Applications of Ferrocement in Strengthening of Unreinforced Masonry Columns

Abid A. Shah

Abstract**—** The load carrying capacity, ductility and serviceability of unreinforced masonry columns can substantially be improved if encased by ferrocement. The parameters such as cement mortar thickness, gage-wire spacing and bond at the interface of ferrocement and brick columns have effects on overall behavior. In the present experimental study, it was found that the first crack load and ultimate load of a ferrocement encased masonary column was increased by 119% and 121% respectively. Cracks developed in ferrocement-encased column were finer and well distributed as compared to plain specimen. However, premature failure is possible when bond at the interface of brick masonry column and ferrocement is poor. At higher reinforcement ratio, severe spalling and delamination is expected.

Keywords**—**columns, delamination, ductility, ferrocement, serviceability, unreinforced masonary.

I. Introduction

Ferrocement is a type of thin reinforced concrete wall commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh [1]. In its role as a thin reinforced concrete product and as laminated cement-based composite, ferrocement has found itself in numerous applications both in the construction of new structures and repair/rehabilitation of existing structures. Compared with conventional reinforced concrete, ferrocement is reinforced in two directions; therefore, it has homogenous isotropic properties in two directions. Benefiting from its usually high reinforcement ratio, ferrocement generally has a high tensile strength and high modules of rupture. In addition, because the specific surface of ferrocement reinforcement is higher than that of reinforced concrete, larger bond forces develops with matrix resulting in average crack spacing and crack width of smaller magnitude than that of conventional reinforced concrete [2], [3]. Other appealing features of ferrocement include ease of fabrication and low cost in maintenance and repair. Based on these advantages, ferrocement can be effectively utilized for water tanks, boats, housing wall panels, roofs, form work and retrofitting [4]–[6] .

Brick masonry columns are very common in low- and medium-rise masonry buildings in Pakistan. They are rarely reinforced and pose serious hazard to the building inhabitants. Due to its low ductility, they are more vulnerable to the lateral forces developed during an earthquake. In many cases due to severe cracks by the repeated earthquakes, they have lost major portion of their strength and stiffness.

Several retrofitting techniques are available to increase strength and ductility of unreinforced masonry elements. One way is to add structural elements such as steel or reinforced concrete frame having main disadvantage of adding significant weight which also requires foundation adjustments resulting in higher retrofit costs as well as higher inertia forces in the event of an earthquake. Another disadvantage of incorporating frame is the loss of valuable space. The second alternative is related to surface treatment, which can be achieved in a number of ways such as ferrocement casing.

The renaissance of ferrocement in recent decades has led to ACI design guidelines [7] and publications [8], [9]. Previously, steel meshes were the primary reinforcement for ferrocement. Recently fiber reinforced plastic (FRP) meshes were introduced as promising alternative to steel meshes [10]–[14]. However, as per the ACI 549R-97 recommendations [1], further research should be carried out to characterize the new material and improve the overall performance of ferrocement.

This research work is based on laboratory experiments. The effect of parameters such as mortar strength and thickness, steel wire distribution, bond between composite materials on serviceability, crack width, cracks spacing has been discussed.

The short columns are subjected to concentric axial load and first crack load, ultimate compressive strength, and failure mode of brick column with surface treatment by ferrocement is reported. Results of control specimen without ferrocement are also presented for comparison. During investigation, good agreement was observed.

II. Objectives and Research Significance

Brick masonry columns are commonly used in rural and urban areas of Pakistan. Because of improper structural design and no maintenance over a period of time, they have lost a major portion of strength and stiffness. Many masonry columns require strengthening due to increase in their share of building loads. Severe cracks due to repeated earthquakes are also very common in these masonry elements. These factors make brick masonry columns unsafe and they require economical, safe and easy remedial measures.

Ferrocement has been used effectively for retrofitting purposes. Ferrocement is likely to increase strength and stiffness. In saline soil, it can provide economical protection against sulphate attack. Fire resistance of ferrocement is also good. Its protective cover will also replace plaster requirement of the masonry unit. The fabrication of ferrocement is possible

A. A. Shah is with the College of Engineering, King Saud University, P. O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia. (corresponding author phone: +96614670631; fax: +96614673600; e-mail: abishah@ksu.edu.sa).

with unskilled man-power. The treatment of a structural member with ferrocement will not increase dead load appreciably. All these suggest that ferrocement has potential for retrofitting of brick masonry columns.

