Examples of high performance steel meshes with unidirectional strength exceeding 2300 MPa for use in ferrocement applications (courtesy A.E. Naaman)
HIGH PERFORMANCE FERROCEMENT AS BEAM-COLUMN CONFINEMENT FOR SEISMIC LOADING

Antoine E. Naaman¹ and Alex Sotiropoulos²

Abstract
This paper describes a preliminary investigation to evaluate the feasibility of using a high performance ferrocement jacket to strengthen reinforced concrete columns at the beam column joints in structures subjected to seismic loading. The term high performance here implies the use of a steel fabric made with high strength steel strands in one direction and a polymeric supporting textile in the other direction. Thus the fabric is strong in only one direction, allowing confinement to improve shear and ductility, without increasing the bending resistance. The strands tensile resistance is close to 2100 MPa, that is, three to four times higher than conventional steel wire meshes used in conventional ferrocement. The study comprises two parts: one dealing with material properties, and the other dealing with three medium-scale sub-assembly specimens representing beam-column connections (one control, and two confined with a ferrocement jacket). Material properties include tensile testing of the high strength reinforcement, some bending tests of plates similar to the ferrocement jacket, and compression tests of confined cylinders. Results are described and the viability of the technique discussed.

Keywords: ductility, ferrocement jacket, high strength reinforcement, RC column, seismic loading, shear strengthening, steel fabric, textile reinforced concrete, welded wire mesh.

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1. Introduction

Repair and rehabilitation of concrete structures is becoming one of the major fields of structural engineering as the demand for upgrading the performance of existing aging structures is increasing with time. This is due not only to the fact that seismic loading has become a common loading to consider, but also because it was either not prescribed or under-estimated in prior codes of practice and thus was not specifically designed for in older structures.

Many existing reinforced concrete frames in housing applications were either poorly designed or under-designed for seismic loading. Their ductility and shear resistance at beam-column joints may be insufficient under the cyclic deformation induced by earthquakes. One way to strengthen these frames is to provide a confining jacket at the base of columns in beam-column joints. Examples of jackets include steel jackets, bonded fiber reinforced polymeric sheets, and ferrocement. This paper describes a preliminary investigation to evaluate the feasibility of using a high performance ferrocement jacket to strengthen reinforced concrete columns at beam-column joints. The term high performance here implies the use of a steel fabric or mesh made with high strength steel strands in one direction and a polymeric supporting textile in the other direction. Thus the fabric is strong in only one direction, allowing confinement to improve shear, compression and ductility, without increasing the bending resistance. It is generally advisable not to increase bending resistance at the base of columns in order to improve their ductility under cyclic loads. The strands tensile resistance is close to 2100 MPa, that is, three to four times higher than conventional steel wire meshes used in conventional ferrocement.

The study comprises two parts: one dealing with material properties and the other dealing with three medium-scale sub-assembly specimens representing beam-column connections (one control, and two confined with a ferrocement jacket). Material properties included tensile testing of the high strength reinforcement, some bending tests of plates similar to the ferrocement jacket, and compression tests of confined cylinders. Results are described and the viability of the technique discussed.

2. Brief Literature Review

Space does not allow to provide a detailed literature review of methods of confinement of reinforced concrete structures. For RC columns, while in the past, confinement methods included the use of steel jackets bonded with epoxy resin, the most practical technique today include the use of externally bonded fiber reinforced polymeric (FRP) sheets.

