PERFORMANCE EVALUATION OF PREDICTION MODEL FOR FERROCEMENT JACKETED RC COLUMN

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ABSTRACT

In Bangladesh, there are several thousands of vulnerable buildings that need to be strengthened to improve their seismic performance. In those vulnerable buildings, many buildings might have shear-deficient columns due to the ignorance of the provision of column tie reinforcements suggested in the building code. A low-cost strengthening scheme is required to strengthen such deficient columns. Ferrocement jacketing is one of the effective schemes to strengthen shear-deficient RC columns to enhance their seismic performance. In this technique, a ferrocement jacket, i.e., a combination of wire mesh and mortar, is utilized to wrap existing columns with a necessary connection between jacket and column. Few experimental studies had been conducted to investigate the performance of lateral behaviour of ferrocement jacketed RC columns, and ferrocement jacketing was very effective. In addition, few researchers proposed lateral strength prediction models. However, there is a paucity of research in this field, and no guidelines have been developed for ferrocement as a RC column jacketing method. In this context, this study focused on verification of the existing lateral strength prediction models utilizing the available experimental data in the literature. The analysis result showed good agreement when predicted lateral strengths were compared with corresponding experimental strength capacity of ferrocement-strengthened RC columns.

Keywords:*Ferrocement, RC column, shear, strengthening, prediction model.*

1. INTRODUCTION

Bangladesh is located in a zonethat is prone to earthquakes. There is a high risk of earthquakes, which is a threat to existing reinforced concrete structures. In previous earthquakes, many reinforced concrete buildings performed poorly because of poor seismic design and detailing(Kazemi and Morshed, 2005). During thefailure of buildings, two different types of failure,i.e., brittle failure and ductile failure can occur in RC columns. In this context, brittle failure, can occur due to insufficient shear reinforcement, which is common in developing countries due to lacking in the practice of building codes. Therefore, there is a significant risk of brittle shear failure in existing concrete columns(Kumar et al., 2005). The existing RC columns can be strengthened to improve shear capacity, and the strengthening can be conducted with FRP, CFRP, steel angles, ferrocement,etc. Among them, ferrocement wrapping is a relatively low-cost solution for developing countries which is also an effective technique to retrofit shear-critical columns(Takiguchi, 2001). Several researchers studied ferrocement due to its effectiveness inincreasing shear strength and simplicity ofinstallation(Wang, 2014). Some of them(Kim and Choi, 2010; Choi, 2008; Abdullah and Takiguchi, 2000)carried out experimental programs to investigate the effect of different key parameters and/or to present analytical modelsfor the prediction of the lateral capacity of ferrocement strengthened RC columns.

Abdullah and Takiguchi (2003) conducted a study on shear-deficient square RC columns with different ferrocement jacketing schemes. Circular-jacketed columns were tested under cyclic lateral loads and different axial loads, and square-jacketed columns were tested under cyclic lateral loads and constant axial loads. The results showed that the flexural capacity of circular-jacketed columns was18% higher under high axial loads. Columns strengthened with afew wire mesh layers showed a stable and ductile response, while those with full-height wire mesh remained intact. Square-jacketed columns experienced early strength degradation, but those with four or six layers displayed high ductility and stable responses.Kumar et al. (2005)conducted a study on the effectiveness of ferrocement jacketing of square RC bridge piers. Three scaled models under simulated seismic loading and constant axial force were tested. The study found that strengthened piers showed increased strength, stiffness, energy dissipation, ductility, and ductile flexure failure instead of brittle shear failure. Shear strength was enhanced by 30-50% in ferrocement-strengthened piers. A shear design equation was proposed to strengthen shear-critical square RC columns based on the number of wire mesh layers. In addition, a three-dimensional finite element analysis of ferrocement-jacketed piers was conducted.Kazemi and Morshed (2005)examined the behaviour of square RC columns strengthened witha ferrocement jacket having expanded steel mesh. The study was conducted under constant axial force and lateral cyclic load.In that study, two layers of mesh were found to be effectivein achieving the expected enhancement in shear strength and ductility, and ferrocement jacketing reduced shear cracking even at significant displacement. Besides experimental investigation, few researchers (Kazemi and Morshed, 2005; Abdullah and Takiguchi, 2003) proposed analytical models to predict the lateral strength of ferrocement strengthened RC columns.

