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DOI:
10.1002/suco.202000801

Document Version
Accepted author manuscript

Citation for published version (APA):
Su, M., Wang, Z., & Ueda, T. (2022). Optimization and design of carbon fabricreinforced cementitious matrix composites. *Structural Concrete*. https://doi.org/10.1002/suco.202000801

Published in:
Structural Concrete

Su, M.N., Zhi, W., Ueda, T. (2022) “Optimization and Design of Carbon Fabric-Reinforced Cementitious Matrix Composites”, Structural Concrete, FIB, pp. 1-16. DOI: 10.1002/suco.202000801

Optimization and Design of Carbon Fabric-Reinforced Cementitious Matrix Composites

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Abstract: Interest in carbon fabric-reinforced cementitious matrix (C-FRCM) composites as structural strengthening materials for reinforced concrete structures has recently increased. In such applications, the mechanical properties of C-FRCM composites are the key to unlocking the corresponding strengthening effects. Therefore, this study explores different optimization approaches to improve the loading behaviors of C-FRCM composites, such as different carbon fabric contents in the cementitious matrix and different surface treatments of the carbon fiber meshes. Then, a series of tensile tests are carried out to evaluate the performance of the modified C-FRCM composites. Furthermore, experimental results of other FRCM composites are collected from the literature to create a larger data pool for analysis. Finally, two existing constitutive models for FRCM composites — the Aveston-Cooper-Kelly (ACK) model and the AC434 model — are compared against these experimental data.

Key words: C-FRCM; carbon fiber mesh; constitutive models; tensile tests

1. Introduction

Externally bonded fiber composite materials have become a common a common means to improve the performance and extend the service life of existing reinforced concrete structures. Over the last 20 years, fiber-reinforced polymer (FRP) plates/sheets/meshes, consisting of continuous fiber sheets and organic epoxy resin, have been the most popular strengthening materials [1,2]. However, externally bonded FRP systems are difficult to construct in low-temperature environments and are not durable in humid and corrosive environments; furthermore, FRP systems have poor fire resistance properties and are incompatible with concrete substrates (due to the different chemical properties between organic and inorganic materials) [3-8]. With the development of structural strengthening technologies, a relatively new composite called fabric-reinforced cementitious matrix (FRCM) composite has attracted attention from researchers and engineers. FRCM composites are a type of composite with one or multiple layers of continuous bidirectional fiber mesh embedded in a cementitious matrix [9-12]. Compared to the bonding material used in FRPs (e.g., epoxy resin), the inorganic cementitious materials used in FRCM composites are superior in terms of fire resistance, durability and compatibility with concrete (i.e., allows vapor permeability and application on a wet surface). FRCM composites also exhibit advantages over FRPs in applications on irregular surfaces [13].

