Applications of Fabric Reinforced Cementitious Mortar (FRCM) in Structural Strengthening

M. Chellapandian and S. Suriya Prakash

Abstract Over the past two decades, the use of advanced composite materials such as Fiber reinforced Polymers (FRP) and Fabric Reinforced Cementitious Matrix (FRCM) has been widely adopted for the strengthening of critical infrastructural assets such as bridges, building, dams, and tunnels. This chapter presents a state-of-the-art review on the use of FRCM for strengthening of reinforced concrete (RC) structures under different load combinations. Initially, the material characterisation of FRCM through the tensile and bond test are described. Then, a detailed overview on the overall behavior and failure mode of FRCM strengthened RC members under compression, shear, flexure, torsion and seismic loads are discussed. Moreover, few studies highlighting the FRCM strengthening of un-reinforced masonry structures are also discussed. In addition, few case studies where the use of FRCM strengthening is preferred over the other techniques are discussed and the key parameters are analysed.

Keywords Strengthening · Fabric reinforced cementitious matrix · Fiber reinforced polymers

1 Introduction

Maintenance of critical infrastructural assets such as bridges, building, dams, and tunnels has become a global issue and requires immediate attention. Some of them have deteriorated and need to be strengthened to ensure safe performance. Most of the strengthening work focus on the deteriorated concrete structures either due to natural calamities (earthquake, fire, etc.) or corrosion, as shown in Fig. 1. As per the statistics from Indian Bridge Management System (IBMS) in 2016, more than

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S. B. Singh et al. (eds.), *Emerging Trends of Advanced Composite Materials in Structural Applications*, Composites Science and Technology,
https://doi.org/10.1007/978-981-16-1688-4_9

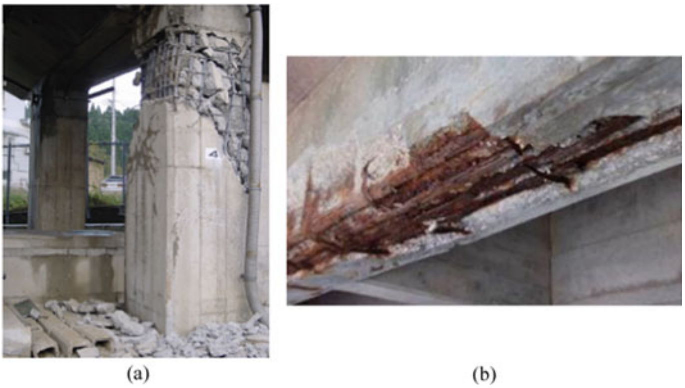

(a) (b)

Fig. 1 Damage of RC members. **a** Shear failure due to earthquake and **b** damaged RC beam due to corrosion (*Courtesy* https://civildigital.com)

40,000 bridges constructed before 60 years are close to complete their service life and require immediate strengthening. In addition, 37,000 railway bridges in India require immediate strengthening (Singh et al. 2002). It is worth mentioning that most of the structures requiring strengthening are under service, which complicates the strengthening process. Moreover, the present status of the structures and their capacity are unpredictable, which further complicates the optimistic strengthening design.

Various strengthening such as steel jacketing, concrete enlargement, FRP retrofitting is commonly used to improve the performance of existing structures. However, these conventional techniques have various disadvantages due to their heavy dead loads, increased installation time and labour requirements. Use of fibre-reinforced polymer (FRP) for structural strengthening of RC elements has become popular since the last two decades. The main advantages of FRP strengthening, when compared to the conventional strengthening techniques, includes (a) Ease of handling, (b) Lightweight, (c) Corrosion resistance, (d) High specific strength and stiffness (strength/stiffness to weight ratio), (e) High impact resistance, (h) High dielectric capability with a nonconductive property, (g) Good insulator with low thermal conductivity, (h) Lower installation cost, lesser maintenance cost, and longer service life. Strengthening of concrete members with different FRP techniques such as near-surface mounting, external confinement and their hybrid combinations were successfully used for improving the overall behaviour under different load combinations (Pachalla and Prakash 2017; Kuntal et al. 2017; Chellapandian et al. 2017, 2019; Jain et al. 2017; Kankeri et al. 2018; Chinthapalli et al. 2020). Despite having numerous advantages, FRP strengthening has a shortcoming which includes the use of organic resin to bond the parent member and fibre. The performance of organic resins is compromised when exposed to high temperature and extreme weather conditions leading to reduced durability of the strengthened systems. Due to the limitations of existing techniques, there is a need for the development of innovative strengthening materials and techniques and fibre reinforced cementitious mortar (FRCM) is one of them.

1.1 Background on FRCM

Textile-based composite materials known as fabric reinforced cementitious mortar (FRCM) or textile reinforced mortar (TRM) comprise of fabric meshes and cementitious mortar. The fabric meshes are fabricated with long-woven, knitted or even unwoven fibre roving in two orthogonal directions (bi-directional). The fabric meshes are bonded to the surface of concrete members using cementitious mortar. Different types of textiles used as reinforcement in the FRCM system includes steel, polyphenylene bezobisoxazole (PBO), glass, carbon and basalt. Among them, PBO, glass and carbon-based fibre textiles showed in Fig. 2 are predominantly used in the structural strengthening of RC members. Steel fibre textile is commercially available in the uni-directional form with several twisted cords (Density = 1–10 cords/cm). Each cord consists of five wires with a total sectional area (A_{cord}) of 0.538 mm^2. Three straight wires from the core area of the cord and two wires are twisted around them in a helical manner (Zou and Sneed 2020). Other non-metallic fibre textiles such as PBO, glass and carbon are commercially available with the mesh size varying between 8 and 30 mm. The weight of these non-metallic textiles varies between 150 and 600 g/m^2 (Koutas and Bournas 2017).

The effectiveness of FRCM application usually depends on the mechanical properties of textiles, spacing of roving in each direction and the degree of penetration of mortar matrix. The spacing of roving and their quantity can be controlled based on the independent requirement to allow the mesh formation. Moreover, this property makes it effective for various strengthening applications. The mechanical interlock, which is the essential characteristics of FRCM strengthened members, can be achieved by providing perforations between the fibre roving. This helps in developing mechanical

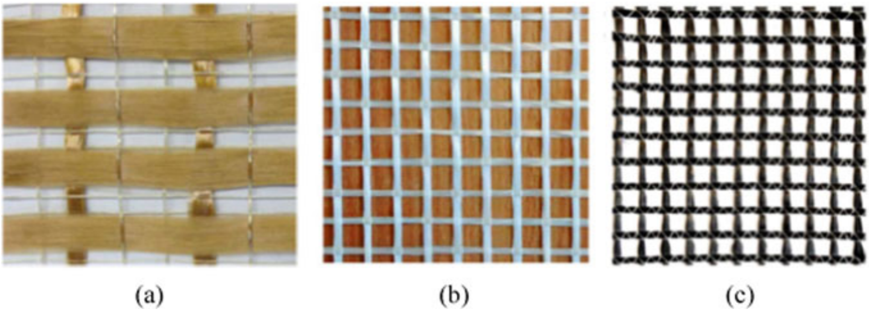


Fig. 2 Different types of fibres used for strengthening. **a** PBO textile fibre; **b** glass textile fibre and **c** carbon textile fibre

interlock between the matrix and FRCM mesh. However, this increased stiffness can limit its application for complex strengthening procedures, i.e., shear strengthening using full wrapping or U-wrapping techniques.

1.2 Advantages of FRCM Over Conventional Strengthening Methods

Use of inorganic cement-based bonding materials as a replacement for organic resin can help in overcoming the issues that concern the use of FRP composites which includes: (a) improved ultraviolet (UV) resistance, (b) better resistance against high temperatures, (c) handling and use are more straightforward as the inorganic resins are water-based, (d) emit no toxic smells during strengthening, and (e) comparable chemical bonding with concrete. However, the direct application of inorganic cement-based mortar over the FRP sheet would result in poor bond performance due to two significant reasons such as (a) the granularity of the mortar, (b) penetration and impregnation of fibre sheets will be difficult. Replacing textiles instead of continuous fibre sheets can help in improving the fibre–matrix interactions. Thus, the use of fabric/textiles with the cement matrix is termed as fabric reinforced cementitious mortar (FRCM). FRCM based strengthening techniques are extensively investigated over the last twenty-five years. FRCM can be used for a wide range of structural strengthening similar to the FRP composites. Moreover, the stability of textile material and the mechanical interlock between the matrix and textile can be significantly improved by coating the non-metallic textiles with polymers. Figure 3 highlights the advantages of using FRCM over FRP for structural strengthening. The various aspects of FRCM, which includes mechanical characterization, strengthening procedure, behaviour under different load combinations and selected case studies are discussed in the following sections.

Fig. 3 Schematic representation of the advantages of FRCM over FRP

2 Mechanical Characterization of FRCM Systems

The composition of the mortar used as the matrix in FRCM systems significantly affects its response as a composite material, because the impregnation of fibres with mortar is quite crucial for achieving a good bond between the fibres and the matrix. The mortar shall include fine granules and have a plastic consistency. It shall be workable with low viscosity (for easy application to vertical or steep surfaces). Minimum shear strength shall be ensured to prevent the debonding of the composite material from the substrate. Due to the shear strength requirements, cement-based mortars are widely used as a matrix in FRCM.

