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Review

Ferrocement composites for strengthening of concrete columns: A review

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HIGHLIGHTS

- Behaviour of ferrocement jacketed concrete columns are reviewed and discussed.
- Confinement mechanism and models for ferrocement confined column are also reviewed.
- Research gaps are identified and suggestions for further development are proposed.

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ABSTRACT

The retrofitting and strengthening of concrete structures are becoming integral parts in construction and structural engineering practices owing to various situations that necessitate the enhancement in the capacity of structural members. Ferrocement composites are widely used for structural strengthening and rehabilitation in developing countries. The uniform distribution and high surface area-to-volume ratio of the reinforcement (wire mesh) of such composites improve the crack-arresting mechanism. Given these properties, ferrocement is an ideal material for repairing and strengthening old and deteriorated structures or structural members. Ferrocement composite has also been used as a jacketing material to strengthen axially loaded reinforced concrete (RC) members. Strengthening of concrete structures is an essential part of construction activities at present because these structures often suffer damage as a result of numerous environmental factors. The significance of these activities also increases with the insufficient capacity of structures that have been designed using old design codes. However, no codes have been developed for ferrocement composites as jacketing material to date. Moreover, a well-defined method for confining RC columns using ferrocement has not been established because of the lack of adequate research in this field. Thus, this study aggregates the current state of knowledge by reviewing available literature on the ferrocement jacketing of concrete columns and on ferrocement confinement effects. This study also determines research gaps in this field and suggests directions for future research to establish ferrocement composites as a feasible material for strengthening axially loaded concrete members.

Contents

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1. Introduction

The strengthening and retrofitting of reinforced concrete (RC) structures are difficult but essential construction tasks [1]. Such activities are increasingly becoming significant because of the insufficient capacity of structures that have been designed using old design codes. In addition, RC structures are often damaged by numerous factors, such as natural disasters, fire or environmental effects. As a result, structures are weakened and must therefore be either strengthened or retrofitted. Effective and constructible techniques and materials should be used to improve deteriorated or substandard structural members. Deteriorated structural members must be examined and analysed carefully to determine its in situ condition prior to strengthening work. Furthermore, strengthening measures must be determined on the basis of the in situ condition of structures.

Columns are essential structural elements designed to support the vertical loads of frame-structured buildings. These elements significantly stabilise such structures vertically and laterally, especially high-rise buildings. RC columns require sufficient lateral confinement to sustain axial loads effectively. This confinement is facilitated by lateral ties in the form of individual rings or continuous spirals that run from the top to the bottom of the columns [2]. Lateral confinement is also necessary to enable large deformation during loading. In the case of a seismic event, a sufficiently confined concrete core can dissipate increased amounts of energy. Thus, the capacity of this core increases when subjected to such dynamic loading events. On the contrary, a poorly confined concrete column is brittle. As a result, a structure may fail suddenly and catastrophically [3]. Tsai and Lin [4] reported that the inadequate axial load capacity and axial ductility of columns are the fundamental factors that are responsible for the collapse of many RC buildings during the 1999 Chi-Chi Taiwan earthquake. Therefore, sufficient lateral confinement must be provided to existing RC columns. Furthermore, existing substandard or deteriorated columns should be retrofitted or strengthened through external confinement to increase ductility and load-carrying capacity.

Various materials and methods have been studied for strengthening substandard or deteriorated RC columns. Ferrocement is a long-established and promising material for use in strengthening concrete structural elements given its inherent toughness and crack-resistant capacity [5]. Nonetheless, research on ferrocement as a confinement material for column-like elements has been limited by the availability and evolution of fiber-reinforced polymer (FRP) composites. In the past two decades, considerable research has been conducted on FRP as a strengthening material for RC columns owing to the various advantages associated with this composite. However, FRP is a costly composite material and is occasionally unavailable in many developing countries given that it must be installed through highly skilled labour. FRP is also challenging to install in hot and humid weather and requires special measures. These disadvantages render FRP unsuitable for use in strengthening deteriorated or substandard structures in developing countries.

By contrast, ferrocement is a cost-effective technology in developing countries given that its raw materials are easily available. Moreover, this material need not be installed though highly skilled labour. Nonetheless, extensive research must be conducted on ferrocement to propose an efficient strengthening technology using this material. The present state of knowledge in this area must also be determined. Although the corrosion susceptibility of ferrocement is a topic of discussion for many years, this material is less vulnerable to corrosion compared with normal concrete as a result of the rich mix mortar that is encapsulated in the wire mesh. Nedwell et al. [6] stated that small-diameter steel wire mesh suffers reduced rate of corrosion and increased passivation whereas large-diameter steel bar shows increased corrosion and reduced passivation. Mansur et al. [7] suggested utilising silica fume in the mortar mix to eliminate the possibility of wire mesh corrosion in ferrocement. Therefore, ferrocement can be utilised to strengthen concrete structures in normal and marine environments, where corrosion susceptibility is particularly high. Several recent studies, which address the effects of concrete strength and the lap splice length of longitudinal reinforcements on the confinement behaviour of ferrocement-confined columns, have been conducted in this area. Researchers have also studied the behaviour of cracked or pre-loaded, square and rectangular ferrocement-confined RC columns. The current study presents a review based on findings regarding the ferrocement confinement of plain and RC concrete column-like elements. This review aims to determine the current state of knowledge in this area and to identify the areas where incurrent knowledge is lacking. This review also detects aspects of the subject that require future research to enhance the feasibility of ferrocement composites as a strengthening material.

2. Ferrocement technology and its advantages

Ferrocement is a composite construction material that consists of closely spaced single or multiple layers of steel mesh with or without skeletal steel support. This material is either completely infiltrated by or is encapsulated in mortar [8]. Naaman [9] defined ferrocement as RC in the guise of high-performing, thin elements with reference to the resistance of ferrocement to elongation, ductility and impact load. This composite material is sometimes referred to as thin-shell concrete.

Ferrocement was introduced as a construction material in 1848 by Frenchman Joseph Louis Lambot, who constructed a ferrocement boat. Although this composite material was created in Europe, it was enhanced further in developing countries owing to its low material cost and labour-intensive construction procedure [10]. No formwork is required for ferrocement construction, and it can be constructed as an extremely thin wall [11]. The tools required for manufacturing ferrocement are also particularly simple. Utilising this material in construction is advantageous because of its various improved engineering properties, such as high tensile and in-plain shear strength, toughness, ductility, crack bridging capability and fatigue and impact resistance [12,13]. This material also exhibits unique fire- and corrosion-resistant properties [8,14,15]. The advantages of using ferrocement as a strengthening material are discussed briefly in the subsequent section.

2.1. Advantages of ferrocement as a confinement material over FRP and steel

Ferrocement has several advantages over novel FRP laminates or conventional steel jackets as an ideal material for confining axially loaded structural members:

1. Ferrocement may be a cost-competitive solution for infrastructure rehabilitation in developing countries given that steel and FRP are low cost [11,16].
2. The use of ferrocement requires minimal skilled labour. This simple requirement there by enhances the cost-effectiveness of this material over FRP jacketing, which needs highly skilled labour.
3. No particular measures must be taken to ensure the bond between ferrocement and the underlying substrate (concrete or masonry). Thus, this process is advantageous over FRP, steel jacketing and plating.
4. Ferrocement displays significantly higher in-plain shear strength capacity than that of FRP sheets [17].
5. Ferrocement exhibits a considerably higher moment capacity than that of FRP sheets [18,19].
6. The ductility of ferrocement-jacketed columns is higher than that of FRP-confined columns under axial compression [20].
7. The shear strength capacity of ferrocement-confined RC columns that are subjected to cyclic loading is higher than that of FRP- or steel-confined RC columns [21,22].
8. Trapko [23] mentioned the sensitivity of FRP materials at high temperatures and the vapour permeability of the epoxy resin used to glue the FRP to concrete substrate. Trapko [24] also noted that this epoxy resin degrades at temperatures of approximately 30 °C. Therefore, the state of strain cannot be reliably estimated in a structural member. Similar problems are not encountered when ferrocement is used.

3. Ferrocement composites for column strengthening

Ferrocement is a popular material used in strengthening and repairing works in developing countries. Most studies on ferrocement-confined concrete columns have been conducted by researchers from similar countries. The following subsections discuss the available literature on this topic. In addition, the research on ferrocement-confined concrete columns is briefly summarised in Table 1 to quickly clarify these studies.

3.1. Ferrocement confinement for plain concrete

The confinement behaviour of ferrocement was firstly investigated by Sandowich and Grabowski [25,26]. They tested circular composite columns made of ferrocement pipes that were filled with concrete under axial and eccentric loading. Firstly, they casted ferrocement pipes with different layers of wire mesh (zero, three, five and seven layers) and then filled these pipes with normal concrete. The results showed that a brittle failure mode is found in specimens without wire mesh whereas ductile failures are observed in specimens with wire mesh. The measured ultimate loads are close to the sum of the individual failure loads of the core concrete and ferrocement pipes that are tested separately [25,26]. However, Kumar et al. [5] mentioned that the potential of ferrocement for confining plain concrete is difficult to maximise through this casting method because of the significant differential shrinkage between the core concrete and the precast ferrocement pipe or mould.

Balaguru [27] tested wire-mesh composite and plain concrete cylinders under axial compressive loading. He placed the wire mesh on the inner circumference of the cylindrical mould and then poured the concrete into this mould. He did not incorporate additional mortar for the ferrocement; the mortar from the plain concrete penetrated through the mesh and formed an outer ferrocement layer. His test variables were the strength of concrete (normal to medium strength) and the volume fraction of wire meshes. According to the results, the strength and ductility of the confined concrete are enhanced; however, the ductility is improved compared with the compressive strength. Subsequently, this researcher proposed a correlation for predicting the strength of wire-mesh composite plain concrete on the basis of experimental results [28]. The proposed correlation is discussed further in Section 4.1.

Singh and Kaushik [29] studied the effectiveness of ferrocement confinement in repairing concrete columns. These researchers tested 200 circular and square short concrete columns under axial compression after confining them in external ferrocement jackets. Singh and Kaushik studied the effects of wire mesh layers and the strength of core concrete. The results showed that the jacketed specimens display enhanced strength and ductility. Vertical cracks are observed in the ferrocement jackets at 80–90% of the ultimate load on these specimens. The yielding of the horizontal mesh wires is observed as well. On the basis of the failure mode of ferrocement jackets, the researchers concluded that the concrete cores are subjected to radial compression in the horizontal direction where as the ferrocement jackets are subjected to hoop tension because of axial compression [29].