In 1967, L’Hermite and Bresson [13] suggested a then pioneering retrofit solution by externally bonding thin steel plates to concrete using a polymeric resin. However, in the 1980s composite materials made of high performance polymeric fibers such as carbon, glass, or aramid, were introduced first in Japan and Europe as an alternative method to steel for repair and strengthening. The technique saw extensive development in the
1990’s during which commercial products were introduced to the market. Strengthening with FRP reinforcements was extended to improve bending, shear, torsion, and combined effects under monotonic or cyclic loading [2]. The initial idea of confining RC columns to improve their ductility under seismic loading was suggested by Park et al in 1983 [20]. Steel spirals and closed stirrups with a small pitch or spacing were then used. Today confinement of RC columns and bridge piers using externally bonded fiber reinforced polymeric (FRP) sheets, particularly carbon fiber reinforced (CFRP), is a common retrofit method for shear strengthening and ductility under seismic loading [2, 23, 29, 30]. Generally an epoxy resin is used as the bonding agent and, in spite of the high initial cost of material, the technique is widely accepted. However, issues related to initial cost of materials, high quality control needed by the technique, and sustainability under fire suggest that there is space for improvement.

Numerous research studies have evaluated ferrocement as a repair and strengthening method for bending and shear in reinforced concrete beams, and as confinement for RC columns. We note in particular studies by Ong, Paramasivam, et al. [18, 19], Jumaat et al. [7], and Kurtz et al. [12] for strengthening of beams in bending, and Rafeeqi et al. [22] for strengthening of beams in shear. But of more direct relevance to this investigation, are studies by Abdullah et al. [3], Balaguru [4], Kaushik et al. [8, 9], Kumar et al. [10], Nedwell et al. [17], Singh et al. [24], and Takiguchi et al. [25, 26] for confining plain concrete or reinforced concrete columns with a ferrocement jacket. The more recent introduction of non-metallic high performance reinforcement such as carbon and aramid fibers as reinforcement of cementitious matrices, has led to a terminology other than ferrocement, namely, textile reinforced concrete or TRC. Thin TRC products, where fiber reinforced polymeric textiles (or fabrics or meshes) are used instead of conventional steel wire meshes, attempt to combine the advantages of using a cementitious matrix instead of a polymeric one, and high performance corrosion resistant synthetic fibers. The field of TRC, FRP reinforcements, and FRP strengthening has taken a direction and dimension on its own and there is a large body of references available to the interested reader. We cite in particular Refs. [2, 5, 27, 32] for general background, and Refs. [28 to 31] by Triantafillou et al. for their direct correlation with the present study.

The use of a ferrocement type jacket as confinement of RC columns offers a low cost, low tech solution, where the jacket material is perfectly compatible with the concrete substrate, while it is also more reliable under fire than polymer based systems. So far, however, to the best of the authors knowledge, no particular attempt was made to avoid two-ways strengthening in columns and to use very high strength steel reinforcement in the jacket. These are the key features of the present investigation in comparison to most existing studies.

3. Research Significance

There is true need to provide not only simple solutions to the strengthening of reinforced concrete columns, but most importantly solutions that do not require a high level of technology and quality control so they can be implemented anywhere using widely
available materials and local labor. This research contributes to such a need by exploring the feasibility of using a high performance ferrocement jacket where the reinforcement consists of high strength steel strands supported by a conventional steel wire mesh. This innovative method of application has potential in larger scale strengthening applications as well, in which case commonly available prestressing strands can be used.

4. Experimental Program

The experimental program included material testing to essentially understand the characteristics of the ferrocement jacket used, and structural testing to evaluate its effectiveness as a column confinement. The material testing part included tests of the bending behavior of ferrocement plates similar to the jackets applied for strengthening, and the compression behavior of concrete cylinders confined by such a plate. The bending test was carried out to ascertain the tensile properties of the mesh with those present in the actual jacket, and the compression test were meant to show the increase in the compressive strength of the concrete substrate due to confinement. Structural testing comprised 3 reinforced concrete beam-column subassembly specimens, one control identified as CCL-0, and two confined by a ferrocement jacket, identified as CCL-1 and CCL-2.

