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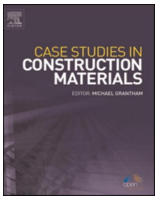

# Prediction of compressive strength and evaluation of different theoretical standards and proposed models of brick columns confined with FRP, FRCM, or SRG system

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## ABSTRACT

The strength capacity of confined masonry column is one of the topics that need to be studied. In this study, the efficiency of using different types of advanced composite (non-corrosive materials) such as fiber reinforced polymer (FRP), fiber reinforced cementitious matrix (FRCM), or steel reinforced grout (SRG) in confining masonry columns is investigated. A wide range of experimental database of masonry column specimens has been collected from the results that available in scientific literatures. Different theoretical standards and proposed models that used to predict the capacity of masonry columns confined with FRP and FRCM are evaluated based on collected experimental database. Since there is no standard code or specific proposed model for SRG system, the confined capacity of this system is predicted and evaluated using the FRCM proposed models. The justification of using these models is that both FRCM and SRG systems have the same concept of using inorganic material as a paste material. An index named “equivalent fiber reinforcement index (EFRI)” is proposed to capture the key factors that control the behavior of the confined masonry columns with different advanced composite. This index is used as reference parameter for the purpose of the comparison between different strengthening systems. As a result, all types of advanced composite presented a significant increase in ultimate capacity. Also, the behavior of the masonry columns was significantly dependent on the type of fabric used. Different modes of failure were reported, including crushing of masonry block, as well as a deboning of FRP from the masonry substrate and deboning or slippage of fabric within inorganic paste matrix. Compared with other models and standards, the American Concrete Institute Committee 440 (ACI 440) and American Concrete Institute Committee 549 (ACI 549) shows very good predictions for the confined capacity of masonry columns strengthened by FRP and FRCM or SRG respectively.

## 1. Introduction

The masonry unit is one of the common constructions materials which is used in constructing a significant number of buildings around the world. The unreinforced masonry structural element is very weak to resist the load come from earthquakes, extreme wind actions or any seismic events due to limited tensile strength [1]. In the last decade, the strengthening of concrete and masonry buildings is one of the hot topics in the field of structural engineering. High percentage of masonry buildings in need for strengthening

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due to many reasons such as aging, deterioration or change the building function [2,3]. In the research, the columns are receiving a great attention due to their importance as a structural element, since the failure of a column can lead to significant consequences to the whole building.

In the past, there are many conventional techniques that used for masonry walls and columns retrofitting such as cross-section enlargement, steel jacketing, and ferrocement jacketing [3–6]. The idea of masonry confining was started early in the 1970 s by Priestley and Bridgeman [7]. In this study, its concluded that the ductility can be obtained by confining the critical compression zone (crushing zone) using a thin stainless-steel plate. The confining steel plate led to eliminate the masonry tension cracks in the vertical direction by preventing the steel reinforcement from buckling [7].

Most conventional techniques are not only time consuming but also result in increasing the dead load, which is not preferable especially for buildings subjected to seismic load [7,8]. Recently, advanced composites like fiber reinforced polymer (FRP), fiber reinforced cementitious matrix (FRCM), or steel reinforced grout (SRG) have become widespread methods used in general for strengthening masonry structures [9–11] and in particular for jacketing columns' [12–14]. In order to upgrade the columns capacity and meet the design provisions, external confinement was chosen as an effective technique for retrofitting. There are many reasons that led to the choice of advanced composites in construction systems, including their light weight which helps to reduce the labour expenses, durability, high resistance to corrosion, and high strength compared to other materials [9].

FRP composites have been considered for masonry or concrete confinement since the early 1980 s. A uniaxial compression experimental test for concrete cylinders encased in FRP was conducted by Fardis and Khalili (1981) [15]. As a result of the FRP confinement, all the specimens experienced significant enhancement in terms of strength and ductility. Also, based on this study, an analytical model for estimating the confined concrete's compressive strength was proposed. Later, different models were proposed to estimate the confined columns' compressive strength; considering spiral confinement with glass fiber reinforced polymer (GFRP) [16], different geometries of the columns'cross section and different types of external advanced composites [17,18].

Despite the many benefits of using FRP, there are some drawbacks to its use, which leads to thinking about solutions to these problems. Some of these problems include susceptibility to fire (without insulation) and the inability of adhesion material (epoxy resin, commonly used) to bond on wet surfaces, and the loss of the bad mechanical properties of bonding material at high temperatures. The second generation of advanced composite is (FRCM). The FRCM system is made up of open mesh fiber and an inorganic adhesive material. This type of advanced composite provides several advantages in terms of structural and environmental aspects. Among its many advantages, the FRCM system provides fire resistance and a good ability to resist high temperatures; ultraviolet (UV) radiation resistance; and compatible permeability with the masonry or concrete substrate [19,20]. Although academic research on using open-mesh fiber in a cementitious matrix as a strengthening technique was started in the early 1980s, this technique was developed very slowly until the late 1990s [21,22]. In the early 2000s, a considerable effort was made to utilize an open mesh fiber in a cementitious matrix as a reinforcement.

Another strengthening system that is used to improve both the strength and ductility of masonry is (SRG). This system consisted of steel fibers embedded in an inorganic paste material. Recent researches have shown that SRG system can upgrade the flexural capacity of masonry structures and improve the column confined capacity [23–25].

In summary, different strengthening techniques are existing that are used for confinement purposes. For each technique, there are limitations and obstacles that prevent its application, as well as the techniques have some advantages that make it preferable in various engineering applications. The purpose of this study is to provide a critical review of existing experimental works and projects on the behavior of masonry columns confining with these strengthening systems. The originality of this paper comes from conducting an evaluation of the standards or guidelines, as well as the proposed models, that are used to predict the capacity of masonry columns fully confined with the FRCM system, and the possibility of using them to find the capacity of the columns when using the SRG system, as there is no standard code or specific proposed model for the SRG system. In addition, the study focused on presenting the differences of these methods in terms of applicability, strength enhancement, and modes of failure. Also, the analytical models used to predict the confined capacity of masonry columns were evaluated using a database of different experimental results.

**Fig. 1.** Brittle Failure of Unconfined Column [26].

## 2. Expected modes of failure

The unconfined masonry columns behave in a brittle manner and the failure was characterized by a crushing mode of failure due to the weak tensile behavior of masonry units. The failure started with a longitudinal crack on the external faces, that developed due to tensile stress in mortar joints. The failure ended with a widening of vertical cracks due to propagation through the masonry units and the mortar of joints [26], as shown in Fig. 1. The modes of failure for masonry columns confined with different strengthening systems are explained as follow:

### *2.1. FRP strengthened masonry columns*

For confined masonry columns subjected to axial compression loads, the most common mode of failure is FRP composite rupture in the hope direction [27]. This type of failure happened due to dilation of the masonry unit during the loading. In addition, It is concluded that the FRP rupture strain obtained from tensile coupon testing is much higher than the hoop strain at failure. [28]. Also, it may have happened due to stress concentration especially at the sharp corners which is called the "knife effect" [29]. It is worthy to mention that rounding the sharp corner is recommended before applying the advanced composite.

Local buckling of FRP sheets is the other mode of failure that is expected to occur due to crushing of masonry unit followed by fiber excessive axial strain developed in the hoop direction [30]. This type of failure is deepened on deformation properties of both advanced composite and the masonry unit, in addition to the direction of the fibers used for confinement purpose.

### *2.2. FRCM strengthened masonry columns*

Based on literature, different modes of failure were reported for masonry columns fully confined with a continuous FRCM system. Rupture of open mesh fiber, i.e.; polyphenylene benzobisoxazole (PBO) or carbon was observed associated with a wide longitudinal crack along the corner as shown in Fig. 2 [14,31]. The compressive capacity of a confined column dropped due to fully damaged of masonry units [32]. The rupture failure of FRCM confined masonry columns has a significant corner effect. The matrix used with advanced composite (mortar jacketing) played an essential role in transferring the applied load between the masonry units and the fiber that was used for confinement purposes. The effectiveness of the confinement system of FRCM is highly dependent on the compressive strength grade of the matrix. So the confinement of FRCM with a high strength matrix is more effective than the same confinement with a low strength matrix [33,34]. It is noted that in many cases, the failure mode is a combination of fibers rupture and partial slippage of the fibers through the matrix, leading to a slightly more gradual failure [35]. Compared with specimens confined using FRP, the mode of failure for specimens confined with FRCM was less brittle due to the gradual failure of the matrix. Overlapping zone failure is the other type of failure that occurred in cases of discontinuous confinement. The vertical cracks appeared along the unconfined masonry unit, then moved to the external advanced composite, ending with completely open FRCM [32].