The potential of ferrocement for strengthening and changes brought by it in the overall performance of the strengthened member need thorough technical evaluation and investigation. The main objective of this research is to evaluate the capability of ferrocement for strengthening un-reinforced brick masonry columns and to make this process of retrofitting effective, economical and easy for practice. The significance of this research work is given as under:

1. Primarily to study the effect of various parameters like mortar strength and thickness, spacing of reinforcement, bond between ferrocement casing and brick core on strength, width, and spacing of cracks.
2. To study the structural interaction between ferrocement casing and brick masonry core on the basis of experimental observations.
3. To provide easy, economical and safe retrofitting guidelines for onward adoption and practice.
4. Necessary recommendations for future research.

III. Experimental Program

Experimental study was made on burnt clay brick column specimens. Locally available burnt clay bricks of 221 mm x 110 mm x 55 mm were used. Ordinary Portland cement and alkaline free sand were mixed together to cast cement mortar joint of 4.6 mm. In addition, locally available 24 gage steel wire having tensile strength of 276 MPa was used in the ferrocement. Masonry columns of 221 mm x 221 mm x 784 mm, were prepared (see Fig. 1).

Fig. 1 Plain (unreinforced) brick masonry column

After a period of one week of wet curing, steel wire was manually wrapped around column in both directions. Cement mortar was then applied and cured for minimum of 10 days before testing in compression. The type of mortar for brick masonry joint was same for all specimens. Specimens without ferrocement application were also constructed for comparison. The details of specimens constructed are given in Table I.

TABLE I
Surface Treatment And Mesh Spacing

Specs	No. of Specs	Detail of Surface Treatment	Mesh Spacing (mm)
BFM-3/4	03	Ferrocement Cover 6.125 mm of 1:2 Cement Sand Mortar (w/c=0.5)	18.38
BFM-1/2	03	Ferrocement Cover 6.125 mm of 1:2 Cement Sand Mortar (w/c=0.5)	12.25
BFM-1	03	Ferrocement Cover 6.125 mm of 1:2 Cement Sand Mortar (w/c=0.5)	24.50
BFM'-1/2	03	Ferrocement Cover 6.125 mm of 1:3 Cement Sand Mortar (w/c=0.55)	12.25
BC	03	No surface Treatment (Control Specimen)	--
BPM'	03	Only Plastered with 1:2 Cement Sand Mortar (w/c=0.5)	--
BPM	03	Only Plastered with 1:3 Cement Sand Mortar (w/c=0.55)	--

Cement sand mortar with mix proportion of 1:6 and w/c of 0.8 was used in the masonry work of brick columns. Cube (49 mm) specimens of this mortar were taken and tested for compression in accordance with ASTM C-109 [15]. In case of ferrocement two types of mortar were used (Mix proportion of 1:2 with w/c of 0.5 and mix proportion of 1:3 with w/c of 0.55). Table II contains the results of compressive strength tests carried out in the laboratory.

TABLE II
Compressive Strength Of Mortar Used In Brick Masonary Work

Age of Mortar Specimen (days)	Maximum load (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
	14.77	6.14	
7	16.37	6.76	6.38
	14.56	6.21	
	19.17	8.21	
14	15.66	6.69	7.31
	16.90	7.00	
	19.30	8.24	
28	20.68	8.83	8.62
	20.64	8.83	

All specimens were tested under axial compression using a Structural Testing Frame at the structural concrete laboratory of Civil Engineering Department, University of Engineering & Technology Peshawar, Pakistan. End conditions for each of the test specimen were kept similar. For the uniform distribution of load, rubber pads of 245 mm x 245 mm x 6.125 mm in size were placed at both ends of specimen and were covered with steel plates of dimensions 392 mm x 392 mm x 6.125 mm. Ferrocement encased specimen was instrumented with electrical resistance strain gages at mid-height of the specimens. Strain gage (or gages) was attached in a direction parallel to loading as shown in Fig. 2.

