A DETAILED INVESTIGATION OF REINFORCED CONCRETE COLUMN JACKETING: EXPERIMENT, THEORY AND NUMERICAL ANALYSIS

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ABSTRACT
In recent days, Reinforced Concrete (RC) column jacketing is been increasingly used in structural strengthening in Bangladesh. This research work investigates the structural capacity enhancement of column by RC jacketing. Twelve jacketed short column samples composed of 25 mm and 31.5 mm jacket thickness were experimented for axial capacity. Samples vary in terms of use of surface preparation, welded ties, and change of clear cover in jacketed part. Analytical equations in terms of Interaction Diagram are formulated. As an outcome, a software is developed to analyse and compare the capacity under combined compression with uniaxial bending. Tested sections are modelled in ETABS 2015 and SAP 2000 for Finite Element analysis. Experimental result shows that new concrete collapses earlier at the interface than that of the old concrete. Welding jacket ties contribute to axial capacity by resisting rebar buckling. Proposed analysis accounts the effect of interface bonding thus differs with Japanese code, ETABS, and SAP. However, test results validated the analytic axial capacity at an accuracy of 89 to 96%. Hence a bondage coefficient of 0.85-0.95 is proposed in determining axial capacity.

Keywords: Column; retrofitting; jacketing; interaction diagram; Finite element

INTRODUCTION

In order to avoid potential earthquake hazard, latest Bangladesh National Building Code (BNBC)-2015 guideline demands more structural resistance that suggests to strengthen many existing building structures of Bangladesh. Recent earthquakes, Rana Plaza incident and some other structural hazards raised the attentions towards the structural strengthening. Previously, many buildings were designed neither following the guideline nor considering lateral load. In addition, changes in live loads and user facilities, deterioration of the load carrying elements, design errors, poor construction quality during erection, and aging of structure, addition and alteration of existing structure force the users to strengthen the structural elements. Column being the most important structural element requires the utmost priority to be retrofitted. In recent years, column jacketing is commonly used to enhance the strength and stiffness of existing RC structure. Applications of RC column jacketing has already been executed in some garments buildings of Bangladesh. Still there is a large number of building structures that requires strengthening work immediately.

Effect of surface preparation, failure criteria and capacity of concrete jacketing has been experimentally and analytically investigated in the past by Bett et al. (1988), Saatcioglu and Ozcebe (1989), Alcocer and Jirsa,(1993), Erosy et al.(1993), Park and Rodriguez(1994), Stoppenhagen et al. (1995), Abu-Tair et al.(1996), Austin et al.(1999), Climaco and Regan (2001), Julio et al.(2003), Eduardo et al. (2005), Beushausen and Alexander (2008), Yuce et al. (2007), Roberto et al. (2008), H. Sezen and Eric A. Miller (2009), Stephanos E. Dritsos et al. (2010), D. W. Zhang et al.(2013), Veena M and Mini Soman (2014) and M. G. Marques et al. (2015). Indian code [3] and Japanese code [4] has separate methodology and equations for designing jacketed section. In Bangladesh, analysis and constructional methodology are recently published as guideline [6] that is modified and based on Japanese guidelines. Due to increasing use of RC jacketing, engineers need a simplified, time saving design and analysis approach. However, no significant research work has been reported yet and also the analysis and design guideline for RC column jacketing is yet to be established authentically.

This paper investigates the structural capacity enhancement of column by RC Jacketing. Hence, experimental investigation on jacketed column were carried out to determine load carrying capacity under pure compression. Simplified analytical equations are proposed to estimate jacketed column capacity in terms of Interaction Diagram which was compared with that of derived from Japanese retrofitting codes. Tested samples are modelled in ETABS 2015 & SAP 2000 v17 for Finite Element (FE) analysis. Finally, a computer program is developed which is able to analyse and compare the capacity of jacketed sections under combined compression with uniaxial bending.

EXPERIMENTAL INVESTIGATION

Twelve short column samples of 610 mm height with a cross section of 102 mm x 102 mm were used as Reference Sample (RS). Four 8 mm bar were used as longitudinal reinforcement. Tie (2.5 mm) with 6.5 mm clear cover (CC) were used at 150 mm spacing. To depict old column section comparatively weaker concrete was used in RS. Eleven samples were retrofitted using RC jacketing with 25 mm and 31.5 mm jacket thickness. Eight longitudinal bars were used with the same diameter as RS. Ties were spaced at 100 mm. Other than two samples as mentioned in Table 1, typical CC was kept as 12.7 mm. Brick and stone chips of 19 mm and 12.7 mm downgraded respectively were used. Local and Sylhet sand of Fineness Modulus (FM) 1.1 and 2.2 respectively were used in test. Mix ratio was 1:2:4 and 1:1.5:3 by percent of volume for RS and jacketed samples respectively. Before jacketing surface were roughened using hand chisel. Afterwards, sand blasting was carried out using coarse sand of FM 2.2.