Walliudin and Raffeeqi [30] focused on the order of casting of ferrocement confined concrete. The studied methods of confinement were as follows: (i) mesh layers cast integrally, (ii) mesh layers in a precast shell and (iii) wrapped mesh layers on a precast core. There searchers also studied the variations in concrete strength and in the number of wire mesh layers. The test results suggested that confinement effect depends on the method of confinement and the optimum number of wire mesh layers. Specifically, the findings indicated that 100% confinement is found for integrally cast core concrete and ferrocement jackets, 88% confinement for ferrocement jackets that are later wrapped around the surface of the precast concrete and 83% confinement for core concrete casts into the precast ferrocement jacket. Walliudin and Raffeeqi [30] also proposed a theoretical design equation for predicting ferrocement-confined concrete. This equation is discussed further in Section 4.1.

Ramesh [31] studied the confinement behaviour of ferrocement in confining steel fiber-reinforced concrete. According to the results, ultimate strength is approximately 10% higher and ultimate strain is 200% higher in this material than in similar ferrocement-confined normal core concrete. This study highlights the significance of ductile confinement for ductile core concrete [31].

Memon et al. [32,33] investigated the behaviour of ferrocement-aerated concrete sandwich blocks. These researchers confined the aerated concrete with ferrocement jackets containing up to four layers of wire mesh and tested the concrete under compressive loading. Two types of wire mesh were used: chicken mesh and square mesh. The aim of this study was to produce lightweight load-bearing blocks of aerated concrete encased in ferrocement. The results showed that the compressive strength of aerated concrete blocks improves significantly without increasing weight considerably. This enhancement in strength is higher for square

Table 1
Summary of research on ferrocement confined concrete column.

Studies	Cross-section of specimen	Type of core column	Type of wire mesh	Variables studied	Type of ferrocement jacket	Type of Experiment
Ferrocement confined plain concrete						
Sandowich and Grabowski [25,26]	Cylindrical	Unreinforced low strength concrete	Woven square mesh	Number of wire mesh layer	Precast ferrocement pipe	Concentric and eccentric loading
Balaguru [27,28]	Cylindrical	Unreinforced normal to medium strength	Woven square mesh	Concrete strength and number of wire mesh layer	Integrally cast circular ferrocement jacket	Concentric loading
Singh and Kaushik [29]	Cylindrical & Square	Unreinforced medium strength concrete	Woven square mesh	Concrete strength and number of wire mesh layer	Post-cast circular/ square ferrocement jacket	Concentric loading
Walliudin and Raffeeqi [30]	Cylindrical	Unreinforced medium strength concrete	Woven square mesh	Concrete strength, methods of confinement and number of wire mesh layer	Precast, integrally cast and post-cast circular ferrocement jacket	Concentric loading
Ramesh [31]	Square	Steel fiber reinforced concrete	Woven square mesh	Concrete strength and number of wire mesh layer	Post-cast square ferrocement jacket	Concentric loading
Memon [32,33]	Square	Unreinforced lightweight aerated concrete	Welded square mesh & chicken mesh	Number of wire mesh layer and type of wire mesh	Post-cast square ferrocement jacket	Concentric and flexural loading
Mourad [34]	Cylindrical	Unreinforced medium strength concrete	Welded square mesh	Number of wire mesh layer and methods of mesh attachment	Post-cast circular ferrocement jacket	Concentric loading
Kondraivendhan and Pradhan [35]	Cylindrical	Unreinforced normal to medium strength	Chicken mesh	Concrete strength	Post-cast circular ferrocement jacket	Concentric loading
Xiong et al. [20]	Cylindrical	Unreinforced medium strength concrete	Welded square mesh	Confining systems (ferrocement & FRP)	Post-cast circular ferrocement jacket	Concentric loading
Shinde and Bhusari [36]	Cylindrical	Unreinforced medium strength concrete	Welded square mesh	Number of wire mesh layer and orientation of wire mesh	Post-cast circular ferrocement jacket	Concentric loading
Shannag and Mourad [37]	Cylindrical	Unreinforced medium strength concrete	Welded square mesh	Number of wire mesh layer	Post-cast circular ferrocement	Concentric loading
Kaish et al. [38]	Cylindrical	Unreinforced low strength concrete	Welded square mesh	Height of the core specimens	Post-cast circular ferrocement	Concentric loading
Kaish et al. [62]	Cylindrical	Unreinforced low strength concrete	Welded square mesh	Number of wire mesh layer and Height of the core specimens	Post-cast circular ferrocement	Concentric loading
Ferrocement confined RC column						
Razvi and Saatcioglu [39]	Square	Reinforced medium strength concrete	Welded square mesh	Various combinations of tie bars and wire mesh	Integrally cast square ferrocement jacket	Concentric loading
Mansur and Paramasivam [40]	Square	Unreinforced medium strength concrete	Woven and welded square mesh	Number of wire mesh layer, arrangements of wire mesh and type of wire mesh	Precast and integrally cast square ferrocement jacket	Concentric and eccentric loading
Ganesan and Anil [41]	Square	Reinforced low strength concrete	Woven square mesh	Number of wire mesh layer and volumetric ratio of tie bar	Precast square ferrocement jacket	Concentric loading
Seshu and Rao [42]	Square	Reinforced low to medium strength concrete	Woven square mesh	Concrete strength and Specific Surface Factor (determined by number of wire mesh layer)	Integrally cast square ferrocement jacket	Concentric loading
Kaushik and Singh [44]	Circular	Reinforced low strength concrete	Woven square mesh	Number of wire mesh layer and different combinations of longitudinal and lateral reinforcements	Integrally cast circular ferrocement jacket	Concentric loading
Kumar [43]	Square	Reinforced high strength concrete	Woven square mesh	Concrete strength, specific surface factor and confinement index	Integrally cast square ferrocement jacket	Concentric loading
Hadi and Zhao [45,46]	Circular	Reinforced high strength concrete	Fiber glass fly mesh and welded square mesh	Type of mesh (fiber glass fly mesh and wire mesh) and loading condition	Post-cast circular ferrocement jacket	Concentric, eccentric and flexural loading
Mourad and Shannag [48]	Square	Reinforced low strength concrete	Welded square mesh	Preloading up to various fractions (0%, 60%, 80%, and 100%) of ultimate load	Post-cast square ferrocement jacket	Concentric loading
Kaish et. al. [49,50]	Square	Reinforced low strength concrete	Woven square mesh	Type of ferrocement jacketing	Post-cast square ferrocement jacket	Concentric and eccentric loading
Yaqub et al. [15]	Square and circular	Reinforced high strength concrete (pre- & post-heated)	Welded square mesh	Type of jacket (ferrocement & FRP)	Post-cast circular ferrocement jacket	Concentric loading
Ho et al. [52]	Circular	Reinforced medium to high strength concrete	Welded square mesh	Number of wire mesh layer, strength of concrete, strength of rendering material and volumetric ratio of tie bar	Post-cast circular high-performance ferrocement jacket	Concentric loading

(*continued on next page*)

Table 1 (*continued*)

Studies	Cross-section of specimen	Type of core column	Type of wire mesh	Variables studied	Type of ferrocement jacket	Type of Experiment
Ferrocement confinement for shear strengthening of RC column						
Takiguchi and Abdullah [21]	Square	Reinforced medium strength concrete	Woven square mesh	Type of jacket (ferrocement, steel and FRP)	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Takiguchi and Abdullah [22]	Square	Reinforced medium strength concrete	Woven square mesh	Type and thickness of jacket (ferrocement, steel and FRP)	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Takiguchi and Abdullah [53]	Square	Reinforced medium strength concrete	Woven square mesh	Number of wire mesh layer, type of column (original or pre-loaded)	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Takiguchi and Abdullah [54]	Square	Reinforced medium strength concrete	Woven square mesh	Number of wire mesh layer	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Abdullah and Takiguchi [55]	Square	Reinforced medium strength concrete	Woven square mesh	Number of wire mesh layer, variation in constant axial load	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Kumar et al. [5]	Square	Reinforced low strength concrete	Woven square mesh	Number of wire mesh layer	Post-cast square ferrocement jacket	Lateral cyclic loading + constant axial load
Kazemi and Morshed [57]	Square	Reinforced low strength concrete	Expanded steel mesh	Number of wire mesh layer and volumetric ratio of tie bar	Post-cast square ferrocement jacket	Lateral cyclic loading + constant axial load
Choi [58]	Circular	Reinforced low strength concrete	Welded square stainless steel wire mesh	Retrofit height using ferrocement	Post-cast circular ferrocement jacket	Lateral cyclic loading + constant axial load
Kim and Choi [59]	Circular	Reinforced low strength concrete	Welded square stainless steel wire mesh	Lap splice length of longitudinal bar and retrofit height using ferrocement	Post-cast circular ferrocement jacket	Lateral cyclic loading

mesh-confined specimens (46%) than for chicken mesh-encased specimens (18%). In addition, ferrocement encasement modifies the failure mode of aerated concrete blocks from brittle to ductile [32,33].

Mourad [34] investigated the behaviour of plain concrete that was confined externally with welded wire mesh (WWM). The test specimens were prepared by warping wire mesh around precast core concrete and then plastering the concrete with non-shrinkage rich mortar mix. This researcher studied the effect of different methods of wire mesh attachment around concrete specimens. The investigated methods were as follows: attachment using high-strength epoxy glue and attachment using screws and fasteners. Apart from the number of mesh layers, the methods of wire mesh attachment, surface bond and the shear interaction between the concrete cylinder and the mortar layer are the factors that also enhance the axial load-carrying capacity of specimens. Furthermore, the attachment of wire mesh with fasteners reduces load-carrying capacity, possibly by limiting the capacity of core concrete. Ferrocement jackets with eight layers of wire mesh can increase the strength of concrete cylinder by approximately 50% of the strength gained from one layer of carbon FRP sheet [34].

