14TH CANADIAN MASONRY SYMPOSIUM
MONTREAL, CANADA
MAY 16TH – MAY 20TH, 2021

COMPARATIVE STUDY OF MASONRY COLUMNS STRENGTHENED WITH DIFFERENT STRENGTHENING SYSTEMS

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ABSTRACT

The confinement of masonry columns using advanced composites is frequently used in order to upgrade the column capacity. In this study, the efficiency of using different types of advanced composite for external confinement as a strengthening method is investigated. A wide range of experimental database of masonry column specimens has been collected from the results that are available in scientific literature. The major parameters considered in this study were the effects of composite material type and the effect of fiber reinforcement ratio. A comparison is also conducted between the experimental results and predicted capacity using available analytical models. As a result, all types of advanced composites presented a significant increase in both ultimate capacity and post-crack stiffness. In addition, 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 FRP debonding from the masonry substrate and debonding or slippage of the external fabric strengthening system within the cementitious matrix.

KEYWORDS: *masonry columns, advanced composite, fiber reinforced polymer, fiber reinforced cementitious matrix, resin*

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INTRODUCTION

The masonry unit is one of the most common construction materials that used in the construction of buildings around the world [1]. Unreinforced masonry (URM) structural elements are very weak in resisting loads that arise from extreme wind actions or any seismic events due to its limited tensile strength. Over the last few decades, the strengthening of concrete and masonry buildings is one of the topics in the field of structural engineering that has drawn great attention. A high percentage of masonry buildings are in need of strengthening due to many reasons such as: aging, deterioration or change the building function [2,3]. In research efforts around the world, columns are receiving a great deal of attention due to their importance as a structural element since the failure of a column can lead to significant consequences to the entire building including collapse.

Historically, there are many conventional techniques that have been used for masonry wall and column retrofitting, such as cross section enlargement, steel jacketing, and ferrocement jacketing [3-5]. The idea of confining of masonry elements was started early in the 1970s by Priestley and Bridgeman [6]. In this study, it was concluded that improved ductility can be obtained by confining the critical compression zone (crushing zone) using a thin stainless steel plate.

Most of conventional techniques are not only time consuming, but also result in increasing the dead load, which is not preferred especially for buildings subjected to seismic loads [5-6]. Recently, advanced composites like fiber reinforced polymers (FRP), fiber reinforced cementitious matrix (FRCM), or steel reinforced grout (SRG) are gaining more widespread attention that are used for general masonry strengthening [7-9], in particular for jacketing columns [10-12]. In order to upgrade column 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 building systems including their lightweight properties that help with installation, their durability, their high resistance to corrosion and high strength compared to other materials.

FRP composites have been considered in masonry or concrete confinement since the early 1980's. Uniaxial compression experimental test for concrete cylinders encased in FRP was conducted by Fardis and Khalili (1981) [13]. As a result of the FRP confinement in this work, all specimens experienced significant enhancement in both strength and ductility. Also, the authors introduced an analytical model for estimating the confined concrete compressive strength. In other work researchers presented different models to predict the confined columns compressive strength considering spiral confinement with GFRP [14] and different geometries of column cross section using different types of external advanced composites [15,16].

Despite the many advantages of using FRP there are some drawbacks in its use. Some of these challenges include: susceptibility to fire (when applied without fire protection), the inability of adhesion material (epoxy resin used commonly) to bond on wet surfaces, and the loss of mechanical properties and bond at high temperatures. The latest generation of advance composite is the fiber reinforced cementitious matrix (FRCM) strengthening system. FRCM system is made up of open mesh fiber (most commonly a PBO fabric) and an inorganic adhesive material. This type of advanced composite provides several advantages in term of structural and environmental aspects. Among many advantages, the FRCM system provides: improved fire resistance and a good ability to resist high temperatures, UV radiation resistance, and compatible permeability with the masonry or concrete substrate [17,18]. Although the academic research on using the open mesh fiber in a cementitious matrix as a strengthening technique was started in the early 1980s, this technique developed very slowly until the late of 1990s [19-20]. In the early 2000s a considerable effort has been made on utilizing an open mesh fiber in a cementitious matrix as a reinforcement.

Another strengthening system used to improve both the strength and ductility of masonry is the steel reinforced grout (SRG) strengthening system. This system consisted of steel fibers embedded in an inorganic paste material. The steel fiber can be in a galvanized or non-galvanized form. Recent research studies have shown that the SRG system can upgrade the flexural capacity of masonry structures and can improve confined column capacity [21,23].