2.1 Tension Test

It is essential to characterize the FRCM composites used for structural strengthening so that the mechanical properties such as tensile strength, ultimate strain and the modulus of elasticity can be determined. Many researchers in the past have developed the procedure for performing the tensile tests on FRCM based composites (Contamine et al. 2011; Ascione et al. 2015; Arboleda et al. 2016; D'Antino and Papanicolaou 2018). Some in the past have also investigated the dynamic tensile behaviour of FRCM coupons (Zhu et al. 2011). The accuracy of results from the tensile tests rely mainly on two factors which include, (a) shape of FRCM coupon (flat plate or dumbbell), (b) gripping methods (Hartig et al. 2012; De Santis et al. 2017; D'Antino and Papanicolaou 2017, 2018). Figure 4a shows the dimensions of the standard FRCM coupon and the setup for direct tension test (ASTM 1996). The specimens were loaded in a displacement-controlled manner (0.5–1.0 mm/min) and the measured displacements were used for calculating the ultimate strain level.

Table 1 shows the comparison of different mechanical properties of FRP and FRCM composites obtained from the material characterization (direct tension test). The values were obtained from the standard coupon samples prepared as per standards and tested under tension. Figure 4b shows the failure mode of FRCM coupons under direct tension. The failure mode of FRCM relies strongly on the gripping method adopted. The failure mode by rupture of textile in the mid-span of the coupon is desirable than the other two failure modes such as rupture of textile at the end or slippage within the matrix (De Santis et al. 2017; D'Antino and Papanicolaou 2018). Moreover, the failure can occur at the grips due to the insufficient grip pressure as a result of which the tensile load is transferred by shear stresses. A minimum of five FRCM coupons needs to be tested for ensuring the reliability of results from a direct tensile test.

Figure 4c shows the stress–strain behaviour of FRCM coupons under tension. The tri-linear stress–strain curve usually characterizes the tensile response with the three major stages such as (a) Stage I—un-cracked stage with the linear response until the formation of the first crack, (b) Stage II—formation of multiple cracks in the matrix

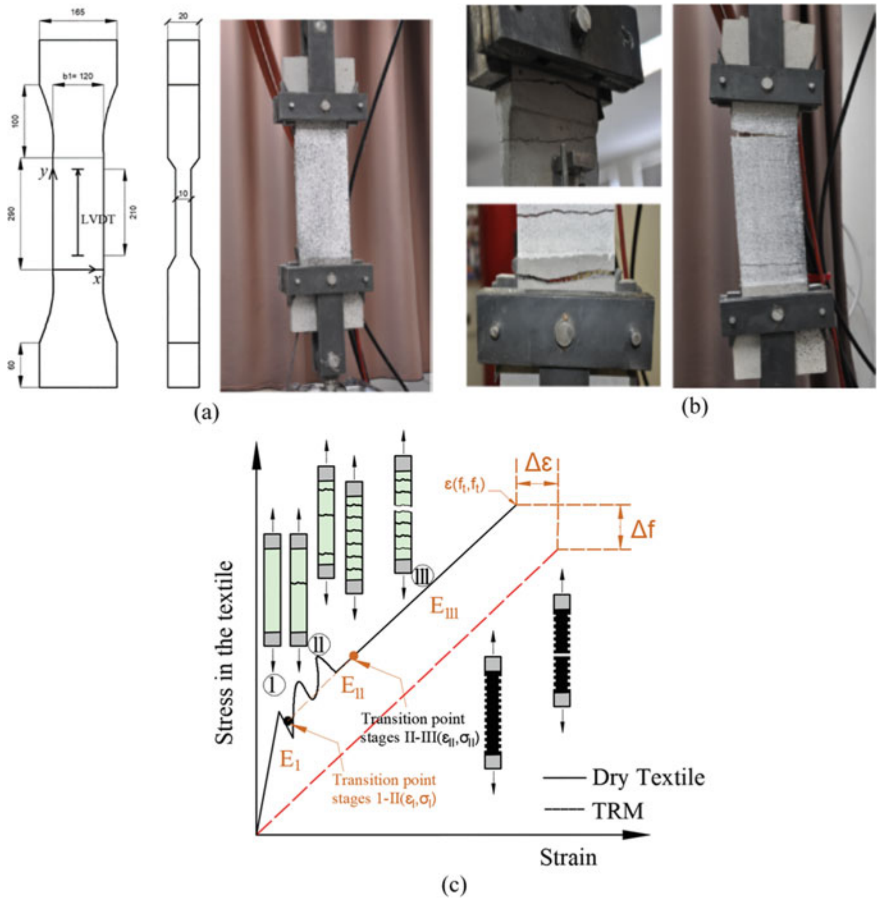


Fig. 4 FRCM under tension. **a** Test setup; **b** failure modes and **c** tensile behavior of FRCM (*Picture Courtesy* D'Antino and Papanicolaou 2018). *Note* All dimensions are in "mm"

Table 1 Comparison of mechanical properties—FRP versus FRCM

Material	Ultimate strength (MPa)		Elastic modulus (GPa)		Ultimate strain (%)	
	FRP	FRCM	FRP	FRCM	FRP	FRCM
Glass	500–1200	600–850	30–65	50–65	2.0–4.5	1.5–5.0
Carbon	1200–2400	800–1350	120–165	80–110	1.0–1.5	0.8–1.5
PBO	–	1250–3100	–	105–210	–	1.5–2.5

and (c) Stage III—end of crack formation with a stiffer response until the rupture of fibres. The transition from Stage-I to II where there are few kinks in the stress–strain graph was due to the development of multiple cracks in the fibre-mortar interface, and the stiffness of the composites was significantly reduced. The extent of cracking relies largely on the properties of textile and mortar used, and the curve stabilises after the cracking.

2.2 Bond Test

Understanding the bond performance of FRCM and the substrate is essential to evaluate the efficacy of strengthening technique. Either single-lap or double-lap shear bond test is performed to evaluate the bond of FRCM system with the concrete or masonry unit. In the single lap test, the FRCM reinforcement is attached to one side of the block and kept fixed. A portion of the textile system is left unbonded and pulled through a displacement controlled mode (ASTM 2013). In the double-lap shear test, the surface is bonded with a U-shaped textile wrap, i.e., on two sides of the substrate. Figure 5 shows the different failure modes under shear bond test. They include (a) debonding with cohesive failure in the substrate, (b) failure at the reinforcement-to-substrate interface, (c) failure at the textile-to-matrix interface, (d) sliding of the textile within the reinforcement thickness, (e) tensile rupture of the textile in the unbonded portion and (f) rupture of the textile inside the mortar matrix (Ascione et al. 2015). Bond tests show the efficiency of load transfer by the substrate-reinforcement interface allowing the weakest failure mechanism to activate. The failure mode usually depends on the following parameters such as (i) shear strength of the mortar matrix, (ii) the tensile strength of the textile, and (iii) the textile-to-matrix bond/interlocking. The first three failure modes are highlighted in Fig. 5. Force-slip diagram of first three failure modes shows a nonlinear curve followed by flat post-peak behaviour and a sudden brittle failure (Fig. 6a). For failure mode ‘D’, a

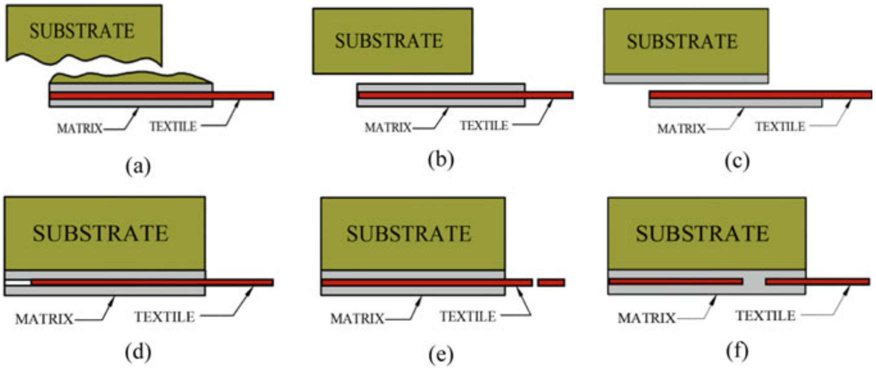


Fig. 5 Comparison of different failure modes under shear bond test

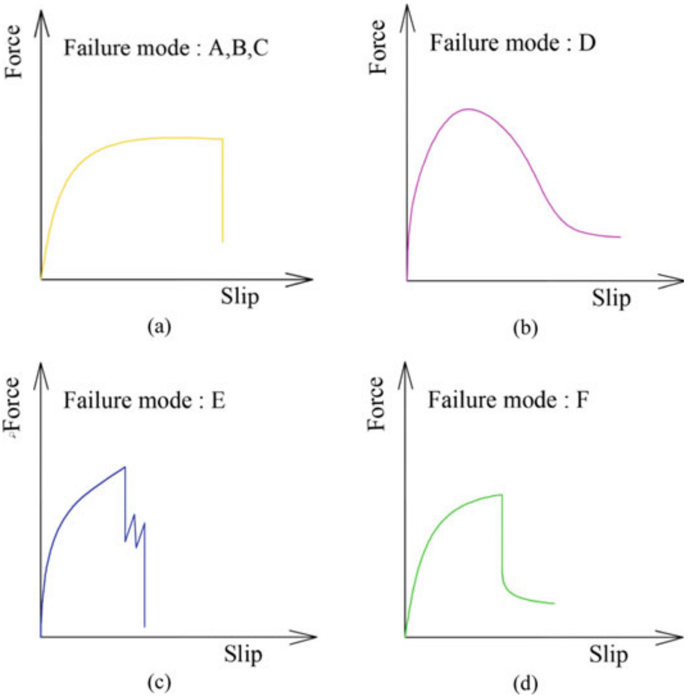


Fig. 6 Overall load–slip behaviour in shear bond test

gradual load reduction (parabolic shape curve) occurs due to the progressive friction loss of the textile sliding within the mortar (Fig. 6b). For the failure mode 'E', an immediate load reduction may occur before the flat branch of the curve is reached (Fig. 6c). Finally, the load-slip behaviour related to failure mode 'F' shows a sudden reduction (Fig. 6d).