5. Materials Used and Materials Test Results

5.1 Concrete Substrate
The same concrete mixture composition was used for the substrate concrete of the control cylinders, the control beam-column subassembly (CCL-0), and the first beam-column subassembly (CCL-1) which had a ferrocement confinement jacket containing one layer of reinforcement. The mixture proportions, by weight of cement, are given in Table 1 where C stands for cement, S for sand (regular masonry sand), A for coarse aggregate (of size ranging from about 1/8 in to 3/8 in or 3 mm to 9 mm) and W/C stands for water to cement ratio. The compressive strength of that mixture obtained from standard 4x8 in (100x200 mm) cylinders was about 34 MPa. The mixture proportions for the second beam-column subassembly (CCL-2) with a ferrocement confinement jacket containing two layers of reinforcement are also given in Table 1. Note that the concrete for CCL-2 led to a slightly smaller compressive strength than CCL-1 in spite of having a smaller water to cement ratio. This could be attributed to the difference in time between preparation and testing.

Control specimens were typical 4x8 in (100x200 mm) cylinders. They were normally cured, capped with a sulfur compound and tested in compression the same day as the confined beam-column specimens discussed below.

5.2 Mortar for the Ferrocement Jacket
One mortar mixture was chosen to accommodate the ferrocement jacket for the confined cylinders and the two beam-column sub-assembly specimens, CCL-1 and CCL-2. Its composition by weight of cement is given in Table 1. Here the sand was finer than for
the beam-column specimens, and passing ASTM standard sieve # 16, that is, of maximum size mostly smaller than 1 mm. The typical compressive strength for this mortar, $f'_c$, obtained from unconfined cylinders was about 9 ksi (63 MPa).

Table 1 – Mixture proportions by weight of cement, and related compressive strength

<table>
<thead>
<tr>
<th>Mixture for</th>
<th>C</th>
<th>S</th>
<th>A</th>
<th>W</th>
<th>$f'_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Substrate CCL-0, CCL-1, and Control Cylinders</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.65</td>
<td>34</td>
</tr>
<tr>
<td>Concrete Substrate CCL-2, and its Control Cylinders</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.55*</td>
<td>32</td>
</tr>
<tr>
<td>Mortar for Ferrocement Jacket and its Control Cylinders</td>
<td>1</td>
<td>1</td>
<td></td>
<td>0.36</td>
<td>9 ksi* (63MPa)</td>
</tr>
<tr>
<td>Concrete for all Confined Cylinders (same as for CCL-1)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.55*</td>
<td>32</td>
</tr>
</tbody>
</table>

* Note: Superplasticizer was used as needed. Confined cylinders used regular sand. Ferrocement jacket used fine sand passing sieve # 16.

5.3 High Performance Ferrocement Jacket

The ferrocement jacket included the use of a high performance steel mesh (or fabric or textile) identified as Fleximat©, from Bekaert S.A.. The mesh contains unidirectional high strength steel strands in one direction, and textile threads holding the strands in the transverse direction. Thus the mesh system has strength in only one direction. The mesh had a center to center strand spacing of about 2 mm. A close view of the strand is given in Fig. 1, and of a piece of mesh in Fig. 2. Figure 3 shows a larger section of the Fleximat© fabric. Description of the strand is given next.

![Figure 1 -- High strength steel strand used](image1)

![Figure 2 -- Fleximat© fabric used for the ferrocement jacket](image2)

The high strength steel strand (Fig. 1) used in the Fleximat© fabric was also obtained from Bekaert in the form of a strand spool (for testing single strand in tension and for wrapping the cylinders spirally). The strand consisted of 13 high strength steel wires, 12 of which running longitudinally and twisted to form a strand while one wire confines the rest by wrapping them spirally throughout the length. The internal wires have a nominal
diameter of 0.22 mm and the external wire, 0.15 mm, leading to a strand with an equivalent diameter of 0.78 mm, and an equivalent cross section of 0.48 mm².