Kondraivendhan and Pradhan [35] studied the behaviour of ferrocement-confined cylindrical concrete specimens with varying compressive strengths. According to the results, the diameter and height of these specimens' are 150 and 900 mm, respectively. Initial cracking load is low (15% of ultimate load) for low-grade concrete (25 MPa); by contrast, this cracking load is high (30.5% of ultimate load) for high-grade concrete (55 MPa). The increment in ultimate load is higher in low-grade concrete (78%) than in high-grade concrete. Regardless of concrete grade, vertical cracks form in all of the specimens because of hoop tension. As a result, the transverse wires yield [35].

Xiong et al. [20] studied the strength and ductility of plain concrete that was encased in ferrocement, including skeletal steel bars (FS) under uni-axial compression. These researchers also investigated three different confining systems, namely, a skeletal steel bar mat-mortar (BM), FS and FRP. The results showed that compressive strength is 30% higher in FS-confined columns than in BM-confined columns. Moreover, the increment in the ductility of FS-confined columns is double than that of BM-confined columns. Crack patterns indicate that the crack spacing in FS-confined specimens is equal to the spacing of wires in the wire mesh. Therefore, more cracks are observed in FS-confined specimens than in BM- and FRP-confined specimens. Thus, the FS-confined specimens exhibit more ductility than that of BM- and FRP-confined specimens [20].

Recently, Shinde and Bhusari [36] examined the confinement behaviour of ferrocement-encased, cylindrical concrete specimens that were120 mm in diameter and 600 mm in height. The effect of wire mesh layer and its orientation was considered. According to the results, the enhancement in strength of double-layered specimens is nearly double that of single-layer specimens. The strength of confined concrete also increases with the change in mesh orientation from 90° to 45°. The effect of this orientation is more dominant in single-layer wire mesh (36% higher) than in double-layer wire mesh [36].

Alternatively, Shannag and Mourad [37] developed a high-strength cementitious matrix for producing ferrocement laminates. These researchers applied various combinations of silica fume and fly ash to develop high-strength mortar matrices with compressive strengths in the range of 48–64 MPa. The authors also examined the performance of the mortar matrix by casting ferrocement jackets for standard cylindrical concrete specimens. These jackets were then tested under uni-axial compression. The ferrocement jackets were developed with either two or four layers of WWMs. The results showed that specimens jacketed with two layers of WWM ferrocement jackets exhibit approximately 16% increase in axial load capacity, roughly 32% increase in axial strain and 30% increase in lateral displacement. By contrast, the percentage increases for the specimens jacketed with four layers of WWM ferrocement jacket are29% in axial stress, 70% in axial strain and approximately 163% in lateral displacement [37]. The crack pattern is shown in Fig. 1.

Kaish et al. [38] investigated the effect of specimen size on the behaviour of ferrocement-confined cylindrical concrete. The researchers tested concrete cylinders of three different diameters, namely, 150, 100 and 75 mm. A constant aspect ratio was maintained. Each type of cylinder was confined by a single-layer WWM ferrocement jacket and tested under concentric loading. The results showed that the addition of the ferrocement layer contributes to enhancing the strength and deflection capabilities of concrete cylinders. Moreover, confinement action is effective in small specimens; the enhancement in ultimate load is 18% higher in such specimens than in unconfined ones [38].

The discussion above suggests that the number of literature on the behaviour of ferrocement-confined plain concrete is limited. The first part of Table 1 summarises experiments undertaken on ferrocement-confined plain concrete. In addition, a significant research gap exists particularly in the period of 1994–2004, during which no study was reported on this topic. Even after 2004, research on this topic is scarce. Thus, a considerable research gap exists with regard to the theoretical knowledge on the confinement behaviour of ferrocement. These research gaps are discussed in detail in Section 5. The following section provides an in-depth review of the application of ferrocement in the confinement of RC columns.

3.2. Ferrocement confinement for RC columns

Nearly all vertical concrete members (such as columns and shear walls) are internally reinforced by steel bars. Selected techniques have been utilised to repair and strengthen deteriorated or damaged concrete columns and thus enhance their load-carrying, ductility and durability characteristics. Many studies have also focused on the behaviour of RC columns confined by ferrocement jackets, as detailed in the following paragraphs.

Razvi and Saatcioglu [39] examined the confinement behaviour of rectangular RC columns that were cast monolithically with welded wire fabric (WWF). The researchers tested 34 scaled-down columns with various combinations of tie bars and WWF as lateral reinforcement. The authors also generated four different WWF arrangements: (i) WWF placed in between the longitudinal and tie bars, (ii) WWF placed in a circular manner inside the core, (iii) WWF placed into the core in a triangular manner and (iv) WWF wrapped around the longitudinal bars without tie reinforcement. According to the results, the strength and ductility of RC columns improve significantly when WWF is used as a confining reinforcement in combination with lateral ties. Specifically, a maximum of 40% increase in column strength is recorded. The authors concluded that WWF cannot facilitate sufficient confinement in RC columns without lateral ties; however, this fabric is beneficial if placed either in the core or in between longitudinal and lateral reinforcements [39].

Fig. 1. Crack pattern of specimens [37].

Mansur and Paramasivam [40] experimented on ferrocement short columns under concentric and eccentric loadings. In particular, these researchers investigated the behaviour of box-section, short ferrocement columns with and without concrete infill. Other studied parameters included the type of wire mesh (woven and welded), wire mesh arrangements and the volume fraction of wire mesh. Specifically, two types of wire mesh arrangements were tested: (a) an arrangement in which wire mesh is uniformly distributed throughout the cross-section and (b) an arrangement in which mesh layers are folded to form a closed cage. The mesh arrangements are shown in Fig. 2. The results showed that welded mesh enhances the strength and ductility of the columns, and the concrete-filled ferrocement box section that is reinforced with a closed mesh cage can be used as a structural column [40].

Ganesan and Anil [41] studied the behaviour of short square RC columns confined in prefabricated ferrocement casings. The researchers firstly casted the ferrocement casing and then used this precast casing as a formwork for casting the RC columns. The studied parameters included lateral reinforcement ratio (0.3, 0.6, 0.9 and 1.8) and the volume fraction of wire mesh (1.2, 1.8 and 2.4). According to the results, the strength, strain at peak strength and energy absorption capacity of RC columns can be enhanced by confinement using a ferrocement jacket. Strength and strain at peak strength are maximised at high lateral reinforcement ratios and volume fractions of wire mesh. Strength is also enhanced by 56% [41].

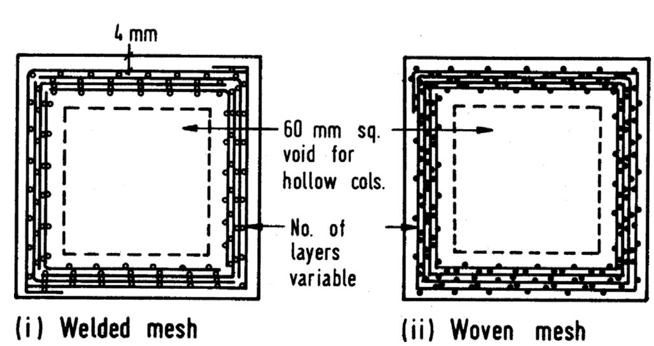

Fig. 2. Arrangements of wire mesh [40].

At the same time, Seshu and Rao [42] investigated the behaviour of ferrocement-confined square RC columns under concentric loading. These researchers casted the ferrocement jacket monolithically, whereas the columns were casted and the wire mesh layers were wrapped over the tie bars. The main variable studied was "specific surface factor" (SSF), which controls the behaviour of ferrocement. SSF is the product of the yield stress of mesh wires in the loading direction and of specific surface ratio (SSR) divided by the compressive strength of the mortar. SSR is the ratio of the total contact surface area of wires present per unit length of the specimen in the loading direction for a given width and thickness of the ferrocement shell to mortar volume. Columns with two different grades of concrete (M15 and M20) were tested. According to the results, additional ferrocement confinement improves ultimate strength, strain at ultimate strength and ductility of columns. This improvement is proportional to that of the SSF of ferrocement. The influence of SSF is greater on strain than on strength. For a given SSF (SSF = 10), the increment in strain at maximum stress is nearly 1.8 times the increment in strength. Moreover, the increase in strain at 85% of maximum stress is approximately 2.8 times the increase in the strength of the ferrocement-confined RC specimens [42].

Kumar [43] extended the work of Seshu and Rao [42] by investigating the behaviour of high-strength concrete (HSC) columns encased in ferrocement jackets [42,43]. All investigated parameters and followed casting procedures were similar to those in the study conducted by Seshu and Rao [42]; the only difference was that Kumar studied medium-strength concrete to HSC columns (M40 and M50). The test variables were SSF and confinement index. The test results indicated that high SSF means low rate of decrease in load beyond the post peak. The peak load in ferrocement-confined plain concrete prisms is observed to be lower than that observed in cases of corresponding tie-confined specimens for specimens with low SSF. In addition, Kumar [43] observed a decreasing post-peak branch in the stress-strain curves for all types of ferrocement confined specimens. Theoretical equations were also proposed for load carrying capacity and strain at the ultimate strength of ferrocement confined, HSC columns. These equations are discussed in Section 4.2 [43].

On the contrary, Kaushik and Singh [44] investigated the behaviour of ferrocement composite circular columns subjected to concentric loading. The variables tested were the number of mesh layers (1–3) and different combinations of longitudinal and lateral reinforcements. The authors also verified theoretical formulas for ferrocement-confined RC columns. The results showed that the strength of ferrocement composite columns increases with the number of wire meshes used. However, the researchers also reported that at least two layers of wire meshes are required to enhance strength substantially because a single-layer wire mesh does not improve the strength significantly. Furthermore, column failure is increasingly ductile with the increase in mesh layers. The experimental and analytical results accord with each other [44]. The theoretical formulas proposed by the authors are discussed in Section 4.2.

Hadi and Zhao [45,46] examined the effect of mesh confinement in reducing the cover spalling of reinforced HSC columns. The researchers presented a new concept of confining HSC columns using relatively low-cost materials. The confinement meshes were placed into the moulds before casting; this process represents a slight deviation by this confining system from conventional external confinement. According to the results, wire mesh confinement significantly increases the load-carrying capacity of the tested column under concentric and eccentric loads. Moreover, the researchers observed 13% and 31% increases in the ultimate loads of columns tested under concentric and 50 mm of eccentric loading, respectively. The ductility of such columns increases slightly under eccentric loading. The ductility of the wire mesh-confined column decreases slightly under concentric loading [45,46].