3 Strengthening Using FRCM—Procedure

Depending on the type of loading, the strengthening scheme using FRCM system is designed. For example, strengthening with a complete wrapping scheme can be used for enhancing the shear resistance and confinement of RC columns. Similarly, bonding FRCM plates at the soffit of the RC beam can help in enhancing its flexural capacity. The strengthening scheme will consist of four essential steps, as shown in Fig. 7.

(a) providing a corner radius to avoid possible stress concentrations followed by surface roughening and pressurizing with a water jet (Fig. 7a).

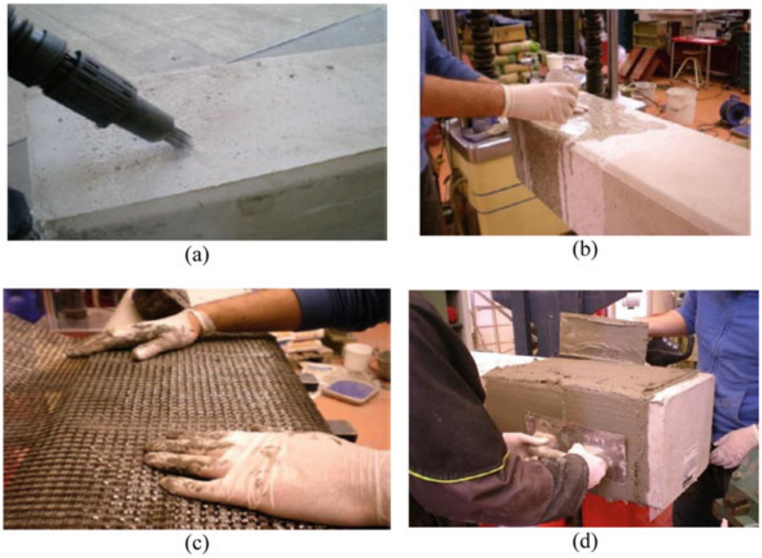


Fig. 7 Strengthening using FRCM system. **a** Surface preparation; **b** surface wetting; **c** FRCM application and **d** finishing (*Picture Courtesy* Escrig et al. 2015)

(b) Surface wetting using water spray to ensure consistency during the application of inorganic based cementitious matrix (Fig. 7b).
(c) Application of the first layer of the inorganic cementitious matrix (4–5 mm thick) and providing externally bonded FRCM system over it (Fig. 7c).
(d) Filling the textiles with the final layer of inorganic based cementitious matrix and surface finishing (Fig. 7d).

4 Different Applications of FRCM

Table 2 summarises the details of different studies which have used FRCM for strengthening RC and masonry structures under different load combinations. FRCM can be used for strengthening under different load combinations which includes:

- Column confinement
- Flexural strengthening
- Shear strengthening
- Strengthening under torsion and combined loading
- Seismic strengthening for RC/masonry structures.

Table 2 Summary of literature for FRCM strengthened members under different loads

Type of loading	Authors investigated	Type of strengthening	Failure modes
Axial load	Triantafillou et al. (2006), Bournas et al. (2007), Peled (2007), Triantafillou (2007), Garcia et al. (2010), Colajanni et al. (2014), Ombres (2014), Trapko (2014) and Thermou et al. (2015)	Full wrapping of FRCM jacket	(a) Debonding of FRCM at the lap end (b) Rupture of FRCM Jacket
Flexure	Bruckner et al. (2006), Papanicolaou and Triantafillou (2006), Triantafillou (2007), Papanicolaou et al. (2009), Ombres (2011), Schladitz et al. (2012), Elsanadedy (2013), Loreto et al. (2013), Babaeidarabad et al. (2014), Napoli and Realfonzo (2015), Ebead et al. (2017), Sneed et al. (2016), Koutas and Bournas (2017) and Raoof and Bournas (2017)	Bonding of FRCM sheets or laminates at the tension side	(a) Slippage of fibres within the matrix (b) Debonding at the concrete-matrix interface (c) Debonding with peeling off of cover concrete (d) Rupture of fibres
Shear	Triantafillou and Papanicolaou (2006), Bruckner et al. (2008), Blanksvard et al. (2009), Al-Salloum et al. (2012), Contamine et al. (2013), Azam and Soudki (2014), Jung et al. (2015), Loreto et al. (2015), Ombres (2015), Tetta et al. (2015), Awani et al. (2016), Tzoura and Triantafillou (2016), Aljazaeri and Myres (2017) and Tetta et al. (2018)	Full wrapping and U-wrapping	(a) Debonding with peeling off of concrete cover (b) Fracture of FRCM jacket (c) Localized FRCM jacket damage (d) Flexure failure

(continued)

Table 2 (continued)

Type of loading	Authors investigated	Type of strengthening	Failure modes
Torsion	Schladitz and Curbach (2012), Alabdulhady et al. (2017) and Alabdulhady and Sneed (2018, 2019)	Full wrapping and U-wrapping	(a) Concrete crushing close to the restrained end (b) Rupture of fibres in the textile
Seismic loading—RC structures	Bournas et al. (2007, 2009), Bournas and Triantafillou (2011a, b) and Bournas (2016)	Full wrapping of FRCM jacket; hybrid combination of NSM + FRCM jacketing	(a) Relocation of the plastic hinge (b) Expansion at the column base
Masonry structures	Prota et al. (2006), Papanicolaou et al. (2007), Papanicolaou et al. (2008), Harajli et al. (2010), Augenti et al. (2011), Faella et al. (2011), Parisi et al. (2011), Koutas et al. (2014), Cascardi et al. (2017), Mezrea et al. (2017) and Akhoundi et al. (2018)	Full coverage of FRCM jackets for the entire wall (in-plane loading) Full coverage of FRCM jackets for the top portion (out-of-plane loading)	(a) Tensile rupture (b) Debonding (c) Crushing (d) Shear cracking (d) Flexure cracking

4.1 Lateral Confinement

Wrapping of compression members using FRCM system can improve the performance under axial compression through increased passive confinement. The of FRCM confinement is to increase both the axial strength and deformation capacity of columns through lateral confinement. The fibres in the hoop direction can improve the confinement and help in increasing the ultimate strain of concrete. However, the confinement effectiveness is better in circular columns than rectangular sections. Due to the presence of sharp corners, the rectangular elements are more susceptible to premature rupture of fibres resulting in reduced peak strength and strain when compared to circular members (Fig. 8). The use of FRCM has been explored extensively in the past as an alternative for FRP based systems (Triantafillou et al. 2006; Bournas et al. 2007; Colajanni et al. 2014; Trapko 2014).

Figure 9a shows the procedure the applying confinement using FRCM. The number of layers required for increasing the lateral confinement usually depends on demand to increase the capacity of the member. It is essential to maintain the minimum corner radius of 25 mm to prevent any possible premature failure at corners. Moreover, a minimum overlap must be provided to prevent the possible early debonding. The important parameters which affect the confinement of FRCM strengthened RC members include (a) FRCM reinforcement ratio, i.e. the number of layers used for confinement, (b) geometry of the section (circular or rectangular), (c) unconfined concrete strength (low strength concrete or high strength concrete),

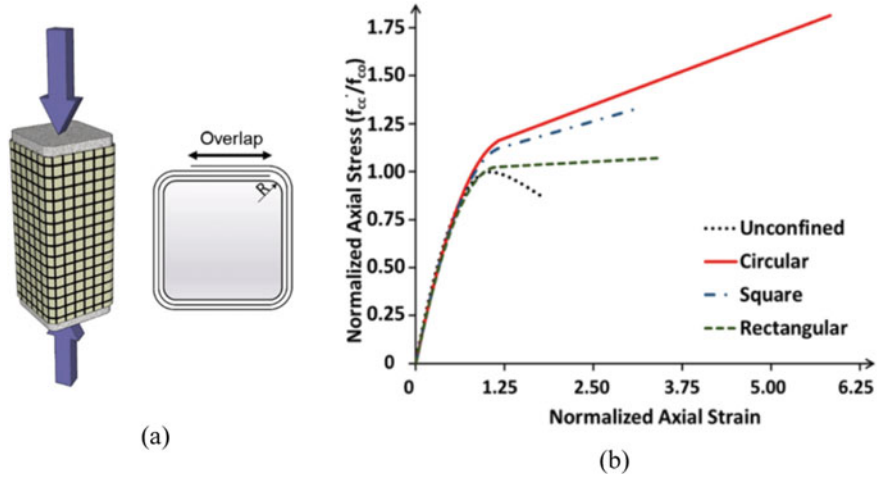


Fig. 8 Confinement of RC columns using FRCM. **a** Overview and **b** typical behaviour