Figure 3 -- Fleximat© fabric using high strength steel strands in one direction

5.4 Preparation of Confined Cylinders
A number of cylinders similar to the control cylinders used for CCL-1 (Table 1) were prepared to be confined by a ferrocement jacket. The confined cylinders had an additional 0.5 inch (12.5 mm) thick ferrocement jacket on their perimeter. Typically, one layer of reinforcement of the jacket comprised: 1) first a layer of conventional square steel welded wire mesh (Gauge 19) with a 0.5 in (12.5 mm) wire spacing and a 0.041 in (1.04 mm) wire diameter; the mesh overlapped over about a quarter of a circle and fine steel wire ties were used to keep it in place; and 2) a strand made from the same material as the high performance mesh described above was tied around the cylinder as a spiral, using the square steel mesh for controlling the pitch of the spiral. The procedure is repeated when several layers are needed to increase the tensile load resistance of the jacket. The welded steel mesh is identified as WSM. A sketch is shown in Fig. 4a. A photograph showing the reinforcement of a confined specimen versus a control specimen is shown in Fig. 4b. It is important to note that the steel strand was continuous and well tight/anchored on the supporting WSM layer to avoid any anchorage or slip failure under tensile forces. The cylinder was then placed in a cylindrical mold form of internal dimensions 5x8 in (125x200 mm) and a mortar was poored in the space between the cylinder and the mold to form the ferrocement jacket. The mortar mixture is given in Table 1. In one case, a series of cylinders confined with a mortar jacket without any reinforcement was also prepared and tested; it is identified as CJ0 in Table 2.

Two reinforcement volume ratios of the confining jacket were used to provide a comparative range with the control specimen. They included a series of specimens reinforced with 3 layers of the Gauge 19 conventional strength square steel wire mesh
(WSM) only, and two series with 3 layers of both the wire mesh and the spiral high strength steel strand. Details are given in Table 2. It was assumed that three layers of combined reinforcement would be indeed a maximum for the application at hand and that for the large scale beam-column specimens, the application would start with one layer, then two layers, then a third layer only if needed. Also, the use of only conventional steel wire mesh in one series allowed to compare with results from other studies using conventional ferrocement jackets.

![Figure 4a – Procedure followed for 1 combined layer of reinforcement in jacket](image1)

![Figure 4b – Cylinder with reinforcement jacket and control](image2)

Table 2 -- Characteristics and properties of confined cylinder series

<table>
<thead>
<tr>
<th>Series ID</th>
<th>Jacket</th>
<th>Welded Square Steel wire Mesh (WSM)</th>
<th>High Strength Strand (Fleximat)</th>
<th>f’c, ksi (MPa)</th>
<th>Strain at ultim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control C0</td>
<td>------</td>
<td>No.</td>
<td>VrL, %*</td>
<td>No.</td>
<td>VrL, %*</td>
</tr>
<tr>
<td>Control CJ0</td>
<td>Plain mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CGS</td>
<td>WSM</td>
<td>3</td>
<td>0.0158</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CGF-1</td>
<td>WSM + Strand</td>
<td>3</td>
<td>0.0158</td>
<td>3</td>
<td>0.0576</td>
</tr>
<tr>
<td>CGF-2</td>
<td>WSM + strand</td>
<td>3</td>
<td>0.0158</td>
<td>3</td>
<td>0.0576</td>
</tr>
</tbody>
</table>

* Assuming a 0.5 in (12.5 mm) thick jacket. Each layer of mesh provides 0.0053 % reinforcement, and each layer of fabric provides 0.0192 %, in the circumferential direction.
5.5 Testing Procedure for Confined Cylinders and Compression Test Results

Testing of the unconfined cylinders followed standard procedure. However, for the confined cylinders, in order to avoid transferring any direct compressive load to the jacket during testing, two cylindrical steel plates of 4 inches (100 mm) in diameter were placed centered at the top and bottom of the cylinder and used to transfer the compressive load to the core cylinder, hence avoid any significant compressive load transfer to the jacket.