Although both FRPs and FRCM composites are mainly subjected to tension when used for structural strengthening, the structural responses of these two composites are quite different. The stress-strain curve of an FRP under tension is linear until reaching the ultimate state, whereas the load transfer in an FRCM composite occurs through the interfacial bond between the cement matrix and the fiber mesh, and the corresponding constitutive model for an FRCM composite is bilinear or trilinear, for which the cracking of the cementitious matrix corresponds to a transition point [14]. Research on FRPs started in the 1940s, and FRPs began to be implemented in a wide range of applications in the 1960s. Compared to FRPs, FRCM composites have more-complex structural responses; research on FRCM composites started in the 1980s. The tensile properties of FRCM composites were significantly connected to the bond behavior between matrix and fiber, while the strengthening intervention also relies on the composite/substrate bond behavior. According to the literatures, the fiber mesh/cementitious matrix interface is normally more critical compared to the composite/substrate interface [11-12, 15-18]. This is because cementitious matrix and concrete are both inorganic materials; the bonding between inorganic materials is typically better than the bonding between inorganic and organic materials. Existing experimental investigations on the tensile behavior of FRCM composites include the clarification of the effects of clamping grips (i.e., different boundary conditions) [19,20], layers of fiber mesh [8,21,22], and chopped fibers in the cementitious matrix [23] on the loading behaviors of the composites. Experimental results have shown that the mechanical properties of FRCM composites could be significantly limited due to the combination of premature filament failure and core filament slippage [11-12, 24-25]. Compared to clevis grips, clamping grips resulted in a better utilization of the capacities of fibre meshes which embed in cementitious matrix, thereby leading to generally higher tensile strength results [19,20]. In the macro level, Larrinaga et al. [21], Caggegi et al. [22] and Donnini and Corinaldesi [8] found that as the number of fiber layers increased, the bond between the fiber bundles and mortar became less effective, and the fiber bundles became more prone to slip. Barhum and Mechtcherine [23] incorporated chopped glass and carbon fibers into a cementitious matrix and reported that the cracking load of the composite materials significantly increased and that a greater number of fine cracks appeared on the specimen surface due to the incorporation of the reinforcing materials; however, the increase in ultimate strength was limited. Studies on the surface treatment of fiber bundles have also been carried out. Contamine and Si Larbi [26] preimpregnated glass fiber meshes with epoxy resin and latex before embedding the fiber meshes into a cementitious matrix; this process significantly increased the strength of the FRCM composites. This increase in strength occurred because the preimpregnation process resulted in the fiber filaments having a more uniform stress distribution [27]. Donnini et al. [15] used different mortar matrices and applied different coating treatments to carbon fabric. The results show that the use of a polymer coating on carbon fabric increases the mechanical capacity of the FRCM system. In addition, applying sand to the surface of carbon fabric further increased the mechanical characteristics of the carbon fabric. Other studies have investigated different anchorage configurations of embedded fiber meshes [28], effective fiber mesh overlap lengths [29] and loop-shaped elements [30] to improve the loading behaviors of FRCM composites. However, the experimental results presented in the literature are still limited. Moreover, as mentioned above, the loading responses of FRCM composites are quite distinct under different conditions, making it difficult to reach consistent conclusions for different FRCM composites, considering that there are a substantial number of variables associated with the cementitious matrix, embedded fiber meshes, loading configurations, etc. Currently, there are two commonly used simplified tensile stress-strain models for FRCM composites: the bilinear model codified in AC434.13 [31] (called the AC434 model in the following discussion) and the trilinear model proposed by Aveston and Kelly [32] (called the ACK model in the following discussion). The appropriateness of these two existing models for different FRCM composites requires investigation.

Thus, this study aims to further optimize FRCM composites with reference to the commercial products and engineering cementitious composites (ECCs) available and to evaluate the appropriateness of the existing FRCM constitutive models against the newly developed and collected experimental results. First, different modifications regarding the cementitious matrix and carbon fiber mesh (CF-MESH) are used to prepare new carbon FRCM (C-FRCM) composites. Although it is the flexural behavior of the FRCM composite which is closely related to the design, tension properties of the FRCM could be used to initially assess the quality of the FRCM composites. Uniaxial tensile tests are carried out to obtain the stress-strain curves of these C-FRCM composites. The types of considered cementitious materials include mortar, mortar with chopped carbon fibers, ECC and commercial mortar; the types of CF-MESH considered in this study include dry CF-MESH without a coating, CF-MESH coated at the nodes and commercial carbon FRP (CFRP) grids. In addition, this paper summarizes the existing results of tensile tests on FRCM composites available in the literature to form a larger data pool with the newly generated test results. Based on this data pool, the AC434 model and ACK model are assessed, and suggestions for FRCM composite design are discussed. To simulate the real load transfer mechanism in structures, beam bending tests are needed in the future, but that should be built on the development of a reasonably good FRCM composite, which is the main purpose of this study.