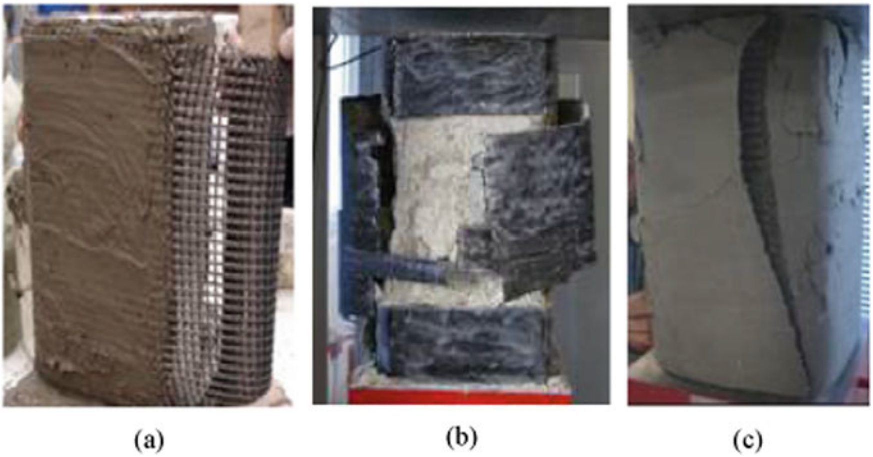


Fig. 9 Failure of columns under compression. **a** Strengthening procedure and failure; **b** textile rupture and **c** debonding (*Picture Courtesy* Bournas et al. 2007)

(d) strength of the inorganic cementitious matrix used, (e) effect of corner radius and overlap length and (f) effect of fibre orientation.

RC columns confined with FRCM can have two possible failure modes, namely:

(a) **Rupture of FRCM jacket** (Fig. 9b)—When the overlap provided is sufficient, the failure of FRCM strengthened members occurs by rupture of FRCM system, i.e., the fracture of fibres in the hoop direction (Bournas et al. 2007; Peled 2007). Similarly, providing a large number of FRCM layers for rectangular members can result in brittle failure at their corners due to stress localization.

(b) **Debonding at the end of the lap** (Fig. 9c)—Due to the use of low strength mortar, the debonding failure occurs where the lap terminates (Triantafillou et al. 2006). The similar failure mode is also possible due to the shorter overlap length and dense mesh with good mortar impregnation (Thermou et al. 2015).

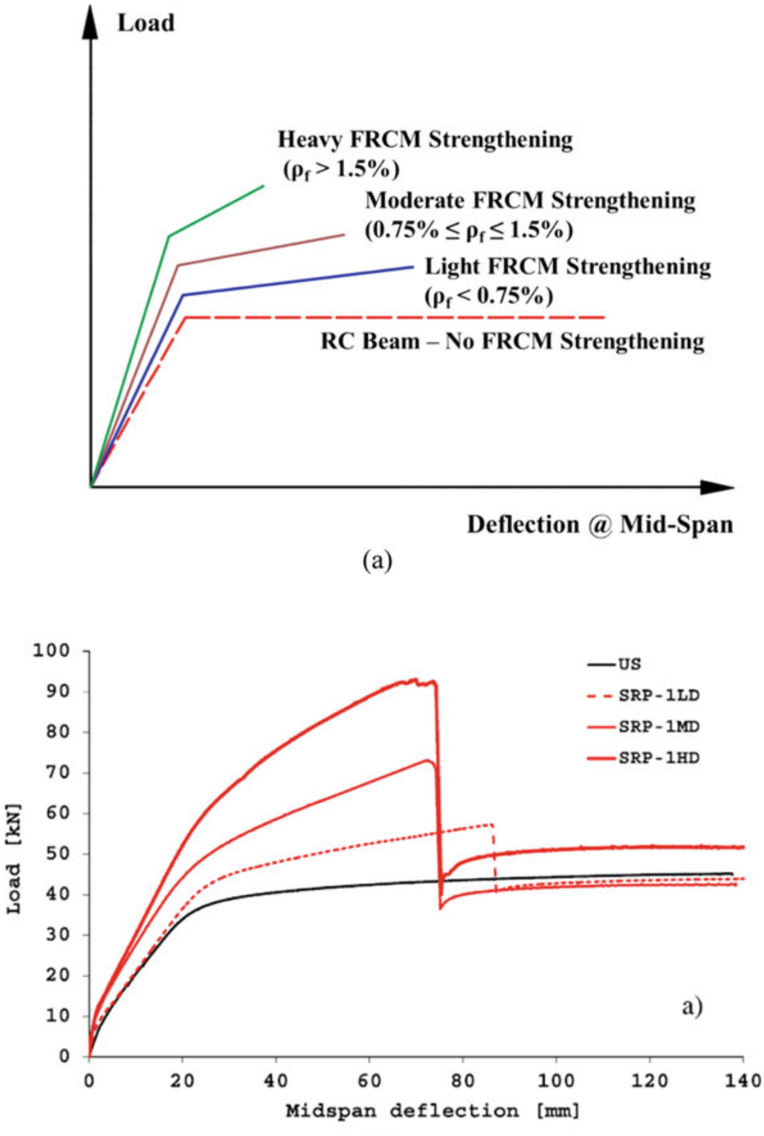
Few researchers have compared the effectiveness of column strengthening using both FRCM and FRP (Triantafillou et al. 2006; Bournas et al. 2007). The researchers concluded that confinement using FRCM is only 10–20% less effective than the FRP confinement. ACI 549.4R-13 provides an idealized bilinear constitutive law for FRCM confined concrete which is very much similar to the FRP confined concrete. The tensile strain in the FRCM composite is limited to 1.2%

4.2 Strengthening Under Flexure

The design of reinforced concrete beams and slabs are usually governed by flexure and may require strengthening due to various reasons. Flexural strengthening of RC members through the FRCM system on the soffit (Bruckner et al. 2006; Papanicolaou and Triantafillou 2006; Triantafillou 2007; Ombres 2011; Schladitz et al. 2012; Elsanadedy et al. 2013; Loreto et al. 2013; Ebead et al. 2017; Sneed et al. 2016; Koutas and Bournas 2017; Raoof and Bournas 2017). FRCM can be used to enhance the additional moment capacity of RC members. Most of the FRCM system have bi-directional textiles, i.e., fibre roving in both directions. The fibres present parallel to the axis of the member helps in developing tensile stress, whereas the fibres in the perpendicular direction help in achieving mechanical interlock.

Figure 10a shows the representation of the load–displacement behaviour of RC members under flexure. Control specimens (under-reinforced sections) with no strengthening typically have a ductile behaviour, i.e., large ultimate displacement before failure. When strengthened with low reinforcement ratio of FRCM, negligible increase in the initial stiffness can be witnessed followed by good improvement in the post-cracking stiffness. However, the specimens undergo failure once after reaching the peak load. The failure mode observed will be similar to the control specimen due to the slippage of fibres within the matrix. With the increase in FRCM reinforcement ratio, i.e., the number of plies more than two, the post-cracking stiffness and peak load increase significantly. However, the ultimate strain reduces significantly, and the member undergoes sudden failure due to debonding with or without peeling off of cover concrete. Similar results were reported by Napoli and Realfonzo (2015). As shown in Fig. 10b, SRP refers to Steel Reinforced Polymer (SRP). LD, MD and HD refer to density of polymer tape used. Example: SRP-1LD denotes the slab strengthened with a single layer of low density (LD) steel tape impregnated with a matrix.

Four failure modes have been reported in the literature which includes (a) Intermediate crack debonding, (b) Fibre slippage through the mortar, (c) Debonding with the peeling off of concrete cover and (d) textile rupture (Ombres 2011; Schladitz et al.

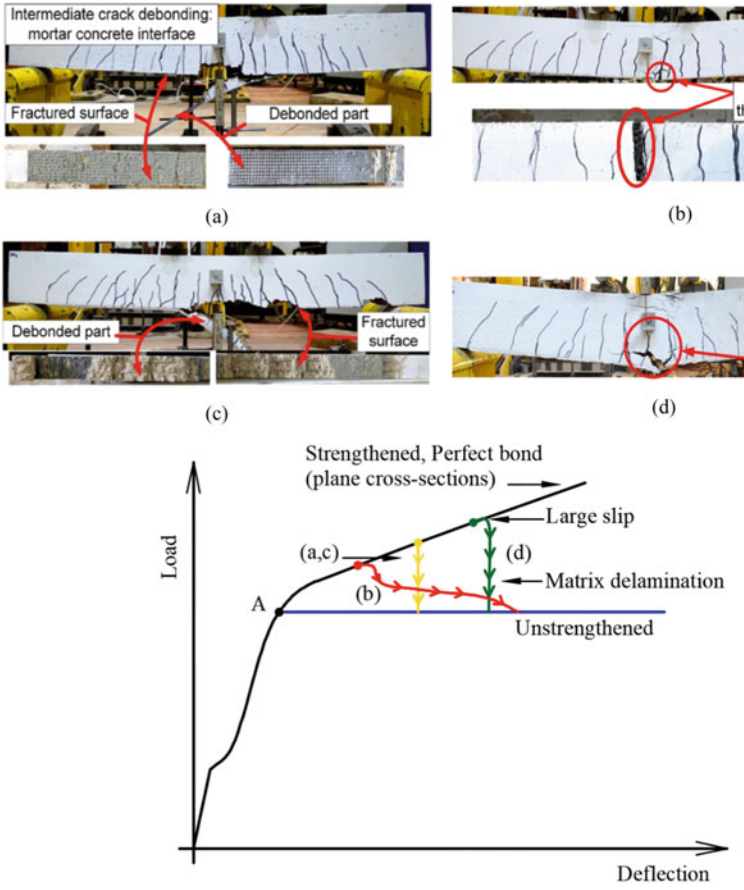


(a)