### *2.3. SRG strengthened masonry columns*

The masonry columns confined by SRG were characterized by ductile behavior due to a slow damage process. In many tests, the specimens experienced a steel cord rupture that occurred at a corner when the cross section of the confined masonry column achieved ultimate load. When the SRG jacket was opened, the condition of the masonry core at the stage of failure was examined, and its

**[14]** **[14]** **[14]** **[31]**

**Fig. 2.** Failure configurations of confined columns [14,27].

condition was reported with the crushing of masonry units. The reason for developing a steel cord rupture is the same reason for other types of confinements, which is the stress concentration at the sharp edge of the corner [23]. he fiber density played the most important role in determining the mode of failure. The masonry columns confined with high density fiber presented a fiber jacket opening and an inverse proportionality between the radius of the corner and the ultimate load. On the other hand, the masonry columns confined with medium density fiber experienced steel fiber rupture. Opening SRG jacket is the other possible mode of failure that happened due to cracks that formed in horizontal (coincident with the location of the masonry column joint) and vertical (along the confined column corner) directions. The same cracks were the reason for detaching the exterior layer of confinement matrix and spalling off the confined masonry specimens. The vertical cracks may have developed at the end of the fiber overlap resulting in fiber debonding failure at the overlap location [30].

### *2.4. Near surface mounted (NSM) strengthened masonry columns*

In order to cover all the strengthening systems used in masonry columns, the NSM technique cannot be ignored. Although this system does not achieve the confinement process, it contributes to increasing the capacity of the structural member.

The tensile rupture of the FRP strips in the cross section of highest moment was the cause of the observed failure mode (column base). When the applied force following NSM strip rupture was compared to the mean recorded strains of FRP at the column base (i.e., at the region of the primary flexural crack), the applied force decreased. The strips lost their lateral restriction during the subsequent loading due to partial debonding caused by strong pullout forces [36]. As a result, the strips developed a vulnerability to high compressive loads that could cause local buckling and damage before the strips fractured under tension at strains lower than the ultimate uniaxial strain.

## 3. Comparison and discussion of different techniques

Various strengthening and repairing techniques have been shown in previous studies and research. The well known techniques that focused on in this study are, FRP (externally bonded), FRCM and SRG. The summary of the advantages and disadvantages of each technique has been presented in Table 1. The selected methods have been compared based on general criteria, which include: strength enhancement, stiffness and ductility improvement, aesthetic and cost issues, and the effect of elevated temperature.

Generally, all the selected strengthening techniques are able to enhance the strength of masonry columns by nearly doubling. Also, in terms of ductility and stiffness, all the techniques can improve the ductility and stiffness, however, the techniques with cementitious matrix are typically more effective than others due to their gradual failure compared to the sudden failure of techniques with epoxy paste material [37,38]. Regarding the effect of temperature, the techniques in which epoxy is used as a paste material are affected by increasing the temperature to a specific limit called glass transition temperature. On the other hand, the effectiveness of strengthening systems with cementitious paste material is not significantly affected by the change in temperature.

## 4. The experimental previous work

Previous experimental work for masonry columns confined with different advanced composites have been gathered and s summarized. The results of the gathered database are classified based on the type of advanced composite, such as FRP (EB and NSM), FRCM, and SRG. In this data, information about the cross section and column dimensions, material properties (masonry and advanced composite), and confined strength characteristics were presented.

**Table 1**
Summary of pros and cons of different strengthening techniques.

| Strengthening technique | Advantages | Disadvantages |
|---|---|---|
| FRP Externally bonded | • Corrosion resistance<br>• Better enhancement in term of strength, ductility and stiffness | • Aesthetics of column affected due to incompatibility between resin and concrete.<br>• Costly material<br>• Poor resistance to the high temperature. |
| FRCM | • Corrosion resistance<br>• Increase strength, ductility and stiffness<br>• Minimum effect on column aesthetic as a result of compatibility between the cementitious material and the concrete.<br>• Very good resistance to the elevated temperature. | • The high cost is due to material and installation process.<br>• Long time for curing |
| SRG | • Increase strength, and very good ductility and stiffness<br>• Minimum effect on column aesthetic as a result of compatibility between the grout material and the concrete.<br>• Very good resistance to the elevated temperature. | • The high cost is due to installation process.<br>• Long time for curing<br>• Rusting and corrosion<br>• Heavy weight |

**Table 2**
Experimental Results of FRP Confined Masonry Columns from Literature.

| **Ref.** | **Column dimensions** | | | | | **Masonry** | **FRP material** | | | | | | **Experimental Results** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shape | b (mm) | d (mm) | h (mm) | $r_c$ (mm) | $f_m$ (MPa) | Type | Fu (MPa) | E (GPa) | e | t (mm) | n | fmc (MPa) | eu mm | Fmc /fm |
| [39] | R | 240 | 240 | 500 | 0 | 5.3 | CFRP | 3500 | 230 | 0.015 | 0.16 | 1 | 13.2 | – | 2.5 |
| | R | 240 | 240 | 500 | 0 | 5.3 | CFRP | 3500 | 230 | 0.015 | 0.16 | 2 | 14.7 | – | 2.8 |
| | R | 240 | 240 | 500 | 0 | 5.3 | GFRP | 2250 | 70 | 0.031 | 0.16 | 2 | 12 | – | 2.3 |
| | R | 240 | 240 | 500 | 0 | 5.3 | GFRP | 2250 | 70 | 0.031 | 0.16 | 3 | 13 | – | 2.5 |
| | R | 240 | 240 | 500 | 0 | 3.6 | CFRP | 3500 | 230 | 0.015 | 0.16 | 1 | 4.7 | – | 1.3 |
| | R | 240 | 240 | 500 | 0 | 3.6 | CFRP | 3500 | 230 | 0.015 | 0.16 | 2 | 5.2 | – | 1.4 |
| | R | 240 | 240 | 500 | 0 | 3.6 | GFRP | 2250 | 70 | 0.031 | 0.16 | 2 | 5.9 | – | 1.6 |
| | R | 240 | 240 | 500 | 0 | 3.6 | GFRP | 2250 | 70 | 0.031 | 0.16 | 3 | 5.9 | – | 1.6 |
| [40] | S | 290 | 290 | 1200 | 25 | 2.5 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 2.6 | – | 1.0 |
| | S | 390 | 390 | 1200 | 25 | 2.6 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 3.7 | – | 1.4 |
| | S | 490 | 490 | 1200 | 25 | 4.2 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 6 | – | 1.4 |
| | S | 290 | 290 | 1200 | 25 | 2.1 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 2.7 | | 1.3 |
| | S | 490 | 490 | 1200 | 25 | 3.4 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 5.8 | – | 1.7 |
| | S | 290 | 290 | 1200 | 25 | 2 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 2.5 | – | 1.3 |
| | S | 290 | 290 | 1200 | 25 | 2.2 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 2.5 | – | 1.1 |
| | S | 390 | 390 | 1200 | 25 | 3.3 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 4.7 | – | 1.4 |
| | S | 390 | 390 | 1200 | 25 | 3.2 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 4.6 | – | 1.4 |
| | S | 490 | 490 | 1200 | 25 | 4 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 5.2 | | 1.3 |
| | S | 490 | 490 | 1200 | 25 | 4.3 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 5.7 | – | 1.3 |
| | S | 490 | 490 | 1200 | 25 | 5 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 6.1 | – | 1.2 |
| | S | 490 | 490 | 1200 | 25 | 4.1 | CFRP | 958 | 73 | 0.001 | 0.165 | 1 | 5.1 | – | 1.2 |
| | S | 115 | 115 | 340 | 10 | 12.1 | CFRP | 3500 | 230 | 0.001 | 0.165 | 1 | 13.6 | – | 1.1 |
| [41] | S | 115 | 115 | 340 | 10 | 12.1 | CFRP | 3500 | 230 | 0.001 | 0.165 | 1 | 16.9 | – | 1.4 |
| | S | 115 | 115 | 340 | 10 | 12.1 | CFRP | 3500 | 230 | 0.001 | 0.165 | 1 | 25.4 | – | 2.1 |
| | S | 115 | 115 | 340 | 10 | 12.1 | GFRP | 2000 | 70 | 0.008 | 0.4 | 1 | 40 | – | 3.3 |
| | S | 115 | 115 | 340 | 20 | 12.1 | CFRP | 3500 | 230 | 0.008 | 0.165 | 1 | 16.9 | – | 1.4 |
| | S | 115 | 115 | 340 | 20 | 12.1 | CFRP | 3500 | 230 | 0.008 | 0.165 | 1 | 23.9 | – | 2.0 |
| | S | 115 | 115 | 340 | 20 | 12.1 | CFRP | 3500 | 230 | 0.008 | 0.165 | 1 | 34.7 | – | 2.9 |
| | S | 115 | 115 | 340 | 20 | 12.1 | GFRP | 2000 | 70 | 0.03 | 0.165 | 1 | 44.9 | – | 3.7 |
| | R | 173 | 115 | 340 | 10 | 6.7 | CFRP | 3500 | 230 | 0.008 | 0.165 | 1 | 11.9 | – | 1.8 |
| | R | 173 | 115 | 340 | 10 | 6.7 | CFRP | 3500 | 230 | 0.008 | 0.165 | 1 | 17.9 | – | 2.7 |
| | R | 173 | 115 | 340 | 10 | 6.7 | GFRP | 2000 | 70 | 0.03 | 0.165 | 1 | 24.4 | – | 3.6 |
| [42] | S | 245 | 250 | 500 | 20 | 14.3 | CFRP | 3388 | 417.6 | 0.008 | 0.165 | 1 | 23.9 | – | 1.7 |
| | S | 245 | 250 | 500 | 20 | 14.3 | CFRP | 1955 | 673.2 | 0.008 | 0.143 | 1 | 21.9 | – | 1.5 |
| | S | 245 | 250 | 500 | 20 | 14.3 | CFRP | 3388 | 417.6 | 0.008 | 0.165 | 1 | 29.4 | – | 2.1 |
| | S | 245 | 250 | 500 | 20 | 14.3 | CFRP | 1955 | 673.2 | 0.008 | 0.143 | 1 | 26.3 | – | 1.8 |
| | O | 245 | 250 | 500 | 20 | 19.8 | CFRP | 3388 | 417.6 | 0.003 | 0.165 | 1 | 38.7 | – | 2.0 |
| | O | 245 | 250 | 500 | 20 | 19.8 | CFRP | 3388 | 417.6 | 0.003 | 0.165 | 1 | 50.4 | – | 2.5 |
| | S | 250 | 250 | 500 | 10 | 13.7 | GFRP | 1605 | 74.1 | 0.003 | 0.48 | 1 | 19.7 | 0.0016 | 1.4 |
| [43] | S | 245 | 245 | 500 | 20 | 11.9 | SFP | 2396 | 143 | 0.0116 | 0.48 | 1 | 26.7 | – | 2.2 |
| | S | 245 | 245 | 500 | 20 | 11.9 | SFP | 2396 | 143 | 0.0116 | 0.48 | 1 | 19.9 | – | 1.7 |
| | O | 245 | 250 | 500 | 20 | 14 | SFP | 3199 | 160 | 0.0155 | 0.48 | 1 | 26.6 | – | 1.9 |
| | O | 245 | 250 | 500 | 20 | 14 | SFP | 3199 | 160 | 0.0155 | 0.48 | 1 | 25.2 | – | 1.8 |
| | O | 245 | 250 | 500 | 20 | 14 | SFP | 2396 | 143 | 0.0116 | 0.48 | 1 | 25.2 | – | 1.8 |
| | O | 245 | 250 | 500 | 20 | 14 | SFP | 2396 | 143 | 0.0116 | 0.48 | 1 | 23.9 | – | 1.7 |
| [44] | S | 250 | 250 | 500 | 10 | 13.7 | GFRP | 2560 | 80.7 | 0.032 | 0.48 | 1 | 19.3 | 0.0153 | 1.4 |