2. Experimental program

2.1 Raw materials

The embedded carbon fibers used in this study are the dry CF-MESH shown in Figure 1(a) (denoted as T1 – TEX of 1200g/km, non-woven), and the coated carbon fiber mesh shown in Figure1(b) (denoted as T2 - weight of the mesh of 200g/m^2, woven). The reason for including the commercial products with polymer-impregnated textiles is to see the possible improvement of bond brought by the coating. CF-MESH T3 represents CF-MESH T1 with coating at selected nodes (see Figure 1(c)), which were along the whole length of the textile strip embedded in the tensile coupon. The material used resulted in coating of the yarns' junctions. Uniaxial tensile tests of a single bundle of fibers from the aforementioned three meshes (three parallel tests for each type of mesh) were carried out using a 10 kN servo-controlled testing machine, and the average test results are presented in Table 1. Note that during the tensile test of T2 fiber, the premature slippage between the fibers and its coating was occurred, which caused the fiber to slip out of the clamping jaws. Whereas, for the other specimens, the failure mode is fiber breakage. This is the main reason causing the large difference of the tensile strength between T2 and the others. Seven different types of cementitious materials were considered in this study; more information about these materials is provided in Table 2. According to the manufacturer, the commercial mortar (M7) contains an activator which can actively react with the coating of CF-MESH, and thus improve the bonding between CF-MESH (T2) and mortar (M7). The compressive, and flexural properties of cementitious materials after 28 days of curing (temperature 20 ℃, relative humidity 100%, complied with Chinese standard GB/T50081-2016 [33] were obtained by tests conducted in accordance with EN 1015-11 [34]. The tensile properties after 28 days of curing were obtained by dog bone tensile test in accordance with JSCE [35], as shown in Table 2, which were thereafter used in the calculation in Section 6. The dimensions of the specimens used for the compression tests are 40 mm × 40 mm × 40 mm, whereas the dimensions for the three-point bending test specimens are 40 mm × 40 mm × 160 mm. Three parallel tests were conducted for each type of cementitious matrix. The length of chopped carbon fibers is 6 mm.

2.2 Test specimens

A total of eight different FRCM composites were considered in this study, and three tests were conducted for each composite. The labeling scheme for the specimens is given in Table 3. The preparation procedure of the FRCM composites includes the following steps: (1) place a 5 mm cementitious matrix in a wooden mold (Figure 2(a)), (2) firmly fix a layer of mesh on top of the cementitious matrix (see Figure 2(b)), (3) place another 5 mm cementitious matrix layer on top of the mesh and trowel its surface, and (4) demold the FRCM composite coupon after 24 hours (Figure 2(c)). The FRCM composite coupons were then cured for 28 days at 20 °C and 70% humidity. Afterwards, each FRCM composite plate was cut into three specimens using a diamond cutter for tests (Figure 2(d)); each specimen contained five fiber bundles in the longitudinal direction. Figure 3 shows the dimensions of a FRCM composite tensile specimen., the length of the FRCM-anchorage plate is 100 mm.

2.3 Test setup and measurements

Uniaxial tensile tests were performed in accordance with ACI 549.4R-13 [36] and AC 434.13 [31]. These tests were conducted on a 10 kN servo-controlled testing machine at a loading rate of 0.2 mm/min. The clevis grip configuration was adopted in the experimental. The specimen deformation was measured with two symmetrically arranged linear variable differential transformers (LVDTs) (Figure 4(a)). The loads and specimen deformations were synchronously collected with a datalogger. Both ends of the specimen were hinged to the machine to avoid bending moments, as shown in Figure 4(b).

3. Experimental results

The stress-strain curves obtained from the tensile tests are shown in Figure 5, and the test results, including the cracking strength (f_t), peak strength (f_u), ultimate strain (ε_u), uncracked modulus (E_1) and post-cracking modulus (E_2), are presented in Table 4. Note that the post-cracking modulus is the linear fitting result of the post-cracking stress-strain curve. In the initial stage of loading, the load was mainly carried by the cementitious matrix and the CF-MESH. The first part of the stress-strain curve is linear. Later, cracks occurred on the surface of the cementitious matrix when the ultimate strain was reached. The load suddenly dropped when new cracks occurred; thus, the stress-strain curves fluctuate during this stage. Afterwards, when the number of cracks became stable, the load started to increase gradually again until reaching the peak value; during this stage, the load was transferred from the cementitious matrix to the CF-MESH and was carried by the CF-MESH. Both this study and previous investigations [2,15,24,37] found that the typical failure mode of FRCM composites is a combination of slippage between the CF-MESH and the cementitious matrix and partial fracturing of external carbon fiber filaments in the CF-MESH.

