCM has superior thermal resistance and better compatibility with the concrete surface. The utilization of FRCM matrix for upgrading and restoring the concrete members is gaining more prominence as a replacement to FRP. This work conducts a thorough analysis of the application of FRCM techniques to concrete structural members like beams, columns, slabs, and beam-column joints. This paper primarily aims to present the FRCM process on structural members and to discuss the flexural, shear, and load carrying FRCM materials that are used in the field.

1. Introduction

In recent decades, the imperative to upgrade existing structures has gained significant prominence due to factors such as aging, deterioration, environmental degradation, inadequate maintenance, and the need to align with contemporary design standards [1][2][3] . To address these challenges, Fiber Reinforced Polymers (FRP) have emerged as a popular solution for externally reinforcing structurally compromised buildings [4][2][5]. Their remarkable attributes, including a high strength-to-weight ratio, resilience to corrosion, quick and straightforward application, and less impact on geometry, have made them a preferred choice [6][7]. However, the utilization of FRP strengthening comes with certain limitations, particularly linked to the use of epoxy resins [8]. Notable issues encompass elevated costs, inadequate performance in high-temperature environments, incapability to be applied on damp surfaces, and interference with underlying materials like concrete or masonry [9].

Various retrofitting techniques include section modification, external post-tensioning, bonded steel plates, NSM steel, and externally bonded FRP laminates [10][11]. Each method offers distinct pros and cons, reflecting considerations of labor, durability, corrosion, fire performance, and cost-effectiveness [4]. Section modification results in an increase in the cross section as a whole by adding more steel reinforcement with stirrups. This raises the additional load since more concrete and steel are added, exposing them to

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higher levels of corrosion [10]. The steel plate bonded to the damaged member's surface in the steel plate bonding method serves as an addition to the existing reinforcement. The exterior steel plate reduces the possibility of cracks and deflection and increases load-bearing capacity. Unfortunately, this method uses heavy-weight steel plates that are prone to corrosion, and installation costs are higher [4]. In the external post-tensioning procedure, tendons are drawn and attached to anchor points using pre-stressing rods or high-strength steel strands. Hence, this approach is ideal for retrofitting bridges [7]. In Near Surface Mounted (NSM) techniques, the FRP bar is glued to the existing concrete element by carving a groove in it and applying a suitable bonding agent. FRP is made of polymer that has been reinforced with fiber which provides it stiffness and strength and carries the load along the length of the fiber [5]. Despite the advantages of FRP, there are drawbacks related to resin properties and application challenges [12]. In response to these epoxy-related concerns, researchers have explored alternatives by advocating for the replacement of organic matrices (epoxy resins) with inorganic ones (mortar) [13]. This shift aims to overcome the challenges posed by epoxies and enhance the overall reinforcement technique [12][14]. However, the integration of fiber sheets into an inorganic matrix, such as mortar, has presented difficulties, primarily attributed to the granule size of the mortar [15]. Even finely textured mortar struggles to impregnate fiber bundles in the same manner as resins [16]. To surmount this hurdle, a breakthrough was achieved by substituting continuous fiber sheets with textiles, leading to improved bonding between fibers and the mortar-based matrix [8]. These novel composite materials were named as Fabric Reinforced Cementitious Matrix (FRCM) or Textile Reinforced Mortar (TRM) [17][18].The utilization of mortar rather than epoxy elevates heat and fire resistance while improving concrete substrate compatibility [19][20]. Fig. 1 represents the types of retrofitting techniques.

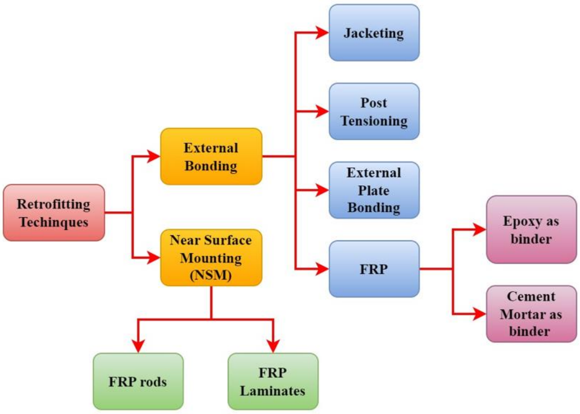
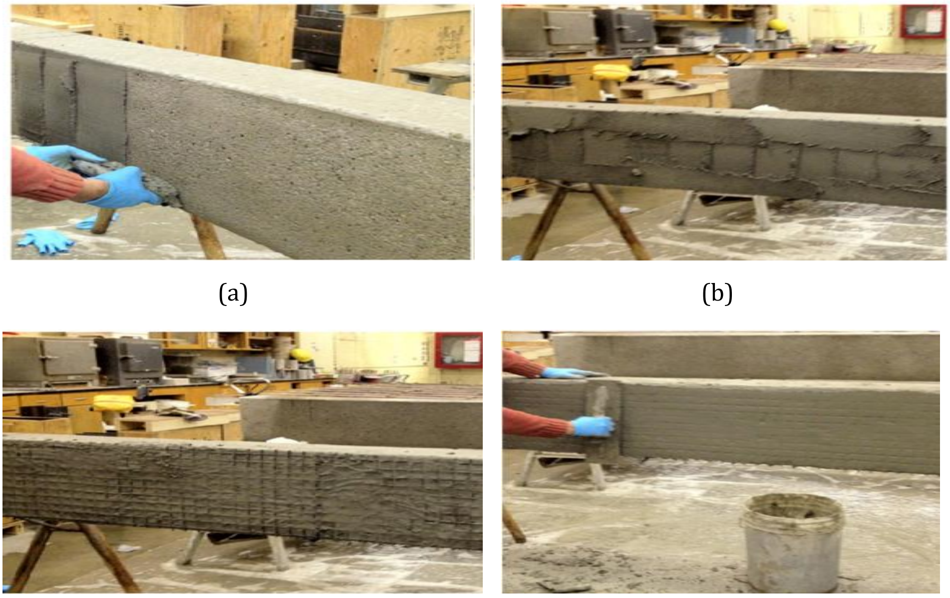


Fig. 1. Types of retrofitting techniques

FRCM combines with durable high-strength fibers in mesh configurations with inorganic matrices like cement or lime-based mortars [21]. This approach offers affordability, ease of use, fire resistance, and compatibility with concrete and masonry [22]. FRCM reinforcement comprises textile/Fabric mesh with oriented fiber roving for mechanical interlocking [23]. Externally bonded fabric-reinforced cementitious matrices exhibit a notable capability to augment the fatigue life of reinforced concrete members (RC) by redistributing stresses from internal steel reinforcement to the external composite fabric material [4]. Furthermore, the efficacy of fabric-reinforced cementitious matrices hinges upon the quality of the bond formed between the reinforced fabric and the concrete structural members [24]. Notably, these matrices demonstrate exceptional performance, particularly at elevated temperatures, surpassing the conventional epoxy-treated (organic) retrofitting methods [25]. Moreover, fabric-reinforced cementitious matrices contribute minimally to the environmental impact of construction materials [26]. The application of polymer coatings into the nonmetallic textiles serves to enhance both the stability of the textile material and the mechanical connection between the textile and its matrix [1]. Nonetheless, this treatment renders the textiles less pliable, making their use on intricate shapes like U-shaped or fully wrapped structures challenging, much like steel fabrics [27]. The formulation of the mortar employed as the matrix within FRCM (Fabric Reinforced Cementitious Matrix)/ TRM (Textile-Reinforced Mortar) systems significantly influences its composite behavior [28]. Impregnating fibers with mortar holds paramount importance for establishing a robust bond between the fibers and the matrix [8]. An ideal mortar should encompass fine particles, possess plastic consistency, favorable workability, low viscosity, and ample shear strength (to prevent detachment from the substrate) [29]. As such, cement-based mortars are extensively utilized as the matrix in FRCM due to their suitability [30]. The mechanical attributes of the mortar, such as flexural strength and the bond with fiber roving, can be markedly enhanced through the incorporation of polymers [31].