Fig. 2 Plastered specimen with a strain gage at mid-height

IV. Results and Discussion

The structural action of the ferrocement encased composite brick column is not perfectly clear as limited experimental data is available. Its failure load (F) can be considered as a summation of failure loads of brick masonry core (F_1), failure load of ferrocement casing (F_2) and strength increase of core due to confinement by ferrocement casing (F_3). As the triaxial compression behavior of brick masonry column is not well known so value of (F_3) is difficult to calculate theoretically. The column when subjected to axial compression tends to expand in lateral directions due to Poisson effect resulting in lateral expansion of both casing and core. However casing is restrained from lateral expansion by the horizontal wire of the ferrocement. It appears often that column failure will be initiated by the failure of casing due to combined action of bending moments and tensile forces in the cross-sectional plane. However, premature failure is possible due to separation of brick core and ferrocement casing.

A. First Visible Crack Load

The load that caused the first visible crack varied over some range. The first visible crack was observed at 51 to 64% of maximum failure load for plain specimens (BC), at 50 to 65% for plastered specimens (BPM') and at 48 to 53% for BPM. For the ferrocement-encased specimens (BFM-1/2) and (BFM'-1/2), the first visible crack appeared at 28 to 29% and 24 to 47% respectively. Similarly for the ferrocement-encased specimen (BFM-1) and (BFM-3/4), the first visible crack appeared at 29 to 62% and 59 to 77% respectively, as shown in Fig. 3.

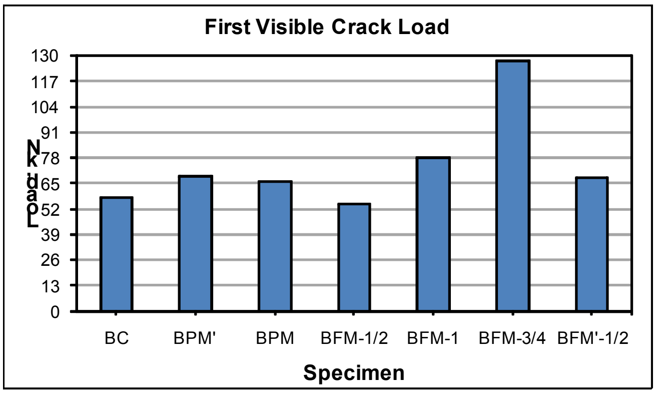

Fig. 3 First visible crack load for different test specimens

This range of variation is most probably due to variation in clear cover to wire reinforcement. In all cases, the first visible crack occurred at the bottom one-third of the test specimen. The average first visible crack load of specimen (BFM-1/2) is lower than that of plain and plastered specimens because for this specimen, the clear cover to wire reinforcement at bottom portion of the specimen was 3 mm due to improper workmanship and the matrix thickness was also more than 6.25 mm. For the remaining ferrocement encased columns, the average value of first visible crack is larger than those of the plain and plastered specimens.

B. Crack Appearance

In plain specimens, vertical cracks developed on all faces of the specimen and increased in width and propagated through the whole depth of the specimen. There was apparent bulging of the specimens in all four directions. At failure, the specimen split into two portions and one portion fell down. The failure at the ultimate load was abrupt. The behavior of brick column specimens at various stages of loading is shown in Figs. 4 and 5.

(a) (b)

Fig. 4 Cracks under the applied load (a) initiation and (b) progression

Fig. 5 Specimen after separation

In case of plastered column, both horizontal and vertical cracks were observed. They had a jagged appearance. They widened rapidly and in some cases large chunks of plaster fell down near or beyond the maximum load. Most cracks of the exposed brickwork did not match with plaster cracks. The plastered specimens' behavior at different loading stages is shown in Figs. 6 and 7.

(a) (b)

Fig. 6 Cracks on plastered specimen (a) first crack at column's edge and (b) development of multiple cracks

Fig. 7 Specimen near failure

The cracks in the ferrocement-encased specimens were different in appearance from those of plain and plastered specimens. The cracks were mainly vertical and occurred at both centers of column faces and near the edges. The central cracks increased in length and extended to the full height. Figs. 8 and 9 show the behavior of ferrocement encased specimens at various stages of the load.