3.1 Effect of chopped carbon fibers

The effect of the number of chopped carbon fibers (see Figure 6) in the cementitious matrix is considered by comparing the performance of specimens M2-T1, M3-T1, M4-T1, and M5-T1 with the reference specimens M1-T1 (specimens without chopped carbon fibers); the results are shown in Figure 5(a) and Table 4. The test program included four different chopped fiber loadings: 0.50%, 0.75%, 1.00% and 1.25% of the cement weight. The cracking strength of the specimens with chopped fibers was 28-45% higher than that of the corresponding reference specimens; this result is consistent with the findings reported in previous studies [23], which stated that chopped fibers can effectively inhibit the cracking of cementitious materials. When the chopped fiber content was less than 0.75% of the cement weight, the mechanical properties of the FRCM composite, such as the cracking strength, ultimate strength and modulus, increased. However, when the chopped fiber content exceeded 0.75% of the cement weight, the excess chopped fibers decreased the FRCM composite strength. It is presumed that the main reason for this phenomenon is that the excess fibers could not be sufficiently dispersed, causing the agglomeration of fibers in the cementitious material.

3.2 Effect of node coating in a CF-MESH

Based on the literature review, coating a CF-MESH could improve the uniformity of the stress distribution in the fiber bundles because the coating can penetrate the core of the yarns, thereby increasing the inner bond between the fiber filaments [27,38]. Therefore, specimens M1-T3 were prepared to investigate the node coating. A comparison of the stress-strain curves of specimens M1-T3 and that of the reference specimens (M1-T1) is shown in Figure 5(b). Before the reference specimens failed, the stress-strain curves of M1-T3 consistently coincided with those of the reference specimens. Afterwards, the M1-T3 curves continued to increase stably. The ultimate strength, ultimate strain and post-cracking modulus of specimens M1-T3 were 42%, 57% and 70% higher than those of the reference specimens, respectively.

In the failed M1-T3 specimens, partial fracturing of the fiber bundles was observed (see Figure 7). Similar experimental results were also reported by Kim et al. [28].

3.3 Performance of ECC as a cementitious material

ECC is also a type of cement-based composite that has recently attracted extensive research interest [39,40] due to its advantageous characteristics such as a high toughness, impact resistance, freeze-thaw resistance and fatigue resistance. The key difference between ECCs and other cementitious materials is the high ductility characteristics of ECCs. In this study, ECC is also used as an alternative bonding material for CF-MESH (i.e., specimen M6-T1); the experimental results are presented in Table 4, and the stress-strain curves are shown in Figure 5(c). The M6-T1 specimens clearly exhibited multiple cracking characteristics, wherein new fine cracks continued to appear throughout the entire loading process until specimen failure (see Figure 8). The number of cracks in the M6-T1 specimens was seven times that in the reference specimens, whereas the crack width in the former specimens was notably smaller. For the reference specimens, before the width of the crack suddenly increased, the load was resisted mainly by the bond capacity of the CF-MESH/cementitious matrix. When a major crack occurred, the carbon fiber bundles and cementitious matrix started to experience slippage, and the load was resisted mainly by friction at the CF-MESH/cementitious matrix interface and the external part of the carbon fiber filaments. It should be noted that before matrix-fiber friction is engaged, the matrix-fiber bond capacity should be exploited [41]. However, for the M6-T1 specimens, no major cracks occurred in the cementitious material, and the load was resisted by both the CF-MESH and the ECC throughout the loading procedure. Therefore, although the cracking loads of the M6-T1 specimens were close to those of the reference specimens, the ultimate strength, ultimate strain and post-cracking modulus results of the M6-T1 specimens were 77%, 18% and 83% higher than those of the reference specimens, respectively.

3.4 Performance of commercial FRCM composite

For comparison, a commercial FRCM composite (specimens M7-T2) was also considered herein to understand the quality parameters of products on the market and explore whether our FRCM composite materials can generally meet the market requirements. The stress-strain curves from the tests of this material are shown in Figure 5(d), and the test results are presented in Table 4. During loading, all the fiber bundles were pulled out from the cementitious matrix, and the coating on the surface of the fiber bundles peeled off, as shown in Figure 9. This failure mode suggests that the poor performance of the commercial FRCM composites was caused by the premature slippage of the fibers and their coating, although the coating had reasonably good bonding with the cementitious matrix. Thus, the mechanical properties of the commercial FRCM composite specimens were not as good as those of the reference specimens: the cracking strength, ultimate strength, ultimate strain and postcracking modulus of M7-T2 were 69%, 84%, 36%, and 59% lower than those of the reference specimens, respectively.