Figure 5 – Test set-up for cylinders confined with ferrocement jacket

Figure 6 -- Examples of confined cylinders near or at failure
A sketch of the transfer plates and typical confined cylinder during testing are shown in Fig. 5. Typical photos of confined cylinders under test prior to complete failure are shown in Fig. 6. It can be observed that full failure generated failure of the reinforcement of the jacket including the high tensile strength strands.

Figure 7 shows the typical stress-strain curves of the confined cylinders in compression compared to the stress-strain curve of the unconfined concrete. It can be observed that the use of only three layers of gauge 19 conventional square steel wire mesh leads to a small improvement in compressive strength and in ductility. Indeed the compressive strength increases from a value of 5 ksi to about 10.5 ksi (see Table 2), but the ductility remains relatively small. However, when the full reinforcement including 3 layers of the high strength fabric is used, the improvement in both strength and ductility is impressive. As can be observed from these results, using a high strength ferrocement confining jacket leads to up to 300% increase in compressive strength and more than ten times increase in strain capacity prior to failure.

![Figure 7 -- Comparison of compression stress-strain curve for the specimens described in Table 2](image)

### 5.6 Tensile Tests of Strand and Fabric
The tensile strength of the strands as given by the manufacturer was 2100 MPa. Direct tensile tests on single pieces of strands (Fig. 8a) produced failure at the grips (jaw-type grips) at a stress substantially lower, due to stress-concentration there. However to ascertain the real strength, ferrocement dogbone tensile specimens reinforced with one strand, strongly anchored at its ends, were prepared and tested in direct tension (Fig. 8b). One specimen was precracked, and the other was used as is. The maximum tensile load was used to determine the tensile resistance of the strand. It led to an average tensile resistance of 2060 MPa, that is, of the same order as the value supplied by the manufacturer.
Assuming a value of 2100 MPa for the tensile resistance of the strands of the Fleximat© fabric reinforcement, the estimated tensile resistance of the high performance ferrocement jacket assuming a thickness of 12.5 mm, could be predicted from the following equation: \( V_{rL} \times f_{tu} \). Thus a tensile resistance of 40.3 MPa (5.84 ksi) can be expected per layer of reinforcement. In the various applications tried in this study, the expected tensile resistance of the jacket would be 80.6 MPa for two layers, and 121 MPa for three layers of reinforcement, respectively.

5.7 Bending Tests of Ferrocement Plates Using High Strength Reinforcement

In order to get a better idea of the resistance of the high performance ferrocement jacket and also correlate with its direct tensile resistance, a number of bending tests were carried out on small ferrocement plates having dimensions of 3x0.5x12 in (75x12.5x300 mm). Two series of tests were prepared one having one layer of high strength fabric (Fleximat©) and the other having two layers. Horizontal molds were used. The first layer of reinforcement was placed at the bottom of the mold before the mortar was poored; for the series with two layers, the second layer was added once about 10 mm of mortar was poored. Unfortunately, this procedure did not insure accurate spacing between layers. The volume fraction of reinforcement in the longitudinal direction is \( V_{rL} = 0.0192 \) for the series with one layer, and \( V_{rL} = 0.0384 \) for the series with two layers. Testing was carried out using a four point bending fixture, with a span of 225 mm as shown in Fig. 9. The load was recorded by the load cell of the testing machine, and the midspan deflection was measured by an LVDT. Typical response curves, plotted as equivalent elastic bending stress versus midspan deflection, are shown in Fig. 10.
A modulus of rupture close to 17.8 ksi (123 MPa) was observed with the two layers of reinforcement. Very fine multiple cracks developed along the ascending branch of the curve with a final crack spacing close to 6 mm. Failure occurred by shear in all specimens as shown in Fig. 12, implying that there was still reserve bending resistance. No strand failure was observed in these tests.
6. **Beam-Column Sub-Assembly Specimens: Preparation and Testing**