In summary, different strengthening techniques exist for confinement purposes. For each technique there are limitations and obstacles that prevent its application offset with advantages that make these techniques preferable in various engineering applications. This study provides a critical review of existing experimental works and projects on the behavior of masonry columns confined with these strengthening systems. This study focused on presenting the differences of these methods in term of applicability, strength enhancement and modes of failure. Based on a collected database of different experimental results in this work, analytical models used to predict the confined capacity of masonry columns has also been evaluated.

EXPECTED MODES OF FAILURE

Unconfined masonry columns behave in a brittle manner and the failure is generally characterized by a crushing mode of failure due to the weak tensile behavior of masonry units. Failure initiates with a longitudinal crack on the external faces caused due to tensile stress development in the mortar joints. Failure precipitates and ends with a widening of the vertical cracking due to propagation through the masonry units and mortar joints [24-26] as shown in Figure 1. The modes of failure for confined masonry columns with different strengthening systems are explained below.

Figure 1: Brittle Failure of Unconfined Column [24-26]

Fiber reinforced polymer (FRP) confinement systems

The rupture of FRP composites is the most common mode of failure for confined masonry columns subjected to an axially compression load. This type of failure happens due to several reasons including dilation of masonry unit during loading, lack of FRP anchoring and insufficient overlap (i.e. bond) length. Failure may also happen due to stress concentrations especially at the sharp corners which is called the *knife effect* [27]. It's worthy to mention that rounding of the sharp edge corners is recommended to reduce stress concentrations before applying the FRP composite.

Local buckling of FRP sheets is the less common mode of failure that occurs due to crushing of masonry unit followed by excessive axial strain developed in the fiber within the hoop direction [26]. This type of failure is dependant upon the deformation properties of the advanced composite and the masonry unit, in addition to the direction of fibers used for confinement purpose.

Fiber reinforced cementitious matrix (FRCM) confinement systems

Based on literature, different modes of failure were reported for masonry columns fully confined with a continuous FRCM system. Rupture of the open mesh fiber (i.e. PBO or carbon) was observed with wide longitudinal cracks along the corner as shown in Figure 2. The compressive capacity of confined column dropped down due to fully damaged of masonry units [28]. 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 used for confinement purpose. The effectiveness of the confinement system of FRCM is highly depend on the compressive strength grade of the matrix. So the confinement of FRCM with high strength matrix is more effective than the same confinement with a low strength matrix [29,30]. It is noted that in many cases, the failure mode is a combination of fibres rupture and partial slippage of the fibres through the matrix, led to slightly more gradual failure [31]. Compared with specimens confined using FRP, the mode of failure for specimens confined with FRCM were less brittle due to gradual failure of matrix. Overlapping zone failure is the other type of failure that occurred in case of discontinuous confinement. The vertical cracks appeared a long the unconfined masonry unit, then moved to the external advanced composite ending with completely FRCM opened [28].

Steel reinforced grout (SRG) confinement systems

The failure of masonry columns confined by SRG was characterized by a ductile behavior due to 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. The condition of masonry core at the stage of failure was examined when the SRG jacket was opened and its reported with crushing of masonry units. The reason for developing steel cord rupture is the same reason for other types of confinements which is the stress concentration at the sharp edge of corner [21]. The fiber density played the important role in determining the mode of failure. The masonry columns confined with high density fiber presented fiber jacket opening and an inverse proportionality between the radius of 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 masonry column joint) and vertical (along the confined column corner) directions. The same cracks were the reason for detachment the exterior layer of confinement matrix and spalling off the confined masonry specimens. The vertical cracks maybe developed at end of the fiber overlap resulting in fiber debonding failure at the overlap location [26].

Figure 2: Failure configurations of confined columns [12,21,28]

THE PREVIOUS EXPERIMENTAL WORK

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

Procedure for strengthening of different strengthening systems FRP strengthening system

The procedure of preparation of the masonry surface includes grinding and the leveling of imperfections. After cleaning the surface, a prime coat (for improving the bonding with surface) is applied and then a layer of putty (for levelling purpose); finally, an epoxy saturant layer is applied. The pre-cut fiber is placed on saturated surface then covered with second layer of saturant to ensure complete impregnation of fibers. It's very important to eliminate all air voids since they can lead to premature failure [32].