4. Experimental data collected from the literature

A number of tensile tests on FRCM composites have been carried out and reported in the literature. This paper summarizes a total of 29 available test results covering different fiber meshes (i.e., carbon, glass, polyparaphenylene benzobisoxazole (PBO) and basalt fibers), cementitious materials and gripping devices (i.e., clamping or clevis grips) in Table 5. These data were used with the 24 newly generated test results from this study to form a large data pool for the following discussions. Note that data of only FRCM composites with a single layer of fiber mesh were collected herein and that the stress of the FRCM composites during the tensile test was calculated by dividing the load by the cross-sectional area of the fiber. In these calculations, note that f_f represents the ultimate tensile strength of the fiber, whereas ε_f represents the ultimate tensile strain of the fiber.

5. Discussion on the testing configuration

The experimental data show that in addition to the parameters of the FRCM composites discussed in Section 3, the gripping devices used also affect the structural responses of FRCM composites. The two commonly used gripping devices are clamping grips and clevis grips. The clamping grip method [36] is to directly clamp the ends of the FRCM specimens using the wedge-shaped chuck of the testing machine (the load can be applied to the specimens), and the clevis grip method [19] is to using metallic plates bonded to the specimen ends and connected to the machine (the load is transferred to the specimens through the metallic plates). The tensile behavior of FRCM composites is related to the test set-up adopted. If clevis grip tensile tests are carried out, a bi-linear behavior is generally observed, whereas clamping grip test set-ups usually provide tri-linear curves [42]. The ultimate strength results of the tested FRCM composites with respect to the ultimate strengths of the fibers is shown in Figure 10. In general, when using clamping grips, the ultimate strength results of the FRCM composites are very similar to those of the dry fiber bundles, which indicates that the clamping force effectively improves the interfacial friction between the cementitious matrix and the CF-MESH. This improved interfacial friction postpones slippage of the CF-MESH at the grip, which enables the mechanical properties of the CF-MESH to be better utilized. In contrast, when using clevis grips, the ultimate strength results of the FRCM composites are notably lower than those of the fiber bundles without extra pressure from the grips. Notably, FRCM composites are generally not subjected to lateral pressure when externally bonded to concrete structures as strengthening materials in practical engineering applications. Therefore, FRCM composites are generally not subjected to lateral pressure when externally bonded to concrete structures as strengthening materials in practical engineering applications and the clevis grip configuration can more closely resemble the *in situ* cases which has limited length to fix both ends of the FRCM composite.

6. Discussion on the constitutive models

6.1 AC434 model and result comparison

The bilinear simplified model for FRCM composites is codified in AC434 [31] with the symbols defined in Figure 11. The model provided by AC434 [31] describes the idealized behavior of a clevis-type test providing a methodology to identify the parameters that will be used in the design of the strengthening intervention, according to ACI 549.4R-13 [36]. In the AC434 model, the stress-strain curve is simplified into two linear parts. The first part of the curve corresponds to the first loading stage (i.e., the uncracked stage). The slope of the linear part corresponding to the uncracked behavior of the specimen can be defined by two points within this linear range [31]. Thus, the tensile elastic modulus $E_{1-AC434}$ of the uncracked specimen is calculated using the following expression:

$$E_{1-AC434} = \frac{\Delta f}{\Delta \varepsilon} \qquad \text{Eq. 1}$$

where Δf is the difference in tensile stress between two selected points and $\Delta \varepsilon$ is the difference in tensile strain between two selected points.

After the specimen cracks, some experimental results [27] suggest that new cracks are generated as the crack expansion and fiber filament slippage occurs. According to AC434, two points are selected on the experimental curve at a stress level equal to 0.90 f_u and 0.60 f_u. The slope of the line that connects these two points represents the tensile modulus at the post-cracking modulus. Note that the tensile specimen must have sufficient fabric area to achieve 50% strength over transition point, so that the selected two points will be in the correct part of the curve. The modulus $E_{2\text{-}AC434}$ (Eq. 2) is used to define the second linear part of the curve.

$$E_{2-AC434} = \frac{0.9 f_u - 0.6 f_u}{\varepsilon_{u@0.9 f_u} - \varepsilon_{u@0.6 f_u}} \qquad \text{Eq. 2}$$

Where f_u is the experimental ultimate strength.