(b)

Fig. 10 Schematic representation of flexural members with different FRCM ratios. **a** Strengthening with different FRCM ratios and **b** typical load–displacement behavior

2012; Loreto et al. 2013; Sneed et al. 2016; Ebead et al. 2017; Raoof et al. 2017). When the specimens are strengthened with more than two plies of FRCM, there is a possibility of failure occurring through debonding mode (Fig. 11a). The debonding at the concrete-matrix interface can occur through two possible modes called as (a) intermediate debonding, i.e., initiation of debonding from the region of maximum bending moment and (b) end debonding, i.e., detachment of FRCM initiates from the end and propagates towards the mid-span. When the specimens are strengthened with less number of FRCM plies (i.e., mild FRCM reinforcement ratio), the failure tends to occur through slippage of fibres within the matrix (Fig. 11b). Similarly, when the bond between the concrete –matrix is strong enough, the debonding of FRCM reinforcement becomes less likely and the entire FRCM peels of along with the cover



(a) (b) (c) (d) (e)

Fig. 11 Failure modes of FRCM strengthened flexural members. **a**–**d** Different failure modes under flexural loading and **e** typical load–displacement behavior with the corresponding failure (*Picture Courtesy* Raoof et al. 2017) concrete (Fig. 11c). The debonding can initiate either from the mid-span (due to flexure) or in shear span (due to flexure-shear crack). Another possible failure mode under flexure may occur due to the rupture of fibres when the maximum moment region is subjected to high tensile stress (Fig. 11d). Here, the fibre rupture occurs in a single section. Moreover, the failure mechanism is brittle, and the specimen experiences a sudden load drop after reaching a peak load.

Different factors that affect the flexure strengthening of RC members using FRCM includes:

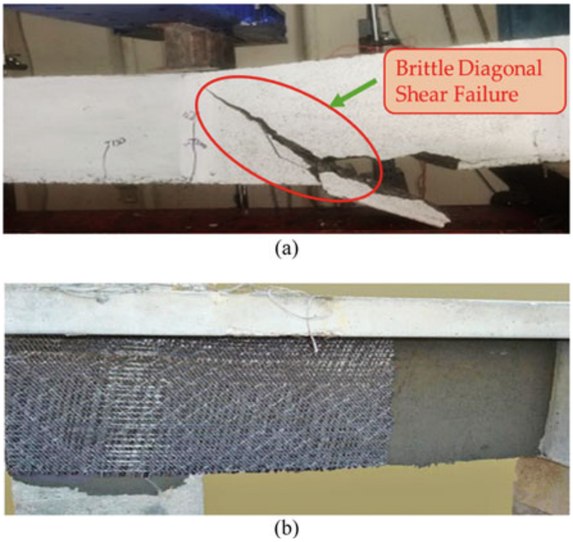
a. FRCM reinforcement ratio—increasing the number of plies or layers of FRCM can help in increasing the overall moment capacity. However, the failure mode may change from one to the other. Example: Application of more than two layers of FRCM may convert the failure mode to debonding with or without peeling off of cover concrete.
b. Steel reinforcement ratio—the efficiency of FRCM strengthening improves significantly for under-reinforced RC members.
c. Influence of inorganic cementitious mortar—Use of polymer modified cementitious mortar can enhance the chemical bond compared to conventional mortar type (Elsanadedy et al. 2013). Similarly, the strength of mortar determines the failure mode of FRCM strengthened members. Use of low strength mortar results in failure due to fracture of the jacket, whereas the use of high strength mortar results in debonding failure.
d. Geometry of textile–spacing and orientation of fibres in the textile.

4.3 Strengthening Under Shear

RC beams/ girders often require strengthening under shear due to various causes such as (a) corrosion issues in existing reinforcement, (b) insufficient shear reinforcement, (c) low strength concrete, (d) increase in demand and (e) convert the failure mode from brittle shear to ductile flexure mode. FRCM may be used to enhance the shear capacity of RC members by applying in the form of either U-wrap or complete wrapping. U-wrap can be used when the strengthening under shear is essential for beams; i.e., the top portion of the member is not accessible due to the presence of the slab (Fig. 12). Complete wrapping is preferred for columns which require strengthening under shear (Fig. 13). A number of studies in the past have investigated the feasibility of FRCM application in shear strengthening of RC members (Triantafillou and Papanicolaou 2006; Bruckner et al. 2008; Blanksvard et al. 2009; Al-Salloum et al. 2012; Contamine et al. 2013; Jung et al. 2015; Ombres 2015; Tetta et al. 2015; Tzoura and Triantafillou 2016; Aljazaeri and Myres 2017; Tetta et al. 2018). The shear behaviour of FRCM strengthened members were studied through testing of beams under static three or four-point bending loads at different shear span to depth ratios.

The schematic representation of the load–deflection behaviour of un-strengthened and FRCM strengthened RC beams is shown in Fig. 14. The un-strengthened speci-

Fig. 12 Typical failure mode and strengthening under shear. **a** Diagonal-shear failure in RC beams and **b** retrofitting solutions using U-Wrap FRCM



(a)

(b)

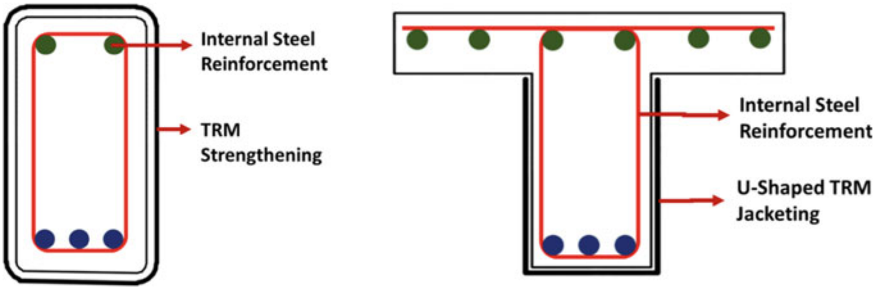
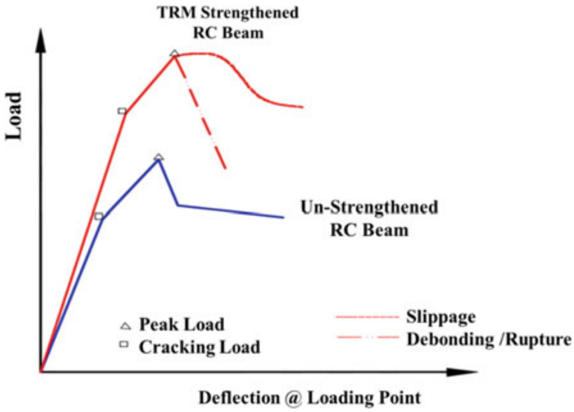


Fig. 13 Types of FRCM shear strengthening of RC members

Fig. 14 Load–deflection behaviour comparison under shear



mens show a brittle failure once after reaching the peak load. The behaviour of the FRCM strengthened specimen is similar to the control one until the cracking load. After cracking, FRCM is activated and shows a significant improvement in the post-cracking behaviour. After reaching the peak loads, two types of failure modes are possible namely (a) debonding or rupture of fibres which are very brittle and show a sudden load drop and (b) localized damage of jacket, i.e., slippage of fibres through the inorganic matrix. The latter one exhibits a pseudo-ductile failure mode, i.e., the degradation is not sudden and is gradual.

Figure 15 shows the different failure modes of FRCM strengthened RC members under shear loads. The un-strengthened control beam, which is shear deficient, can fail due to shear-tension mode, as shown in Fig. 15a. Strengthening will aim to exploit the full capacity of the member and convert the failure mode from shear dominant to bending dominant. Four major failure types under shear are possible for FRCM strengthened members which includes.

a. Debonding with peeling off of concrete cover (Fig. 15b)—This type of failure occurs predominantly for U-wrapped members. This failure type helps in exploiting the full shear capacity of the members.
b. Fracture of FRCM jacket—Mainly occurs in members applied with full wrapping scheme. However, this failure mode does not utilize the full capacity and makes the member less effective (Tzoura and Triantafillou 2016).
c. Localized FRCM jacket damage—One of the predominant failure modes observed in most of the FRCM shear strengthened specimens with dry textile