(a) (b)

Fig. 8 Cracks in ferrocement encased specimen (a) initiation of first crack and (b) development of multiple cracks

(a) (b)

Fig. 9 Test specimens (a) spalling of mortar at the upper left cornor and (b) mortar cracking through-out the specimen's face

C. Average Crack Spacing

The average crack spacing decreased with reduction in the spacing of wire reinforcement. The average crack width for BFM-1/2, BFM-3/4 and BFM-1 was 10 mm, 13.5 mm, and 20 mm, respectively. Average crack spacing for the different specimens is presented in Table 3.

D. Effect of Bond between Ferrocement Casing & Brick Column

One specimen (BFM*-1/2) with intentionally developed weak bond was also tested to failure in compression. The first visible crack occurred at load of 35.60 kN. Ultimate failure load was 120 kN. Delimitation of ferrocement casing was most prominent aspect of its behaviour.

TABLE III
CRACK SPACING DETAIL

Specimen Designation	Average Spacing of Cracks (mm)
BC	98
BPM’	37
BPM	37
BFM/1/2	10
BFM/1	20
BFM/3/4	13.5

E. Effect of Loose Wire

Specimen (BFM**-1/2) was also developed with loose wire wrapping. The first visible crack was noted at of 32 kN, and the ultimate failure load at 112 kN. In some portions, wire reinforcement came out of casing at first visible crack. There was an apparent spalling of ferrocement casing.

F. Effect of Wire Spacing

Ultimate failure load increased with decrease in the center to center (c/c) spacing of the wire. The maximum increase with 12.25 mm spacing was 132%. However, the decrease of wire spacing or the increase of quantity of steel wire will not always increase the strength if the bond at the interface of brick core and ferrocement casing is weak. In some cases, premature failure due to spalling of casing is possible due to excess reinforcement.

G. Effect of Matrix Strength

During this experimental study, it was observed that mortar strength has small effect on the ultimate failure load of the column specimen. Ultimate failure load for plain specimen BPM’ & BPM was 120 and 130 kN, respectively. For ferrocement-encased specimens BFM-1/2 and BFM’-1/2, the ultimate failure load was 199 and 190 kN, respectively as shown in Fig. 10. In addition, percent increase in ultimate load of the test specimens was also calculated and plotted as shown in Fig. 11.