Fig. 3. Failure mode of the repaired columns [47].

Mourad and Shannag [47] studied the behaviour of square RC columns repaired with ferrocement jackets. The researchers firstly preloaded the columns with various fractions (0%, 60%, 80% and 100%) of its ultimate load. Then, the authors repaired the columns with ferrocement jackets containing two WWM layers. They observed 28% and 15% increases in the load-carrying capacities of columns that are preloaded to maximum values of 60% and 80% of ultimate capacity, respectively. The load-carrying capacity of non-preloaded columns is increased by 33%. The load-carrying capacity and stiffness of completely damaged columns can also be restored to nearly the original values of control columns prior to failure. Furthermore, the load-displacement response of damaged columns repaired using ferrocement nearly matches that of the control columns. The failure mode of the repaired columns is ductile in nature; however, the ductility of the damaged columns that are repaired is low [47]. The failure pattern is shown in Fig. 3.

Subsequently, Mourad and Shannag [48] investigated the behaviour of rectangular RC columns that were strengthened and repaired using ferrocement laminates. The researchers preloaded, repaired and tested the columns as in their previous study [47]. The authors observed an increase of 25% in the strength of the strengthened column. Such increments are 20% and 15% in the cases of repaired columns that are preloaded to maximum values of 60% and 80% of ultimate capacity, respectively. The load-displacement response and the failure modes of damaged rectangular columns that are repaired using ferrocement are similar to those of square columns. The failure mode of jacketed specimens is ductile, whereas the non-jacketed specimens fail under a sudden brittle mode [48].

Conventional square ferrocement jacketing (square jacketing with single or multiple layers of wire mesh) cannot facilitate uniform lateral confinement in the process of re-strengthening square

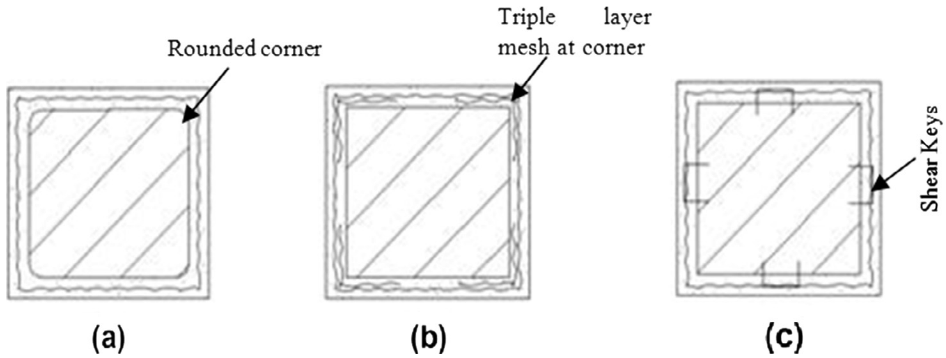

Fig. 4. Improved square ferrocement jacketing techniques (a) RSL, (b) SLTL, and (c) SKSL [49].

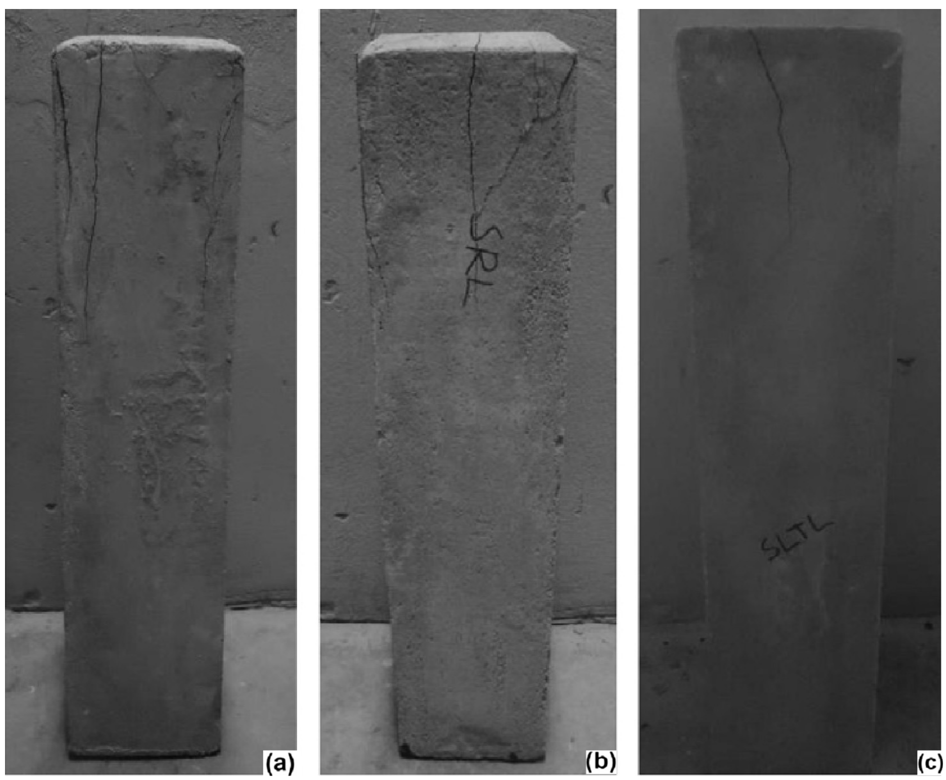

Fig. 5. Crack pattern of improved square ferrocement jacketed columns (a) SKSL, (b) RSL, and (c) SLTL [49].

RC columns owing to the concentration of stress on the corners of the column. Kaish et al. [49–51] proposed a number of improved square ferrocement jacketing techniques to strengthen square RC columns. The proposed techniques were square jacketing with a single layer of wire mesh and rounded column corners (RSL), square jacketing with a single layer of wire mesh and two extra layers of mesh at each corner (SLTL) and square jacketing using a single layer of wire mesh with shear keys at the centre of each column face (SKSL). These techniques are depicted in Fig. 4. The specimens were tested under concentric and eccentric loading modes. Moreover, two types of tie-bar arrangements were tested, namely, uniformly spaced ties and seismically detailed ties. Amongst the three techniques, the results showed that SLTL displays the best load-carrying and deflection capabilities under concentric load. However, RSL performs best under eccentric loading. Overall, all the enhanced techniques effectively overcome the drawbacks of conventional square ferrocement jacketing techniques [49–51]. The crack pattern of improved ferrocement jacketed RC columns is shown in Fig. 5.

Yaqub et al. [15] experimented on post-heated square and circular RC columns repaired with ferrocement and FRP jackets. The researchers used one layer of either glass FRP or carbon FRP sheets in FRP-strengthened, post-heated columns and four layers of wire meshes for ferrocement-confined, post-heated columns. FRP confinement improves the strength of post-heated RC columns but does not increase stiffness. By contrast, the strength and stiffness of the post-heated columns increase with ferrocement confinement. Ferrocement-jacketed, post-heated columns exhibit load-carrying capacities that are nearly equal to those of non-heated circular column specimens. However, the load-carrying capacity of square columns is 22% lower than that of non-heated columns because the stress concentration at the corners of the square jacket induces subsequent corner cracking. Crack patterns for circular columns are shown in Fig. 6. The researchers recommended that FRP

Fig. 6. Crack pattern of ferrocement jacketed circular columns [15].

and ferrocement jackets be combined to restore the strength and stiffness of fire-damaged concrete [15].

Ho et al. [52] investigated the behaviour of high-performance ferrocement (HPF)-confined circular plain and RC columns under monotonic axial load. The researchers constructed HPF-confined RC columns by replacing the concrete cover of an unconfined column with HPF. Three different types of high-performance mortar mixes were examined as confining material for ferrocement with one or three layers of wire mesh. According to the results, confinement action increases with the increase in the tensile strength of HPF mortar. Furthermore, the peak strength of HPF-confined plain concrete columns increases between 30% and 50% in unconfined specimens. HPF-confined RC columns with a volumetric ratio of transverse reinforcement (ρ_s) of 0.230% achieve a peak strength that is comparable to that of unconfined columns with a ρ_s of 0.918% [52]. On the basis of the experimental results, the researchers proposed a set of empirical formulas to predict the strength of HPF-confined RC columns. These formulas are discussed in Section 4.2.

The studies discussed above are briefly summarised in the middle part of Table 1. According to the table and the discussion above, nearly all the researchers have used square woven or WWM in their studies. Moreover, they have not examined all of the variables that may influence the confinement behaviour of ferrocement-retrofitted RC columns. The other shortcomings of these studies are discussed in Section 5. Reviews of research on the shear strengthening of RC columns using ferrocement jackets are presented in the following section.

3.3. Ferrocement confinement for the shear strengthening of RC columns

RC columns are subject to lateral cyclic force during seismic events and lateral shear force during cyclones or tornados. Therefore, columns with insufficient shear capacity must be retrofitted to enhance their shear strength. The following discussion summarises the studies on the seismic behaviour of ferrocement-strengthened RC columns.

In 2000, Takiguchi and Abdullah [21] studied the strengthening of seismically deficient RC columns through ferrocement jacketing. These researchers strengthened square RC columns using circular-type ferrocement jackets and compared the outcomes with those obtained from similar circular RC columns jacketed with FRP. The researchers modified the shape of the square RC columns by circularising and then confining these columns with either circular ferrocement jackets or FRP jackets. All the specimens were tested simultaneously under constant axial load and cyclic lateral load. The dimensions of the columns were as follows: 600 mm long with a cross-section of 120 mm × 120 mm. The diameter of the circular jacket was 200 mm. The thicknesses of the ferrocement and FRP jackets were 15 and 0.2 mm, respectively. The hollow portion in the jacket was filled with medium-strength mortar (30 MPa) in all cases. The results showed that the maximum shear and drift capacity of the ferrocement-jacketed columns are higher than those of FRP-jacketed columns. The same result is found for energy absorption capacity. Maximum shear strength increases by 12% in the circular FRP-jacketed, square RC column and by 28% in the circular, ferrocement-jacketed column [21].