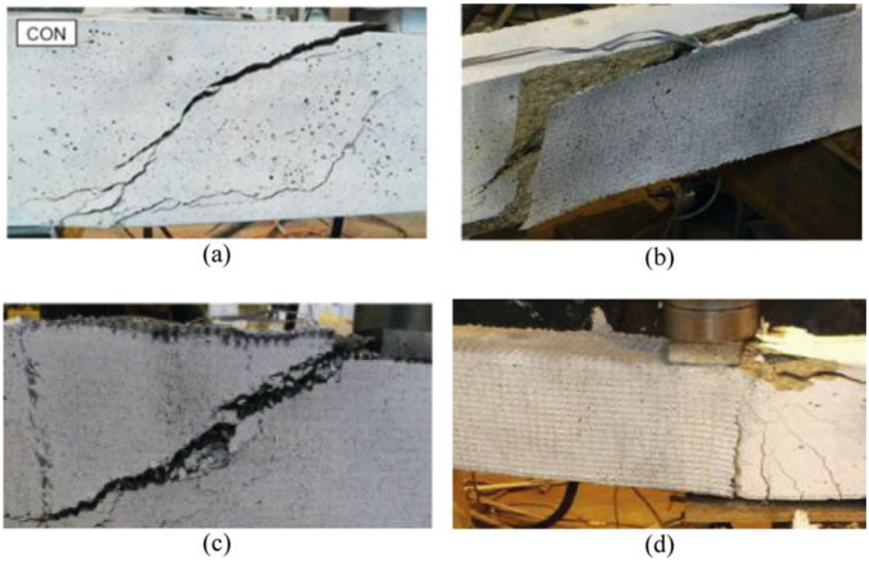


Fig. 15 Possible failure modes under shear. **a** Shear–tension failure; **b** fracture of FRP jacket; **c** damage of FRCM jacket and **d** flexure failure (*Picture Courtesy* Tetta et al. 2018)

materials (Loreto et al. 2015; Tetta et al. 2016). Here, the failure occurs due to the slippage of the mortar through the matrix.

d. Flexure failure (Fig. 15d)—development of shear crack is stopped due to the effectiveness of FRCM jacket, and the failure occurs due to the opening of flexure crack.

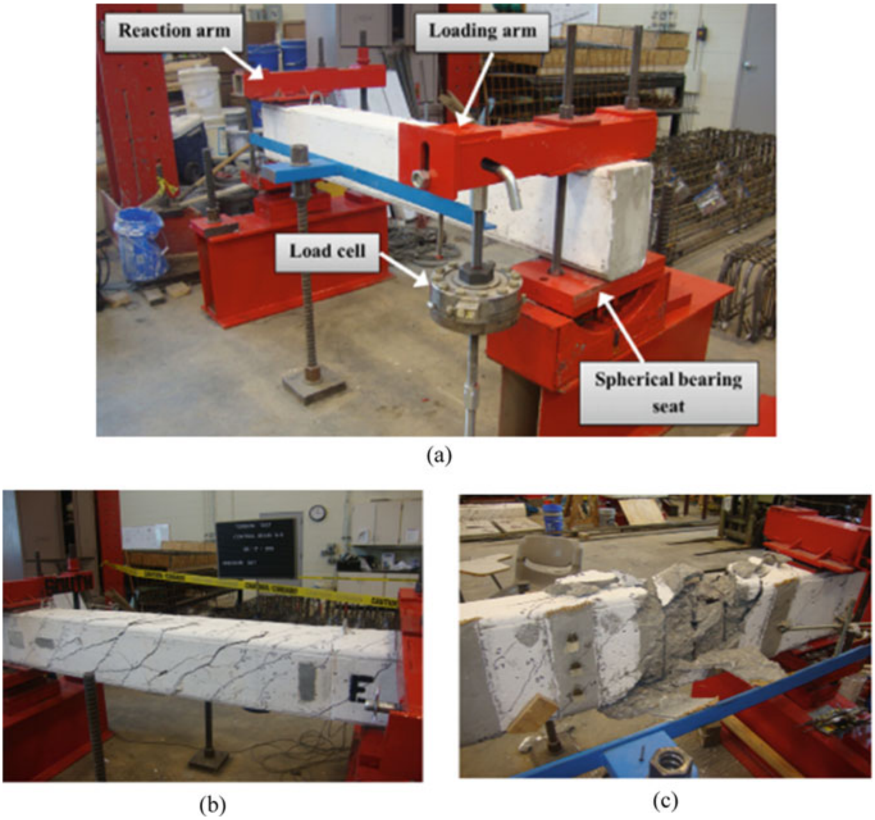
4.4 Strengthening Under Torsion or Combined Loads

Reinforced Concrete (RC) bridges, buildings and other structures are subjected to torsional loading in addition to other load combinations. Several studies have reported the effect of torsion on the behaviour of RC members strengthened with FRCM composites (Alabdulhady et al. 2017; Alabdulhady and Sneed 2018, 2019). The wrapping scheme used for torsional strengthening was similar to the one used for shear dominant ones, i.e., full wrapping (with and without spacing along the length) and U-wrapping schemes (T-beams where the top portion is not accessible) may be employed.

Figure 16a shows the test setup used for applying torsional load (Alabdulhady et al. 2017). The torque will be generated to the specimen using the loading arm with some eccentricity relative to the centroid of the section. Threaded steel rods which are anchored to the strong floor were used to support the reaction arm (Fig. 16a). The control specimens without any strengthening had failure initiation with the formation of two complete spiral cracks at an angle of 45° to the longitudinal axis (Fig. 16b). The final failure was due to the concrete crushing in the mid-span of the test specimen. The specimens strengthened with U-wrapping system had a similar failure mode to the control specimen expect the location of crushing, which was close to the restrained ends. In addition, slippage of fibres into the matrix was also observed. It is worth mentioning that the 3-sided configuration shows only a marginal increase in torsional strength enhancement. For specimens strengthened with complete wrapping scheme, the failure initiated due to rupture of fibres in the textile. The specimen also had concrete crushing after the loss of confinement at the mid-span and near the reaction end. The full-wrapping with FRCM helps in complete utilization of torsional capacity (torque increase more than 100%) and the failure surface is distributed throughout the member.

4.5 Seismic Strengthening of RC Structures

FRCM jackets can be used for enhancing the deformation and energy dissipation capacity of reinforced concrete (RC) columns (Bournas et al. 2007, 2009; Bournas and Triantafillou 2011a, b). RC columns require strengthening for avoiding global failure under seismic actions. The reasons for strengthening includes: (a) better confine the plastic hinge locations, (b) improve the cyclic deformability of columns



(a)

(b)

(c)

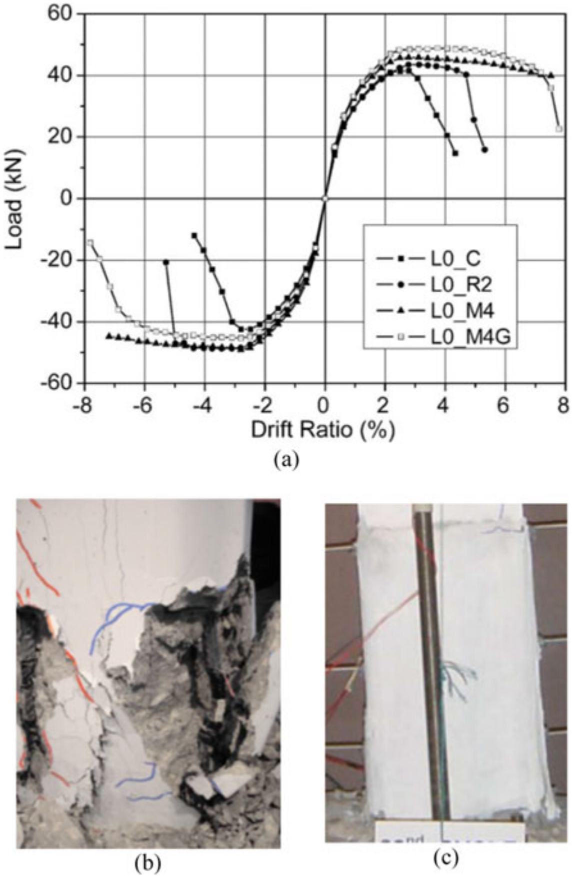
Fig. 16 Test setup and failure mode comparison under torsion. **a** Typical test setup; **b** crack pattern at initial stages and **c** ultimate failure (*Picture Courtesy* Alabdulhady et al. 2017)

by increasing their energy dissipation, (c) improve the behaviour of poorly detailed old RC columns, (d) prevent buckling of longitudinal reinforcements and (e) protect the locations of lap-splices.

Earlier, researchers used FRP as a useful material for improving the deformability of RC columns under seismic loads. However, recent studies have shown that FRCM increased the energy dissipation and cyclic deformation of old type RC columns with poor detailing. Moreover, the effectiveness of FRCM was found similar to the FRP strengthened RC columns under seismic loads.

Figure 17a shows the load–drift response of columns with and without FRCM strengthening. In the graph, L0_M4 and L0_M4G correspond to carbon and glass FRCM used for seismic strengthening of columns. Both the FRCM strengthened specimens showed superior deformability and energy dissipation capacity of poorly detailed RC columns under seismic actions. Moreover, the control specimen failed due to the buckling of longitudinal reinforcement and disintegration of concrete at the base. In the case of FRCM strengthened RC columns, both the carbon and glass

Fig. 17 Seismic behaviour of un-retrofitted and FRCM retrofitted RC columns. **a** Load–drift ratio behaviour; **b** ultimate failure of control specimen and **c** ultimate failure of FRCM retrofitted specimen (*Picture Courtesy* Bournas and Triantafillou 2011a, b)



fibres in textiles developed excellent composite action and were able to resist loads without any early fibre rupture. The ultimate failure was due to the lateral expansion at the base of the column without rupture of fibres in the FRCM jacket (Fig. 17c).