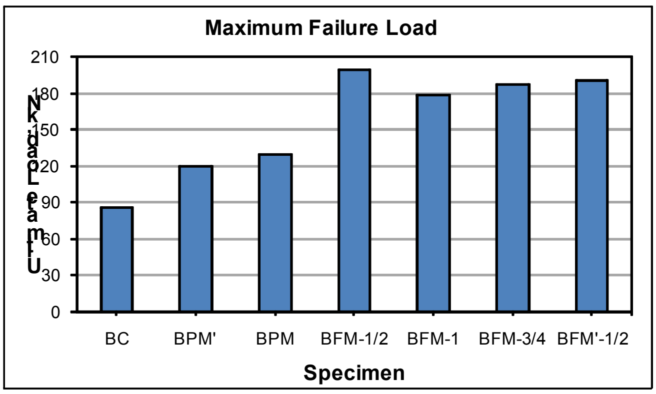

Fig. 10 Maximum failure load for different test specimens

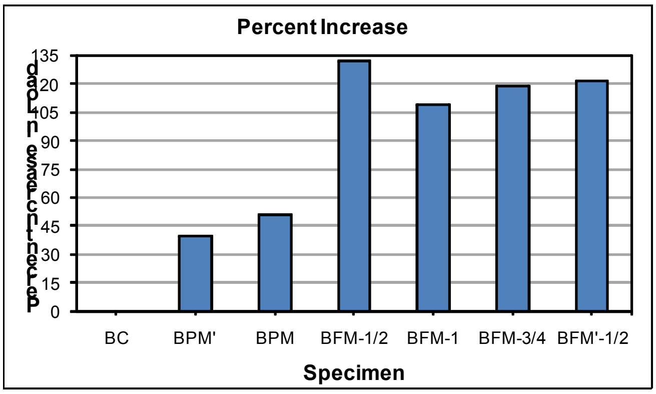

Fig. 11 Percent increase in ultimate load for different test specimens

H. Stress-Strain Curves

Stress-strain curve for plain specimen (Figs. 12 and 13) shows that strain is developed initially at slower rate than for ferrocement encased specimens. For specimen BPM, stress-strain relation is $\sigma = -1 \times 10^7\varepsilon^2 + 10333\ \varepsilon$. For BPM’ specimen, the stress-strain relation is $\sigma = -2 \times 10^7\varepsilon^2 + 12608\ \varepsilon$. Data for BPM’ is more scattered as compared to BPM.

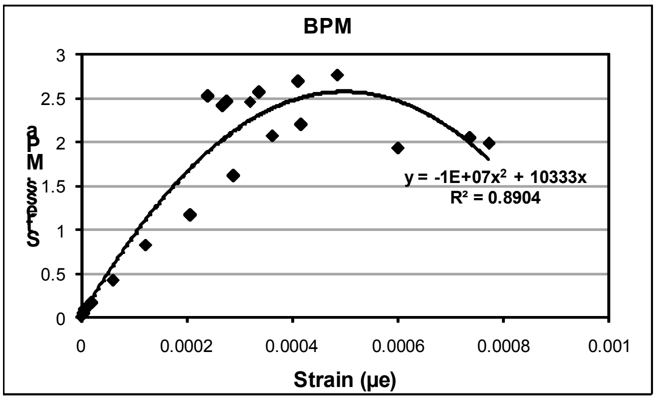

Fig. 12 Stress-Strain curve for BPM specimen

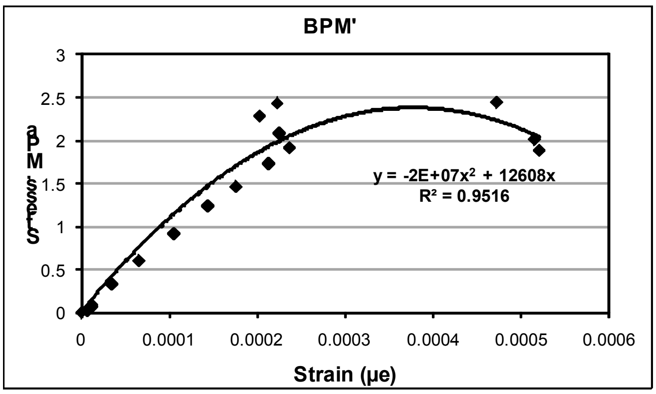

Fig. 13 Stress-Strain curve for BPM’ specimen

For ferrocement encased specimen, the rate of development of strain is initially higher as compared with that of plain specimens. For specimen BFM-1/2, the stress-strain relation is $\sigma = -5 \times 10^6\ \varepsilon^2 + 9041.7\ \varepsilon$ and for BFM/1 specimen it is $\sigma = -4$

x 10^6 ε^2 + 6994 ε as shown in Fig. 14 for BFM-1/2 specimen and Fig. 15 for BFM-1 specimen. The area under stress-strain curve for ferrocement-encased specimens is maximum than all other plain specimens. For ferrocement-encased specimens, the area under stress-strain curve is greater for BFM-1/2.