The intersection point of the initial and secondary parts of the curves corresponds to the cracking strength $f_{t\text{-}AC434}$ and the cracking strain. Thus, the cracking strength can be calculated by the mathematical relationship according to Figure 11, as shown in Eq. 3:

$$f_{t-AC434} = E_{1-AC434}\varepsilon_{t-AC434} = E_{2-AC434}\varepsilon_{t-AC434} + (f_u - E_{2-AC434}\varepsilon_u) \qquad \text{Eq. 3}$$

By converting Eq. 3, the cracking strain $\varepsilon_{t\text{–}AC434}$ can be obtained as follows:

$$\varepsilon_{t-AC434} = \frac{f_u - E_{2-AC434}\varepsilon_u}{E_{1-AC434} - E_{2-AC434}} \qquad \text{Eq. 4}$$

The cracking strength $f_{t\text{-}AC434}$ can be calculated with the following expression:

$$f_{t-AC434} = E_{1-AC434}\left(\frac{f_u - E_{2-AC434}\varepsilon_u}{E_{1-AC434} - E_{2-AC434}}\right) \qquad \text{Eq. 5}$$

The stress-strain curves obtained from the experiments are compared to the results from the AC434 simplified in model Figure 12. For the AC434 model, the prediction curves fit closely with most of the experimental curves except those of M7-T2. The uncommon stress-strain curves of the M7-T2 specimens might be due to the premature debonding between the fiber bundles and their coating.

Furthermore, the predictions of the cracking strength and postcracking modulus by the AC434 models are also compared to the new and collected test results, as shown in Figure 13. For cracking strength (see Figure 13(a)), the AC434 model generally underestimated the test results. In terms of the postcracking modulus (see Figure 13(b)), the predictions of the AC434 model were more accurate and consistent with the experimental results.

6.2 ACK model and result comparison

The ACK model for FRCM composites (see Figure 14) was proposed by Aveston and Kelly [32] and Bertolesi et al. [7]. The ACK model can predict the tensile behavior of the FRCM composite once the properties of its components are known. In this model, the stress-strain curve has three stages: the uncracked stage, the crack development stage, and the crack expansion stage. The uncracked stage is the first elastic stage of the curve, which is defined by the initial elastic modulus $E_{1\text{-}ACK}$, as given by Eq. 6:

$$E_{1-ACK} = E_f V_f + E_m V_m \qquad \text{Eq. 6}$$

where E_f and E_m are the tensile Young's modulus of the fiber and cementitious matrix, respectively, and V_f and V_m are the volume fractions of the fiber and the cementitious matrix, respectively.

The crack development phase begins with the occurrence of the first crack (point T1 in Figure 14), and the cracking strength ($f_{t\text{-}ACK}$) can be calculated by Eq. 7:

$$f_{t-ACK} = \frac{E_{1-ACK}\, f_m}{E_m} \qquad \text{Eq. 7}$$

where f_m is the tensile ultimate strength of the cementitious matrix.

Multiple fine cracks appear on the specimen as the load continues to increase [44,45]. Slips at cementitious matrix and CF-MESH interface begin to take place after the first crack occurs. It is assumed that the frictional shear stress between the cementitious matrix and the CF-MESH (τ) is constant. The spacing of the cracks (δ) is expressed with Eq. 8 based on the force equilibrium along the loading axis of the fiber [21]:

$$\delta = \frac{r f_m V_m}{2\tau V_f} \qquad \text{Eq. 8}$$

where r is the radius of a single filament.