(*continued on next page*)

**Table 2** (*continued*)

| Ref. | Column dimensions | | | | | Masonry | FRP material | | | | | | Experimental Results | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shape | b (mm) | d (mm) | h (mm) | $r_c$ (mm) | $f_m$ (MPa) | Type | Fu (MPa) | E (GPa) | e | t (mm) | n | fmc (MPa) | eu mm | Fmc /fm |
| | S | 250 | 250 | 500 | 25 | 14 | GFRP | 2560 | 80.7 | 0.032 | 0.48 | 1 | 26.2 | 0.0408 | 1.9 |
| | S | 250 | 250 | 500 | 25 | 14 | GFRP | 2560 | 80.7 | 0.032 | 0.48 | 1 | 21.2 | 0.0826 | 1.5 |
| | S | 250 | 250 | 500 | 25 | 14 | GFRP | 2560 | 80.7 | 0.032 | 0.96 | 2 | 35.1 | 0.0669 | 2.5 |
| | S | 380 | 383 | 492 | 25 | 8.5 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 12 | 0.032 | 1.4 |
| | S | 387 | 375 | 485 | 25 | 8.5 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 12.8 | 0.031 | 1.5 |
| | S | 377 | 380 | 488 | 25 | 8.5 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 14.2 | 0.0349 | 1.7 |
| | S | 383 | 378 | 486 | 25 | 8.5 | GFRP | 1600 | 65 | 0.025 | 0.46 | 2 | 15.5 | 0.0373 | 1.8 |
| | S | 377 | 378 | 481 | 25 | 8.5 | GFRP | 1600 | 65 | 0.025 | 0.46 | 2 | 16 | 0.0452 | 1.9 |
| | S | 250 | 248 | 470 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 17.7 | 0.0316 | 1.6 |
| | S | 250 | 249 | 470 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 16.3 | 0.0284 | 1.5 |
| | S | 250 | 247 | 470 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.23 | 1 | 16 | 0.0344 | 1.4 |
| | S | 248 | 247 | 462 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.46 | 2 | 19.1 | 0.0266 | 1.7 |
| | S | 245 | 248 | 471 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.46 | 2 | 20.6 | 0.0371 | 1.8 |
| | S | 246 | 251 | 473 | 25 | 11.2 | GFRP | 1600 | 65 | 0.025 | 0.46 | 2 | 21.5 | 0.0351 | 1.9 |
| [45] | S | 264 | 265 | 560 | 20 | 6.4 | GFRP | 1371 | 69 | 0.021 | 0.48 | 1 | 9.9 | 0.011 | 1.5 |
| | S | 267 | 265 | 560 | 20 | 6.4 | GFRP | 1371 | 69 | 0.021 | 0.48 | 1 | 8.5 | 0.017 | 1.3 |
| | S | 266 | 265 | 560 | 20 | 6.4 | GFRP | 1371 | 69 | 0.021 | 0.48 | 1 | 11.2 | 0.021 | 1.8 |
| | S | 266 | 266 | 560 | 20 | 6.4 | BFRP | 1814 | 91 | 0.019 | 0.24 | 1 | 10.3 | 0.02 | 1.6 |
| | S | 265 | 264 | 560 | 20 | 6.4 | BFRP | 1814 | 91 | 0.019 | 0.24 | 1 | 9.8 | 0.026 | 1.5 |
| | S | 265 | 264 | 560 | 20 | 6.4 | BFRP | 1814 | 91 | 0.019 | 0.24 | 1 | 10.1 | 0.025 | 1.6 |
| [46] | S | 290 | 290 | 1020 | 20 | 3.7 | CFRP | 3790 | 230 | 0.001 | 1 | 1 | 3.7 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.7 | CFRP | 3790 | 230 | 0.001 | 1 | 1 | 3.7 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.4 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 3.4 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.4 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 3.4 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 4 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 4 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 4 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 4 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.7 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 3.7 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.7 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 3.7 | – | 1.0 |
| | S | 290 | 290 | 1020 | 20 | 3.7 | GFRP | 3240 | 72.7 | 0.0022 | 0.66 | 1 | 3.7 | – | 1.0 |

### 4.1. Procedure for strengthening and database of masonry columns confined with FRP

The procedure of preparing a masonry surface includes grinding and leveling of imperfections. Following cleaning, layers of priming coat (to improve bonding with the surface) and putty (for leveling purposes) should be applied, followed by a saturate layer. The pre-cut fiber is placed on a saturated surface, then covered with a second layer of saturant to ensure complete impregnation of the fibers. It's very important to eliminate all air voids since they lead to premature failure [37].

The database for this part consists of 76 experimental tests and that belong to 8 different references. This database [39–46] is summarized in Table 2. All the specimens had a rectangular, square, or octahedral cross section shape and were constructed using clay masonry units. Different types of fibers are considered, such as basalt (BFRP), carbon (CFRP), and glass (GFRP).