(a) (b)

(c) (d)

Fig. 2. FRCM strengthening steps: (a) Mortar application; (b) applying first layer of cement mortar; (c) FRP sheet embedded with first layer (d) finished with second layer of cement mortar [36]

Different types of fabric reinforcement material possess different types of physical properties such as Carbon-FRCM employs carbon fibers as reinforcement, renowned for their impressive strength-to-weight ratio, making them ideal for applications requiring both lightweight construction and high strength, such as the reinforcement and retrofitting of concrete structures [32]. Glass FRCM, on the other hand, incorporates glass fibers as reinforcement, providing corrosion resistance that makes it a preferred choice for environments exposed to harsh conditions, notably marine structures [24][33]. Basalt FRCM offers a balanced solution, blending the robust strength characteristics of carbon FRCM with the corrosion resistance of glass FRCM, and it finds applications across a spectrum of structural needs [34]. Additionally, polyparaphenylene benzobisoxazole (PBO) FRCM, utilizing PBO fibers like Zylon, offers exceptional strength and modulus within a cementitious matrix, catering to specialized high-performance requirements [35]. Fig. 2 shows the strengthening steps involved in FRCM techniques.

The strengthening process through FRCM/TRM jacketing encompasses several steps. Step 1 involves surface preparation to prepare the surface for bonding, it must be scrubbed, sandblasted, and cleaned. Step 2 entails mortar application on the concrete surface- A bonding primer is often applied to the prepared surface to improve the adhesion between the existing substrate and the FRCM/TRM system. Step 3 followed the placing of fabric sheet and step 4 involves applying a final layer of mortar on top of the fabric stratum. A specially formulated mortar mix, which often includes cement, aggregates, and additives, is applied over the reinforcement layer. This mortar encapsulates and bonds with the fibers, creating a composite material that enhances the strength and durability of the structure. The mortar layer is typically applied in multiple coats, with each coat allowed to cure before the next one is added [36]. Fig. 2 shows the strengthening steps involved in FRCM techniques.

This review paper provides a thorough analysis on the applications of FRCM to strengthen the structural RC members. The insights presented herein are synthesized from a thorough examination of past studies and research endeavors. This paper aims to shed light on the remarkable potential and implications of FRCM in advancing the field of structural engineering.

1.1. Significance of Research

FRCM is extensively employed for strengthening and renovating the existing the concrete structures, such as buildings, dams, bridges, and other infrastructure. It is a useful technique for prolonging the lifespan and enhancing the performance of structures because it gives higher stiffness and load-bearing capability. Fig. 3 displays the research methodology adopted to review the paper.

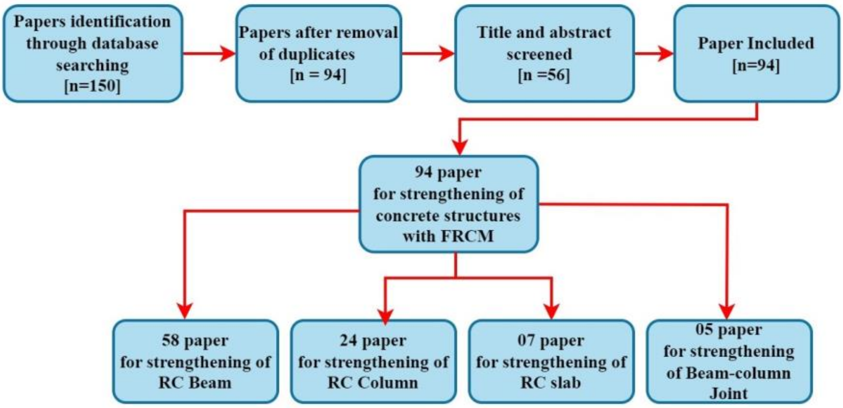
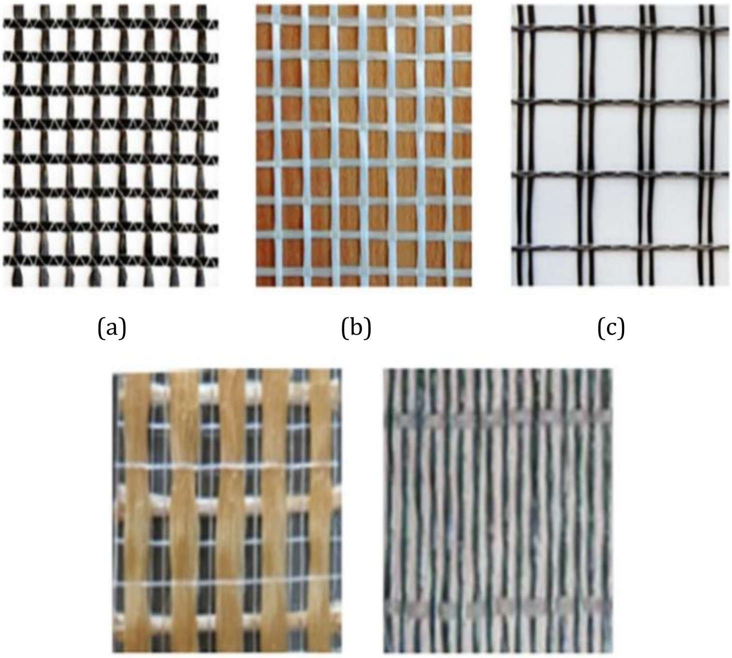


Fig. 3. Research methodology

2. Mechanical Properties

2.1. Properties of Fabric

The Fiber Reinforced Cementitious Matrix (FRCM) approach utilizes composite materials in the form of grids, meshes [18], and fabrics reinforced with fibers, including basalt, carbon, glass, steel and Polyparaphenylene Benzobisoxazole (PBO) [37][38][4][39]. These fibers exhibit varying densities, among these CFRP has high tensile strengths and also more stronger than steel [40]. The unit densities of CFRP vary between 1.5 to 1.6 g/cm^3, whereas AFRP has 1.3 to 1.5 g/cm^3 and GFRP has 1.2 to 2.1 g/cm^3 [41]. Effective bonding in FRCM relies on a substantial contact area between the matrix and the surface, with the line of debonding determined by mortar properties, especially tensile strength, and the bond between reinforcement and mortar [42]. Fig. 4 represents the different types of fabric available in market.



(a) (b) (c)

(d) (e)

Fig. 4. Fabric reinforcement (a) Carbon (b) Glass (c) Basalt (d) Polyphenylene benzobisoxazole and (e) Steel fiber [1]

The strength of the composite mainly depends on the fibers. Table 1. represents the properties of fabric. FRCM are normally composed of one or multiple fabric with varying properties and its strength were mainly depends on the bond between the fabric and concrete substrate. When the bond has an adequate bonding strength, the capacity of the strengthened beam is examined by the quantity of fabric utilized. Trapko et al. reported that small scale concrete cylinder confined with PBO-FRCM increases while increasing the fabric layers [43]. The strengthening of concrete structures discussed in detail in section 3.