4.6 Strengthening of Masonry Structures

Un-reinforced masonry structures when subjected to in-plane seismic loading can undergo failure due to diagonal cracking (cracking along the bed joints) or shear sliding. Therefore, the strengthening of un-reinforced masonry structures is of great importance. FRCM can be used for strengthening masonry frames subjected to different loading cases such as (a) confinement of masonry columns, (b) strengthening against in-plane bending and shear demand of masonry spandrels and piers, (c) improving the out-of-plane bending capacity of bridge piers and spandrels, (d) strengthening of other masonry structures like arches, domes and vaults. Strengthening masonry structures by confinement is usually not required as they possess sufficient axial capacity. However, different factors such as ageing, deterioration, eccentricity during loading reduces the capacity significantly. The original axial capacity of masonry structures can be restored by providing FRCM confinement in the circumferential direction to increase its peak strength and deformation levels.

Several studies have investigated the effect of FRCM confinement on the behaviour of masonry structures (Faella et al. 2011; Cascardi et al. 2017; Mezrea et al. 2017). Moreover, the models which are used for predicting the axial capacity of FRP strengthened masonry members can be used for FRCM strengthened as well (Cascardi et al. 2017; Mezrea et al. 2017).

Another failure of masonry walls is due to the in-plane bending and shear occurring as a result of seismic action parallel to the wall. The combination of shear and bending occurs with or without the influence of axial loads. FRCM composites are provided with the vertical fibres at the extremities as close as possible to the highly stressed areas for protecting the masonry walls from the in-plane bending stresses, (Fig. 18a). However, if the walls are to subjected to a combination of stress, full coverage of wrapping should be carried out, as shown in Fig. 18b. Effect of in-plane loading on the behaviour of masonry walls have been extensively investigated (Prota et al. 2006; Papanicolaou et al. 2007; Augenti et al. 2011; Parisi et al. 2011; Koutas et al. 2014).

Out-of-plane failure of masonry walls is also possible due to the inertial forces acting in the horizontal direction. Figure 18c shows the overturning of masonry wall due to the plastic hinge formation at the base or certain height from the base. This can be due to the different parameters like slenderness of the wall and boundary conditions. For this loading combination, FRCM can be applied to the top portion of the wall and anchored correctly to the orthogonal walls like a belt, as shown in Fig. 18d. FRCM based strengthening of masonry walls subjected to out of plane bending (cyclic loading) showed good improvement in strength and deformation capacity (Papanicolaou et al. 2008; Harajli et al. 2010).

Koutas et al. (2015) investigated three-storey full-scale masonry infill frames strengthened with FRCM jacketing (Fig. 19). They wanted to understand the contribution of masonry infills to the in-plane seismic loading on the existing RC structures when strengthened using FRCM. The test results revealed that the masonry infills strengthened using FRCM scheme exhibited more than 50% increase in lateral strength and deformation capacity when compared to the un-strengthened specimen. Moreover, the energy dissipation capacity increased by more than 25% when compared to the un-strengthened one.

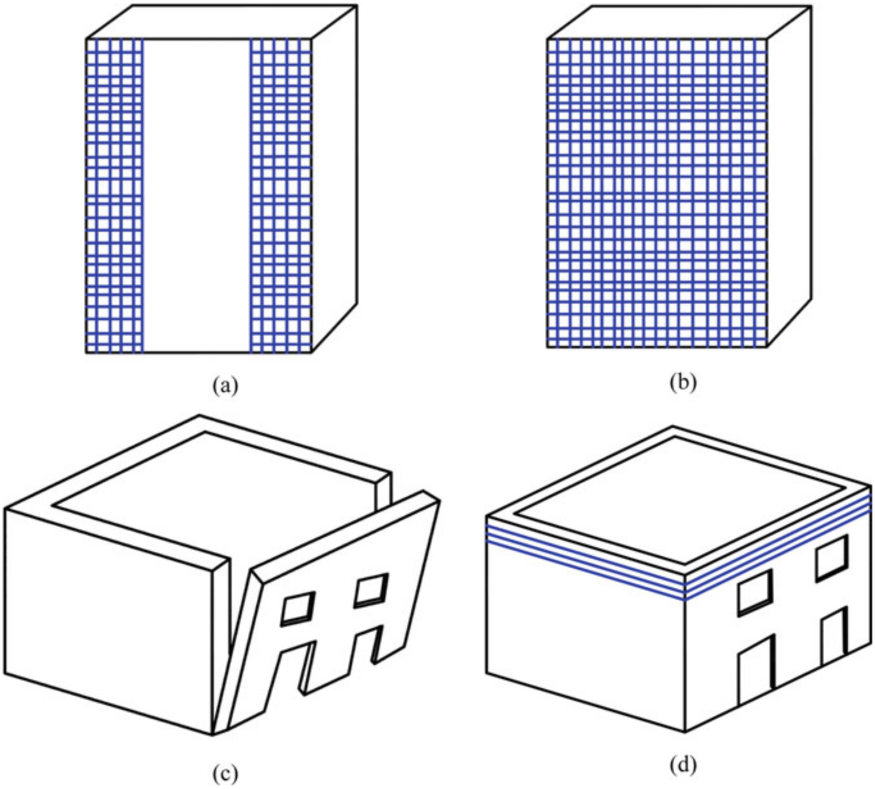


Fig. 18 Seismic strengthening of masonry walls. **a** Partial wrapping scheme against in-plane bending stresses; **b** full wrapping scheme against in-plane bending stresses; **c** out of plane failure and **d** strengthening against out of plane failure

5 Case Studies and Special Applications

5.1 Strengthening San Siro Stadium, Italy

San Siro stadium, located in Milan, Italy, was constructed in the year 1925. The bearing structure of the lower portion of the stadium is an RC frame, as shown in Fig. 20a. The building was renovated in the year 2002, which was new steel structures but left unconnected with the existing RC structure (Trimboli and Mantegazza 2004). A new foundation system was laid for transferring the additional load to the ground. During preliminary condition assessment, and a significant deterioration in the RC beam was detected (Fig. 20b). U-shaped FRCM wrapping is used often for enhancing the flexural and shear capacity of the RC beam (Fig. 20c).

Other strengthening techniques such as concrete jacketing, steel plate bonding and FRP strengthening were preferred earlier. However, those techniques could not

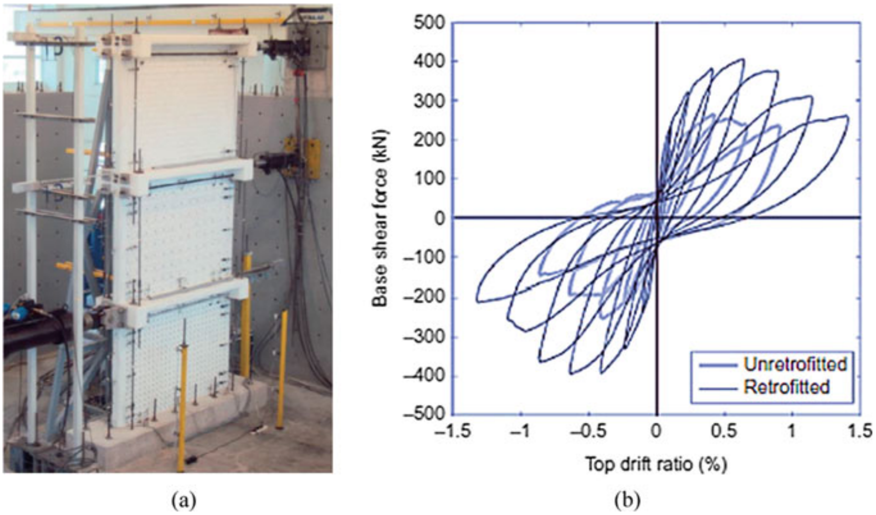


Fig. 19 Seismic strengthening of infilled masonry walls. **a** Failure mode and **b** overall behaviour comparison (*Picture Courtesy* Koutas et al. 2015)

Fig. 20 Strengthening San Siro stadium. **a** Site view; **b** preliminary assessment; **c** strengthening by U-shaped FRCM and **d** surface finishing with cementitious grout (*Picture Courtesy* Trimboli and Mantegazza 2004)

be chosen due to several site constraints and shorter time required to complete the project. Moreover, FRCM jacketing turned out to be an ideal solution for this repair as the no preparation for the damaged surface was essential. The damaged RC beam was first applied with the inorganic cementitious matrix followed by the installation of FRCM jackets. The surface of the FRCM jacket was again filled with the mortar, and uniform surface finishing was carried out (Fig. 20d). Bi-directional carbon fibre textiles were used in this project which had a tensile strength and modulus of elasticity of 3400 MPa and 227 GPa, respectively.

5.2 Strengthening of Cooling Towers, Niederaussem Power Station

The Niederaussem lignite power station located in Bergheim, Germany was constructed in 1963 with a total output power capacity of 3864 MW. The cooling towers in the power station are always subjected to extreme weather conditions and are continually deteriorating. Due to various causes like high wind pressure, high-temperature stresses and flue gas discharge, a natural cooling tower was damaged. More information about the cooling tower and damage mechanism can be found at Altmeyer et al. (2012). During the inspection, a detailed assessment of the tower was carried out to determine its present load-carrying capacity. From the calculations from the rational methods, it was found that the tower which was built as per the old code did not meet the revised code recommendations. Hence, it was proposed to strengthen the cooling tower for safeguarding its operation. PBO based FRCM was preferred over FRP due to the presence of inorganic cementitious matrix, which can provide better long term durability without degradation under extreme environmental conditions and high-temperature stresses. The strengthening procedure adopted is shown in Fig. 21.