6.1 **Specimen Preparation**

Three specimens were considered for this part of the program. One was a control specimen (here identified as CCL-0) without a ferrocement jacket and the two others had a ferrocement jacket. The control specimen, CCL-0, was part of another study carried out by Parra-Montesinos and Chompreda [21]; their objective was to strengthen the beam portion of the joint for shear to increase resistance under cyclic loading; their test results were used to compare with the two specimens with the ferrocement jacket prepared for this part of the study. Note however that in the context of this research, the objective was to strengthen the RC column for same loading; therefore, the horizontal elements on each side of the joint shown in Fig. 13 represent the columns, while the vertical stubs represent the beams. Mixture proportions of the matrix for both the beam-column subassembly specimen and the ferrocement jacket are given in Table 1. It can be observed that the substrate concrete had a normal compressive strength of about 5.1 ksi (34 MPa).

Specimen dimensions are given in Fig. 13, and details of the reinforcement are given in Fig. 14, where all dimensions are in inches. Use about 25 mm per inch. Table 3 summarizes the main properties of the reinforcement obtained from direct tensile tests on bar samples, and Fig. 15 shows a photo of the reinforcing armature ready prior to pouring the concrete. Note that the wire used for the stirrups of the column portion is a low strength steel wire with a very high ductility.

![Figure 13 – Dimensions of beam-column subassemblage specimen prior to addition of the ferrocement jacket](image)

The dimensions for the two specimens with the ferrocement jacket are given in Fig. 16. Note that the jacket design called for a thickness of about 0.5 in (12.5 mm). Note also
that the intent of the beam-column reinforcement was to initially have a strong beam weak column and thus strengthen the column part, by providing a ferrocement jacket. Thus the column has increased confinement reinforcement but no additional longitudinal reinforcement to improve bending resistance. The idea was to force failure into the column and thus check the ability of the jacket to enhance the resistance of the column against shear failure, and to improve ductility under cyclic loading.

Table 3 Properties of reinforcing steel bars used in the beam-column sub-assembly for CCL-0, CCL-1 and CCL-2

<table>
<thead>
<tr>
<th>Reinforcing steel</th>
<th>Beam Region</th>
<th>Column Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield Strength, ksi (MPa)</td>
<td>Ultimate Strength, ksi (MPa)</td>
</tr>
<tr>
<td>#2 Stirrups</td>
<td>85 (586)</td>
<td>120 (828)</td>
</tr>
<tr>
<td>#5 Main</td>
<td>65 (448)</td>
<td>100 (690)</td>
</tr>
<tr>
<td>0.162 wire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4 Main</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2 Preparation of Column Confinement Jacket

The ferrocement jacket used to confine the columns followed the same procedure described earlier for confining the cylinders, except that instead of using strands from a spool, the Fleximat fabric was used. Two specimens were prepared. One with a jacket having one layer of reinforcement (CCL-1) and the other having two layers of reinforcement (CCL-2). Each layer consisted of one layer of conventional strength square steel wire mesh and one layer of high strength steel strand fabric (Fleximat©) strongly tied together to prevent slip. Although, initially, a third specimen with 3 layers of reinforcement was planned, it was found unnecessary given the success of the first two in achieving the intended result.

After placement of the layers of reinforcement, the specimen was placed horizontally, a wooden mold was built around the jacket, and a mortar of same composition as described above for the confined cylinders was poured in the mold; a light vibration was
applied and the top surface, representing the side of the confined column was hand finished with a trowel. The procedure is illustrated in Fig. 17.

Figure 17 -- Typical construction steps of ferrocement jacket around column: a) first layer of wire mesh; b) layer of high strength fabric (Fleximat©) above the wire mesh; c) reinforcement jacket ready; d) poured mortar completing the jacket

6.3. Testing and Measurements Procedures

The beam column subassembly specimens were tested using a standard servo-controlled hydraulic testing machine. A special heavy duty steel fixture was used at the supports and at the loading point (the beam stubs) to allow for application of cyclic loading. The two ends of the columns were simply supported on rollers, but constrained from movement in the vertical direction. The test set-up is shown in Fig. 18. The specimens were subjected to slow cyclic loading, with a time history presented in Fig. 19 as a function of cycles and drifts, as initially followed by Parra-Montesinos and Chompreda [21].