The objective of this study is to assess the performance of available lateral strength prediction models of ferrocement strengthened square RC columns.The performance has been assessed by comparing the predicted and experimental lateral capacities of ferrocement strengthened RC columns available in the literature.

2. REFERENCE EXPERIMENTAL SPECIMENS

A literature survey has been conducted to collect available experimental data on ferrocement strengthened RC columns. A few researchers (Abdullah and Takiguchi, 2003; Kazemi and Morshed, 2005;Kumar et al., 2005) tested square RC columns strengthened with ferrocement jackets under seismic loading. The test specimens are summarized in Table 1, and ferrocement characteristics of those specimens are given inTable 2.

Abdullah andTakiguchi (2003) examined two square RC columns with ferrocement lamination, namely SJ-AL15-4L and SJ-AL15-6L, under combined axial and lateral loads. The lateral capacities of the test specimens were 32.5 kN and 32.1 kN for SJ-AL15-4L and SJ-AL15-6L, respectively. Both columns showed similar responses, i.e., ductile flexural failure occurred without any indication of shear failure. The ferrocement jackets of both columns fractured within the plastic hinge zone.Kazemi and Morshed (2005) strengthened three specimens with ferrocement wrapping of short shear critical RC column, namely C1-SC, C2-SF, and C3-SF, respectively, which showed lateral capacities of 102.2 kN, 102.4 kN, and 105.2 kN, respectively. At lower lateral displacements, shear cracks were not observed, even though columns reached the ultimate flexural capacity. However, at larger lateral displacements, the lateral load capacities of retrofitted columns were reduced, and shear cracks in jackets appeared.Kumar et al. (2005) investigated the performance of two ferrocement laminated RC columns with four and six layers of wire mesh in ferrocement, which yields lateral strengths of 149.8 kN and 165.9 kN, respectively. The ferrocement jacketed RC columns showed a ductile response with vertical cracks on the ferrocement jacket. The experimental lateral capacity and failure modes of all of the reference specimens are given in Table 3.

Table 1: Reference specimens used in the study.

	Specimen name	Width, $b=D$ (mm)	Height, h (mm)	Concrete, f_c(MPa)	Reinforcing bars, f_y(MPa)	Shear reinforcing bars, f_{ty}	Axial Load, N kN	Reinforcing Rebar	Tie bar
Abdullah and Takiguchi (2003)	SJ-AL15-4L	120	570	33.4	374	697	68	12no #6mm	2mm @ 50 mm
	SJ-AL15-6L	120	570	32.9	374	697	68	12no #6mm	2mm @ 50 mm
Kazemi and Morshed (2005)	C1-SC	150	400	35	500	300	118.125	4no #16mm	6mm @ 260 mm
	C2-SF	150	400	35	500	300	118.125	4no #16mm	6mm @ 130 mm
	C3-SF	150	400	35	500	300	118.125	4no #16mm	6mm @ 130 mm
Kumar et al. (2005)	4 layer ferrocement	360	1000	30	400	300	1.47	8no #19mm 8no #13mm	6mm @ 300 mm
	6 layer ferrocement	360	1000	30	400	300	1.47	12no #16mm 8no #13mm	6mm @ 300 mm

Table 2: Ferrocement details of reference specimens.