Samples are named according to their thickness. Suffix letter used to describe the jacketing process; ‘N’-no bonding agent, ‘B’-surface prepared and bonding agent, ‘M’- monolithic casting, ‘W’-welded ties, and ‘C’ change of clear cover. CC was changed from 12.7 to 8.5 mm and 15 mm for 25 mm and 31.5 mm jacket thickness respectively.

Compressive capacity was tested in Universal Testing Machine (UTM) as in Fig. 1. Steel base plate of 205 mm x 205 mm cross section and 15 mm thick was used for uniform distribution of axial load. Load was applied at a rate of 1 mm/ min rate. Machine was programmed to stop at 40 % strain after reaching to the maximum axial load. Peak axial capacity was displayed in both the dial meter and in computer monitor system generating required graph of load, stress and strain.

(a) (b) (c) (d) (e) (f)

Fig. 1: (a) Surface roughening (b) Sand blasting (c) application of epoxy bonding agent (d) Jacketing of sample (e) UTM machine (f) Test Setup

ANALYTIC ASSESSMENT

Both weighted average concrete strength ($f_{c'avg}$) and old concrete strength ($f_{c'old}$) are used for analysis of jacketed section as in [6] and [7]. However, lower elastic modulus need to be considered in design as mentioned in [2]. Compressive strength is increased for the active confinement determined by various equationsby Scott et al. (1982), Uzumeri (1982), Mander et al. (1988) and Yong et al. (1988). In this regard, a concrete model is proposed to account confining stress generated by the jacket thickness. Effect of longitudinal reinforcement is negligible in pure compression according to P. Christou et al. (2013). Thus, thickness of jacket concrete in between longitudinal bar and old column face $t_{jacket_{inner}}$ is only used to determine confining stress. Volumetric ratio of the concrete to old column sections $\rho_{concrete} = (4 \times t_{jacket_{inner}}) / b_0$ [Modified to concrete according to FRP formula of R. Benzaid and H.A.

Mesbah, (2013)]. Confinement coefficient $k_e = 1/(1-\rho_{concrete})$. Tensile strength of concrete f_{rc} and volume of confine concrete to the volume of column section ratio ρ_{cc} is determined to find out confining stress $fl' = 0.5 \times k_e \times \rho_{cc} \times f_{rc}$. Finally jacketed compressive stress $f_c'_{Jacket}$ is determined using Mander concrete model [5].

Proposed Interaction Diagram Equations

Simplified five-point interaction diagram is formulated by deriving equations which are based on column interaction diagram with ACI code 318-08. It is considered that, old rebar is corroded hence cross sectional area is considered negligible in analysis to contribute in compression which is agreed with V. C. Marlapalle et al. (2014). Thus, pure compression for jacket sections can be written as:

$$P = CB \times [0.85 f_c'_{jacket} \times (A - A_{s\ old} - A_{s\ jacket})] + (A_{st\ jacket} + A_{sc\ jacket}) \times f_{y\ jacket} \quad (1)$$

CB = Coefficient of bondage; to account the reduction factor due to bonding effect at interface of different concrete. A = cross section after jacketing, $A_{s\ old}$ and $A_{s\ jacket}$ =area of longitudinal steel in existing column and jacket respectively, $A_{st\ jacket}$ and $A_{sc\ jacket}$ = area of tension and compression steel respectively in jacket, $f_{y\ jacket}$ = yield strength of jacket longitudinal steel.

Bending capacity of old rebar is considered to contribute along with jacketed bar. To account for the remaining contribution of old longitudinal bar, a partial value of their original bending capacity is assumed. It is denoted as Coefficient of moment (*CM*). It is considered that, these bar had reached to yield strength and their remaining ductility is added in the bending capacity of jacketed section. Thus $CM = 1 - (f_{yold} / f_{uold})$ in which (f_{yold} / f_{uold}) is ratio of yield and ultimate strength of old column rebar. Generally CM gives a value ranging from 0.20-0.35. Thus pure bending point is denoted as:

$$M = [A_{st\ jacket} \times f_{y\ jacket} + CM \times A_{st\ old} \times f_{y\ old}] \times (d_n - \frac{a_n}{2}) \quad (2)$$

$A_{st\ old}$ = area of tensile steel in old column, d_n = distance of centroid of tensile jacketed steel from top fibre, a_n = dimension of equivalent stress block in jacketed section.