Takiguchi and Abdullah [22] compared the findings in their previous study with those obtained with circular, steel-jacketed, square RC columns of similar dimensions in a subsequent investigation. The researchers modified the shape of the square RC columns by circularising the columns before confining them in steel jackets. All specimen specifications were similar to those in the previous study, with the exception of the thickness of the steel jacket at 0.8 mm. According to the results, the performance of the circular, steel-jacketed, square RC column is not as high as that of either circular FRP- or ferrocement-jacketed columns. In fact, the maximum shear strength of circular, steel-jacketed RC columns increases by only 6%. This value is significantly lower than those generated with either circular FRP or ferrocement jacketing [22].

Takiguchi and Abdullah [53] also studied the behaviour of RC columns that were tested until the point of failure and repaired using a circular-type ferrocement jacket. The results were compared with those obtained using as built-ferrocement-jacketed and non-jacketed RC columns. The proposed circular-type ferrocement jacketing effectively repairs damaged or cracked RC columns. In particular, circular ferrocement jackets with six layers of wire mesh can be used to repair damaged RC columns that experienced shear failure at its full shear carrying capacity [53].

Subsequently, Takiguchi and Abdullah [54] analysed the behaviour of shear-deficient, square RC columns using circular-type ferrocement jackets with different numbers of wire mesh layers. Specifically, the researchers incorporated two, three, four and six layers of wire mesh into external ferrocement jackets. The stiffness, ductility and strength of square RC columns improve significantly when strengthened with circular ferrocement jacketing. The ductility of the columns also improves significantly even with only three layers of wire mesh in the external jacket. RC columns strengthened with a ferrocement jacket containing four layers of wire mesh effectively enhance the seismic capacity of shear-deficient columns. The researchers also proposed a design method to improve the shear strength of shear-deficient square RC columns with circular ferrocement jacketing. The jacket presumably operates in a series of independent spiral reinforcements [54].

Subsequently, Abdullah and Takiguchi [55] tested shear-deficient, square RC columns with different ferrocement jacketing schemes, namely, circular and square jacketing, to study the effect of different ferrocement jacket shapes. In particular, the researchers investigated circular-jacketed columns under cyclic lateral loads with different axial loads (48, 68 and 88 kN) simultaneously after strengthening with six layers of wire mesh. The authors also tested circular ferrocement-jacketed columns that were strengthened with a small number of wire mesh layers (three layers) at the centre to study the shear capacity of a jacket in the plastic hinge regions. Square-jacketed columns were tested under cyclic lateral loads and constant axial load (68 kN) after strengthening with four and six layers of wire mesh. The results showed that the flexural capacity of circular-jacketed columns is approximately 18% higher when the columns are tested under high axial loads than when the columns are tested under low axial loads. Columns strengthened with few wire mesh layers at the centre exhibit an extremely stable and ductile response of up to a drift ratio of roughly10%. Jackets fail at a drift ratio of approximately18% in this case. By contrast, columns strengthened with full-height wire mesh remain intact even at a drift ratio of approximately 20%. Column specimens strengthened with square jackets experience early strength degradation especially when lateral displacement is significant. Columns strengthened with square jackets containing four and six layers of wire mesh display high ductility and stable responses. The strengthened columns exhibit excellent ductility regardless of the type and characteristics of the ferrocement jackets used, as per the experimental findings. On the basis of the experimental results and on the shear design equation proposed previously for circular ferrocement jackets [55], the authors presented another shear design equation for square ferrocement jackets (discussed in Section 4.3). Crack patterns of some of the specimens are provided in Fig. 7.

Kumar et al. [56] studied the effectiveness of ferrocement jacketing in the seismic retrofitting of square RC bridge piers. The researchers tested three scaled models under simulated seismic loading and constant axial force. The piers in the models were cast together with the foundations. In this study, the parameter for comparison was the variation in the number of wire mesh layers. The researchers strengthened the square piers with square ferrocement jackets containing either four or six layers of wire mesh. The experimental results suggested that the strengthened columns exhibit increased strength, stiffness, energy dissipation and ductility and ductile flexure failure instead of brittle shear failure. Shear strength is enhanced by 30–50% in ferrocement-strengthened piers. The researchers also proposed a shear design equation to strengthen shear-critical, square RC columns in terms of the number of the wire mesh layers (as discussed in Section 6.3.). Kumar et al. [56] also conducted a three-dimensional finite element (FE) analysis of ferrocement-jacketed piers by including the foundation within the elastic range and by applying the MARC 2001 FE code. The researchers analysed the columns on the basis of deflection and stress alone, and their results agree with the experimental values of deflections and stresses on the top, bottom and mid-height of the columns [56].

Kazemi and Morshed [57] studied the behaviour of shear-deficient, square RC columns after strengthening with ferrocement jackets containing an expanded steel mesh. The variables studied were the spacing of tie bars and the mesh layers in the ferrocement

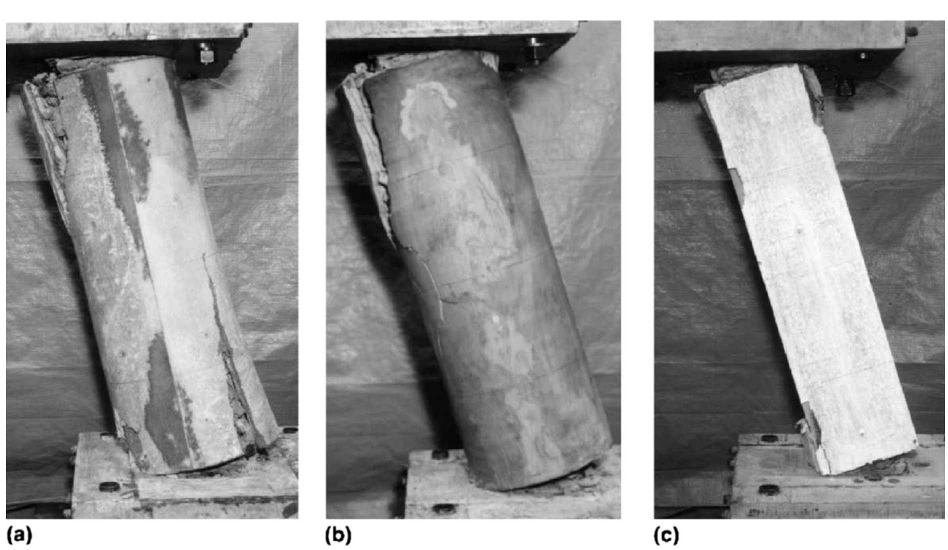

Fig. 7. Crack pattern (a) circular jacket (6 layer mesh), (b) circular jacket (3 layer mesh), (c) square jacket (6 layer mesh) [55].

jacket. The researchers tested the columns under constant axial force and lateral cyclic load. Although one layer of mesh can enhance the shear strength and ductility capacity of columns, two layers of mesh are required to achieve the expected enhancement in shear strength and ductility capacity. In addition, ferrocement jacketing can reduce shear cracking even at significant displacement [57].

At the same time, Choi [58] studied the seismic performance of circular RC columns retrofitted with stainless steel wire mesh (SSWM) composites. These composites consisted of permeable polymer concrete mortar that was reinforced with SSWM, which is a material similar to ferrocement. He retrofitted the circular columns (1:5 scale in typical 2.0 m-diameter columns) with a lap splice length of 20 d_b (d_b is the longitudinal bar diameter) [58]. Columns were jacketed using the SSWM composite at various retrofit heights in the potential plastic hinge (PPH) region. These regions were tested simultaneously under simulated cyclic load and constant axial load. Furthermore, the retrofit heights were 384, 512 and 640 mm. According to the results, columns retrofitted with SSWM composite only in the PPH zone exhibit a stable hysteresis response with increased capacity and ductility. The displacement ductility of retrofitted columns increases with retrofit height at a fixed lap splice length. Choi [58] concluded that retrofitting with SSWM composites in the PPH region can significantly improve the flexural strength and ductility of circular RC columns.

Kim and Choi [59] investigated the behaviour of earthquake-damaged, circular RC columns repaired with SSWM composite. The researchers tested three as-built circular columns (1:5 scale in typical 2.0 m- diameter columns) with three different lap splice lengths (15, 20 and 30 d_b) under reversed cyclic loading until the point of failure. Then, the authors repaired the tested columns with SSWM composite in the PPH region at three different retrofit heights (384, 512 and 640 mm). The results showed that the repaired columns exhibit a low rate of stiffness degradation and are stiffer than the original column at high displacement ductility. Shear capacity, displacement ductility and energy dissipation capacity improve significantly, thereby enhancing the seismic performance of SSWM-repaired circular RC columns [59].

Findings regarding the seismic strengthening of RC columns are summarised in the last part of Table 1. Although studies have investigated the shear strengthening of RC columns using ferrocement, most of these works have covered only the strengthening of square RC columns. Investigations on circular RC columns are scarce, and the seismic behaviour of ferrocement-confined rectangular RC columns has not been analysed thus far. Other research gaps are highlighted in Section 5.

4. Analytical models for ferrocement confined columns

Existing analytical models for confined columns can be categorised into two types: design-and analysis-oriented models [60,61]. Design-oriented models are empirical in nature and are developed by fitting experimental data. This type of model is usually uncomplicated in form and can be applied directly in design following systematic verification and validation. On the contrary, analysis-oriented models are developed using the numerical analysis approach. This type of model is generally sophisticated but is sometimes complicated and challenging to implement in practice. Therefore, all existing confinement models for ferrocement-confined columns are design oriented. To the best knowledge of the authors, no analysis-oriented confinement model has been developed for ferrocement-confined RC or plain concrete columns. The following sections discuss the analytical models that have been developed by various researchers to model the axial and shear strengths of plain and RC columns.

4.1. Confinement models for ferrocement confined plain concrete columns

At present, only three confinement models are established to predict the strength of ferrocement-confined plain concrete columns. Balaguru [28] was the first to propose a confinement model for wire mesh composite plain concrete cylinders as follows:

$$p = \frac{2R}{d}, \tag{1}$$

where d is the diameter of the cylinder; p denotes the confining pressure in the preceding equation; R is the ring pressure, which can be computed using the following equation:

$$R = \frac{P}{l}, \tag{2}$$

where l is the height of the cylinder and P is the force exerted by the transverse wires. P is computed by

$$P = A_s f_y, \tag{3}$$

where A_s is the cross-sectional area of all the wires lain across the height of the cylinder and f_y is the yield strength of the wires.