**Table 3**
Experimental Results of FRCM Confined Masonry Columns from Literature.

| Ref. | Column Dimensions | | | | | Masonry | FRCM Properties | | | | | Experimental Results | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shape | b (mm) | d (mm) | h (mm) | $r_c$ (mm) | $f_m$ (MPa) | Type | E (GPa) | e | t (mm) | n | fmc (MPa) | eu mm | fmc / fm |
| [48] | S | 290 | 290 | 1000 | 25 | 14.5 | GFRCM | 63.3 | 0.021 | 0.02 | 1 | 17.6 | 0.004 | 1.2 |
| | S | 290 | 290 | 1000 | 25 | 14.3 | GFRCM | 63.3 | 0.021 | 0.02 | 1 | 17 | 0.004 | 1.2 |
| | S | 290 | 290 | 1000 | 25 | 14.5 | GFRCM | 63.3 | 0.021 | 0.04 | 1 | 17.8 | 0.004 | 1.2 |
| | S | 290 | 290 | 1000 | 25 | 14.3 | GFRCM | 63.3 | 0.021 | 0.04 | 1 | 18.3 | 0.003 | 1.3 |
| | S | 390 | 390 | 1000 | 25 | 12.5 | GFRCM | 63.3 | 0.021 | 0.02 | 1 | 14.2 | 0.003 | 1.1 |
| | S | 390 | 390 | 1000 | 25 | 12.2 | GFRCM | 63.3 | 0.021 | 0.02 | 1 | 14.2 | 0.002 | 1.2 |
| | S | 390 | 390 | 1000 | 25 | 12.5 | GFRCM | 63.3 | 0.021 | 0.04 | 1 | 14.4 | 0.003 | 1.2 |
| | S | 390 | 390 | 1000 | 25 | 12.2 | GFRCM | 63.3 | 0.021 | 0.04 | 1 | 15.6 | 0.002 | 1.3 |
| [49] | S | 250 | 250 | 650 | 20 | 8.16 | CFRCM | 240 | 0.018 | 0.06 | 1 | 14.6 | – | 1.8 |
| [50] | R | 200 | 90 | 380 | 0 | 36.3 | PBO | 270 | 0.014 | 0.012 | 1 | 52.6 | 0.006 | 1.5 |
| | R | 200 | 90 | 380 | 0 | 36.3 | PBO | 270 | 0.014 | 0.012 | 1 | 34.9 | 0.005 | 1.0 |
| | R | 200 | 90 | 380 | 0 | 36.3 | PBO | 270 | 0.014 | 0.012 | 1 | 38.5 | 0.005 | 1.1 |
| | S | 102 | 100 | 332 | 0 | 29.1 | PBO | 270 | 0.014 | 0.012 | 1 | 41.9 | 0.008 | 1.4 |
| | R | 102 | 152 | 332 | 0 | 22 | PBO | 270 | 0.014 | 0.012 | 1 | 38.4 | 0.017 | 1.8 |
| | R | 102 | 152 | 332 | 0 | 22 | PBO | 270 | 0.014 | 0.012 | 1 | 37.4 | 0.016 | 1.7 |
| | R | 102 | 152 | 332 | 0 | 22 | PBO | 270 | 0.014 | 0.012 | 1 | 38 | 0.01 | 1.7 |
| | R | 102 | 152 | 332 | 0 | 8.9 | PBO | 270 | 0.014 | 0.012 | 2 | 36.5 | 0.004 | 4.1 |
| | R | 102 | 152 | 332 | 0 | 8.9 | PBO | 270 | 0.014 | 0.012 | 2 | 34.1 | 0.008 | 3.8 |
| [51] | S | 290 | 290 | 890 | 20 | 3.45 | CFRCM | 240 | 0.018 | 0.05 | 2 | 8.19 | 0.002 | 2.4 |
| | S | 288 | 288 | 875 | 20 | 3.46 | CFRCM | 240 | 0.018 | 0.05 | 2 | 8.17 | 0.002 | 2.4 |
| [52] | S | 360 | 360 | 900 | 0 | 1.6 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.9 | 0.016 | 1.2 |
| | S | 360 | 360 | 900 | 0 | 1.6 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.7 | 0.02 | 1.1 |
| | S | 360 | 360 | 900 | 0 | 1.6 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.8 | 0.025 | 1.1 |
| | S | 360 | 360 | 900 | 0 | 1.6 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.6 | 0.031 | 1.0 |
| | R | 360 | 630 | 900 | 0 | 1.5 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.4 | 0.017 | 1.0 |
| | R | 360 | 630 | 900 | 0 | 1.5 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.5 | 0.027 | 1.0 |
| | R | 360 | 630 | 900 | 0 | 1.5 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.5 | 0.017 | 1.0 |
| | R | 360 | 630 | 900 | 0 | 1.5 | BFRCM | 70 | 0.018 | 0.022 | 1 | 1.4 | 0.012 | 1.0 |
| [53] | S | 230 | 230 | 950 | 25 | 4.7 | BFRCM | 65 | 0.018 | 0.03 | 1 | 8.5 | 0.022 | 1.8 |
| | S | 230 | 230 | 950 | 25 | 4.7 | BFRCM | 65 | 0.018 | 0.03 | 1 | 7.8 | 0.02 | 1.67 |
| | S | 230 | 230 | 950 | 25 | 9.4 | BFRCM | 65 | 0.018 | 0.03 | 1 | 11.2 | 0.013 | 1.2 |
| | S | 230 | 230 | 950 | 25 | 9.4 | BFRCM | 65 | 0.018 | 0.03 | 1 | 10.3 | 0.016 | 1.1 |
| | S | 230 | 230 | 950 | 25 | 9.4 | SFRCM | 200 | 0.02 | 0.03 | 1 | 9.6 | 0.016 | 1.0 |
| | S | 230 | 230 | 950 | 25 | 9.4 | SFRCM | 200 | 0.02 | 0.03 | 1 | 12.5 | 0.02 | 1.3 |
| [54] | S | 250 | 250 | 770 | 20 | 4.9 | BFRCM | 70 | 0.02 | 0.02 | 1 | 5.6 | 0 | 1.1 |
| [55] | S | 390 | 390 | 1030 | 20 | 12.63 | CFRCM | 210 | 0.01 | 0.02 | 1 | 13.17 | 0.002 | 1.0 |
| | S | 390 | 390 | 1030 | 20 | 12.63 | CFRCM | 210 | 0.01 | 0.02 | 1 | 13.01 | 0.002 | 1.0 |
| | S | 390 | 390 | 1030 | 20 | 12.63 | GFRCM | 60 | 0.018 | 0.02 | 1 | 11.97 | 0.001 | 1.0 |
| | S | 390 | 390 | 1030 | 20 | 12.63 | GFRCM | 60 | 0.018 | 0.02 | 1 | 13.5 | 0.002 | 1.1 |
| [56] | S | 240 | 240 | 310 | 20 | 4.99 | CFRCM | 230 | 0.018 | 0.02 | 1 | 3.5 | 0.017 | 0.7 |
| | S | 240 | 240 | 310 | 20 | 4.99 | CFRCM | 230 | 0.018 | 0.02 | 1 | 7.7 | 0.019 | 1.5 |
| | S | 240 | 240 | 310 | 20 | 4.99 | CFRCM | 230 | 0.018 | 0.02 | 1 | 9 | 0.036 | 1.8 |
| | S | 240 | 360 | 310 | 10 | 4.8 | CFRCM | 230 | 0.018 | 0.02 | 2 | 5.1 | 0.014 | 1.1 |
| | S | 240 | 360 | 310 | 10 | 4.8 | CFRCM | 230 | 0.018 | 0.02 | 2 | 6.1 | 0.032 | 1.3 |
| | S | 240 | 360 | 310 | 10 | 4.8 | CFRCM | 230 | 0.018 | 0.02 | 2 | 7.4 | 0.038 | 1.6 |
| | S | 240 | 480 | 310 | 10 | 7.38 | CFRCM | 230 | 0.018 | 0.02 | 3 | 7.1 | 0.02 | 1.0 |
| | S | 240 | 480 | 310 | 10 | 7.38 | CFRCM | 230 | 0.018 | 0.02 | 3 | 8.7 | 0.02 | 1.2 |
| | S | 240 | 480 | 310 | 10 | 7.38 | CFRCM | 230 | 0.018 | 0.02 | 3 | 9.1 | 0.027 | 1.2 |
| [57] | S | 250 | 250 | 770 | 20 | 5.3 | PBO | 211.4 | 0.025 | 0.02 | 1 | 10.6 | 0.028 | 2.0 |
| | S | 250 | 250 | 770 | 20 | 5.3 | PBO | 211.4 | 0.025 | 0.02 | 2 | 13.6 | 0.027 | 2.6 |
| | S | 250 | 250 | 770 | 20 | 5.3 | PBO | 211.4 | 0.025 | 0.02 | 3 | 15.2 | 0.029 | 2.9 |
| | S | 250 | 250 | 770 | 20 | 5.3 | BFRCM | 60.7 | 0.018 | 0.02 | 1 | 7.7 | 0.017 | 1.5 |
| | S | 250 | 250 | 770 | 20 | 5.3 | BFRCM | 60.7 | 0.018 | 0.02 | 2 | 6.9 | 0.026 | 1.3 |

### *4.2. Procedure for strengthening and database of masonry columns confined with FRCM*

The FRCM system consisted of open mesh fibers embedded in an inorganic matrix. There are many steps required for a specimen's preparation before installing the advanced composite. The corners of columns need to be rounded in order to reduce stress concentrations since it has been reported that the sharp edge leads to fiber rupture. Also, the surface should be cleaned and preferably saturated with water before applying the first layer of inorganic material (cementitious material). The thickness of the fresh matrix layer can be controlled by using a foam template and then applying a pre-cut open mesh fiber. The specimens were cured daily with water for 28 days before the time of testing [47].