Table 1. Properties of fibers

Properties	Basalt	Carbon	Glass	PBO	Steel
Ultimate Tensile Strength [MPa]	3080	4320	2610	5800	3200
Young's Modulus [GPa]	95	240	90	270	206
Ultimate Strain [%]	3.15	1.8	2.9	2.15	1.55
Weight [g/m^2]	200	168	225	88	600
Width of tows/cords [mm]	5	4	3	5	0.9
Equivalent Thickness [mm]	15	10	25	10	5.5

2.1.1. Properties of Inorganic (Cement) Binders

The properties of FRCM mortar, particularly its tensile strength influence the performance of FRCM by reducing the cracking in the composite matrix. Gopinath et al. showed that an organic (Epoxy) binder used as an adhesive for concrete cylinders and strengthened with AR-glass fiber grid was found to be similarly bound by inorganic binders which include cement, silica fume, and fly ash has a compressive strength of 56 MPa [44]. When basalt-FRCM was used to strengthen RC beams against shear, it was shown that the polymer-modified mortar matrix performed better than cement mortar, with an improvement of almost 10%. Salloum et al. found that the hardness and strength of polymer-modified mortar were superior to those of cement mortar. Garcia et al. found that cement mortar provides an increased strength than pozzolanic mortar. Using cement mortar and polymer-modified mortar as binder, to strengthen RC beams with two layers of basalt fabric showed a maximum capacity of about 46% and 36%, respectively [45]. The beam strengthened with carbon and glass fabric showed an increases in flexural strength and also observed that use of an inorganic binder having a compressive strength of 20Mpa resulted in debonding failure during loading [46]. Enhancing cement mortar performance involves adding silica fume and polymers as binders [47]. Wu et al. observed that using cement mortar with PVA fibers, the strength of the RC beam improved [48]. The mechanical properties of inorganic binders retrofitted with concrete elements using fabric was collected and found that investigation is required to develop a new inorganic binder. Ameer Baiee et al. examined the influence of cement mortar with densified silica fume, un-densified silica fume, Ground Granulated Blast Furnace Slag, and Fly ash. The test result shows that binary replacement consisting of 15% ground granulated blast furnace slag and 15% undefined Silica fume provides the optimum results [49].

3. Strengthening of Concrete Members with FRCM

3.1. Strengthening of RC Beams with FRCM

The performance of FRCM strengthened reinforced concrete (RC) beams is influenced by numbers of factors [21]. These factors include internal shear reinforcement quantity, fabric orientation, geometric configuration, bond scheme, end anchorage presence, application method (externally bonded, near surface embedded, or hybrid), strength of the substrate concrete, and composite stiffness [21][50][51]. Understanding these factors and their interplay is crucial in determining the shear capacity and failure modes of FRCM-strengthened beams [21]. Rizwan Azama et al. investigated on shear strengthening of RC deep beams with cement-based composites and these authors revealed that cement-based composites significantly improved the load-carrying capacity, with a 23% increase in ultimate load for CFRCM-strengthened beams [52]. Cement-based systems outperformed epoxy-based ones, attributed to bi-directional fabric providing better control of diagonal shear cracking and improved bond performance. CFRP grids embedded in mortar exhibited the highest shear strengthening efficiency due to enhanced bond [52]. Tadesse et al. examined the three different types of failure modes for RC beams strengthened in shear. These authors observed the failure mode of strengthened beam as detachment of the FRCM laminates from the concrete substrate, particularly in the case of side bonded and U-jacketing. For fully wrapped FRCM system, observed the fabric rupture failure in the strengthened beams [21]. Maaddawy et al. investigated on strengthened corroded T-beams using FRCM. These authors found that corrosion caused significant strength reduction with a 22% loss in tensile steel which leads to 28% decrease in load carrying capacity of un-strengthened beams. The combination of externally bonded and internally embedded carbon FRCM layers proved more effective in increasing the flexural response [25]. Wang et al. investigates the residual bond behavior of different CFRP reinforcements in notched concrete beams exposed to elevated temperatures. Their findings show that the failure modes and load-displacement curves of the strengthened beams vary with temperature. The strength of cement-bonded CFRP grids outperforms epoxy-bonded CFRP sheets under high-temperature conditions, making the former system more fire-resistant [26]. Christian Escrig et al. done an experimental comparison of reinforced concrete beams strengthened against bending using various types of cementitious-matrix composite materials and found that there is a clear relationship between the strengthening materials and the development of crack patterns in the tested beams. While, examining the load-bearing capacity, it's observed that all the strengthening materials contribute to an increase in flexural displacement at the onset of the first crack and the yielding flexural displacement compared to an unmodified beam. This enhancement ranges from approximately 35% to 27%, depending on the specific material used. And also, when considering FRCM as reinforcement, it's noted that they have the effect of reducing the ductility of reinforced concrete beams while increasing their capacity by about 135% compared to beams without strengthening [32]. Fig. 5 shows the failure modes of strengthened RC beams.

Imran Rafiq et al. show that cementitious interfaces can control the debonding of FRCM to reduce the failure mode of strengthened beams. In addition, it concludes that the use of FRCM in the strengthening of RC beams increases ultimate load and cracking [53]. The TRM-based strengthening technique's lifetime and endurance were reported by Baiee et al. The findings showed that a corrosion degree of more over 10% can cause the cover to separate, losing its strengthening efficiency. For this reason, it is important to remove the cover before reinforcing RC beams [54].

The factors that control the failure mode of the strengthened beam are fabric type, matrix composition, arrangement and orientation of fabric layers, surface preparation, and environmental conditions. Different fabrics exhibit different behaviors due to their varying tensile strength, elastic modulus, and interaction with the cementitious matrix. The properties of matrix which includes cement types and additives affect the bond between the fabric and matrix. The fabric arrangement and orientation play an essential role to determine the failure mode. Poor surface preparation may lead to debonding failure. The durability of the FRCM system may be affected by variation in temperature and moisture conditions. The use of FRCM for strengthening the beam in flexural changed the failure mode from debonding to flexural failure and increased the ultimate load to 93% [55].

Mandor et al. explored the flexural performance of RC continuous beams enhanced with PBO-FRCM systems. The beams strengthened with one or two FRCM layers often failed due to fabric slippage or delamination. End anchors played a significant role in preventing fabric delamination [56]. FRCM strengthening improved the flexural stiffness in sagging, with increased layer count enhancing yielding and ultimate capacities [56][57].Several factors have an impact on the fatigue performance of RC beams strengthened with FRCM, including parameters such as reinforcement ratio, strengthening method, degree of damage, and the presence of sustained load-induced corrosion [58]. Their investigation involves the analysis of various aspects, including failure modes, crack progression, fatigue lifespan, mid-span deflection, and behavior at the interface between materials. They assess the efficacy of both U-shaped and single-sided strengthening techniques and highlights the influence of textile and reinforcement ratios on fatigue endurance. The combined influence of corrosion and sustained loading on fatigue life is explored, including the identification of different stages in mid-span deflection evolution. Additionally, the study underscores the impact of corrosion on the bonding of the FRCM layer and provides a formula for evaluating fatigue stiffness to assess the safety of strengthened beams subjected to fatigue loads [58]. Wang et al. investigated the beam strengthened with CFRP grid using polymer cement mortar at the varying temperature up to 600°C. They found that bi-directional fabric utilized in cement-based strengthening techniques has a better bond to the concrete substrate than unidirectional sheets deployed in epoxy-based strengthening techniques. And also, they identify that load carrying capacity increase of about 23%. Ombres et al. studied the flexural analysis of reinforced concrete beams strengthened with a PBO-FRCM. The strengthened beam significantly increases the flexural capacity about 44% than the un-strengthened beams [31].