Subsequently, Walliudin and Raffeeqi [30] proposed another confinement model as follows on the basis of their test results for 144 standard cylinders:

$$\mathrm{f_{cf}} = \mathrm{f}_{cu} + K f_y \tag{4}$$

where

$$K = K_m K_g K_r, \tag{5}$$

where K_m is the coefficient for the method of confinement. Coefficient values are 1.00, 0.88 and 0.83 for integrally cast mesh layers, wrapped wire mesh layers impregnated with mortar and previously cast shells with mesh layers, respectively. K_g is the coefficient for concrete grade with a value of 1.0 for normal concrete. K_r is the coefficient for the number of wire mesh layers and is equal to 35 V_f-K_r, where K_r is the ratio of the cross-sectional and surface areas of the shell.

Xiong et al. [20] proposed a strength prediction model as follows for plain concrete confined by ferrocement, including skeletal steel bars:

$$P_u^c = f_{cc} A_{core} = f_c (1 + 1.98\lambda_t) A_{core}, \tag{6}$$

where f_{cc} is the compressive strength of confined concrete, A_{core} is the area of the core concrete based on the diameter of the column before strengthening) and f_c is the compressive strength of unconfined concrete. The confinement ratio λ_t is defined by the following equation:

$$\lambda_t = \frac{\mu_s f_y + \mu_w f_{yw}}{f_c}, \tag{7}$$

where μ_s is the reinforcement ratio generated by transverse and longitudinal steel bars; f_y and f_{yw} are the yield stresses of steel bars and wires, respectively; μ_w is the reinforcement ratio generated by transverse and longitudinal mesh wires.

Kaish et al. [62] proposed a simple strength model for ferrocement confined plain concrete under axial load. The proposed model can be used for specimens with different sizes. The model is of the following form:

$$\frac{\mathrm{f_{cc}}}{\mathrm{f_{cu}}} = 1 + 11.2\ \mathrm{K_1} \frac{\mathrm{f_{yw}}}{\mathrm{f_{cu}}} \tag{8}$$

where f_{cc}, f_{cu} and f_{yw} are the strength of confined concrete, strength of unconfined concrete and the yield stresses of steel wire, respectively. K_1 is a constant, and its value can be obtained using the following equation:

$$\mathrm{K_1} = \frac{2\mathrm{NA_w}\ (\mathrm{H_j} + \mathrm{b_w})}{(\mathrm{D_c H_j b_w})} \tag{9}$$

where N is the number of mesh layer, A_w is the cross-sectional area of individual wire, b_w is the opening of wire mesh, H_j is the height of ferrocement jacket and D_c is the diameter of core concrete.

Rafeeqi and Ayub [10] conducted a comparative study to identify a suitable strength prediction model for plain concrete columns confined with ferrocement. The researchers reviewed all the experimental results and compared them with the findings obtained with existing prediction models. The authors concluded that the model proposed by Walliudin and Raffeeqi [30] can predict ultimate strength accurately [10]. However, Rafeeqi and Ayub did not consider the model proposed by Xiong et al. [20] because the model has not yet been developed at the time of the study. However, Kondraivendhan and Pradhan [35] reported that the model presented by Walliudin and Raffeeqi [30] overestimates the strength of medium- to high-strength ferrocement-confined concrete by approximately 11–13%. This finding clearly indicates that a strength model that is more refined than that developed by Walliudin and Raffeeqi must be established to predict the strength of ferrocement-confined concrete accurately.

4.2. Confinement models for ferrocement-confined RC columns

Five confinement models have been proposed in literature to compute the strength of ferrocement-jacketed RC columns. Amongst these models, three were developed for square RC columns, and the remaining two were established for circular RC columns. Ganesan and Anil [41] were the first researchers to propose an empirical equation for predicting the strength of square RC columns that were encased in prefabricated ferrocement. This equation is expressed as follows:

$$\frac{P}{\sigma_{cu} bd} = 0.0654 V_f \rho_s + 0.6366, \tag{10}$$

where P is the ultimate load that can be applied to the column, σ_{cu} is the strength of the concrete cube, b and d are the lateral column dimensions, V_f is the volume fraction of the wire mesh and ρ_s is the volumetric ratio between transverse reinforcement and core concrete.

At the same time, Seshu and Rao [42] proposed a model for predicting the load-carrying capacity and strain at ultimate strength of monolithically cast, ferrocement-confined square RC columns. The proposed equations are as follows:

For load carrying capacity,

$$P = f'_c\ (1.0 + 0.55\ C_i)(0.912 + 0.055\ S_f)A_g + f_y A_s \tag{11}$$

For strain at ultimate strength,

$$\varepsilon_{cf} = \varepsilon'_c\ (1.0 + 5.2\ C_i)(0.90 + 0.178\ S_f) \tag{12}$$

In these equations, f'_c is the strength of unconfined concrete, C_i is the confinement index, S_f is the SSF, A_g is the gross area of concrete, f_y is the yield strength of the longitudinal tie/mesh steel, A_s is the cross-sectional area of longitudinal steel, ε_{cf} is the strain at the ultimate strength of confined concrete and ε'_c is the strain at the ultimate strength of unconfined concrete.

Kumar [43] extended the work of Seshu and Rao [42] and proposed similar equations for predicting strength and strain for HSC columns confined with ferrocement jackets at ultimate strength. The equations developed by Kumar [42] are as follows:

For load carrying capacity,

$$P = f'_c(1.607\ C_i^{0.107})(0.824 + 0.0146\ S_f)A_g + f_y A_s \tag{13}$$

For strain at ultimate strength,

$$\varepsilon_{cf} = \varepsilon'_c(5.139 C_i^{0.286})(1.023 + 0.107 S_f) \tag{14}$$

All the symbols represent the same parameters as in the study conducted by Seshu and Rao [42].

Kaushik and Singh [44] proposed analytical models for calculating the strength and strain of circular RC columns jacketed with ferrocement at peak strength. The formulas proposed by these researchers are as follows:

For the strength of confined columns,

$$\sigma_c = \sigma_o + K_1 \sigma_L. \tag{15}$$

For the strain at peak strength,

$$\varepsilon_c = \varepsilon_o + K_2 \frac{\sigma_L}{\sigma_O}. \tag{16}$$

σ_c and σ_o are the strengths of confined and unconfined concrete, respectively; σ_L is the lateral confining pressure; ε_c and ε_o are the strains of confined and unconfined concrete at peak strength, respectively; K_1 is the strength increase factor with a value of 4.2; K_2 is the strain increase factor with a value of 18.

Ho et al. [52] proposed a set of empirical formulas for predicting the strength of HPF-confined RC columns. The equations are as follows:

For the peak load of HPF-confined RC columns,

$$P = K(P^R + P^F) + A_{st} f_y \tag{17}$$

where P^R, P^F and $(A_{st}f_y)$ are the contributions of RC columns, HPF and longitudinal reinforcements, respectively; K is a coefficient and a function of f_l^R and f_l^F; f_l^R and f_l^F are the lateral confining pressures generated by transverse reinforcement and HPF, respectively.

$$P^R = f'_{co} A_{core} \left[1 - 0.357 \left(\frac{S}{d_s} \right)^{0.48} + 847.385 \left(\frac{f_l^R}{f'_{co}} \right)^{5.377} + 1.349 \left(\frac{f_l^R}{f'_{co}} \right)^{0.405} \right]. \tag{18}$$

$$f_l^R = 0.5 \rho_s f_{yh}. \tag{19}$$

$$P^F = f'_{co} K_1 A_{core}. \tag{20}$$

$$K_1 = 0.064 \left(\frac{f_l^F}{f'_{co}} \right)^{-0.551} + 26.92 \left(\frac{f_l^F}{f'_{co}} \right). \tag{21}$$

$$f_l^F = \frac{2T}{d_{ext}}, \tag{22}$$

where d_{ext} is the diameter of the concrete core measured at the centre line of HPF.

$$T = f_R A_R + f_R A_W \left(\frac{E_W}{E_R} \right) \tag{23a}$$

or

$$T = f_w A_W \tag{23b}$$

Eq. (23a) focuses on HPF, and Eq. (23b) is developed for normal ferrocement, where the tensile strength of mortar can be neglected.

$$K_1 = 1 - 0.513 \left(\frac{f_l^R}{f_l^F} \right)^{-0.551}. \tag{24}$$

Existing models for predicting the strength and strain of square and circular RC columns confined with ferrocement jacket at ultimate strength are proposed mainly on the basis of experimental findings obtained by the same researchers. None of the models are verified experimentally by other researchers. Moreover, some of the models are extremely complicated for practical use in design. No analytical model has been established for rectangular RC columns. The model proposed by Ganesan and Anil [41] can predict the strength of ferrocement-confined rectangular RC columns. However, this model has not been verified through experimental study. Furthermore, a model has not been developed for predicting the stress–strain behaviour of ferrocement-confined RC columns. Therefore, a practical model must be developed to predict the strength and stress-strain behaviour of ferrocement-confined RC columns in addition to extensive experimentation.

4.3. Shear strength models for ferrocement confined RC columns

Ferrocement exhibits high plain shear strength [19]; thus, the material enhances seismic performance when used to confine RC columns. Several models have been proposed for the shear strengthening of RC columns. For example, Takiguchi and Abdullah [54] proposed a shear design equation for square RC columns confined with circular ferrocement jackets. The proposed shear design equation is expressed as follows:

$$V_j = \frac{0.125 n \pi^2 d_w^2 f_{yj} D'}{g_w}. \tag{25a}$$

Alternatively, the number of wire mesh layers required to strengthen a shear-deficient, square RC column is given by the following equation [54]:

$$n = \frac{0.81 g_w V_j}{d_w^2 f_{yj} D'}, \tag{25b}$$

where V_j is the nominal shear strength generated by the ferrocement jacket, d_w is the diameter of the wire mesh, f_{yj} is the allowable stress in the wire mesh, n is the number of wire mesh layers, D' is the core diameter of the strengthening jacket and g_w is the spacing of mesh wires.