The database for this part consists of 53 experimental tests that belong to 10 different references. This database is summarized in Table 3 [48–57]. All the specimens have rectangular or square cross section shape and were constructed using clay masonry units. Different types of open mesh fibers are considered, such as basalt (BFRCM), carbon (CFRCM), glass (GFRCM), and PBO.

**Table 4**
Experimental Results of SRG Confined Masonry Columns from Literature.

| **Ref.** | **Column dimensions** | | | | | **Masonry** | **Steel Fiber** | | | | **Experimental Results** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shape | b | d | h | $r_c$ | $f_m$ | E | e | t | n | fmc | eu | fmc / fm |
| | | (mm) | (mm) | (mm) | (mm) | (MPa) | (GPa) | | (mm) | | (MPa) | mm | |
| [54] | S | 250 | 250 | 770 | 0 | 4.9 | 200 | 0.004 | 0.04 | 1 | 5.7 | – | 1.2 |
| | S | 250 | 250 | 770 | 0 | 4.9 | 200 | 0.004 | 0.04 | 1 | 6.5 | – | 1.3 |
| [23] | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.3 | 0.1 | 1.4 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.5 | 0.09 | 1.3 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.1 | 0.1 | 1.2 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 8.5 | 0.07 | 1.2 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.2 | 0.08 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.1 | 0.16 | 1.2 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10 | 0.09 | 1.4 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.7 | 0.12 | 1.3 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.4 | 0.09 | 1.4 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 11 | 0.11 | 1.5 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.5 | 0.14 | 1.4 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.4 | 0.09 | 1.4 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.7 | 0.06 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.8 | 0.07 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.1 | 0.06 | 1.4 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.1 | 0.11 | 1.2 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.1 | 0.09 | 1.4 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.4 | 0.07 | 1.3 |
| | S | 350 | 350 | 750 | 0 | 7.36 | 205 | 0.004 | 0.16 | 3 | 8.7 | 0.09 | 1.2 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.5 | 0.13 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.1 | 0.12 | 1.4 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.8 | 0.11 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10 | 0.17 | 1.4 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.8 | 0.17 | 1.3 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 11.2 | 0.18 | 1.5 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.3 | 0.18 | 1.4 |
| | S | 350 | 350 | 750 | 38 | 7.36 | 205 | 0.004 | 0.16 | 3 | 9.8 | 0.17 | 1.3 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.7 | 0.08 | 1.45 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 11.1 | 0.12 | 1.5 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.1 | 0.1 | 1.4 |
| | S | 350 | 350 | 750 | 9 | 7.36 | 205 | 0.004 | 0.16 | 3 | 10.1 | 0.08 | 1.4 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.16 | 1 | 11.1 | 0.01 | 2.1 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.16 | 1 | 7.8 | 0.01 | 1.5 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.16 | 2 | 10.3 | 0.01 | 1.9 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.16 | 3 | 15.1 | 0.02 | 2.9 |
| [53] | S | 230 | 230 | 950 | 25 | 4.7 | 200 | 0.004 | 0.16 | 1 | 6.1 | 0.04 | 1.3 |
| | S | 230 | 230 | 950 | 25 | 4.7 | 200 | 0.004 | 0.16 | 1 | 6.3 | 0.03 | 1.4 |
| [59] | S | 250 | 250 | 700 | 20 | 2.2 | 190 | 0.004 | 0.16 | 1 | 4.3 | 0 | 2.0 |
| | S | 250 | 250 | 700 | 20 | 2.2 | 190 | 0.004 | 0.16 | 2 | 6.1 | 0 | 2.8 |
| | S | 250 | 250 | 700 | 20 | 2.2 | 190 | 0.004 | 0.16 | 3 | 13.1 | 0 | 6.1 |
| [57] | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.1 | 1 | 11.1 | 0.01 | 2.1 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.1 | 1 | 7.8 | 0.01 | 1.5 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.1 | 2 | 10.3 | 0.01 | 1.9 |
| | S | 250 | 250 | 770 | 20 | 5.3 | 200 | 0.019 | 0.1 | 3 | 15.1 | 0.02 | 2.9 |

### 4.3. Procedure for strengthening and database of masonry columns confined with SRG

Steel cords embedded in fresh cementitious matrix make up the SRG system. The steps for preparing the specimen are nearly identical to those for the FRCM strengthening system; the only difference is the preparation of the steel fiber sheet [58]. The preparation of the steel jacket started with measuring the required width and length, then cutting the steel fiber sheets, ending with bending the fiber sheets at the corner using a special tool (The GeoSteel bender.). As mentioned in FRCM strengthening system, after completing

**Table 5**
Experimental Results of NSM Strengthened Masonry Walls from Literature.

| Ref | **Geometry** | | | **Masonry** | **Fiber Properties** | | | | | | **Results** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | h (mm) | l (mm) | t (mm) | fm (Mpa) | tf (mm) | bf (mm) | d bar (mm) | No. of bars or strips | Ef (MPa) | Fu (MPa) | P ultimate (kN) |
| [61] | 1710 | 355 | 110 | 17 | 3.6 | 10 | – | 1 | 165,000 | 2700 | 58.4 |
| | 1710 | 355 | 110 | 17 | 3.6 | 10 | – | 1 | 165,000 | 2700 | 59.3 |
| | 1710 | 355 | 110 | 17 | 3.6 | 10 | – | 1 | 165,000 | 2700 | 49.3 |
| | 1710 | 230 | 110 | 17 | 3.6 | 10 | – | 1 | 165,000 | 2700 | 48.6 |
| | 2310 | 1070 | 110 | 17 | 7.2 | 10 | – | 1 | 165,000 | 2700 | 83.1 |
| | 2310 | 1070 | 110 | 17 | 4.8 | 7.5 | – | 2 | 165,000 | 2700 | 65.3 |
| | 2310 | 1070 | 110 | 17 | 3.6 | 10 | – | 3 | 165,000 | 2700 | 70.6 |
| | 2310 | 1070 | 110 | 17 | 4.8 | 5 | – | 3 | 165,000 | 2700 | 49.3 |
| | 2310 | 1070 | 110 | 17 | 3.6 | 10 | – | 1 | 165,000 | 2700 | 56.3 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 76.9 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 69 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 66 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 77.4 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 73.1 |
| | 2310 | 1070 | 110 | 17 | 4.2 | 10 | – | 2 | 165,000 | 2700 | 56.9 |
| [62] | 4100 | 1150 | 330 | 18.3 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 35 |
| | 3000 | 1150 | 330 | 24.5 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 38 |
| | 4100 | 1150 | 230 | 23.16 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 15 |
| | 4100 | 1150 | 230 | 23.16 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 25 |
| | 3000 | 1200 | 240 | 9.4 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 19 |
| | 4000 | 1250 | 250 | 9.7 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 25 |
| | 3300 | 1170 | 150 | 3.3 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 5.5 |
| | 2700 | 1170 | 270 | 3.3 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 17 |
| | 2730 | 3480 | 130 | 13.8 | 1.2 | 15 | – | 1 | 165,000 | 2700 | 55 |
| [63] | 3890 | 2792 | 190 | 27.6 | – | – | 0 | 0 | – | – | 11 |
| | 3890 | 2792 | 190 | 27.6 | – | – | 5 | 4 | 147,500 | 2343 | 14 |
| | 3890 | 2792 | 190 | 27.6 | – | – | 5 | 6 | 147,500 | 2343 | 18 |
| | 3890 | 2792 | 190 | 27.6 | – | – | 0 | 0 | – | – | 11 |
| | 3890 | 2792 | 190 | 27.6 | – | – | 5 | 4 | 147,500 | 2343 | 18 |
| | 3890 | 2725 | 190 | 27.6 | – | – | – | – | – | – | 4.75 |
| | 3890 | 2725 | 190 | 27.6 | – | – | 5 | 4 | 147,500 | 2343 | 7 |
| | 3890 | 2725 | 190 | 27.6 | – | – | 5 | 1 | 147,500 | 2343 | 5.5 |
| | 3890 | 2725 | 190 | 27.6 | – | – | 0 | 1 | – | – | 4.75 |
| | 3890 | 2725 | 190 | 27.6 | – | – | 5 | 4 | 147,500 | 2343 | 5.5 |
| [64] | 3300 | 1170 | 150 | 3.2 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 9.38 |
| | 3300 | 1170 | 150 | 3.2 | – | – | 6 | 2 | 165,000 | 3100 | 6.14 |
| | 2700 | 1200 | 270 | 3.2 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 21.56 |
| | 3000 | 1200 | 240 | 9.6 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 14.04 |
| | 4000 | 1250 | 255 | 9.7 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 40.6 |
| | 2730 | 3850 | 130 | 13.8 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 24.5 |
| | 2730 | 3480 | 130 | 13.8 | 1.2 | 15 | – | 2 | 165,000 | 3100 | 32 |
| | 2940 | 4100 | 130 | 13.8 | 1.2 | 15 | – | 1 | 165,000 | 3100 | 34 |
| | 2940 | 4100 | 130 | 13.8 | 1.2 | 15 | – | 2 | 165,000 | 3100 | 38.5 |
| [65] | 1220 | 610 | 150 | 21 | – | – | – | – | – | | 42 |
| | 1220 | 610 | 150 | 21 | 2 | 16 | – | 1 | 124,000 | 1965 | 58 |
| | 1220 | 610 | 150 | 21 | – | – | 6.35 | 1 | 124,000 | 2250 | 68.97 |
| | 1220 | 610 | 150 | 21 | – | – | 6.35 | 1 | 46,200 | 900 | 55 |
| | 1220 | 610 | 150 | 21 | – | – | 6.35 | 2 | 46,200 | 900 | 67 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 2 | 46,200 | 825 | 65.66 |
| | 1220 | 610 | 150 | 21 | – | – | 6.35 | 2 | 46,200 | 900 | 58 |
| [66] | 1220 | 610 | 150 | 21 | 4.5 | 16 | – | 2 | 124,000 | 1965 | 99.7 |
| | 1220 | 610 | 150 | 21 | 4.5 | 16 | – | 1 | 124,000 | 1965 | 74 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 1 | 124,000 | 2170 | 90.33 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 1 | 46,200 | 825 | 63.1 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 2 | 46,200 | 825 | 85.85 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 1 | 46,200 | 825 | 70.28 |
| | 1220 | 610 | 150 | 21 | – | – | – | – | – | – | 38.25 |
| | 1220 | 610 | 150 | 21 | – | – | 6.35 | 2 | 46,200 | 900 | 60 |
| | 1220 | 610 | 150 | 21 | – | – | 10 | 2 | 46,200 | 825 | 80.48 |