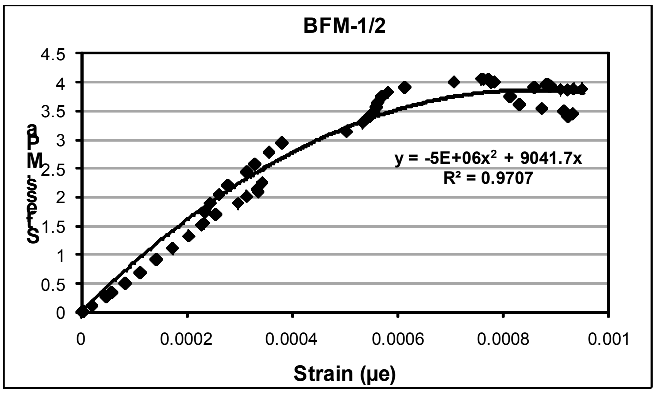

Fig. 14 Stress-Strain curve for BPM-1/2 specimen

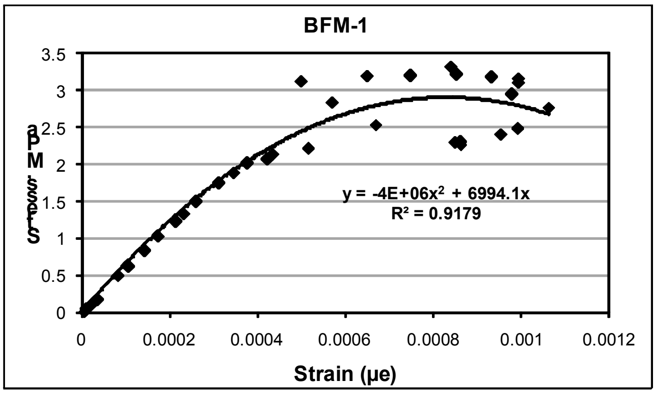

Fig. 15 Stress-Strain curve for BPM-1 specimen

V. Conclusion

This experimental study was made on burnt clay brick column specimens. Locally available burnt clay bricks of 221 mm x 110 mm x 55 mm were used. Ordinary Portland cement and alkaline free sand were mixed together to cast cement mortar joint of 4.6 mm. In addition, locally available 24 gage steel wire having tensile strength of 276 MPa was used in the ferrocement. Masonry columns of 221 mm x 221 mm x 784 mm, were prepared. The test results analysis led to the following conclusions.

1. Encasement of unreinforced brick masonry columns by ferrocement doubles the failure load.
2. Average crack spacing reduces with reduction in spacing of wire.
3. Premature failure is possible if mesh is not properly wraped and plaster does not fully penetrate into it.
4. Mortar strength has comparatively smaller influence on failure load.
5. Ferrocement casing can be used to repair un-collapsed column which have been loaded close to failure, provided it is possible to relieve them of major portion of load.
6. Clear cover to reinforcement shall not be greater than 2 mm and for each 6 mm thickness of ferrocement casing one layer of reinforcement may be satisfactory.

VI. Recommendations

The following recommendations were made for future research.

1. Behavior of brick masonry column under triaxial compression should be studied in detail to get a more representative mode of failure.
2. Behavior of casing under compression, laterally applied load and due to combination of both should be examined.
3. For bond at the interface of ferrocement casing and brick core, a detailed investigation should be made.
4. Utilizing the experimental data of this research work, a finite element model should be developed to quantify the effectiveness of the process.

Acknowledgment

This research was supported by the College of Engineering, Kind Saud University Riyadh, Saudi Arabia which is thankfully acknowledged.

References

[1] ACI Committee 549, "State-of-the-art report on ferrocement", *ACI549-R97,* in Manual of Concrete Practice, ACI, Detroit, 1997, 26 pp.

[2] S. P. Shah, and A. E. Naaman, "Crack control in ferrocement and its comparison with reinforced concrete," *Journal of Ferrocement*, vol. 8, no. 2, pp.67-80, 1978.

[3] A. E. Naaman, and S.P. Shah, "Tensile test of ferrocement", *ACI Journal, Proceedings,* vol. 68, no. 9, pp.693-698, 1971.

[4] A. E. Guera, A. E. Naaman, and S. P. Shah, "Ferrocement cylindrical tanks: cracking and leakage behavior," *ACI Journal, Proceedings*, vol. 75, no. 1, pp. 22-30, 1978.

[5] P. Nimityongskul, B. S. Chen, and P. Karasudhi, "Impact resistance of ferrocement boat hulls," *Journal of Ferrocement*, vol. 10, no. 1, pp. 1-10, 1980.

[6] M. R. A. Kadir, A. A. A. Samad, Z. C. Muda, and A. A. Abang Abdullah, "Flexural behavior of composite beams with ferrocement permanent formwork," *Journal of Ferrocement*, vol. 27, no. 3, pp. 209-214, 1997.