	Specimen name	Thickness of ferrocement jacket, t_f(mm)	Number of layers of wire mesh, n	Diameter of wire mesh,d_w (mm)	Grid size of wire mesh, g_w(mm)	Yield strength of wire mesh, (MPa)	Volume fraction of ferrocement , v_f	Type of wire mesh
Abdullah and Takiguchi (2003)	SJ-AL15-4L	10	4	0.45	2.5	267	0.0510	Woven square mesh
	SJ-AL15-6L	10	6	0.45	2.5	267	0.0763	
Kazemi and Morshed (2005)	C1-SC	25	1	3	40	400	0.024	Expanded steel mesh
	C2-SF	25	2	0.8	15	400	0.016	
	C3-SF	25	1	0.8	15	400	0.008	
Kumar et al. (2005)	4 layer ferrocement	20	4	0.44	2.76	300	0.0294	Woven square mesh
	6 layer ferrocement	20	6	0.44	2.76	300	0.0346	

Table 3: Experimental lateral capacity and failure modes.

	Specimen name	Experimental	
		Lateral strength(kN)	Failure mode
Abdullah and Takiguchi (2003)	SJ-AL15-4L	32.50	Flexural
	SJ-AL15-6L	32.10	Flexural
Kazemi and Morshed (2005)	C1-SC	102.20	Flexural
	C2-SF	102.40	Flexural
	C3-SF	105.20	Flexural
Kumar et al. (2005)	4 layer ferrocement	149.80	Flexural
	6 layer ferrocement	165.90	Flexural

3. ANALYTICAL MODELS

Ferrocement exhibits high plain shear strength; thus, the material enhances seismic performance when used to confine RC columns. Several models have been proposed for the shear strengthening of RC columns.

3.1 Abdullah and Takiguchi (2003)

Abdullah and Takiguchi (2003) proposed an equation onthe number of layers of wire mesh required tostrengthen a column weak in shear,which is given as:

$$n = \frac{0.78 g_w V_j}{d_w^2 f_{yj} D'} \tag{1}$$

where,n is the number of wire mesh layers; V_j isnominal shear strength provided by the ferrocement jacket; d_w is the diameter of wire mesh; f_{yj} is the allowable stress of wire mesh, $D'$is the core diameter of strengthening jacket; and g_w is the spacing of wires in mesh.
From equation (1) we can get the nominal shear strength provided by the ferrocement jacket$V_j$as:

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

In the design method for ferrocement strengthening, the ultimate shear capacity of an RC column with inadequate shear strength is given by:

$$V_{su} = V_C + V_s + V_j \tag{3}$$

where, V_{su} is the ultimate shear strength; V_c is the nominalshear strength provided by concrete;V_s is the nominalshear strength provided by transverse reinforcement,and V_j is the nominal shear strength provided by ferrocement jacket. $V_c$and V_s are calculated according to ACI standard(ACI 318-19):

$$V_C = \left[0.17\lambda\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d \tag{4}$$

$$V_s = \frac{A_v f_{yt} d}{S} \tag{5}$$

Abdullah and Takiguchi (2003) suggested calculating shear demand at flexural yielding of columns (V_{mu}) utilizing the ultimate flexural strength according to AIJ standards(AIJ,1994) as following:

$$M_u = 0.8 a_t \cdot \sigma_y \cdot D + 0.5 N \cdot D \cdot \left(1 - \frac{N}{b \cdot D \cdot F_c}\right) \tag{6}$$

$$V_{mu} = \frac{M_u}{h} \tag{7}$$

where, M_u= moment capacity of column; N= Axial Force; a_t= Total Cross-sectional area of tensile reinforcing bar; b= Column width; D= Column depth; σ_y=Yield strength of reinforcing bars;F_c= Compressive strength of concrete and h= height of column.

3.2 Kazemi and Morshed (2005)

Kazemi and Morshed (2005) proposed a shear strength equation for square ferrocement jacketed square RC columns as follows:

$$V_n = V_{no} + V_{sf} \tag{8}$$

$$V_{sf} = 2\eta V_f t_f \alpha_f f_{yf} \tag{9}$$

$$V_{no} = \left[0.115 K_s K_p \frac{17.6 + f_c'}{\frac{a}{d} + 0.12} + 0.85\sqrt{\rho_v f_{yv}} + 0.1\frac{N}{bh}\right] bjd \tag{10}$$