the process of strengthening, the specimens were wrapped in saturated cloths for 28 days to provide hydration for the paste material [26].

Due to the limited studies on this type of confinement, the database for this part consists of 46 experimental tests and its belong 5 different references. This database is summarized in Table 4 [23,53–54,57–59]. All the specimens have a square cross sectional shape and are constructed using brick masonry units.

### 4.4. *Procedure for strengthening and database of masonry columns confined with NSM*

In order to strengthen specimens using NSM system, FRP bar was inserted into a groove that had been cut at the specimen's surface. no surface preparation was required in this process. To prevent the splitting failure of the epoxy coating, grooves with diameters twice the diameter of the bar were carved using a special concrete saw [60]. The bond between the FRP bars and bonding material was improved by using deformed FRP bars with a sand covering. Bonding material was inserted into the grooves to fill up the bottom two-thirds of the groove depth. As the FRP bar was forced into the bonding agent, which flowed around it to achieve a perfect bond between the bar and the groove's sides, it was fitted to mid-groove depth. The database for this part consists of 60 experimental tests and that belong to 6 different references. This database is summarized in Table 5 [61–66].

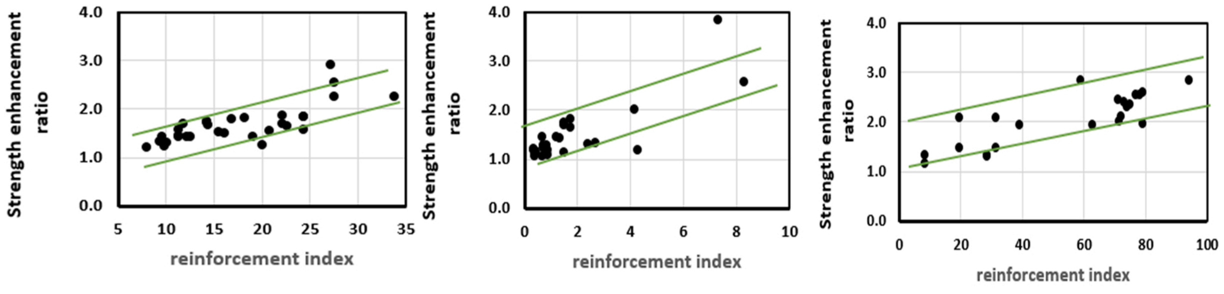
## 5. Equivalent fiber reinforcement index

It is difficult to make a comparison between the different strengthening systems or the different materials used in the strengthening process because of the different mechanical properties of the fiber or the adhesive material for each system. In order to propose an appropriate index to capture the key factors that control the behavior of confined masonry columns, the equivalent fiber reinforcement index (EFRI) was considered. EFRI is a factor combining the geometry, masonry, and fiber properties together, as represented in Eq. (1).

$$\omega_f = \rho_f E_f / f_m (h/d) \tag{1}$$

Where the$\omega_f$ is equivalent fiber reinforcement index, $\rho_f$ is fiber reinforcement ratio, $E_f$ is fiber tensile modulus of elasticity, $f_m$ is compressive strength of masonry, $h/d$ is the slenderness ratio. Simply, the concept of this index is the ratio between the fiber and masonry axial stiffness (modulus of elasticity for fiber or masonry x cross sectional area for fiber or masonry). The index considers masonry compressive strength instead of masonry modulus of elasticity since the latter is directly proportional to compressive strength. The geometry slenderness ratio (h/d) is adapted just to reflect the ability of the brick column behavior to be controlled by flexure rather than shear. The slenderness ratio is considered in the denominator to represent the inverse proportion with respect to load. The idea of using EFRI has been used in conducting a comparison study between different strengthening systems that strengthened reinforced and unreinforced masonry walls [67,68] Fig. 3 shows the relationship between EFRI ($\omega_f$) and the strength enhancement ratio, which represents the ratio of confined column capacity to the control (unconfined) column capacity.

In terms of increasing the strength capacity of different cross-sectional shapes (square or rectangular) columns, all specimens strengthened with different advanced composites followed a similar trend. The FRCM system is considered better than other systems in terms of obtaining the highest strength capacity using lowest percentage of fiber reinforcement ratio. In terms of convergence of the results corresponding to the same fiber reinforcement index value, columns strengthened with FRP exhibited better performance and recorded 8% as a maximum percentage of variation. On the other hand, the maximum percentage of variation in the strength enhancement ratio for the same fiber reinforcement index was 25% and 20% in the case of using the SRG and FRCM systems, respectively. It can be obvious to get many points falling on each other (looking like one point) when the specimens are strengthened with the same type of fiber but slightly different geometries. These specimens have the same strength enhancement ratio since they have the same EFRI. However, special care should be taken due to the scatter of the limited database results that presented in this study. The behavior of specimens' jackets reinforced with glass fiber is better than others (in terms of strength enhancement) since it is



FRP system FRCM system SRG system

**Fig. 3.** Reinforcement index vs. Strength enhancement ratio relationship.

required to increase the number of layers to get the same EFRI of the specimens strengthened with stronger material. The increasing number of layers led to exhibit better performance due to thicker jacket. It could be concluded that, on average, the trend of improving the strength enhancement ratio is nearly linear with the EFRI. For the FRP database, the band width (parallel green lines) to cover a high percentage of data is very narrow and has less scatter compared with other systems. The concept of EFRI can be expanded to include various structural elements, such as beams and walls, in order to use it for comparison purposes among different strengthening systems. It can also be used in various strengthening techniques, such as (NSM) with different types of fiber (carbon and glass). Based on gathered data in Table 5, the trend between the reinforcement index and the capacity enhancement ratio for masonry walls strengthened with the NSM technique is shown in Fig. 4. Its notice from this figure that the data are distributed in a consistent manner so that the two variables are directly proportion. The idea of adopting all variables (geometry, fiber and steel properties) in one dimensionless index has been carried out by previous researchers [66,68] for the purpose of finding the values of the fiber failure strain for various structural elements as shown in Fig. 5.

## 6. Analytical models for confined compressive strength

The following common equation that is used to predict the compressive strength of confined masonry columns is developed from the confined concrete columns: [69].

$$f_{mc} = f_{mu}\left[\alpha + k'\left(\frac{f_{eff}}{f_{mu}}\right)^{\alpha_1}\right] \tag{2}$$

Where $f_{mc}$ is the masonry confined compressive strength, $f_{mu}$ is the masonry unconfined compressive strength, $f_{eff}$ is the effective lateral confinement pressure. $\alpha$, $k'$and $\alpha_1$ are non dimensional parameters that explained for each analytical model. The effective lateral confinement pressure is represented as

$$f_{eff} = k_a f_1 \tag{3}$$

Where $k_a$ is an efficiency factor defined as:

$$k_a = 1 - \left(b'^2 + d'^2\right)/3A_m$$

Where (b, d, $b'$, $d'$) are defined in Fig. 6, $A_m$ is the cross section area of the masonry column.