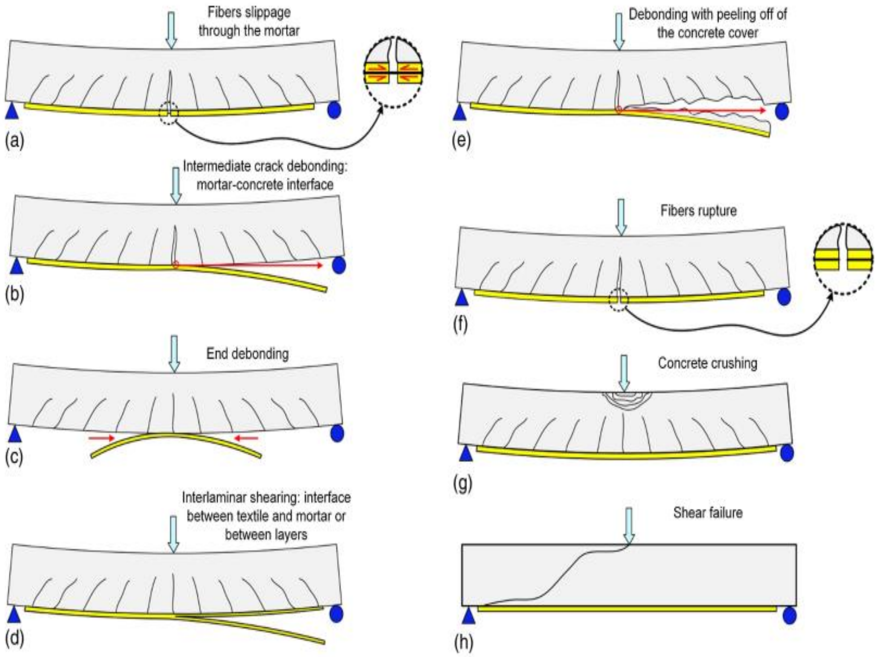


Fig. 5. Failure mode of Strengthened RC beam [1]

3.1.1. Theoretical study of RC beam strengthened with FRCM

The modeling of FRCM in finite element analysis (FEA) software involves defining materials, selecting suitable elements, and implementing interface modeling into practice to simulate the interaction among the various components. Define the parameters of the concrete material using appropriate model to response under loading conditions. The fabric reinforcement is modeled using shell element to define the behaviour of fabric and assigned the non-linear elastic material properties to define the fabric performance. By utilizing the solid element to model the cementitious matrix and define the three-dimensional performance od the matrix. Fig. 6 represent the modeling of fabric, matrix, polypropylene and composite matrix. Fig. 7 shows the failure mode of hemp, sisal and glass fabric.

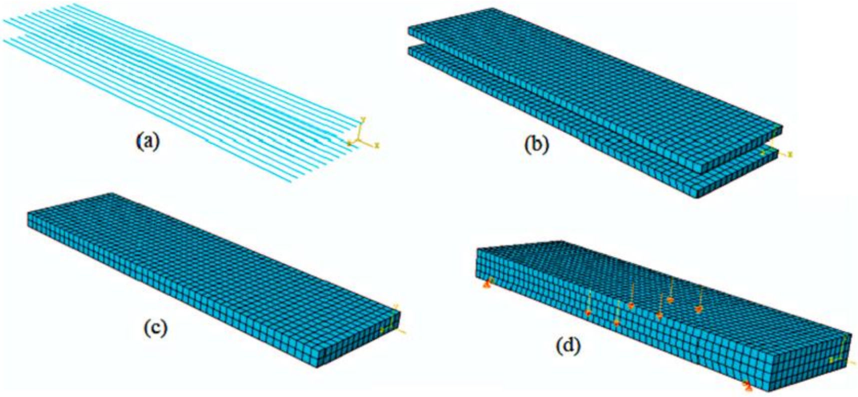


Fig. 6. Modeling (a) Fabric (b) Fabric (c) Polypropylene (d) Composite matrix [59]

Mercedes et al. studied the bending response of composite panels using different fabric. These authors compared the experimental results with the numerical simulation. The displacement for panels with hemp fabric attained the variation between 10 to 41% and for sisal and glass fabric attained the variation of about 1 to 14% [59]. A numerical study was conducted by Kalyani et al. to examine the flexural strengthened RC beams made of glass, Aramid, and hybrid FRP sheets. The study's findings demonstrate that utilizing hybrid FRP increases loading capacity of about 202.63% [60]. Ombres et al. studied that the beam strengthened with PBO-FRCM significantly increases the flexural capacity of about 44% than the un-strengthened beams [61]. Table 2. shows the summary of literature review of strengthened concrete beams.

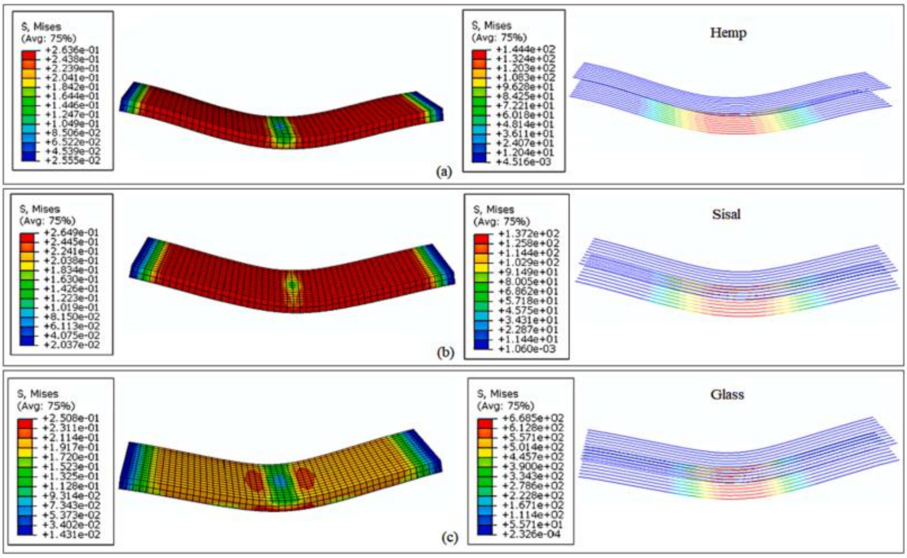


Fig. 7. Failure modes (a) Hemp fibers(b) Sisal Fibers (c) Glass Fiber [59]

Table 2. Summary of literature review of strengthened concrete beams

Ref.	Beam ID	Bonding Agent	Compressive strength of bonding agent (MPa)	Fabric Type	Tensile strength of Fabric (MPa)	No. of layers	σ_C (MPa)	σ_y (MPa)	Strengt. Method	Cont. Beam, Pc (kN)	Yield Load, Py (kN)	Ult. Load, Pu (kN)	(Pu/Pc)	Failure modes
(23)	M1-B3	Cement-based with polymers	25.37	Basalt	1540	3	33.1	662	Strip	56.7	59	66.8	1.18	IS
	M1-B6					6					60.2	73.7	1.3	IS
	M1-G3			Glass	1375	3					58.9	68.2	1.2	FR
	M1-G6					6					62.3	77.9	1.37	IS
	M2-B3	Cement Mortar	20.09	Basalt	1540	3					58.1	61.6	1.09	D
	M2-B6					6					29.5	60.9	1.07	D
	M2-G3			Glass	1375	3					57.2	68.4	1.21	FR
	M2-G6					6					61.6	66.2	1.17	D
(50)	S0-CGM	Cement Mortar	58	Carbon	0.325	1	61	494	U-wrap	1173.6 1310.1	-	1407.5	1.07	FR
	S250-CGM											1412.7	1.08	FR
	S0-CM											1446.6	1.1	FR
	S250-CM											1522.7	1.16	FR
	S0-CP											1322.3	1.01	FR
	S250-CP											1429.2	1.09	FR
(56)	S1-T1-P1-1	Cement Mortar	29	PBO	5800	1	22.77	515.44 521.89	Strip	74.85	80.1	87.42	1.17	CC

	S1-T1-P1-2					2					80.04	87.6	1.17	CC & D
	S2-T1-P1					1	23.02	525.9 535.6		49.65	45.03	54.24	1.09	CC
	S2-T1-P2-1										50.4	64.06	1.29	D
	S2-T1-P2-2					2					50.01	66	1.33	D
	S2-T1-P3-1					1					52.74	71.39	1.44	D
	S2-T1-P3-2					2					46.1	61.44	1.24	D
	S2-T2-P2					2	22.39	525.9 535.6		43.02	44.94	52.86	1.23	D
	S2-T2-P3					3					49.77	55.71	1.29	D
(44)	BS2	Cement Mortar	23.9	Basalt	623	2	20	684	U-wrap	60.8	-	82.66	1.36	SF
	BS3										-	83.51	1.37	SF
	BS4					4					-	88.74	1.46	SF
	BS5										-	92.53	1.52	SF
	BS6	PMM	56.4			2					-	83.38	1.37	SF
	BS7										-	83.38	1.37	SF
	BS8					4					--	96.26	1.58	SF
	BS9										-	114.1	1.876	SF
(57)	S0-FRCM1	Cement mortar	74	Carbon	3800	1	45	520	U-wrap	80.4	-	169.1	2.1	IS
	S0-FRCM2					2					-	196.7	2.45	IS
	S0-FRP-1					1						184.1	2.29	IS
	S1-FRCM1									143.5	-	234.7	1.64	IS
	S1-FRCM2					2					-	239.6	1.67	IS
	S1-FRP-1					1						239.8	1.67	IS
	S2-FRCM1					1				177.7	-	267.9	1.51	IS