5.3 Strengthening of RC Columns in Hot Industrial Area, India

Due to the extreme temperatures more than 100 °C, severe corrosion and micro-cracking were found in the RC frame, which supports a 25 years old coke oven structure. The requirement from the client was to enhance the overall capacity of RC columns with two restrictions such as (a) no change in the section of the column, and (b) proposed strengthening system should work at extreme temperatures more than 100 °C. Carbon FRP was the first choice made for enhancing the load-carrying capacity of RC columns. However, CFRP was not chosen as the proposed strengthening system should be stable under sustained high-temperature exposure.

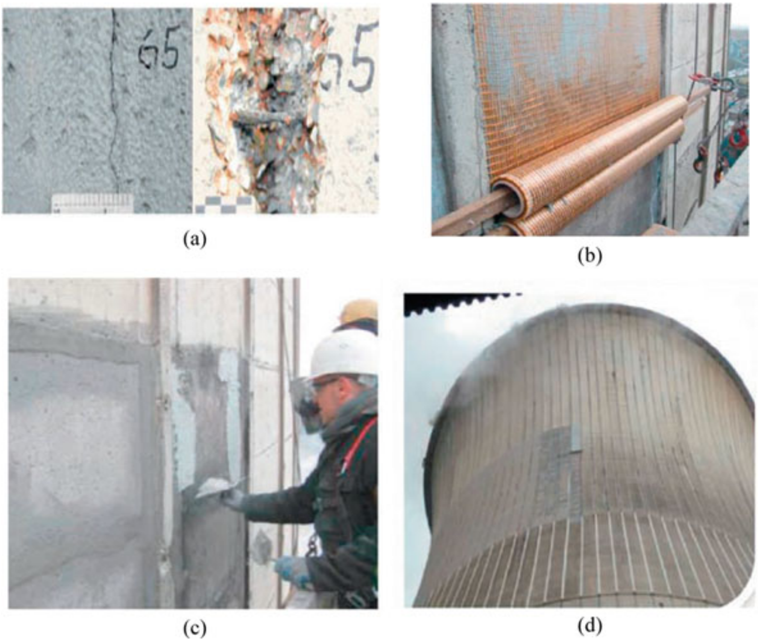


Fig. 21 Strengthening of cooling tower, Germany. **a** Damage extent; **b** strengthening using PBO-FRCM; **c** surface finishing and **d** final view (*Picture Courtesy* Ruredil SPA)

Sanrachana Solutions Ltd., which carried out the renovation work for this work, proposed a combination of shotcrete and SRM hot-wrap FRCM jacketing. SRM hot-wrap comprises of bi-directional carbon fibres with a high tensile strength and modulus of elasticity ($f_t = 3200$ MPa and $E_f = 230$ GPa). Moreover, the mortar used (SRM-CM-MORTAR-250) is a cementitious based hydraulic binder that adheres well with the carbon fabric mesh when used for strengthening concrete or masonry structures. The detailed procedure for the strengthening of RC column using FRCM is shown in Fig. 22. In total, 172 RC columns were strengthened using the proposed FRCM technique. FRCM was successfully applied after conducting a pilot testing program to check both strength enhancement and high temperatures exposure in an accelerated manner. FRCM system was applied on site after pilot tests ensured the desired performance.

5.4 Romanesque Church of San Roque, Spain

Romanesque Church of San Roque, Spain belonged to the ancient medieval period and was made of stonework, masonry and timber elements. During a seismic event, the outer walls of the church underwent out of plane separation (Fig. 23a). More-

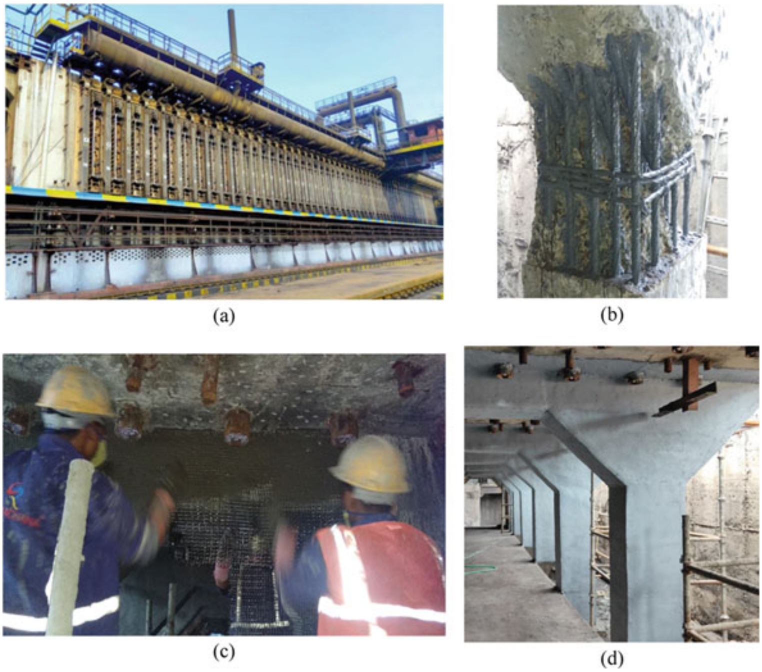


Fig. 22 Strengthening of corrosion damaged RC column in hot industrial area using FRCM. **a** Site view; **b** extent of damage in column; **c** SRM hot-wrap FRCM jacketing and **d** FRCM strengthened members (*Picture Courtesy* Sanrachana Solutions Ltd.)

over, several locations of the main vault had large cracks and required strengthening (Fig. 23b). Though the church was stable under live loads, few localized zones were severely cracked. FRCM system was applied to the damaged vault to prevent the formation of new cracks and prohibit the growth of the existing longitudinal crack. First, the damaged vault was shored up. Before strengthening, all the dirt and debris were removed. As shown in Fig. 23b, basalt fibre anchors were installed, followed by the installation of basalt fabric. The cementitious mortar was used to cover the fabric and provide surface finishing.

6 Opportunities and Scope for Further Work

The experimental data available until now shows that the use of FRCM will be extensively possible for the strengthening of masonry and reinforced concrete members under different load combinations. To make the design engineers utilize the FRCM based strengthening system for the potential projects, still, some test data is essential along with the availability of proper design guidelines. Recently, some design

(a)

(b)

Fig. 23 Strengthening of Romanesque Church. **a** Damage due to out of plane separation and **b** FRCM strengthening and Basalt fibres anchors (*Picture Courtesy* Fyfe Europe SA)

specifications and guidelines have been made available by the technical organization for the design of FRCM based strengthening solution (ACI 2013; Triantafillou 2007; Triantafillou 2016). In specific, the use of FRCM may become possible for projects where special design requirements are to be met, i.e., high temperature and durability aspects of the retrofitted structures. A classic example where FRCM system was adopted to strengthen the cooling tower in Niederaussem Lignite power station, Germany, where the cooling tower was predominantly subjected to high temperatures.

Several previous research works have studied the effectiveness of FRCM based strengthening solution for RC and masonry members under different load combinations. However, a lot of research and innovative solutions are required to make it more implementable in the field. One such innovative system is the use of hybrid strengthening system which combines two strengthening techniques such as near-surface mounting and externally bonded FRCM jackets. Some preliminary works on hybrid strengthening systems on the behaviour of RC members under combined compression and bending has been investigated (Bournas and Triantafillou 2009, 2013). However, the effect of hybrid strengthening under shear and torsion loads are still not explored. RC bridge columns with irregular three-dimensional (3D) bridge configurations can undergo axial, bending, and shear forces during earthquake events. The addition of torsion is more likely in skewed or horizontally curved bridges, bridges with unequal spans or column heights, and bridges with outrigger bents. Torsional loadings can significantly affect the flow of internal forces and the deformation capacity of RC columns. Moreover, the presence of torsional loading increases the possibility of brittle shear–dominated failure, which may result in a fatal catastrophe. Besides, the presence of tensile cracks in the principal compression plane softens the stress–strain behaviour of concrete struts. For designing a strengthening system under such a loading scenario where torsion occurs in combination with compression, bending and shear, the hybrid technique can be an effective solution. The hybrid strengthening system should consist of high ratios of confinement (EB fabric) with some NSM as additional longitudinal reinforcement for achieving better performance.

7 Summary

The advantages of FRCM as a strengthening solution for RC and masonry structures were discussed. The behaviour of FRCM strengthened members under various loading conditions such as flexure, shear, torsion, axial loads were explained. The applicability of FRCM strengthening to improve the plastic hinge behaviour of concrete columns and masonry infills under seismic loads was discussed. FRCM has the potential to contribute to the strengthening projects in the coming decades due to its unique advantages such as long durability and high-temperature resistance. Limited case studies were also presented to highlight the improved performance of FRCM to restore the service level of older structures. Opportunities and challenges in increasing the widespread use of FRCM for strengthening applications were also discussed.

Acknowledgements The authors would like to thank Dr Mangesh Joshi, Sanrachana Solutions Ltd, Thane for the help with the required inputs for preparing the case study on FRCM strengthening of severely damaged RC columns.

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