The lateral confinement pressure is defined as

$$f_1 = \frac{b+d}{b.d} t_f E_f \varepsilon_f \tag{4}$$

### 6.1. ACI standard design guideline

Based on ACI 440 provisions, the maximum confined masonry compressive strength and the maximum confinement pressure are calculated as follow with an additional reduction factor ψf = 0.95. This factor was chosen based on the committee's judgment.

$$f_{mc} = f_{mu} + \psi_f .3.3. f_{eff} \tag{5}$$

$$f_{eff} = k_a f_1 \tag{6}$$

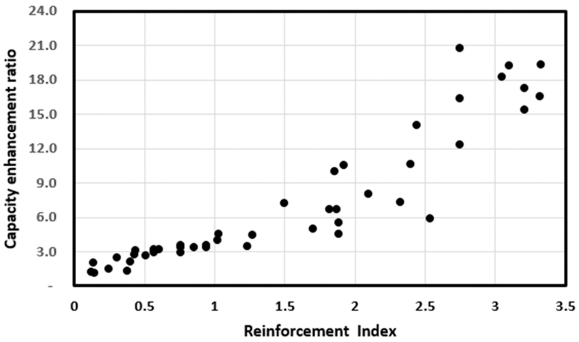


**Fig. 4.** Reinforcement Index vs. capacity enhancement ratio relationship.

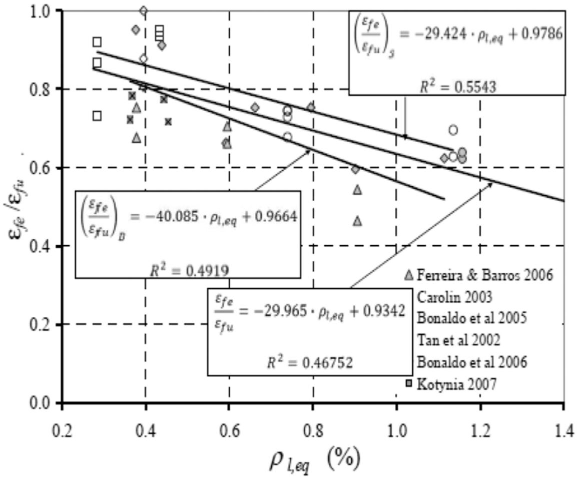


**Fig. 5.** Debonding factor vs. equivalent reinforcement ratio for reinforced concrete beams and slabs [62].

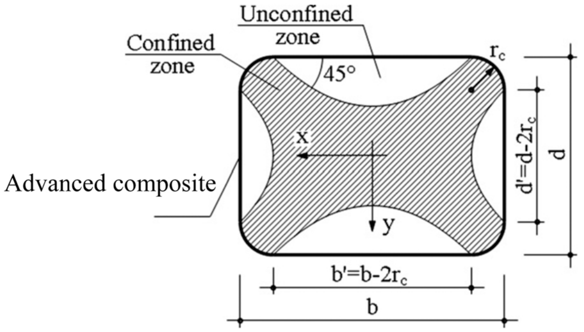


**Fig. 6.** Confinement of rectangular sections externally wrapped with advanced composite [64].

$$f_1 = \frac{2n}{\sqrt{b^2 + d^2}} t_f E_f \varepsilon_f \tag{7}$$

$$k_a = \left(\frac{b}{d}\right)^2 \left[1 - \left(\frac{b}{d}(b - 2r)^2 + \frac{d}{b}(d - 2r)^2\right)/3A_m\right] \tag{8}$$

Based on ACI 549 The maximum confined concrete compressive strength, $f_{mc}$, and the maximum confinement pressure, $f_1$ is calculated as follow

$$f_{mc} = f_{mu} + 3.1 f_{eff} \tag{9}$$

$$f_{eff} = k_a f_1 \tag{10}$$

$$f_1 = \frac{2n}{\sqrt{b^2 + d^2}} t_f E_f \varepsilon_f \tag{11}$$

$$k_a = 1 - \left((b - 2r)^2 + (d - 2r)^2\right)/3A_m \tag{12}$$

### 6.2. CNR-DT standard design guideline

For both strengthening systems, the compressive strength of the confined brick columns can be found based on the calculation of the confined pressure, which is limited by the performance of the fiber and matrix before the failure as follow:

$$f_{mc} = f_{mu}\left[1 + k\left(\frac{f_{eff}}{f_{mu}}\right)^{0.5}\right] \tag{13}$$

Where $\grave{k}$ can be adopted using the following formula

$$\grave{k} = \beta\left(\frac{g_m}{100}\right)^{\gamma} \tag{14}$$

Where gm is the mass density of masonry in (kg/m$^3$),$\beta, \gamma$ are coefficients which can be assumed conservatively equal to 1.0.

### 6.3. Proposed models

For the masonry columns confined with FRP, the proposed model provided by Faella et al. [70] was consider as follow,

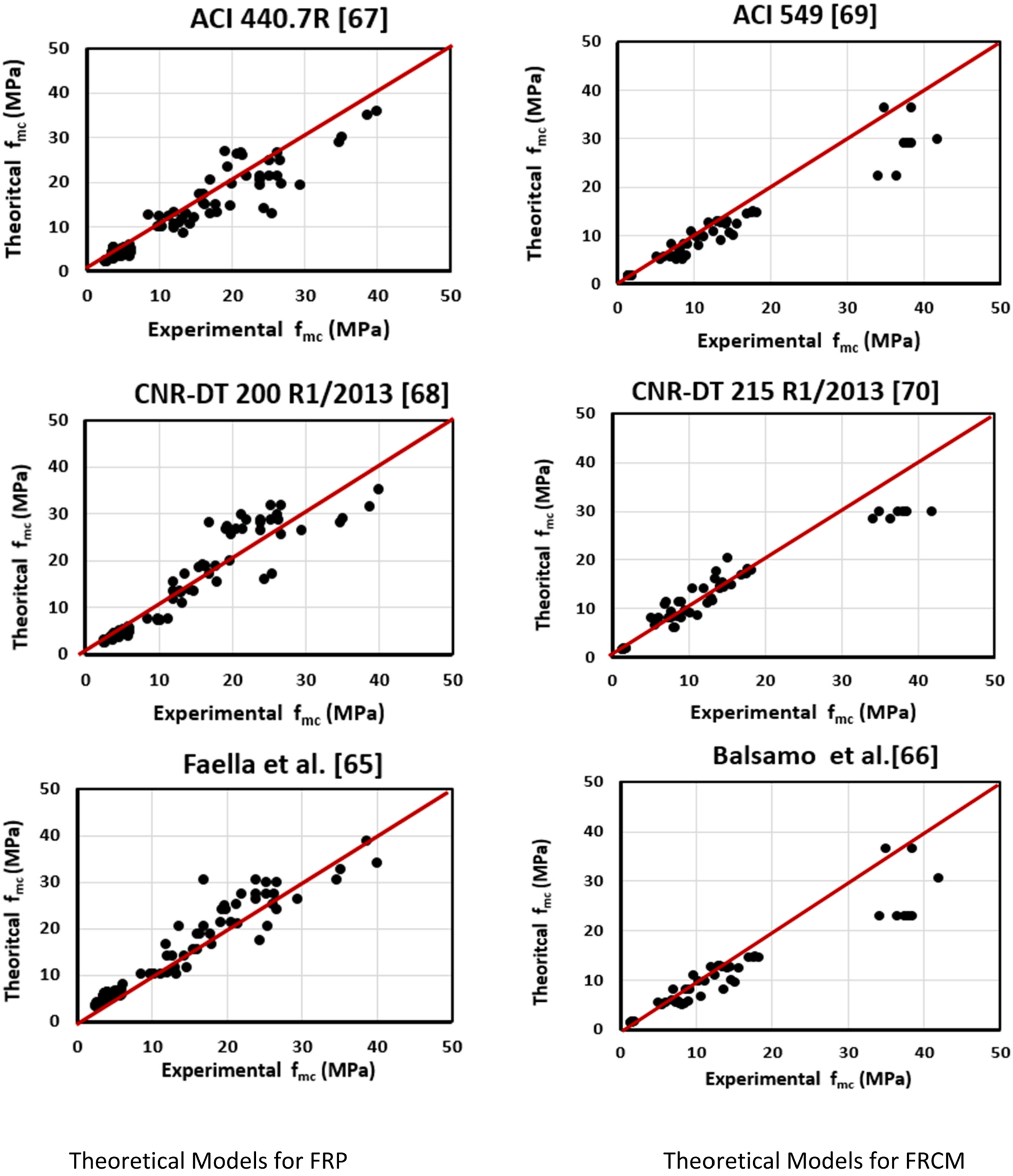


**Fig. 7.** The comparison between the experimental results and theoretical models of FRP and FRCM systems.

$$f_{mc} = f_{mu}\left[1.618 + \grave{k}\left(\frac{\grave{f}_{eff}}{f_{mu}}\right)^{1}\right] \tag{15}$$

$$\grave{k} = \beta\left(\frac{g_m}{100}\right)^{\gamma} \tag{16}$$

Where $\beta = 0.013 and\gamma = 6.324$.