	S2-FRCM2					2						275.8	1.55	IS
	S2-FRP-1					1						281.4	1.58	IS
(35)	SB-GT	Cement mortar	58	Glass	100	1	35	480	side-bonded	123.5	-	146.3	1.18	DT
	UW-GT								U-wrap		-	180.2	1.46	DT
	SB-CT1			Carbon	135				side-bonded		-	155.5	1.26	DT
	UW-CT1								U-wrap		-	151.8	1.23	DT
	SB-CT2					2			side-bonded		-	254.4	2.06	SF-D
	UW-CT2								U-wrap		-	253.4	2.05	SF-D
(51)	SH1	Cement mortar	43.9	PBO	5800	1	49.7		U-Wrap	272	261	279	1.03	FS
	SH2					2	49.4				266	289	1.06	D & FS
	SH4					4	47.8				263	306	1.13	CC
	SS1					1	48.5			206	176	226	1.09	FS
	SS2					2	48.8				184	249	1.21	FS
	SS4					4	49.7				213	267	1.29	FS
(52)	HP2	Cement mortar	43.9	PBO	5800	2	43.9	890	U-Wrap	272	266	285	1.05	FS-D
	HP4					4					263	302	1.11	FS
	HC2			Carbon	4300	2					257	286	1.05	FR
	SP2			PBO	5800	2					184	249	0.92	FS-D
	SP4					4					213	267	0.98	FS
	SC2			Carbon	4300	2					264	280	1.03	FR
(58)	B-A-S-Ao	Alkali-Activated Slag (AAS)	53.5	carbon	2300	-	42.5	1800	Strip	65.5	61.7	72.1	1.1	FS-FR
	B-A-L-Ao			carbon		-					63.4	75.9	1.16	FS-FR
	B-A-L-1.5Ao			carbon		-					67.8	82.8	1.26	FS-FR

	B-A-L-2Ao			carbon		-					66.8	74.4	1.14	FS-FR-D
(20)	BL-C	Cement Mortar	20	Carbon	4800	2	39.5	595 627	U-wrap	39.9	-	83.3	2.09	FS
	BL-P		30	PBO	5800						-	82.7	2.07	FS
	BL-G		40	Glass	2600						-	58.2	1.46	D
	BH-C		20	Carbon	4800						-	144	3.61	FR
	BH-P		30	PBO	5800						-	136	3.41	FS
	BH-C		40	Glass	2600						-	124	3.11	D
(59)	BS1-01	Cement Mortar	-	Carbon	834	1		834	wrap	239	-	239	1	D &SF
	BS2-01			Glass	460		50				212	132	0.55	D &SF
	BS2-01			Carbon	834	2					-	113	0.47	D &SF
	BS2-02			Glass	460						-	166	0.69	D &SF

where, SF- Shear failure; IS- Interlaminar shearing; D- Debonding; SS-Splitting of strut; CC-concrete crushing, FS- Fabric slippage, FR- Fabric rupture.

3.1.2. Summary

The efficiency of the strengthening system can vary greatly based on a variety of factors, including the number of layers, the material's characteristics, and the specifics of the reinforcement of the RC member. The flexural and shear capacity increase with the increases of externally applied fabric reinforcement and also the failure mode changes, while increasing the fabric layers. The use of fabric with multiple layers prevents the fibers from slippage failures. The mode of failure was shifted to interlaminar shearing, debonding at the matrix/concrete interface, and debonding with slippage of the concrete cover. The uses of polymer modified mortar shows better performance for FRCM.

3.2. Strengthening of RC Column using FRCM

Strengthening of reinforced concrete (RC) columns with FRCM is an effective technique to improve the structural performance and load-carrying capacity of existing columns. Strengthening of RC columns with FRCM offers a many advantages like improved the load-carrying capacity, increases the durability, and enhanced the fire resistance capabilities [62][63].The resistance to axial loads and serviceability of columns can be considerably improved by the subsequent application of a TRC layer [62]. FRCM allows to increase the strength of eccentrically loaded reinforced concrete columns; with respect to the un-confined specimen [64]. This technique is a versatile and cost-effective solution for enhancing the structural performance of existing columns and also minimizing the disruption to the building or structure [65]. However, the effectiveness of FRCM strengthening depends on proper design, material selection, and installation, and it should be carried out by experienced professionals following industry guidelines and standards. Fig. 8 shows the schematic diagram for RC column strengthened with FRCM. Jinlin et al. reported that by adding three textile layers, the ultimate load was increased to 44%. They also noticed that transverse cracks that originate on the tension side of the structure extend towards the compression side and are accompanied by significant concrete crushing [66]. Liu et al. investigated the axial behavior of fire-damaged reinforced concrete (RC) columns strengthened with a textile reinforced externally bonded reinforcement system. This study reveals that TRE-strengthened specimens exhibited a failure mode characterized by tensile rupture of fiber rovings and increased the load carrying capacity and ultimate displacement by 18% to 107% and 36% to 146% [26].

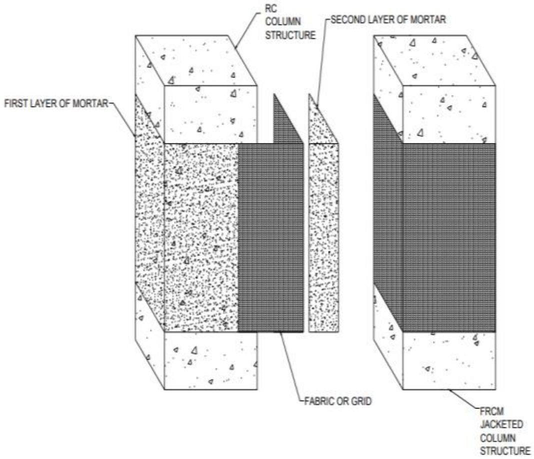


Fig. 8 Schematic diagram for RC Column strengthened with FRCM

Guo et al. investigated the seismic behavior of RC columns retrofitted with textile-reinforced mortar. These researchers revealed that the TRM jacket substantially enhanced shear capacity of about 54.3% to 55.2% and also noticed that displacement increases from 40.34% to 78.62%. By increasing the reinforcement ratio of carbon textiles, capacity of energy-dissipation increases with deformation. And also, it was observed that with an increase in axial load ratios, shear resistance exhibited a slight uptick, and also accompanied by a decrease in ductility as well as the energy-dissipation ability [29]. Alhoubi et al. studied the performance of reinforced concrete columns strengthened with PBO-FRCM systems was rigorously examined under pre-damage conditions. Their findings highlight the number of FRCM layers played a pivotal role in the failure mechanisms. The columns strengthened with two layers experienced internal delamination, while those with four layers suffered fabric rupture. [67]. Fig. 9 represents the mode of failure of FRCM-confined concrete members.

Zhang et al. investigates the effectiveness of Carbon Textile-Reinforced Concrete confinement (CTRC) in improving the performance of square concrete columns using uniaxial compression tests [17]. These scientists reported that substantial increases in load-carrying capacity and ductility, especially when utilizing four layers of textile. And also, they observed that adding short glass fibers with mortar mixer improved the performance of the strengthened beam [68]. The compressive strength of FRCM-confined concrete elements is significantly influenced by cross-sectional size, corner radius, scale effect, type of fiber mesh, and the number of FRCM layers [69] while, the fabric has less of an impact on the mortar stiffness. [70]. Alhoubi et al. assess the performance of RC columns strengthened with PBO-FRCM systems under two pre-damage conditions and they found that columns strengthened with two layers failed due to internal delamination, while those with four layers failed due to fabric rupture [71].