Besides the data records obtained from the load cell of the testing machine and the displacement of the cross head of the machine, additional instrumentation included two middle LVDT’s and two clinometers positioned on the center block (beam-column joint) of the column in order to measure elastic and plastic deformation and rotation at the plastic hinges formed at that location. Moreover, a non-contacting motion measuring instrument (Optotrak system), which measures displacements of specific markers attached to the surface of the specimen by using infrared cameras, was also used to
record the displacement of specific points on the jacket. These were placed in a grid along the surface of the jacket as shown in Fig. 18.

Figure 18 -- Beam-column sub-assembly specimen with ferrocement jacket under test (note the column is in the horizontal direction)

Figure 19 -- Loading history of the beam-column subassembly specimens
According to Parra-Montesinos and Chompreda [21] (who have in their research tested similar beam-column subassemblies without jacketing), in order to account for the differential rotation of the section at the beam column interface under loading, it is more appropriate to use an adjusted drift measure of the specimen instead of the directly measured drift (Fig. 20). This adjusted drift measure was used in this research as well.

Figure 20 -- Definition of adjusted drift measure as used in this study and devised in Ref. 21

7. Beam-Column Subassembly Specimens: Test Results

7.1 Control Specimen: CCL-0
The control specimen simulated a typical reinforced concrete column, not designed for seismic loading [21]. The specimen essentially failed in shear as designed to simulate RC columns in need of strengthening for seismic loading. A shear crack started from the beam column connection and progressed throughout an inclined path; a similar process repeated with cyclic loading. At failure, by shear, damage was extensive (Fig. 21a). The moment drift relation of the specimen is presented in Fig, 21b [21]. It can be observed that the maximum moment attained is around 23 k-ft and is attained only once. About 7 full cycles led to a moment between 20 k-ft and 23 k-ft prior to failure. The hysteresis loops are pinched in the middle indicating damage due to shear or possibly bond-slip damage of the reinforcing bars of the columns.
7.2. Retrofitted Specimen 1: CCL-1

Recall that specimen CCL-1 was retrofitted with a ferrocement jacket having only one layer of reinforcement, that is the combined high strength steel strand fabric and regular strength steel wire mesh. These two were tied together with sufficient overlap so as to prevent debonding under tensile loading.
Upon loading following the loading history shown in Fig. 19, the specimen eventually failed in bending at the beam-column connection interface. The hysteresis response of moment versus drift is shown in Fig. 22b. Note that quickly a steady hysteresis loop develops with a constant response under both positive and negative moment and a full body loop with little pinching, suggesting the formation of a plastic hinge. Prior to the formation of plastic hinges on both sides of the beam stubs (middle block), almost no crack could be observed on the surface of the ferrocement jacket. However, after the formation of the plastic hinges, some cracking developed in the jacket, indicating that the jacket is providing confinement resistance and helping increase the shear strength of the member (Fig. 22a). Failure occurred at a drift of almost 5% and was due to longitudinal rebar fracture, indicating that all the displacement capacity of the column member was utilized.

In comparing the response of specimen CCL-1 with the control specimen (Figs. 21 and 22) note the following: 1) the maximum load attained is about the same in both specimens indicating that indeed the maximum bending resistance is not increased (as intended in the design) due to the ferrocement jacket; 2) failure in CCL-1 occurred in bending, not shear, indicating the effectiveness of the jacket in improving shear resistance of the column; and 3) the ductility of CCL-1 as evidence by the steady plastic hinge response and the number of cycles to failure is significantly improved by the presence of the ferrocement jacket. The hysteresis loops were very full illustrating energy absorption and minimum bond-slip damage for the reinforcing bars of the columns under loading.