FRCM strengthening system

The FRCM system consists of open mesh fibers embedded in an inorganic matrix. Many steps required as a specimen's preparation before installing the advanced composite. The corners of columns need to be rounded in order to reduce stress concentrations since sharp edges lead to stress concentration and fiber rupture. In addition, the surface should be cleaned and it is preferred to be saturated with water before applying the first layer of inorganic material (cementitious material). The thickness of fresh matrix layer can be controlled by using a foam template then applying a pre-cut open mesh fiber. Strengthened elements should be cured daily with a water for 28 days before the time of testing [41].

SRG strengthening systems

The SRG system is comprised of steel cords embedded in fresh cementitious matrix. The steps required for specimen preparation are almost the same steps for the FRCM strengthening system; the only difference is the steel fiber sheet preparation. The steel jacket preparation starts with measuring the required width and length, then cutting the steel fibers sheets, ending with bending the fiber sheets at the corner using special tool (GeoSteel bender.). As mentioned for the FRCM strengthening system, after completing the process of strengthening, the elements are wrapped in saturated cloths for 28 days to provide a hydration for the paste material [26].

Database of masonry columns confined with different strengthening systems

The database of masonry confined columns with FRP consisted of 76 experimental tests were collected from 8 different references [33-40]. All specimens are rectangular, square or octahedral in cross section shape and constructed using clay masonry unit. Different types of fibers included basalt (BFRP), carbon (CFRP), and glass (GFRP).

The database of masonry columns strengthened with FRCM consisted of 53 experimental tests from 10 different references [42-51]. All specimens are rectangular or square in cross section shape and constructed using clay masonry unit. Different types of open mesh fibers included basalt (BFRCM), carbon (CFRCM), glass (GFRCM) and PBO.

Due to limited studies on SRG confined masonry columns, the database of this part consists of 46 experimental test results from 5 different references [21,48,51-53]. All specimens are a square cross-sectional shape and constructed using brick masonry unit. The data base is available by contacting the paper authors.

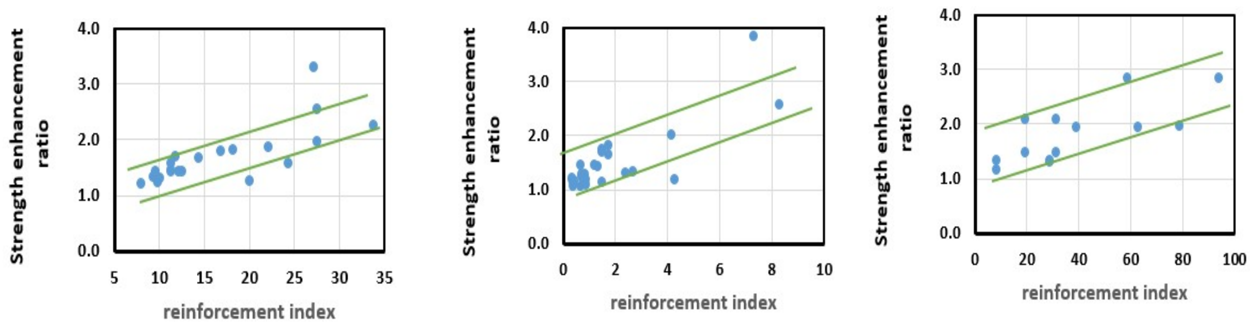
EQUIVALENT FIBER RENIFORCEMNT INDEX (EFRI)

To propose an appropriate index to capture the key factors that control the behavior of confined masonry columns, the EFRI was considered. EFRI is a factor combining the geometry, masonry, and fiber properties together as represented in Equation 1.

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

Where ρ_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. The index considers masonry compressive strength instead of masonry modulus of elasticity since the latter is directly proportional to compressive strength. Figure 3 shows the relationship between EFRI (ω_f) and the strength enhancement ratio, which represents the ratio of confined column capacity to the control (unconfined) column capacity.

All specimens strengthened with different advanced composite systems followed a similar trend in enhancing the strength capacity of different cross sectional shaped (square or rectangular) columns. In some cases, columns strengthened with FRP exhibited a better performance, but this may be within the margins of statistical error. When the specimens are strengthened with the same type of fiber and slightly different geometries, data points overlapped. 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 in this study. In terms of strength enhancement, the behavior of specimens jacketed with glass fiber was better than others since it required multiple layers to obtain the same EFRI of the specimens strengthened with a higher tensile material. Increasing the number of layers led to better performance due to a thicker jacket. 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 percent of data is very narrow and less scatter compared with other systems.