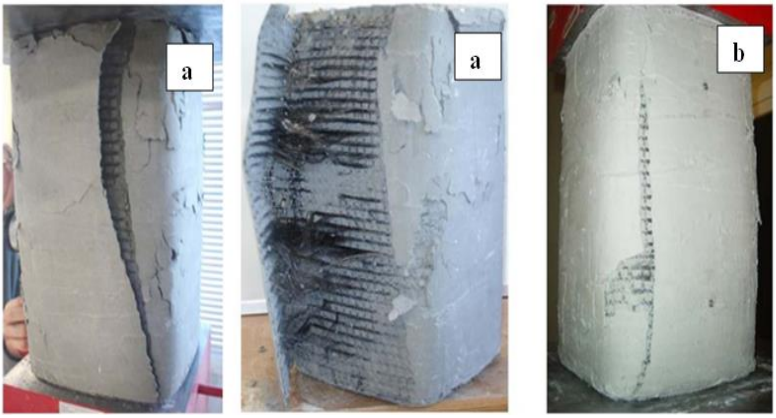


Fig. 9. Failure modes of FRCM-confined concrete members (a) Debonding (b) Rupture of the fabric [1]

Tello et al. studied the concentrically loaded columns strengthened with varying numbers of PBO-FRCM layers and reported that circular columns with two and four PBO-FRCM layers have higher capacity than the square columns [67]. Faleschini et al. examined the RC columns strengthened with CFRCM and observed the wide crack pattern in the specimens. As increasing the fabric layers the compressive strength of confined column increases as well as increases the ductility [72]. Napoli et al. examined the compressive strength of concrete externally confined with FRCM systems and they reveals that glass and carbon fabric systems exhibit the lowest strength than PBO as well as Steel [73]. Fig. 10 shows the crack pattern for strengthened RC column. Toska et al. studied the effectiveness of RC column strengthened with FRCM through confinement and observed that the strengthened specimen enhanced the concrete strength ranging from 1.4 to 2.18 than the control specimen [74]. Chen et al. examined that textile-reinforced ECC-confined columns performed better in terms of strength and ductility than TRM-confined columns.[75].

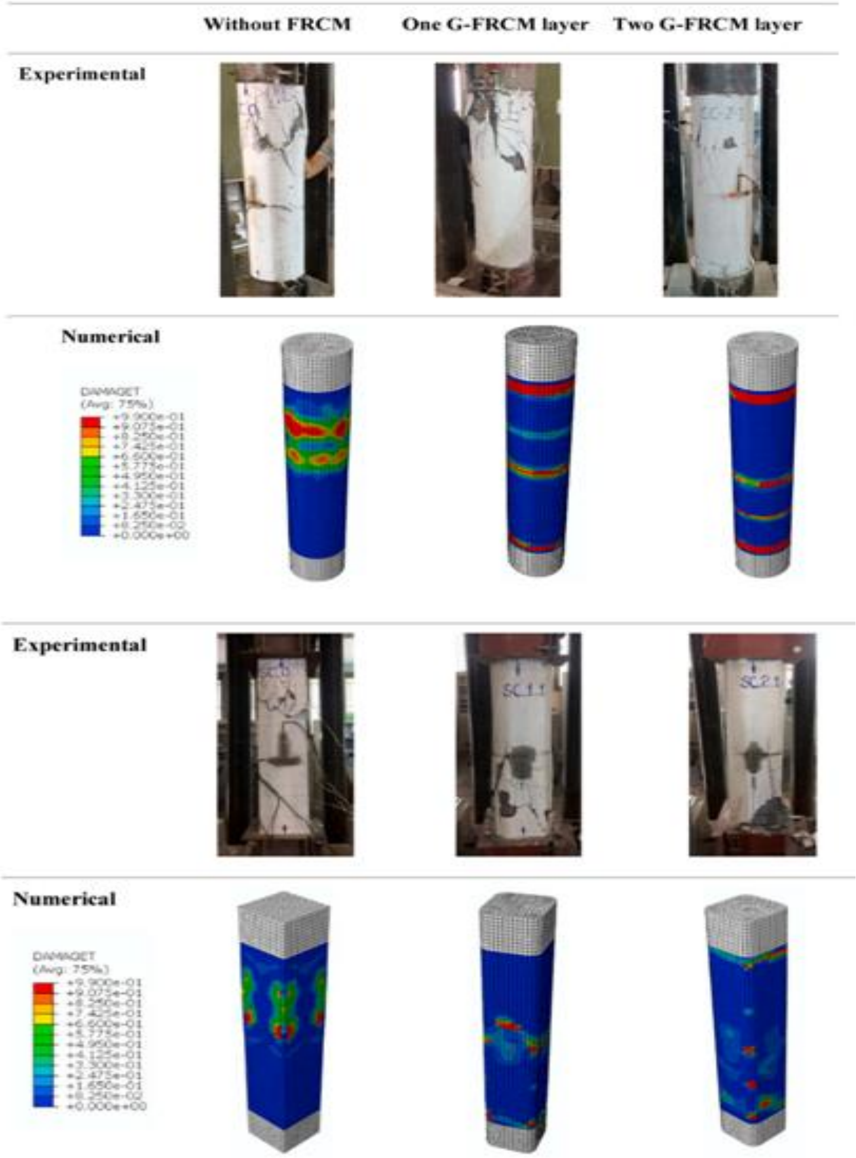


Fig. 10. Crack pattern for Strengthened RC Column [77]

According to Mohammad et al. study of FRCM-reinforced concrete columns using a probabilistic approach increased the axial load carrying capability of the strengthened beams. These authors also investigated the load-carrying capacity of FRCM-strengthened with FEM, Artificial neural network, and Monte Carlo simulation. The failure of concrete columns was simulated in the FEM using Concrete Damage Plasticity Modeling. The results indicated failure on the column’s tensile face, particularly tensile cracking. As a result, the experimental test and damage pattern were appropriately changed, increasing the CDPM stability in numerical calculations. It was found that column performance can be affected by changing the configurations instead of increasing the fabric layers [76].

Table 3. displays the summary of literature review of strengthened concrete columns. Glass fabric reinforced cementitious matrix was examined by Quyen et al. as a confinement material for RC column which meet the slenderness ratio. The authors report that for both single and double layers of FRCM, the Strengthening column increased by 22.1% and 55.5%, respectively. [77]. Reducing the fabric spacing, decreasing the core strength of concrete, and thickening the Engineered Cementitious Composites helps to improve the compressive response of pre-damaged columns [78]. Nguyen et al. reported that the non-linear computation of G-FRCM predicted more results than experimental results [69]. Ludovico et al. noticed that confinement made of basalt fibers that were bonded using cement mortar performed better than epoxy-based laminates [79][80]. The confined concrete column strengthened with FRCM shows good ductility property and increased the strength up to 20% [81], whereas using basalt as strengthening fabric, the load carrying capacity increased to 34% [82]. The column confined with CFRCM exhibited a considerable increase in compression strength, energy absorption, and deformability [83][84][85].