Abdullah and Takiguchi presented a model modified from their previous model for shear-deficient, square RC columns confined with square ferrocement jackets [55]. The equation is written as follows:

$$n = \frac{0.78 g_w V_j}{d_w^2 f_{yj} D'}. \tag{26}$$

At the same time, Kumar et al. proposed another shear strength model for square RC columns that were confined with square ferrocement jacket on the basis of their experimental findings [56]. In this model, the number of wire mesh layers required to determine the nominal shear strength generated by ferrocement is determined using the following equation:

$$n = \frac{0.637 g_w V_j}{f_{yj} d_w^2 h}, \tag{27}$$

where h is the overall dimension of the column that is parallel to the applied shear force. All other notations are similar in definition to those reported by Takiguchi and Abdullah [54], as is the proposed correlation. Nonetheless, the value of the correlation increases by 22%.

Kazemi and Morshed proposed the following equation for predicting the shear strength of square ferrocement-jacketed square RC columns [57].

$$V_n = V_{no} + V_{sf} \tag{28}$$

$$V_{sf} = 2\eta \eta V_f t_f \alpha_f f_{yf} \tag{29}$$

where V_n is the nominal shear strength of jacketed column, V_{no} is the nominal shear strength of core RC column, V_{sf} is the nominal shear strength provided by ferrocement jacket, η is the global efficiency factor for ferrocement reinforcement (0.65 for the long diagonal direction of expanded mesh), V_f is the volume fraction of wire mesh, t_f is the thickness of ferrocement jacket, α_f is the distance between the load point and the edge of jacket (a gap distance that is less than that of shear span) and f_{yf} is the yield strength of wire mesh.

All the models presented in this paper for the shear strengthening of RC columns focus only on square columns. None of these models can be applied to predict the strength of either circular or rectangular RC columns confined with ferrocement. Moreover, none of these models have been verified by other researchers through experiment.

5. Research gaps

Much research focuses on FRP-confined plain or RC columns. Various parameters of FRP confinement have been investigated experimentally and numerically. However, a limited number of studies report on the confining effects of concrete columns with ferrocement. Thus, a wide research gap exists in the field of ferrocement confinement for plain or RC columns. Selected research gaps are discussed in this section.

i. Numerical analysis is an important structural engineering tool for analysing complex structures and for parametric study. Many studies conduct FE analyses on FRP-confined plain or RC columns [63,64]. On the contrary, information on the FE analysis of ferrocement-confined plain or RC columns is limited. Kumar et al. performed FE analyses using the MARC FE code to analyse only deflection and stress under static load (experimental maximum load) [55]. Thus, the findings of this study cannot be used as a reference for further parametric study.
ii. External jackets cannot facilitate full confinement given sharp-cornered square or rectangular columns. Nonetheless, the effect of corner sharpness on the behaviour of ferrocement-confined columns has not been reported in current literature.
iii. Information on the behaviour of ferrocement-confined rectangular RC columns is limited in published literature. The aspect ratio of the cross-section is an important parameter that influences the behaviour of rectangular columns. However, no study has observed the effect of this parameter on ferrocement-confined rectangular RC columns.
iv. The confining pressure on square or rectangular specimens influences only the corners of the external jacket; the middle zone of each face is not subject to this pressure. Thus, the corners of such columns experience stress concentration and subsequent cracking. This problem has not yet been addressed comprehensively. Kaish et al. [49–51] conducted a preliminary investigation into this problem and proposed improved ferrocement jacketing techniques for strengthening square RC columns; however, an in-depth study must be conducted to establish a feasible approach that overcomes this limitation.
v. Lap splice length is an important parameter that influences the behaviour of RC columns subjected to seismic loading. However, this parameter has been studied only in the context of circular columns confined with ferrocement jackets.

vi. The slenderness ratio of RC columns influences the overall behaviour of confined columns as well. However, the effect of the slenderness of RC columns on the confinement behaviour of ferrocement has not yet been investigated.
vii. Theoretical stress-strain models are necessary to predict the pre- and post-peak behaviour of ferrocement-confined columns regardless of column shape. However, theoretical stress-strain model has not been proposed for ferrocement-confined plain or RC columns in previously published studies.
viii. Theoretical models have been developed to predict the load-carrying capacity and strain of ferrocement-confined plain or RC columns at ultimate strength. However, these models are applicable only to either circular or square specimens. A unified model has not been proposed for such columns. In addition, no strength model has been presented in existing literature for ferrocement-confined, rectangular plain or RC columns.
ix. Moreover, analysis-oriented theoretical models have not been generated to accurately predict the behaviour of ferrocement-confined plain and RC columns.
x. No shear strength model has been developed for ferrocement-jacketed circular and rectangular RC columns subjected to seismic loading. Moreover, shear-deficient circular RC columns jacketed with ferrocement composites and tested under simulated cyclic loading are rarely studied. Existing studies on this topic cover only ferrocement jacketing at the plastic hinge region.
xi. Yaqub et al. suggested that a combination of FRP and ferrocement jackets can enhance the strength and stiffness of fire-damaged RC columns [15]. However, no study has investigated the combined use of FRP and ferrocement.
xii. Full-scale laboratory testing of ferrocement jacketed RC column is extremely important before implementing it practically. However, no previous researchers have performed full scale testing on ferrocement jacketed RC columns because of the limitation on laboratory test facilities, especially due to the requirement of high capacity compressive testing machine.

6. Recommendations for future study

On the basis of the research gap in the field of ferrocement confinement, the authors suggest the following recommendations for further study:

i. A comprehensive FE analysis of ferrocement-confined plain or RC columns should be conducted for using as a benchmark in modelling ferrocement-confined columns under complex types of loading and in modelling structural frames composed of ferrocement-confined columns.
ii. The effects of aspect ratio and corner sharpness on the behaviour of ferrocement confined square or rectangular column must be investigated in detail.
iii. Different types of the improved ferrocement jacketing techniques were proposed by Kaish et al. [49–51]. All the variations of these improved ferrocement jacketing techniques must be studied to establish a suitable method for confining square or rectangular columns. The feasibility of these improved techniques for strengthening RC columns subjected to lateral cyclic loading must also be investigated further.
iv. The effect of lap splice length on ferrocement-confined square and rectangular columns under seismic loading must be explored in detail.
v. Slenderness ratio of RC column also needs to be examined for all types of columns (circular, square and rectangular).
vi. A straightforward, design-oriented stress-strain model needs to be established for direct application in strengthening design.
vii. A unified strength model must be developed to predict the strength of a ferrocement-confined specimen regardless of the cross-sectional shape. Some of the proposed models are complex in terms of formation and application. Although these models are design oriented, they are infeasible for direct use in design because of the complexity of theoretical calculations.
viii. Circular and rectangular RC columns subjected to seismic loading needs to be studied whilst their full length is confined with ferrocement. Shear strength model for such columns must also be developed for design purposes.
ix. Analysis-oriented stress-strain must be developed for all types of columns to predict the stress-strain behaviour accurately.
x. Shear strength models for ferrocement-jacketed circular and rectangular RC columns subjected to seismic loading must be developed.
xi. The combination of FRP and ferrocement jackets can be studied in terms of their capability to strengthen RC columns to optimise the contributions of both materials.
xii. Full-scale laboratory testing on ferrocement jacketed RC columns (for all cross-sectional shapes) is required to understand the exact confining mechanism of externally applied ferrocement jacket.

7. Concluding remarks

The application of an effective and long-lasting strengthening technique can significantly increase the service life of concrete structures and thus reduce maintenance requirements. All the studies discussed in the current paper suggest that ferrocement jacketing effectively enhances the load-carrying and ductility capacities of RC columns. Although ferrocement is a labour-intensive technology, it can be converted into labour-saving technology through modern mechanised pre-fabrication technology and the use of bolted connections to join precast units. Using high-performance mortar and high-strength reinforcing wire mesh can enhance the performance of ferrocement as strengthening material. The high in-plane shear strength and other improved engineering properties of ferrocement render it as an ideal, low-cost technology that is preferable over FRP or steel jacketing in strengthening RC columns, especially when increased shear strength is required. However, the theoretical and scientific background for the practical application of ferrocement must be enhanced through further extensive research. In addition, a practical guideline must be developed in relation to the use of this material to assist practicing engineers in structural strengthening.

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References

[1] M. Kaminski, T. Trapko, Experimental behaviour of reinforced concrete column models strengthened by CFRP materials, J. Civil. Eng. Manage. 12 (2) (2006) 109–115.