FRP system FRCM system SRG system

Figure 3: Reinforcement Index vs. Strength Enhancement Ratio Relationship

EVALUATING DIFFERENT ANALYTICAL MODELS

The results available in the collected database have been compared to confined compressive strength provisions that exist in literature. Six analytical models have been chosen (three for the FRP system and the other three for the FRCM system) for the purpose of evaluation based on the following general expression:

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

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. $\alpha, \grave{k}$ and α_1 are non-dimensional parameters that are further explained in Table 1 for each analytical model. The effective lateral confinement pressure is represented as:

$$f_{eff} = k_a f_1 \quad (3)$$

Where k_a is an efficiency factor defined as: $k_a = 1 - (\acute{b}^2 + \acute{d}^2)/3A_m$
Where (b, d, $\acute{b}$, $\acute{d}$) are defined in Figure 4, A_m is the cross-sectional area of the masonry column.

The lateral confinement pressure is defined in Eq. 4, where t_f is the thickness of the composite sheet, E_f is the stiffness of the fiber sheet, and ε_f is the strain level in the sheet.

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

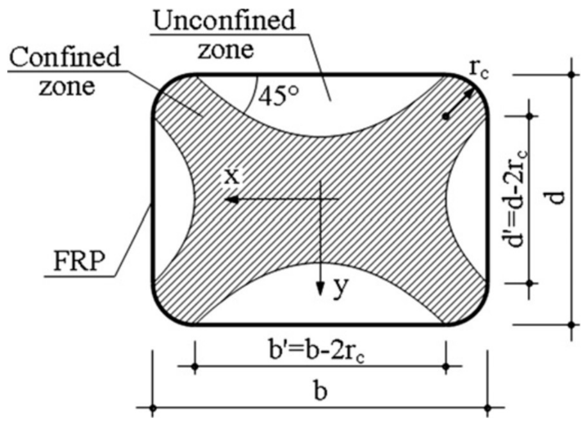


Figure 4: Confinement of Rectangular Sections Externally Wrapped with Advanced Composite [54]

Table 1- Numerical Coefficients Provided by Different Analytical Models

Theoretical formulation	α	$\acute{k}$	$\acute{a}_1$
FRP models			
CNR-DT 200-13 [59]	1	$g_m/1000$	0.5
Faella et al. [57]	1.618	$0.013(g_m/1000)^{6.324}$	1
ACI 440.7R-10 [60]	See equations from 5 to 8		
FRCM models			
CNR-DT 215-19 [61]	1	$g_m/1000$	0.5
Balsamo et al. [58]	1	$(g_m/1000)^{0.662}$	1
ACI 549.4R-20 [62]	See equations from 9 to 12		

g_m= nominal density of the masonry (kg/m^3)

Based on ACI 440.7R-10 [60] provisions, the maximum confined masonry compressive strength and the maximum confinement pressure are calculated as follow with an additional reduction factor $\psi_f = 0.95$. This factor was chosen based on the committee's judgment.

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

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

$$f_1 = \frac{2n}{\sqrt{b^2+d^2}} \; t_f E_f \varepsilon_f \quad [n = \#\, of\ plies] \tag{7}$$

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

Based on ACI 549.4R-20 [62] the maximum lateral confined concrete compressive strength, f_{mc}, and the maximum confinement pressure, f_1 is calculated as follows:

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

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

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

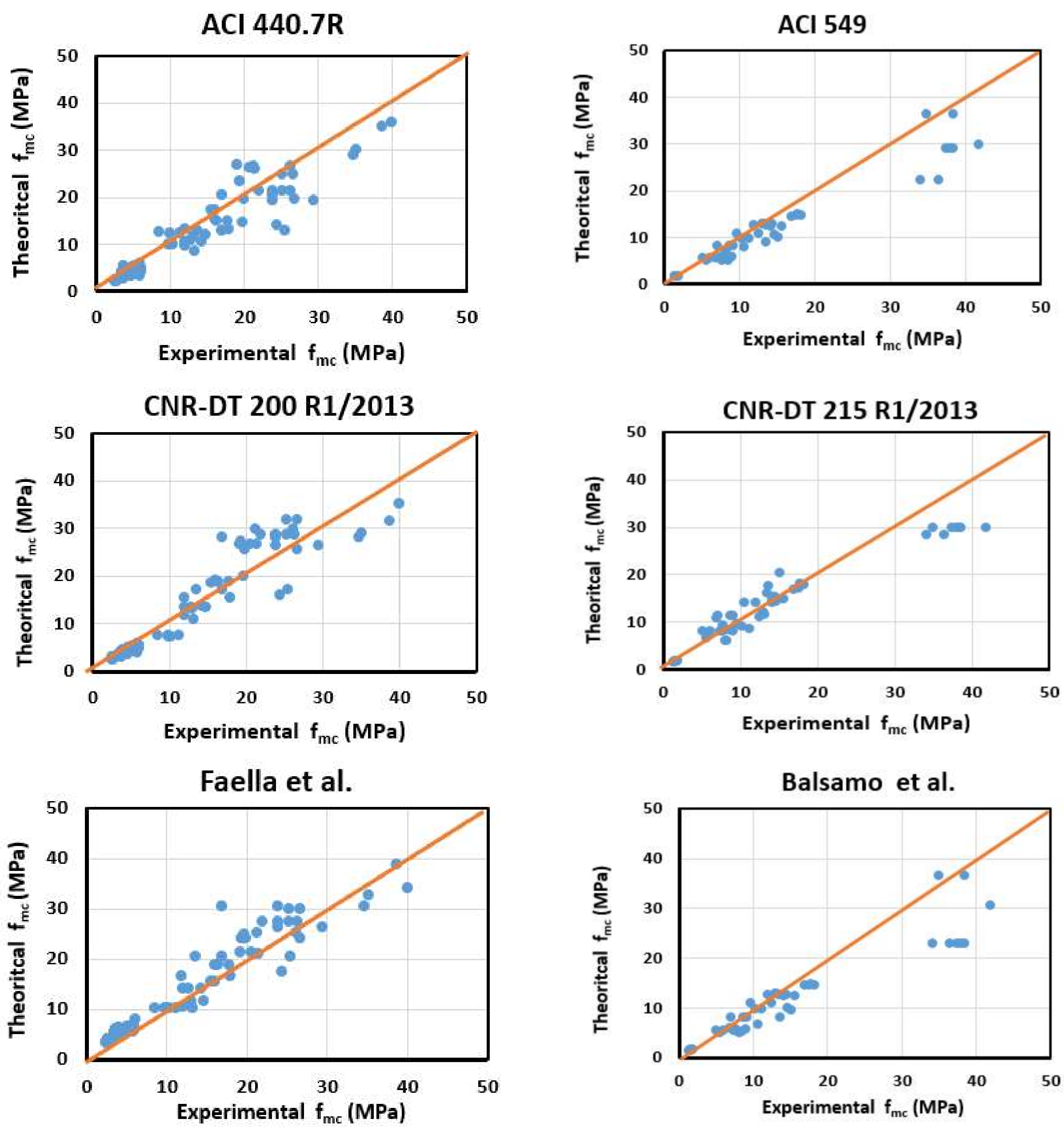
$$k_a = 1 - ((b - 2r)^2 + (d - 2r_c)^2\,)/3A_m \tag{12}$$

The applicability of these proposed models (from literature & standard codes) has to be verified across wide ranges of experimental results. For instance, the common thickness of FRP used in literature is 0.167 mm [55-56]. The comparison between the experimental and theoretical confined compressive strengths of masonry columns are shown in Figure 5. Since there is no standard code or specific proposed model for the SRG system, the confined capacity of this system has been predicted using the FRCM proposed model. 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.

Based on the distributed data in Figure 5 for the experimental results of specimens strengthened with FRP the following can be concluded: the formulation given in ACI 440 [60] and CNR-DT 200 [59] are very predictable, but ACI 440 is more conservative among the proposed models since it estimates the column confined capacity closest to the experimental results. On the other hand, the model proposed by Faella at el. [57] is very good in predicting the confinement capacity, but it overestimates the theoretical capacity compared to the experimental results for many tests in the dataset. For the models proposed to predict the capacity of columns confined with FRCM, all selected models are predictable and conservative. The ACI 549 [62] FRCM model is comparatively better than other FRCM models.

Furthermore, Figure 6 presents the comparisons of three selected models to predict the confinement capacity of masonry columns. All models presented good agreement with the experimental results, but the ACI 549 [62] and Balsamo et al. [58] were more conservative compared with the CNR- DT 215 [61].

In summary, the comparisons of various analytical models reveal that the analytical formulations given in ACI 440 [60] and ACI 549 [62] yield the lowest percentage of data scatter that falls above the theoretical-experimental line of equality. On average, these standards yield more conservative theoretical predictions along with the Balsamo et al. model and can be used to estimate the confined compressive strengths of masonry columns strengthened with FRP and FRCM or SRG respectively.