On the other hand, the proposed analytical model for the confined masonry columns with FRCM system provided by Balsamo et al. [71] was considered as follow:

$$f_{mc} = f_{mu}\left[1 + \grave{k}\left(\frac{\grave{f}_{eff}}{f_{mu}}\right)^{1}\right] \tag{17}$$

$$\grave{k} = \beta\left(\frac{g_m}{100}\right)^{\gamma} \tag{18}$$

Where $\beta = 1 and\gamma = 0.662$.

## 7. Evaluation of the proposed models and standards

The results from the gathered database were compared to confined compressive strength predictions found in many literatures. Six analytical models have been chosen for evaluation, three for FRP systems such as ACI 440 [72], CNR-DT 200 [73], and Faella et al. [70], and three for FRCM systems such as ACI 549 [74], CNR-DT 215 [75], and Balsamo et al. [71]. The applicability of these proposed models (from literature and standard codes) has to be verified across a wide range of experimental results. These models are used to predict the confined compressive strength of masonry columns, so in case of missing any required data, it will be considered as a common data that is widely referred to in literature. For instance, the common thickness of FRP used in literature is 0.167 mm [76,77].

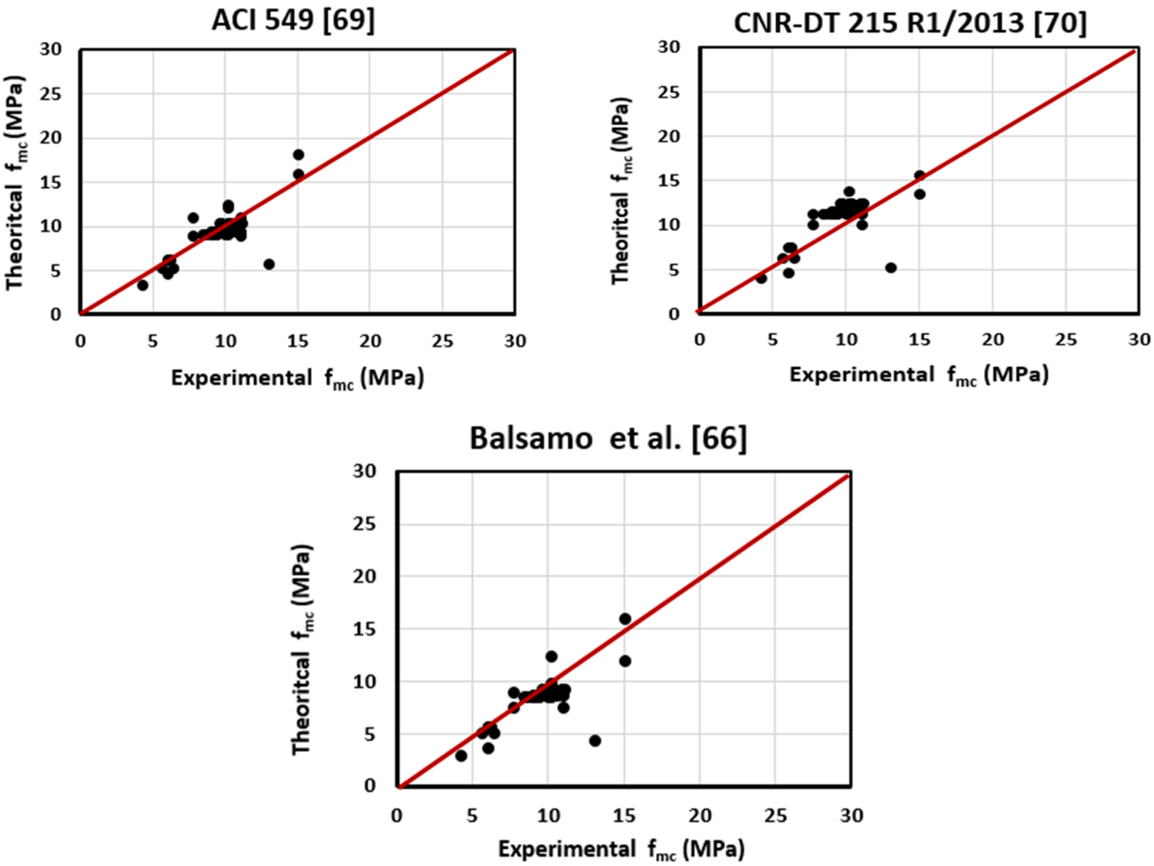


Fig. 8. The comparison between the experimental results and theoretical models of SRG System.

The comparison between the experimental and theoretical confined compressive strengths of masonry columns is shown in Fig. 7. Since there is no standard code or specific proposed model for SRG systems, the confined capacity of this system will be predicted using the FRCM proposed model. The justification for using these models is that both FRCM and SRG systems have the same concept of using inorganic material as a paste material [78,79].

Based on the distributed data in Fig. 7, for the experimental results of the specimens strengthened with FRP, it can be concluded that the formulations given in ACI 440 and CNR-DT 200 are very predictable, but the ACI 440 is more conservative among the proposed models since it estimates the column confined capacity close to experimental results. On the other hand, the model proposed by Faella et.al. [70] is very good at predicting the confinement capacity but it is over estimated in many data points. For the models proposed to predict the capacity of columns confined with FRCM, all selected models are predictable and conservative. Again, the ACI 549 model is comparatively better than other models.

The ACI standard is more accurate in predicting the load capacity of columns strengthened with FRCM compared to columns strengthened with FRP. The same thing is true for the CNR-DT 200 standard, where the slope of the line that passes the data is closed to one in the case of column strengthened with FRCM system. This reflects the accuracy of column strength prediction. Finally, the model proposed by Faella et al. [70] is more conservative in the case of columns strengthened with FRCM compared with the same column strengthened with FRP.

Fig. 8 also compares three selected models for predicting the confinement capacity of masonry columns. All the models of FRCM system that used for capacity prediction present a good agreement with the experimental results, but the ACI 549 and Balsamo et al. [71] are more conservative compared with the CNR- DT 215.

In summary, the comparisons of various analytical models reveal that the analytical formulations given in ACI 440, and ACI 549 can be conservatively used to estimate the confined compressive strengths of masonry columns strengthened with FRP, FRCM. In addition, since there is no standard code or specific proposed model for predicting the capacity of columns strengthened with SRG system, it is possible to use the standards (ACI 549 and CNR-DT 215) and the model proposed by Balsamo et al. [71] for this purpose.

## 8. Conclusions

Various advanced composites have been used to improve the confinement capacity of masonry columns subjected to axial loads. The strengthening techniques that were considered in this study are, FRP, FRCM, and SRG. This study is presented as an attempt to critically review and evaluate these three techniques in terms of failure mode and strength enhancement ratio. A new term was introduced in this study (equivalent fiber reinforcement index) which is used to compare different strengthening techniques based on this common index.

Using the developed experimental databases, different modes of failure were reported, such as crushing of masonry due to weak tensile behavior of masonry units, rupture of fiber due to dilation of masonry units or stress concentration developed at sharp corners, and local buckling of fiber sheets due to fiber excessive axial strain developed in the hoop direction. Another mode of failure is the combination of fibers rupture and partial slippage of the fibers through the matrix of FRCM or SRG system, leading to a slightly more gradual failure. Finally, opening the SRG jacket is the other possible mode of failure that happened due to cracks developing on the column surface.

Furthermore, different analytical models have been proposed in the previous studies to predict the confined compressive strength capacity. The applicability and predictabilities of these proposed models and standards were evaluated based on previous results gathered from different literatures. Most of the selected models predict the confined capacity conservatively, despite the scatter in the experimental data. However, the models given in ACI 440 and ACI 549 show very good predictions for the confined capacity of masonry columns strengthened by FRP, FRCM or SRG respectively. Moreover, it could be concluded that, on average, the trend of improving the strength enhancement ratio is nearly linear with the EFRI. For the FRP database, the band width to cover a high percentage of data is very narrow and has less scatter compared with other system.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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