where, $V_n$is the nominal shear strength of the jacketed column, V_{no} is the nominal shear strength of core RC column, V_{sf} is the nominal shear strength provided by the ferrocement jacket, η is the global efficiency factor for ferrocement reinforcement (0.65 for long diagonal direction of expanded mesh; and 0.5 for woven and welded mesh);$V_f$is the volume fraction of wire mesh, $t_f$is the thickness of ferrocement jacket, $\alpha_f$is the distance between the load point and edge of the jacket (a gap distance less than shear span) and $f_{yf}$is the yield strength of wire mesh.f_c' and f_{yv} are concrete compressive strength and transversereinforcement yield strength, respectively (inMPa); b and h are column dimensions (in mm); d isthe effective depth and jd is distance between the tensileand compressive force resultants; a is theshear span; N is the compressive axial force (in N).

Kazemi and Morshed (2005) suggested calculating shear demand at the flexural yielding of the column (V_{mu}) utilizing the ultimate flexural strength according toOhno-Arakawa's equationas follows:

$$M_n = 0.5 A_{st} f_y g h + 0.5 N h\left(1 - \frac{N}{bhf_c'}\right) \tag{11}$$

$$V_{mu} = \frac{M_n}{h} \tag{12}$$

where A_{st} is the total longitudinal reinforcement ratioand g is the ratio of distance between the centers of longitudinal reinforcement in tension and compression tothe column thickness.

4. ANALYSIS AND RESULT

4.1 Analytical result of the Reference test specimens

In this section, two analytical models (by Abdullah and Takiguchi, 2003; Kazemi and Morshed, 2005) were appliedto predict lateral strength of reference ferrocement confined RC columns subjected to seismic loading. The predicted and observed lateral strengths and failure modes of RC columns strengthened by ferrocement jacket arepresentedinTable 4and Table 5 using the prediction models by Abdullah and Takiguchi (2003)andKazemi and Morshed (2005), respectively.

Table 4: Lateral capacity of the RC Columns calculated by Abdullah and Takiguchi (2003) model
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Abdullah and Takiguchi (2003)										
	ACI shear strength					Predicted		Observed		
Specimen name	V_c	V_s	Takiguchi ferrocement jacket, (V_j)	shear strength (V_{su})	AIJ Flexural Strength (V_{mu})	Lateral strength min (V_{mu},V_{su})	Failure	Lateral strength	Failure	V_{cacl}/ V_{exp}
SJ-AL15-4L	27.31	10.95	13.86	52.12	31.59	31.59	Flexural	32.50	Flexural	0.97
SJ-AL15-6L	27.18	10.95	20.80	58.93	31.56	31.56	Flexural	32.10	Flexural	0.98
C1-SC	52.43	11.42	20.19	84.04	107.46	84.04	Shear	102.20	Flexural	0.82
C2-SF	52.43	22.84	7.66	82.92	107.46	82.92	Shear	102.40	Flexural	0.81
C3-SF	52.43	22.84	3.83	79.09	107.46	79.09	Shear	105.20	Flexural	0.75
4 layer	94.05	15.83	28.92	138.80	192.08	138.80	Shear	149.80	Flexural	0.93

ferrocement										
6 layer ferrocement	94.05	15.83	43.71	153.59	200.40	153.59	Shear	165.90	Flexural	0.93

Table 5: Lateral capacity of the RC Columns calculated byKazemi and Morshed (2005) model.