Table 3. Summary of literature review of strengthened concrete columns

Ref.	Column ID	Bonding Type	Compressive strength of Bonding agent (MPa)	Fabric Type	Tensile strength of fabric (MPa)	No. of Fabric Layers	Compressive Strength of FRCM Confined Concrete, *fcc* (MPa)	Peak strength on unconfined specimens, fco (MPa)	Average of (Fcc / Fco)	Average of (Ɛccu /Ɛcu)	Failure Mode
(77)	S3	Cement Mortar	30	Glass	1814	2	22.35	15.52	1.12	1.34	RF
	S10					1	18.01	17.83	1.37	1.58	
	S11						20.15		1.37	1.58	
	S12						21.93		1.37	1.58	
	S13					2	23		1.12	1.34	
(78)	C-S2-D0	Cement Mortar	22.9	Carbon	1487	2	19.2	36.8	1.09	0.83	D
	C-S3-D0						22.4		1.33	3.33	
	C-S4-D0						20		1.18	2.53	
	C-S5-D0						21.9		1.25	1.9	
	C-S6-D0						23.5		1.31	1.55	
	G-S3-D0			Glass	586	2	19.3		1.15	2.25	
	G-S4-D0						18.6		1.1	1.34	
	G-S5-D0						18.9		1.08	1.77	
	G-S6-D0						18.6		1.04	1.29	
(79)	G1-GRO3-Y-A,B	Grout		Glass		1	36.81	34.62	1.06	-	D
	G1-GRO3-Y-A,B						42.31		1.22	-	
	G2-GRO3-Y-A,B					2	50.12		1.44	-	
	C1-GRO2-Y-A,B			Carbon		1	43.82		1.26	-	
	C1-GRO3-Y-A,B						43.04		1.24	-	

	C2-GRO3-Y-A,B					2	57.6		1.66	-	
(80)	M1-1	Pozzolanic Mortar	22.4	Basalt	894	1	25.51	21.8	1.17	1.24	DF
	M1-2						25.94		1.19	1.35	
	M1-3						27.47		1.26	1.28	
	M1-4						27.03		1.24	1.34	
	M1-5						24.42		1.12	1.33	
	M1-6					2	26.81		1.23	1.49	
	M2-1						29.21		1.34	1.44	
	M2-2						27.9		1.28	1.38	
	M2-3						26.38		1.21	1.52	
	M2-4						24.85		1.14	1.21	
	M2-5						27.25		1.25	1.38	
	M2-6						27.69		1.27	1.39	
	C1-1	Cement Mortar	31.5			1	29.21		1.34	-	
	C1-2						27.69		1.27	-	
	C1-3						29.87		1.37	-	
	C1-4						28.56		1.31	-	
	C1-5						28.99		1.33	-	
	C1-6						27.69		1.27	-	
	C2-1					2	28.34		1.3	-	
	C2-2						27.47		1.26	-	
	C2-3						27.25		1.25	-	
	C2-4						30.08		1.38	-	
	C2-5						28.78		1.32	-	

	C2-6						30.74		1.41	-	
(81)	CF2M-A	Pozzolanic Mortar		Carbon		2	20.83	16.8	1.24	3.81	RF
	CF2M-B						20.58	16.08	1.28	4.4	
	CF3M-A					3	23.69	16.8	1.41	3.41	
	CF3M-B						23.96	16.08	1.49	2.79	
(84)	LDG-A-1	Cement Mortar	31.1	Glass	3240 4840	1	29.4	20.4	1.44	3.88	RF
	LDG-A-2					2	24.3		1.19	3.5	
	LDG-H-1					1	30		1.47	3.4	
	LDG-H-2					2	30		1.47	3.07	
	HDG-A-1					1	25.1		1.23	2.71	
	HDG-A-2					2	23.9		1.17	8.38	
	HDG-H-1	Portland Cement Mortar	2.49			1	31.9		1.56	1.69	
	HDG-H-2					2	28.1		1.38	4.51	
	BGP-A-1	Cement Mortar	31.1	Glass, Basalt		1	28.5		1.4	-	
	BGP-A-2					2	29.1		1.43	1.12	
	BGP-H-1	Portland Cement Mortar	2.49			1	32.9		1.61	3.13	
	BGP-H-2					2	30.7		1.5	2.47	
(83)	M15_CF_1	Cement Mortar	17	Carbon	240	1	13.32	11.4	1.2	1.63	DF
	M15_CF_2				270	2	13.98		1.23	1.53	
	M45_PBO_1			PBO		1	18.14		1.64	3.23	
	M45_PBO_2				240	2	17.27		1.51	2.96	
	M45_CF_1			Carbon		1	13.85		1.25	1.41	
	M45_CF_2					2	13.46		1.18	1.34	
(70)	C20-1		31.9	Carbon	1487	1	23	21.2	1.08	1.82	RF

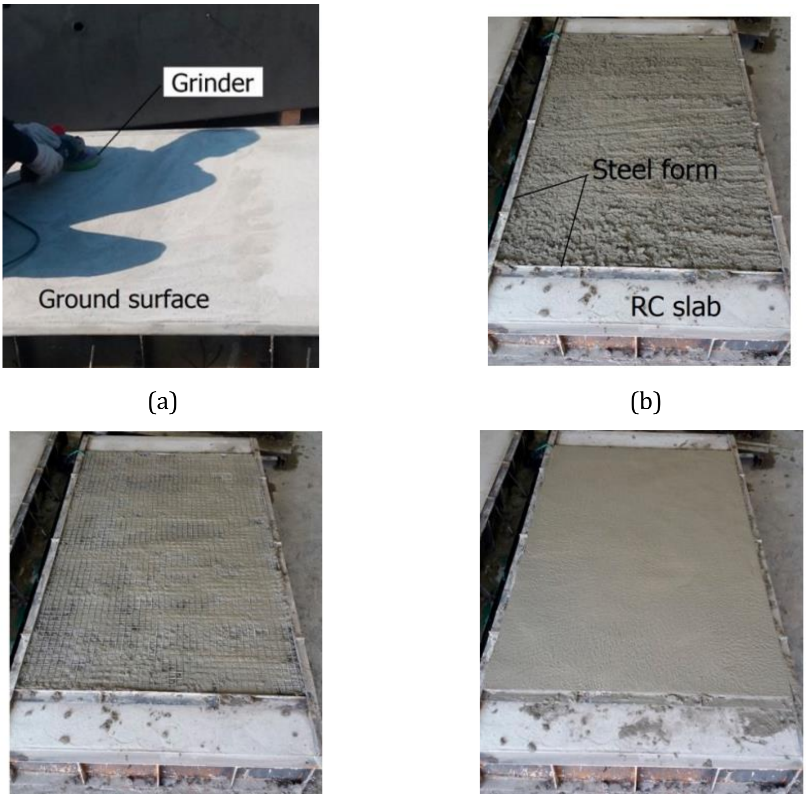
	C20-2	Cement Mortar				2	26.2		1.23	1.68	
	S20-1					1	20.3		0.95	1.97	
	S20-2					2	21.2		1	1.88	
	C33-1					1	19.8		0.93	1.49	
	C33-2					2	21.9		1.03	1.67	
	S33-1					1	17.1		0.8	2.43	
	S33-2					2	20.9		0.98	1.31	
(72)	C20_D0_C2	Cement Mortar	28.2	PBO	1487	1	17.63	13.15	1.34	1.276	CC
	S20_D0_C2					2	14.34	14.2	1.01	1.222	
	S33_D0_C2					3	21.09	16.58	1.27	1.2	
	C20_D1_C2						17.62	13.15	1.34	0.655	
	S20_D1_C2						14.67	14.2	1.03	0.777	
	S33_D0_C2						14.98	16.58	0.9	1.1	

where, D- Debonding, RF- Rupture Failure, DF – Ductile failure, CC- Concrete Crushing, SY-Steel Yielding.

The compressive strength and strain of the confined concrete improved with an increase in the number of applied FRCM layers. As the number of layers increases, the effectiveness generally decreases and the increase is typically non-proportional to the number of reinforcement. The efficiency of TRM jackets in enhancing the axial load-carrying capacity of confined concrete is largely dependent on the strength of the unconfined concrete; the jackets are more effective for lower unconfined concrete strength values.