Theoretical Models for FRP Theoretical Models for FRCM

Figure 5: The Comparison Between the Experimental Results and Theoretical Models of FRP and FRCM Systems

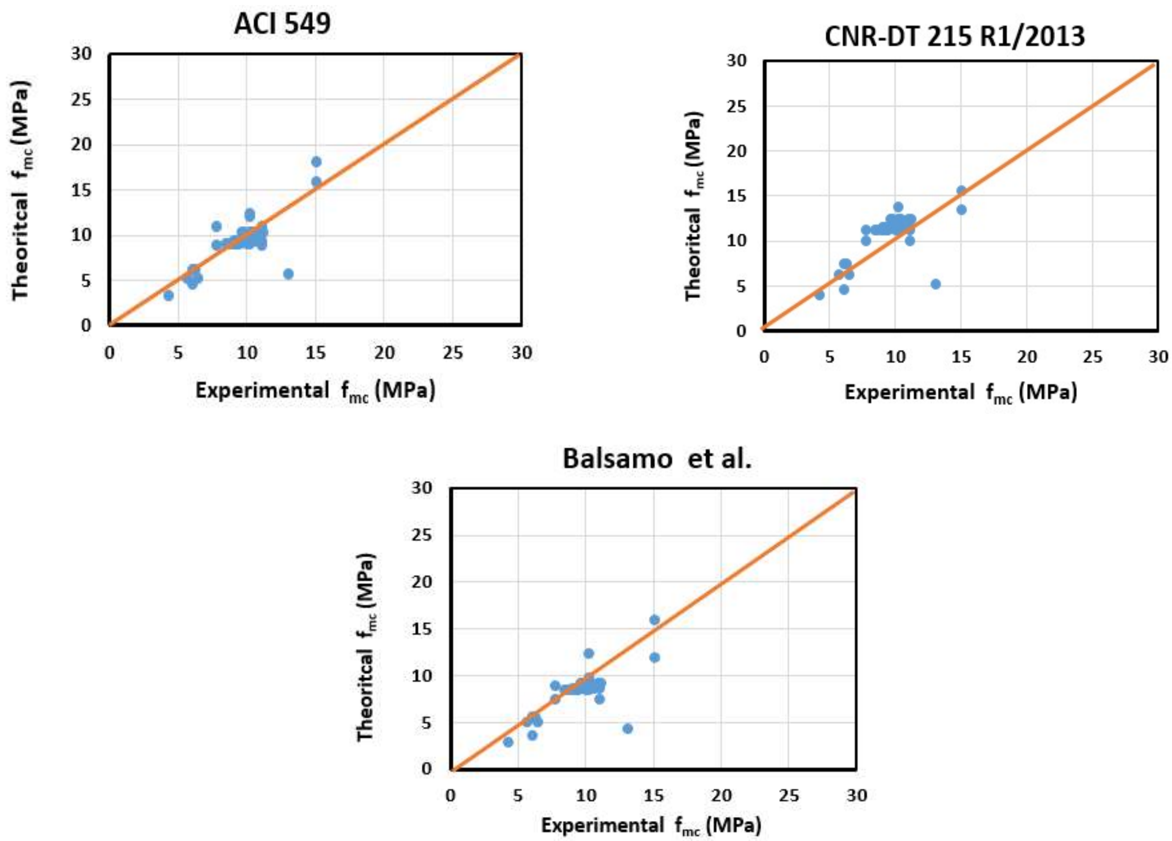


Figure 6: The Comparison Between the Experimental Results and Theoretical Models of SRG System

CONCLUSIONS

Various advanced composites have been used to improve the confinement capacity of masonry columns subjected to axial load. The strengthening techniques considered in this study are FRP, FRCM and SRG. This study presented an effort to review critically 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 or EFRI), which is used to compare different strengthening technique 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 unit or stress concentration developed at sharp corners, and local buckling of fiber sheets due to fiber excessive axial strain developed in hoop direction. Another mode of failure is the combination of fiber rupture and partial slippage of the fibers through the matrix of FRCM or SRG system. This led to slightly more gradual failure compared to other failure modes. Finally, opening of the SRG jacket is the other possible mode of failure that happened due to cracks developed on 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 current literature. Most of the selected models predict the confined capacity conservatively, despite the scatter in the experimental data. However, the models in ACI 440 and ACI 549 show very good predictions for the capacity of confined masonry columns strengthened using 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 with less scatter compared with other systems.

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