Kazemi and Morshed (2005)									
Specimen name	V_m	V_{no}	v_{sf}	V_n	Predicted		Observed		V_{cacl}/V_{exp}
					Lateral strength min (V_m, V_{su})	Failure	Lateral strength	Failure	
SJ-AL15-4L	40.90	24.17	8.85	33.02	33.02	Shear	32.50	Flexural	1.02
SJ-AL15-6L	40.87	24.08	13.24	37.32	37.32	Shear	32.10	Flexural	1.16
C1-SC	104.02	67.40	81.12	148.52	104.02	Flexural	102.20	Flexural	1.02
C2-SF	104.02	73.44	54.08	127.52	104.02	Flexural	102.40	Flexural	1.02
C3-SF	104.02	73.44	27.04	100.48	100.48	Shear	105.20	Flexural	0.96
4 layer ferrocement	155.26	85.47	206.39	291.86	155.26	Flexural	149.80	Flexural	1.04
6 layer ferrocement	164.66	86.34	242.89	329.23	164.66	Flexural	165.90	Flexural	0.99

4.2 Comparison between analytical result and experimental result

The calculated lateral strengths of the reference specimens using the prediction models by Abdullah and Takiguchi (2003) and Kazemi and Morshed (2005),, along with the experimental strengths, are plotted in Figure 1 and Figure 2 respectively.In the case of the prediction model by Abdullah and Takiguchi (2003), the average of the ratio of calculated to experimental lateral strength is 0.86, with a coefficient of variation of 9.36%, which indicates a conservative prediction. From Table 4, it is evident that Abdullah and Takiguchi (2003) model can also predict the correct failure mode of somereference specimens, i.e., SJ-AL15-4L and SJ-AL15-6L. For other specimens, Abdullah and Takiguchi (2003) model cannot predict the failure mode correctly.

In the case of the prediction model of Kazemi and Morshed (2005), the average of the ratio of calculated to experimental lateral strength is 1.02, with a coefficient of variation of 5.84%, which indicates a fair prediction. From Table 5, it is evident that Kazemi and Morshed (2005) model can also predict the correct failure mode of most of the reference specimens, i.e., C1-SC, C2-SF, 4 layer wire mesh, and 6 layer wire mesh.

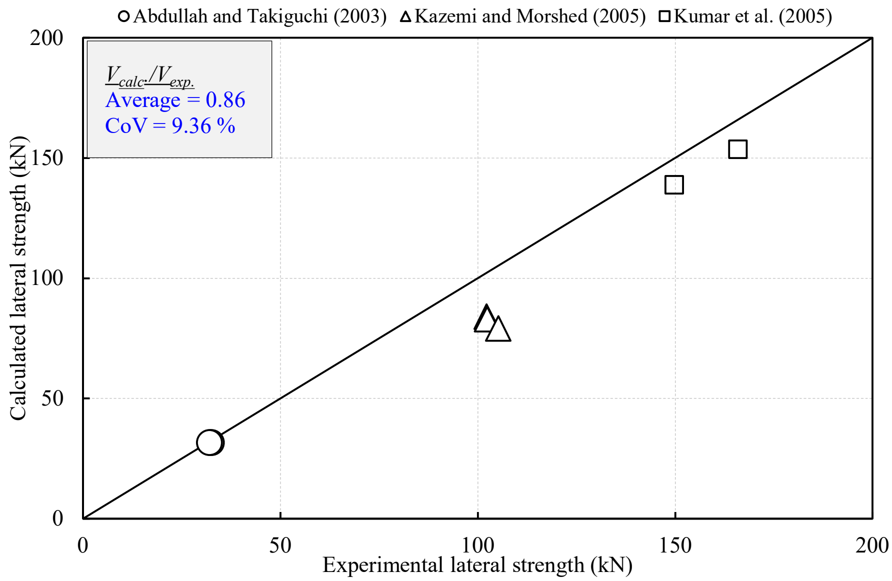

Figure 1:Comparison of calculated and experimental lateral strength of reference specimens using the prediction model byAbdullah and Takiguchi(2003).