In the crack development stage, the distances between cracks are between δ and 2δ. The cracks initiate randomly until new cracks can no longer be generated. According to Widom [46] and Cuypers and Wastiels [44], the average distance between cracks is 1.337δ, so the strain at the end of the second stage (ε_{t2}) can be calculated with Eq. 9 [21,47]:

$$\varepsilon_{t2} = \frac{f_{t-ACK}}{E_{1-ACK}} + 1.337\delta\frac{\tau}{E_f} \qquad \text{Eq. 9}$$

Substituting Eq. 7 and Eq. 8 into Eq. 9 yields the following expression:

$$\varepsilon_{t2} = \left(1 + 0.666\frac{E_m V_m}{E_f V_f}\right)\frac{f_m}{E_m} \qquad \text{Eq. 10}$$

The third stage (starting from point T2 and continuing to the peak) is the crack expansion stage, in which the widths of the existing cracks increase and the fiber filaments slip or fracture, causing failure. In this stage, the load is carried by only the embedded CF-MESH [19]. The modulus E_{2-ACK} in this stage can be obtained from Eq. 11.

$$E_{2-ACK} = E_f V_f \qquad \text{Eq. 11}$$

Note that Eq. 11 does not consider the presence of tension stiffening, which could be relevant for the high-performance matrices considered in this study. However, since the purpose of this study is to compare the predictions by the ACK model with the tensile behavior of the FRCM composites obtained from tests, the existing equations in the ACK model are remained.

The stress-strain curves obtained from the experiments are compared to the results from the ACK model in Figure 15. The ACK model can accurately predict the stress-strain curves in the uncracked stage for all the tested specimens. In the crack development stage, the ACK model curve is also close to the experimental curves of most specimens, with the exception of those of M6-T1 and M7-T2. However, the ACK model predictions for the crack expansion stage are significantly different from all the test curves. According to the discussion in Section 5, a possible reason for these discrepancies might be the use of clevis grips in this study; hence, the strength of the FRCM composite specimens did not continue to increase significantly after cracking without the presence of additional clamping pressure.

Furthermore, the predictions of the cracking strength and post-cracking modulus by the ACK models are also compared to the new and collected test results, as shown in Figure 16. For cracking strength (see Figure 16(a)), the ACK model significantly overestimated most of the test results. In terms of the post-cracking modulus (see Figure 16(b)), the predictions of the ACK model cannot accurately predict experimental values.

7. Conclusions

In this study, a total of eight different types of FRCM composites were considered by optimizing the cementitious matrix and carbon fiber meshes. Uniaxial tensile tests were carried out to obtain their structural responses and mechanical properties. The experimental results showed that including a small content of chopped carbon fibers (up to 0.75% of the cement weight) in the cementitious matrix and a preimpregnated epoxy coating on the nodes of the fiber meshes were beneficial for the mechanical properties of FRCM composites. In addition, ECC was also found to be a good bonding material for use in FRCM composites. Both coating the nodes of the fiber meshes and the use of ECC as a bonding material can delay the slippage of carbon fibers. Existing tensile test data of FRCM composites, covering different types of fiber meshes, cementitious materials and experimental gripping devices, were also collected from the literature. Both the newly generated experimental and the collected data are compared with AC434 model and ACK model. The AC434 model was found to be able to capture the experimental curves rather accurately; however, the predictions by the ACK model seems inaccurate. The prediction result of the ACK model overestimates most experimental data.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1 Material properties of the carbon fiber meshes

Type of fiber meshes	Tensile strength (MPa)	Elastic modulus (GPa)	Break elongation	Fiber area (A_f) (mm^2/mm)
T1	2077	196	0.011	0.0462
T2	441	66	0.007	0.1170
T3	2225	195	0.012	0.0462

Table 2 Mixing proportion and material properties of the cementitious matrix

Components	M1 (%)	M2 (%)	M3 (%)	M4 (%)	M5 (%)	M6 (%)	M7 (%)
Cement	100	100	100	100	100	100.00	unavailable
Limestone powder	/	/	/	/	/	14.29	
Silica fume	/	/	/	/	/	21.43	
Ground granulated blast furnace slag	/	/	/	/	/	107.14	
Silica sand	100	100	100	100	100	71.43	
Water	35	35	35	35	35	46.14	
PE fiber	/	/	/	/	/	2.86	
Carbon fiber	0	0. 5	0. 75	1	1.25	/	
Polycarboxylate-based high range water	0.18	0.18	0.18	0.18	0.18	9.71	
Water / (Cement + Silica fume + Ground granulated blast furnace)	0.35	0.35	0.35	0.35	0.35	0.22	0.35
Compressive strength (MPa)	60.1	53.2	51.7	52.4	52.0	79.4	34.3
Tensile strength (MPa)	3.3	3.9	4.3	4.0	4.1	3.7	4.7
Elastic modulus (GPa)	12.4	35.2	30.6	43.2	27.1	36.7	20.1