The maximum moment attained was around 24 k-ft. The number of cycles prior to failure, where the moment ranged between 20 k-ft and 24 k-ft was 20, that is, almost three times the number (7) observed for the control specimen.

7.3 Retrofitted Specimen 2: CCL-2
Specimen CCL-2 was similar to specimen CCL-1 except that it was retrofitted with a ferrocement jacket having two layers of reinforcement instead of one, where each layer consists of the combined high strength steel strand fabric (Fleximat©) and regular strength square steel wire mesh (gauge 19, WSM).

The failure of this specimen CCL-2 was identical to the failure of specimen CCL-1. However, its ferrocement jacket presented less damage at failure. Upon loading following the loading history shown in Fig. 20, the specimen eventually failed in bending at the beam-column connection interface. The hysteresis response of moment versus drift is shown in Fig. 23b. Note that quickly after loading, a steady hysteresis loop develops with a constant response under both positive and negative moment and showing a full body loop with little pinching, suggesting the formation of a good plastic hinge. Prior to the formation of plastic hinges on both sides of the beam middle block, almost no crack could be observed on the surface of the ferrocement jacket. However, after the formation of the plastic hinges, some cracking developed in the jacket, indicating that the jacket is providing confinement resistance and helping increase the
shear strength to the member (Fig. 22a). Failure occurred at a drift of almost 5% due to longitudinal rebar fracture, indicating that all the displacement capacity of the column member was utilized. The fine cracking illustrates the small extent of damage observed in the ferrocement jacket at failure, that is failure of the reinforcing bars at the interface between the column and the beam.

In comparing the response of specimen CCL-2 with the control specimen CCL-0 and with specimen CCL-1, it can be observed that the response of CCL-2 is very similar to that of CCL-1. It comprises full body hysteresis loops with evidence of plastic hinging at a maximum moment of about 24 k-ft (Figs. 17b). The number of cycles prior to failure, where the moment ranged between 20 k-ft and 24 k-ft, was 21, that is, just one cycle more than for CCL-1 and three times the number (7) observed for the control specimen.

Since the behavior of CCL-2 did not differ much from that of CCL-1, it was concluded that, for this type of specimen, only one layer of reinforcement is needed. A third specimen initially planned with a jacket having three layers of reinforcement was cancelled.

8. Conclusions

1. An innovative idea for a high performance ferrocement jacket designed for confining RC columns was developed in this study. The idea of the jacket is to combine a standard steel wire mesh with a high performance unidirectional
mesh (or fabric or textile) made out of high strength steel strands; alternatively the unidirectional fabric can be equivalently replaced by spirally placing a prestressing strand, around a conventional RC column with the desired pitch.

2. At the material level, the ferrocement jacket provides sufficient confinement to the concrete substrate to lead to up to 3 times increase in compressive strength.

3. At the structural level, the ferrocement jacket provides sufficient resistance to compensate for shear deficiency in the beam-column subassembly tested.

4. The use of a high performance ferrocement jacket can increase up to three times the life of a structural column subjected to seismic loads by ensuring a desired ductile type of failure and increased energy dissipation under earthquake loading.

As initially intended and further observed from the tests results, the use of a ferrocement jacket did not lead to any noticeable increase in the moment capacity of the column. However, the specimens confined with the ferrocement jacket presented higher shear capacity and increased ductility and energy dissipation capacity. Concrete shear failure was prevented as opposed to the control specimen, and failure by fracture of the steel reinforcing bars indicates that the full displacement capacity of the specimens was achieved. Thus, confinement of reinforced concrete columns using a high performance ferrocement jacket (with high strength steel strands) is a viable rehabilitation technique. It presents a strong alternative to the use of FRP reinforcements since it offers better resistance to fire, lower material cost, and lower level of technology for wider spread applications.

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10. References

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