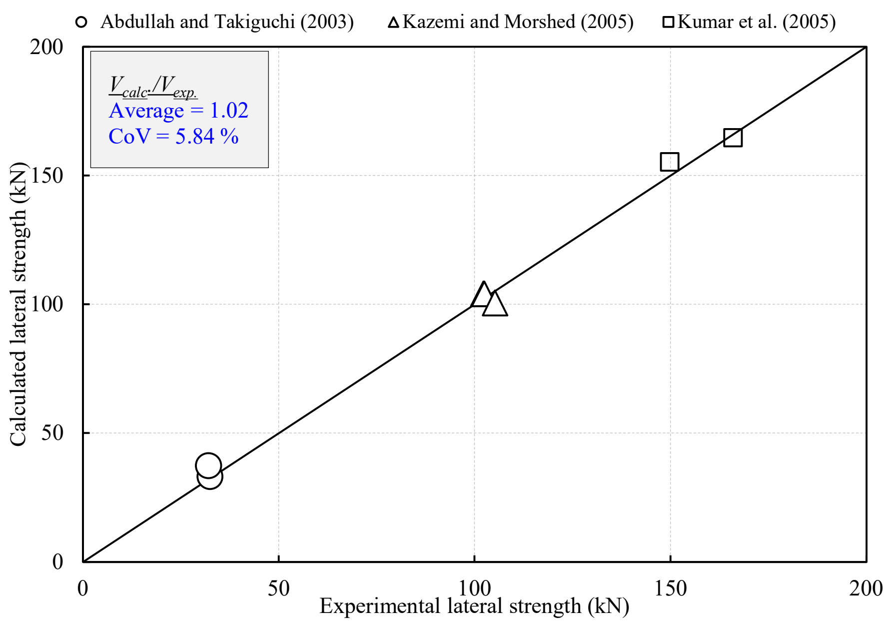

Figure 2: Comparison of calculated and experimental lateral strengths of reference specimens using the prediction model by Kazemi and Morshed (2005).

5. CONCLUSION

In this study, two analytical prediction models by Abdullah and Takiguchi (2003) and Kazemi and Morshed (2005) were applied to predict the lateral capacities of some reference ferrocement jacketed RC columns available in the literature. The computed analytical results were compared with experimental results to evaluate the performance of the prediction models. Based on the results of analysis, following conclusions can be drawn:

- The prediction model by Abdullah and Takiguchi (2003) can predict the lateral strength conservatively, with an average ratio of calculated to experimental lateral strength of 0.86 and a coefficient of variation of 9.36%. In some cases, it can also predict thecorrect failure mode.
- The prediction model by Kazemi and Morshed (2005) can predict the lateral strength fairly, with an average ratio of calculated to experimental lateral strength of 1.02 and a coefficient of variation of 5.84%. In most cases, it can also predict the correct failure mode.

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REFERENCES

Abdullah, A., & Takiguchi, K. (2000). Experimental Investigation on Ferrocement as an Alternative Material to Strengthen Reinforced Concrete Column. *Journal of Ferrocement*, *30*(2), 177-190.

Abdullah, & Takiguchi, K. (2003). An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets. *Cement and Concrete Composites*, *25*(2), 233-242.

ACI, American Concrete Institute. Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary. ACI 2019.

AIJ, Structural design guidelines for reinforced concrete building. Architectural Institute of Japan; 1994

Choi, J.-H. (2008). Seismic retrofit of reinforced concrete circular columns using stainless steel wire mesh composite. Canadian Journal of Civil Engineering, 35(2), 140-147.

Kazemi, M. T., & Morshed, R. (2005). Seismic shear strengthening of R/C columns with ferrocement jacket. *Cement and Concrete Composites*, *27*(7-8), 834-842.

Kim, S.-H., & Choi, J.-H. (2010). Repair of earthquake damaged RC columns with stainless steel wire mesh composite. *Advances in Structural Engineering*, *13*(2), 393-401.

Kumar, P. R., Oshima, T., Mikami, S., & Yamazaki, T. (2005). Seismic retrofit of square reinforced concrete piers by ferrocement jacketing. *Structure and Infrastructure Engineering*, *1*(4), 253-262.

Takiguchi, K. (2001). Shear strengthening of reinforced concrete columns using ferrocement jacket. *Structural Journal*, *98*(5), 696-704.

Wang, J. (2014). *Behaviour of ferrocement columns under static and cyclic loading*. The University of Manchester (United Kingdom).