3.3. Strengthening of RC Slab using FRCM

The RC slabs are stressed bi-axially and have a larger bottom surface area than RC beam, therefore adopting bi-directional fabric is more appropriate for strengthening the slabs. A study on the flexural behavior of two-way RC slabs reinforced with FRCM was carried out by Koutas et al. Their findings revealed that the stiffness and cracking stress of the slab were significantly enhanced by adding more layers [86]. Utilizing polymer-modified cement mortar as the binder, Bing L et al. investigated the strengthened slab's performance under fire exposure and found that the strengthening layer could withstand the fire for about 30 minutes [87]. Fig. 11 illustrate the strengthening method of RC slabs.



(a) (b)

(c) (d)

Fig. 11. Strengthening of RC slabs (a) surface preparation (b) Placing 1st mortar (c) Placing Fabric reinforcement (d) Finishing with 2nd layer of mortar [88]

Zhang et al. studied the flexural behaviour of RC slab using Geopolymer mortar as binder and found that strengthened slab delays the development of cracks, improves the post-cracking stiffness, and flexural capacity [89]. A study conducted by Kadhim et al. employed Carbon-FRCM to analyze two-way slabs strengthened in flexure. They observed that raising the FRCM reinforcement's width from 0 to 0.25 enhanced the final strength by 84%. Moreover, significant gains in strength of about 19% were observed when the width-to-span ratio increased from 0.25% to 1% [90]. Yoel et al. investigated the flexural strengthening of concrete slab with textile reinforced concrete and found that ultimate flexural capacity and stiffness of the strengthened slabs were increased to 165% and 112%, respectively than unstrengthened slab [88]. The researchers Sabbaghian et al. studied the flexural behavior of reinforced concrete (RC) slabs strengthened with thin laminates of High-Performance Fiber-Reinforced Cementitious Composite (HPFRCC). The laminates contain varying percentages of steel fibers (1% and 2%) and are applied with different binding methods (epoxy or mechanical anchorage), with or without internal bars (steel or GFRP). Experimental results show the enhancements in the load-bearing capacity and reduced the development of cracks and increased the ductility [91].

3.3.1. Summary

The RC slab capacity increases with FRCM techniques. By adding a greater number of layers to an RC slab greatly increased the slab's stiffness and cracking stress. And, also the strengthened slab delays the cracks development post-cracking stiffness, and increases the ductility.

3.4. Strengthening of Beam-Colum Joint using FRCM

When a structure experiences a lateral cyclic load caused by an earthquake, the bending of adjacent members results in large magnitude stresses that can be directed in various directions, which leads to the failure of a beam-column connection. The beam-column joint is one of the most important structural parts. Its failure is viewed as undesirable since it can drastically reduce stiffness and strength, eventually causing the building to collapse as a whole. Exterior beam-column joints are restricted by surrounding beams in four directions, are more susceptible to failure during an earthquake than interior joints. The majority of the joints that failed in the most recent earthquake all over the world, to strengthen the beam-column joint of older and newly constructed building is required to prevent the gradual collapse of structures.


(a) (b) (c)

Fig. 12. Strengthening of beam-column joint (a) Applying the first layer of binder (b) Applying the fabric (c) Applying the second layer of binder [93]

An experimental study was carried out by Faleschin et al. to study the cyclic behavior RC exterior joints that were strengthened with FRP and FRCM composites. It was found that while FRP and FRCM composites were not able to restore the joint specimens capacity, FRCM composites were better than FRP at increasing the load capacity [92]. Yang et al. increased the shear strength of RC beams by employing basalt-FRCM and carbon-FRCM with polymer-modified mortar and ECC [42]. Fig. 12 represents the strengthening of beam-column joint using FRCM

FRCM composites were applied by El-Maaddawy et al. to strengthen the corroded RC T-beams with basalt and carbon FRCM. They observed that the flexural capacity of the beam was found to be totally restored by the embedded carbon FRCM system, but not by the basalt FRCM [25]. Lim et al. study the beam-column joint strengthened by CFRP grid with ECC using high strength mortar. Their findings indicate that failure mechanism of the specimens may be changed by transferring the load joint to beam and the specimen's strength performance increases. Furthermore, the specimen exhibits enhanced ductility, enabling them to delay the failure [94]. Zuhair Murad et al. carried out an experimental study of the cyclic behaviour of retrofitted beam-column joints using FRCM by adopting U-shaped and X-shaped configuration. The specimens drift ratio, ductility, and stiffness were all greatly increased by the strengthened specimen up to 166%, 66%, and 11%, respectively. And, also U-shaped techniques performed better than X-shaped configuration [93].

3.4.1. Summary

The load capacity of the beam-column joint was greatly increased by the FRCM strengthening approach. The failure modes modify from changing the load from joint to beam and increase the strength of the specimens. Additionally, the strengthened beam-column joint enhances its ductility, drift ratio, and stiffness of the strengthened specimen.

4. Conclusion

The application of FRCM presents unprecedented prospects for structural renovation and repair. The ensuing conclusions are distilled from a thorough analysis of the previously conducted studies. This summary covers the RC beam, column, slab, and beam-column joint strengthened with FRCM are briefly discussed.

The strengthening of RC beams with FRCM is found to be effective method for increasing the ultimate flexural and shear strength of the strengthened members. The strength gain increases non-proportionally as the number of FRCM layers increases.

The failure modes of flexural and shear strengthened concrete members are fabric roving, fabric rupture, debonding at the fabric-matrix interface, and concrete cover separation. Flexural strengthened beam elements exhibit more debonding at the fabric-matrix interface than shear strengthened beam.

The main effects of concrete confinement increased the compressive strength with greater axial deformation capacity. The strength gain in concrete columns strengthened by FRCM is reduced by eccentric loading.

The mode of failure for column is usually ductile failure due to rupture failure develops in the fabric. The mode of failure tends to be ductile because the rupture failure gradually spread towards the other fabric inside the reinforcement through the limited number of fibers. Debonding failures occurs at the end of the FRCM systems. Additionally, observed the fabric slippages, concrete crushing without causing damage to the fabric. Therefore, FRCM provide a versatile and cost-effective solution for upgrading the existing structures.

The fabric used for strengthening the structural members plays a vital role. The selection of fabric type varies on the application of FRCM. The carbon and PBO have high tensile strength, therefore for heavy damaged structural members' carbon and PBO fabric can be adopted to improve their performance.

The FRCM mortar that is used as a binder needs to be selected with carefully. The silica fume and fly ash used with cement mortar showed a higher compressive strength. As a result, cement containing silica fume and fly ash can be employed as binder for FRCM.

It is possible to prevent debonding failure modes by properly preparing the surface, selecting the right fabric and mortar, and proper implementation of FRCM techniques.

The RC slab capacity increases with FRCM techniques. By adding a greater number of layers to an RC slab greatly increased the slab's stiffness and cracking stress. And, also the strengthened slab delays the cracks development post-cracking stiffness, and increases the ductility.

The load capacity of the beam-column joint was greatly increased by the FRCM strengthening approach. The failure modes modify from changing the load from joint to beam and increase the strength of the specimens. Additionally, the strengthened beam-column joint enhances its ductility, drift ratio, and stiffness of the strengthened specimen.

According to the authors, using fabric-reinforced cementitious matrix composites to strengthen the concrete structures is a very promising method that is gaining interest from the worldwide scientific society. Future studies in this area should focus on the enhancing the fabric strengthening, studying the durability of the strengthening techniques with elevated temperature and developing design guidelines within the framework of existing design formulations. It is essential to investigate the behaviour of FRCM in different conditions, such as fire, gas blasting, extreme loading conditions, etc. It is necessary to conduct extensive research on the impact of FRCM under fire by experimentally with slow and quick heating rates which causes damages in strengthened members.

Abbreviations

FRCM-Fabric Reinforced Cementitious Matrix; TRM – Textile Reinforced Mortar; FRP – Fiber Reinforced Polymer; FEM-Finite Element Modeling; RC –Reinforced concrete; NSM – Near Surface Mounted; GFRP-Glass Fabric Reinforced Polymer; CFRP-Carbon Fabric Reinforced Polymer; AFRP – Aramid Fabric Reinforced Polymer.

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