[2] A. Rajasekaran, P.N. Raghunath, K. Suguna, Effect of confinement on the axial performance of fibre reinforced polymer wrapped RC column, Am. J. Eng. Appl. Sci. 1 (2) (2008) 110–117.
[3] Parretti R. Nanni A. Axial testing of concrete columns confined with carbon FRP: effect of fiber orientation 2002;,<http://www.quakewrap.com/frp%20papers/Axial-Testing-Of-Concrete-Columns-Confined-With-Carbon-Frp-Effect-Of-Fiber-Orientation.pdf>.
[4] K.C. Tsai, M.L. Lin, Seismic jacketing of RC columns for enhanced axial load carrying performance, J. Chinese Inst. Eng. 25 (4) (2002) 389–402.
[5] P.R. Kumar, T. Oshima, S. Mikami, Ferrocement confinement of plain and reinforced concrete, Prog. Struct. Eng. Mater. 6 (2004) 241–251.
[6] P.J. Nedwell, O.O. Damola, N. Stevens, Corrosion in Ferrocemen, 11th International Symposium on Ferrocement and Textile Reinforced Concrete, Germany, June, Aachen, 2015, pp. 267–273.
[7] M.A. Mansur, M. Maalej, M. Ismail, Study on corrosion durability of ferrocement, ACI Mater. J. 105 (1) (2008) 28–34.
[8] ACI 549.1R-93. Guide for design, construction & repair of ferrocement. Michigan (USA): ACI, 1993.
[9] A.E. Naaman, Prospect in ferrocement materials, applications and technology, J. Ferrocem. 15 (2) (1985) 165–167.
[10] S.F.A. Rafeeqi, T. Ayub, Investigation of versatility of theoretical prediction models for plain concrete confined with ferrocement, Asian J. Civil Eng. (Build. Housing) 12 (3) (2011) 337–352.
[11] J.P. Romualdi, Ferrocement for infrastructure rehabilitation. Concrete International 1987 (September): pp. 24–28.
[12] R. Kumar, C.B.K. Rao, Constitutive behavior of high-performance ferrocement under axial compression, Mag. Concr. Res. 58 (10) (2006) 647–656.
[13] R.B. Williamson, F.L. Fisher, Fire resistance of a load bearing ferrocement wall. Report no. UCBFRG-83-1, Department of Civil Engineering, University of California, Berkeley, USA, 1983.
[14] V. Greepala, P. Nimityongskul, Structural integrity of ferrocement panels exposed to fire, Cem. Concr. Compos. 30 (5) (2008) 419–430.
[15] M. Yaqub, C.G. Bailey, P. Nedwell, Q.U.Z. Khan, I. Javed, Strength and stiffness of post-heated columns repaired with ferrocement and fibre reinforced polymer jackets, Compos.: Part B: Eng. 44 (2013) 200–211.
[16] J.P. Hartog, Understanding Ferrocement, Volunteers in Technical Assistance (VITA), Arlington, Virginia, USA, 1988.
[17] H.M.H. Ibrahim, Shear capacity of ferrocement plates in flexure, EngStruct 33 (2011) 1680–1686.
[18] M.A. Mashrei, N. Abdulrazzaq, T.Y. Abdalla, M.S. Rahman, Neural networks model and adaptive neuro-fuzzy inference system for predicting the moment capacity of ferrocement members, Eng. Struct. 32 (2010) 1723–1734.
[19] A.H. Gandomi, D.A. Roke, K. Sett, Genetic programming for moment capacity modeling of ferrocement members, Eng. Struct. 57 (2013) 169–176.
[20] G.J. Xiong, X.Y. Wu, F.F. Li, Z. Yan, Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars, Constr. Build. Mater. 25 (5) (2011) 2263–2268.
[21] K. Takiguchi, Abdullah, Experimental investigation on ferrocement as an alternative material to strengthen reinforced concrete column, J. Ferrocem. 30 (2) (2000) 177–190.
[22] K. Takiguchi, Abdullah, Experimental Study on Reinforced Concrete Column Strengthened with Ferrocement Jacket, 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 2000.
[23] T. Trapko, Behaviour of fibre reinforced cementitious matrix strengthened concrete columns under eccentric compression loading, Mater. Design 54 (2014) 947–954.
[24] T. Trapko, Fibre Reinforced Cementitious Matrix confined concrete elements, Mater. Design 44 (2013) 382–391.
[25] M. Sandowich, J. Grabowski, The Properties of Composite Columns Made of Ferrocement Pipes Filled with Concrete Tested in Axial and Eccentric Compression, International Symposium on Ferrocement, Bergamo, Italy, 1981, pp. 1/93–1/99.
[26] M. Sandowich, J. Grabowski, The properties of composite columns made of ferrocement pipes filled with concrete tested in axial and eccentric compression, J. Ferrocem. 13 (4) (1983) 319–326.
[27] P. Balaguru, Use of ferrocement for confinement of concrete, Proceedings of the third International Conference on Ferrocement, Roorkee (India), 1988, pp. 296–305.
[28] P. Balaguru, Use of ferrocement for confinement of concrete, J. Ferrocem. 19 (1989) 135–140.
[29] K.K. Singh, S.K. Kaushik, Ferrocement composite columns, Proceedings of the third International Conference on Ferrocement, Roorkee (India), 1988, pp. 216–225.
[30] A.M. Walliuidin, S.F.A. Rafeeqi, Study of behaviour of plain concrete confined with ferrocement, J. Ferrocem. 24 (2) (1994) 139–145.
[31] K. Ramesh, Confined ferro fiber concrete. Proceedings of the National Conference on Materials and Structures (MAST), Department of Civil Engineering, National Institute of Technology, India, 2004.
[32] N.A. Memon, S.R. Sumadi, M. Ramli, Strength and behaviour of lightweight ferrocement-aerated concrete sandwich blocks, Malaysian J. Civil Eng. 18 (2) (2006) 99–108.
[33] N.A. Memon, S.R. Sumadi, M. Ramli, Ferrocement encased lightweight aerated concrete: a novel approach to produce sandwich composite, Mater. Lett. 61 (2007) 4035–4038.
[34] S.E.M. Mourad, Performance of Plain Concrete Specimens Externally Confined with Welded Wire Fabric Research Report, College of Engineering Research Center, King Saud University, Saudi Arabia, 2006.
[35] B. Kondraivendhan, B. Pradhan, Effect of ferrocement confinement on behavior of concrete, Constr. Build. Mater. 23 (2009) 1218–1222.
[36] V.M. Shinde, J.P. Bhusari, Response of ferrocement confinement on behavior of concrete short column, IOSR J. Mech. Civil Eng. (2012) 24–27.
[37] M.J. Shannag, S.M. Mourad, Flowable high strength cementitious matrices for ferrocement applications, Constr. Build. Mater. 36 (2012) 933–939.
[38] A.B.M.A. Kaish, M. Jamil, S.N. Raman, M.F.M. Zain, Behaviour of ferrocement jacketed cylindrical concrete specimens under compression, in: Grantham (Ed.), Concrete Solutions, 2014, pp. 291–296.
[39] S.R. Razvi, M. Saatcioglu, Confinement of reinforced concrete columns with welded wire fabric, ACI Struct. J. 86 (5) (1989) 615–623.
[40] M.A. Mansur, P. Paramasivam, Ferrocement short columns under axial and eccentric compression, ACI Struct. J. 87 (5) (1990) 523–529.
[41] N. Ganesan, J. Anil, Strength and behavior of reinforced concrete columns confined by ferrocement, J. Ferrocem. 23 (2) (1993) 99–107.
[42] D.R. Seshu, A.K. Rao, Behaviour of ferrocement confined reinforced concrete (FCRC) under axial compression, Mater. Struct. 31 (11) (1998) 628–633.
[43] G.R. Kumar, Behaviour of high strength concrete confined with ferrocement shell in addition to lateral ties, J. Ferrocem. 31 (3) (2001) 215–222.
[44] S.K. Kaushik, S.P. Singh, Behavior of ferrocement composite columns in compression, ACI Special Publ. 172 (36) (1999) 669–681.
[45] M.N.S. Hadi, H. Zhao, Experimental study of high-strength concrete columns confined with different types of mesh under eccentric and concentric loads, J. Mater. Civil Eng. 23 (6) (2011) 823–832.
[46] H. Zhao, M.N.S. Hadi, experimental investigation on using mesh as confinement materials for high strength concrete columns, Procedia Eng. 14 (2011) 2848–2855.
[47] S.M. Mourad, M.J. Shannag, Repair and strengthening of reinforced concrete square columns using ferrocement jackets, Cem. Concr. Compos. 34 (2) (2012) 288–294.
[48] S.M. Mourad, M.J. Shannag, Repairing reinforced concrete rectangular columns using ferrocement laminates, in: Grantham, Mechtcherine, Schneck (Eds.), Concrete Solutions, 2012, pp. 757–763.
[49] A.B.M.A. Kaish, M.R. Alam, M. Jamil, M.F.M. Zain, M.A. Wahed, Improved ferrocement jacketing for restrengthening of square RC short column, Constr. Build. Mater. 36 (11) (2012) 228–237.
[50] A.B.M.A. Kaish, M.R. Alam, M. Jamil, M.A. Wahed, Ferrocement jacketing for restrengthening of square reinforced concrete column under concentric compressive load, Procedia Eng. 2013 (54) (2013) 720–728.
[51] A.B.M.A. Kaish, M. Jamil, S.N. Raman, M.F.M. Zain, M.R. Alam, An approach to improve conventional square ferrocement jacket for strengthening application of short square RC column, Mater. Struct. 49 (3) (2016) 1025–1037.
[52] I. Ho, E. Lam, B. Wu, Y. Wang, Monotonic behavior of reinforced concrete columns confined with high-performance ferrocement, J. Struct. Eng. 139 (4) (2013) 574–583.
[53] K. Takiguchi, Abdullah, On strengthening and repairing of shear failure type R/C columns with circular ferrocement jacket, J. Struct. Constr. Eng. (Transactions of AIJ) 541 (2001) 145–153.
[54] K. Takiguchi, Abdullah, Shear strengthening of reinforced concrete columns using ferrocement jacket, ACI Struct. J. 98 (5) (2001) 696–704.
[55] Abdullah, K. Takiguchi, An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets, CemConcr. Compos. 25 (2) (2003) 233–242.
[56] P.R. Kumar, T. Oshima, S. Mikami, T. Yamazaki, Seismic retrofit of square reinforced concrete piers by ferrocement jacketing, StructInfrastructEng 1 (4) (2005) 253–262.
[57] M.T. Kazemi, R. Morshed, Seismic shear strengthening of R/C columns with ferrocement jacket, CemConcr. Compos. 27 (4) (2005) 834–842.
[58] J.H. Choi, Seismic retrofit of reinforced concrete circular columns using stainless steel wire mesh composite, Can. J. Civil Eng. 35 (2) (2008) 140–147.
[59] S.H. Kim, J.H. Choi, Repair of earthquake damaged RC columns with stainless steel wire mesh composite, Adv. Struct. Eng. 13 (2) (2010) 393–401.
[60] J.G. Teng, L. Lam, Behavior and modeling of fiber reinforced polymer-confined concrete, J. Struct. Eng. 130 (11) (2004) 1713–1723.
[61] L. Lam, J.G. Teng, Design-oriented stress-strain model for FRP-confined concrete, Constr. Build. Mater. 17 (6–7) (2003) 471–489.
[62] A.B.M.A. Kaish, M. Jamil, S.N. Raman, M.F.M. Zain, Axial behavior of ferrocement confined cylindrical concrete specimens with different sizes, Constr. Build. Mater. 78 (2015) 50–59.
[63] B. Hu, J.G. Wang, G.Q. Li, Numerical simulation and strength models of FRP-wrapped reinforced concrete columns under eccentric loading, Constr. Build. Mater. 25 (5) (2011) 2751–2763.
[64] M.K. Zaki, Investigation of FRP strengthened circular columns under biaxial bending, Eng. Struct. 33 (5) (2011) 1666–1679.