[7] ACI committee 549-1R-88, "Guide for design construction and repair of ferrocement," *ACI 549-1R-88 and 1R-93*, in Manual of Concrete Practice, ACI, Detroit, 1993, 27 pp.

[8] B. Bingham, "Ferrocement design, techniques, and applications," Cornell Maritime Press, Cambridge, Maryland, 1974, pp 444.

[9] A. E. Naaman, "Ferrocement and laminated cementitious composites," Techno Press 3000", Ann Arbor, Michigan, 2000, pp 372.

[10] A. E. Naaman, and J. Al-Shannag, "Ferrocement with fiber reinforced plastic meshes: preliminary investigation," *Proceeding of the Fifth Symposium on Ferrocement*, Manchester, England, September 1994. P. Nedwell and N.R. Swamy, Editors, E. and Fnspon, London.

[11] P. Guerrero, and A. E. Naaman, "Bending behavior of hybrid ferrocement composites reinforced with PVA meshes and PVA fibers," *Ferrocement 6- Lambot symposium, Proceeding of sixth International Symposium on Ferrocement*, A. E. Naaman, Editor, University of Michigan, June 1998.

[12] A. E. Naaman, and P. Gurrero, "Bending behavior of thin cement composites reinforced with frp meshes," *Proceedings of First International Conference on Fiber Composites in Infrastructures*, ICCI 96, Edited by H. Saadatmanesh and M. Ehsani, University of Arizona, Tucson, January1996, pp.178-189.

[13] A. E. Naaman, and K. Chandrangsu, "Bending behavior of laminated cementitious composites reinforced with FRP meshes", *High Performance Fiber Reinforced Concrete Thin Sheet Products*, Edited by A. Peled, S.P. Shan and N.Banthia, ACI SP-190, American Concrete Institute, Farmington Hills, 2000, pp. 97-116.
[14] M. Lopez, and A. E. Naaman, "Study of shear joints in fiber reinforced plastic (frp) ferrocement bolted connections," *Ferrocement 6-Lambot Symposium, Proceedings of Sixth International Symposium on Ferrocement*, A.E., Editor, University of Michigan, June 1998.
[15] ASTM Standard C109/C109M-08, "Standard test method for compressive strength of hydraulic cement mortars (50 mm cube specimens)," *ASTM International*, West Conshohocken, PA, 2008, DOI: 10.1520/C0109_C0109M-08, www.astm.org.

Abid A. Shah. This author was born on November 02, 1974 at Bannu Pakistan. He earned his B.S. degree in Civil Engineering from N.W.F.P. University of Engineering and Technology, Peshawar, Pakistan in 1996, in 2000 he received his M.S. degree in Structural Engineering from National University of Sciences and Technology, Islamabad, Pakistan, and in 2004 he got his Ph.D. degree in Structural Engineering from the University of Leipzig, Leipzig, Germany.

He worked for one and half years (2005-2006) as Senior Lecturer in Civil Engineering at the University of Botswana, Gaborone, Botswana (Southern Africa). Afterwards, he joined Tokyo Institute of Technology, Tokyo, Japan as Postdoctoral Fellow under a fellowship from Japan Society for the Promotion of Science (JSPS) in 2006. He worked there in the area of Nondestructive Evaluation of Distributed Damages in Concrete using Nonlinear Ultrasonics and Acoustic Emission Techniques. Presently, he is working as Assistant Professor, Specialty Units for Safety and Preservation of Structures, College of Engineering, King Saud University, Riyadh, Kingdom of Saudi Arabia. He is doing research in the area of Infrastructure Health and System Monitoring. He has published 24 papers in refereed journals, 14 papers in international conference, submitted 3 research reports, and delivered three invited talks. He has also published one book on the subject of Punching Shear of Flat-Plate Slab-Column Connections with Book on Demand, GmbH, Norderstedt, Germany in 2005. His current and previous research interests include Structural Health Monitoring, Rehabilitation of Concrete Structures using FRP, Nonlinear Ultrasonics and Acoustic Emission based Assessment of Damage in Concrete, and Punching Shear of Flat-Plate Slab-Column Connections.

D. Shah is registered as Professional Engineering with Pakistan Engineering Council since 2000. He is also a member of Saudi Council of Engineers (SCE).