Table 3 Labeling scheme used for the test specimens

Specimens	Type of cementitious matrix	Type of fiber mesh	Node treatment
M1-T1	M1	T1	No
M2-T1	M2	T1	No
M3-T1	M3	T1	No
M4-T1	M4	T1	No
M5-T1	M5	T1	No
M6-T1	M6	T1	No
M7-T2	M7	T2	No
M1-T3	M1	T3	Yes

Table 4 Average test results for FRCM

Specimens	Carbon fiber content* (%)	f_t (MPa)	f_u (MPa)	ε_u (%)	E_1 (GPa)	E_2 (GPa)
M1-T1	0.00	682	1225	0.81	2904	74
M2-T1	0.50	916	1257	0.82	7634	50
M3-T1	0.75	991	1307	0.75	6638	80
M4-T1	1.00	876	1276	0.90	9367	57
M5-T1	1.25	898	1251	0.70	3650	75
M1-T3	0.00	725	1740	1.27	3201	126
M6-T1	0.00	640	2168	0.96	5970	136
M7-T2	0.00	210	196	0.52	1110	30

* Percentage to cement weight

Table 5 Collected tensile test results for FRCM composites

References	Type pf fiber mesh	Type of grips	f_t (MPa)	f_u (MPa)	f_f (MPa)	ε_u (%)	ε_f (%)	E_1 (GPa)	E_2 (GPa)
Larrinaga et al. [21]	basalt	clamping	338	1088	1160	2.15	1.73	1446	43
Bertolesi et al. [7]	PBO	clamping	495	3316	3905	1.69	1.69	878	157
Arboleda et al. [19]	carbon	clamping	482	1492	1900	0.74	0.94	798	186
	PBO	clamping	890	3316	3900	1.69	1.80	1877	216
Ascione et al. [47]	carbon	clamping	137	1222	1914	0.83	1.18	164	131
	glass-aramid	clamping	511	1784	1829	2.02	2.15	274	96
	basalt-stainless steel	clamping	124	345	1471	0.54	3.00	101	61
Carozzi & Poggi [44]	PBO	clamping	724	3319	3900	1.69	1.81	1298	216
	glass	clamping	307	872	1233	0.69	2.22	699	64
	carbon	clamping	438	1492	1944	0.74	0.94	943	186
Santis & Felice [48]	glass-aramid	clamping	404	1851	1829	2.20	1.80	911	91
Caggegi et al. [22]	basalt	clamping	592	912	1089	0.75	1.94	1053	53
D'Antino & Papanicolaou [20]	carbon	clamping	229	838	938	0.73	1.80	1432	114
	carbon	clamping	1645	2745	1890	0.86	0.94	3351	188
	glass	clamping	722	1221	660	1.38	1.41	1288	53
Minafò and Mendola [49]	glass	clamping	606	1317	1400	4.00	4.38	47	32
Arboleda et al. [19]	carbon	clevis	458	1031	1900	1.00	0.94	349	80
	PBO	clevis	375	1664	3900	1.76	1.80	1877	128
Santis & Felice [48]	glass-aramid	clevis	404	1238	1829	1.40	1.80	911	53
Donnini et al. [15]	carbon fiber	clevis	986	575	4900	0.01	2.00	67669	/
	carbon fiber	clevis	1088	713	4900	0.01	2.00	67669	30
	carbon	clevis	875	1358	4900	0.02	2.00	67669	42
	carbon	clevis	782	1366	4900	0.03	2.00	67669	49
D'Antino & Papanicolaou [20]	carbon	clevis	333	417	938	0.79	1.80	693	417
	carbon	clevis	433	1393	1890	0.86	1.18	1131	172
	glass	clevis	281	593	660	1.97	1.41	630	39
Donnini et al. [29]	glass	clevis	604	1275	1405	4.90	2.40	1709	29
Ebead & Younis [50]	carbon	clevis	260	970	3580	1.25	1.50	378	75
	PBO	clevis	487	1235	4980	0.90	1.80	601	112