Jacketed concrete strain $\varepsilon_{ujacket}$ is taken as 0.003 in analysis. However, old concrete strain ε_{uold} is considered up to 0.005. Basing on strain compatibility a single concrete strain is considered for simplification. Basing on strain and force, weighted average concrete strain ε_{uavg} is calculated. Finally following equations are proposed for balanced, compression and bending control points:

$$P = 0.85 f'_{c\ jacket} \times a_n \times b_{new} + A_{sc\ jacket} \times f_s'_{jacket} + A_{st\ jacket} \times f_{y\ jacket} \quad (3)$$

$$M = 0.85 f'_{c\ jacket} \times a_n \times b_{new} \times (\frac{h_{new}}{2} - \frac{a_n}{2}) + A_{sc\ jacket} \times f_s'_{jacket} \times (\frac{h_{new}}{2} - d'_{new}) +$$
$$A_{st\ jacket} \times f_{y\ jacket} \times (d_{new} - \frac{h_{new}}{2}) + CM \times A_{st\ old} \times f_{y\ old} \times (d_{old} - \frac{h_{old}}{2}) \quad (4)$$

Interaction Diagram using Japanese equations

Following [4] and [6] maximum theoretical axial capacity P_{max} and bending equations are formulated.

$$P_{max} = A_{st\ jacket} \times f_{y\ jacket} + A_{st\ old} \times f_{y\ old} + b_{new} \times h_{new} \times f_{c'avg} \quad (5)$$

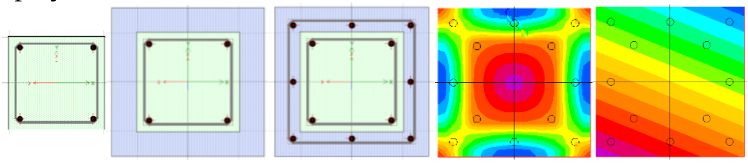
[According to 3.3.4-2 a of Japanese guidelines]

$$M = (A_{st\ jacket} \times f_{y\ jacket} \times g_{jacket} + A_{st\ old} \times f_{y\ old} \times g_{old} + 0.12 \times b_{new} \times h_{new}^2 \times f_{c'avg})$$
$$\times (\frac{P_{max-} P}{P_{max-} 0.4 \times b_{new} \times h_{new} \times f_{c'avg}}) \quad (6)$$

g_{old} and g_{jacket} are distance between tensile and compressive longitudinal steel in jacket portion and existing column respectively

FINITE ELEMENT MODELLING USING ETABS 2015 AND SAP 2000

Section designer is used to model jacketed column section in ETABS 2015 and SAP 2000 v17. Material properties were defined according to the test samples. Rectangle and box section was used to model samples. Longitudinal and tie bar were placed in the model following the actual dimensions of samples. After modelling, interaction diagram and moment vs. curvature diagram can be extracted as output. SAP 2000 produces advance features for analysis stress and strain in different conditions as well as moment vs. concrete and steel strain and compression data. Interaction diagram are formulated using these data. Fig. 2 displays the model and stress distributions.



(a) (b) (c)

Fig. 2 (a) Old column section (b) Jacketed column (c) Stress distributions

RESULTS AND DISCUSSIONS

Results of the test and analytical assessment are shown in Table 1. Bonding does not follow a liner behaviour and vary greatly according to construction, material property and types of surface preparation, moisture content of substrate [8]. Effect of creep and any direct tension stress caused by shrinkage are ignored in analysis. All these factors contribute in the deviations of test with analytic results. Monolithic samples 25-M and 31.5-M had the less deviation due to absence of different concrete interface. Whereas 25-N and 31.5-N had the larger deviation. Since there is no provision of reduction factors due to bonding interface in FE analysis and Japanese code therefore proposed pure compression point differs as much as 26% as in Fig. 3. Other points agree with the Japanese code by a variation of 8-12% while pure bending resulted deviation by only 1-2.5%. On the other hand, for maximum bending capacity, proposed analysis agrees well with an accuracy of 93.5-98 % with the Japanese code. However, both differ with ETABS and SAP with a deviation of 16.5-25% due to liner addition and composite action account which is shown in Fig. 7.

Table 1. Experiment vs. Analytical Results

Sample Name	fc'$_{old}$ (MPa)	fc'$_{jacket}$ (MPa)	Analytic capacity (KN)	Test capacity (KN)	% variation	Area Ratio A/A_{old}	Capacity ratio P_n/P_{old}	
							Analytic	Test
25-N	11.12	19.35	243.29	226.21	7.02	2.220	1.522	1.521
25-B	11.13	21.63	289.64	258.51	10.74		1.948	1.739
25-B-W		21.98	289.75	264.38	8.78		1.813	1.778
25-M		21.80	289.69	302.5	4.36		1.812	2.030
25-B-C		21.89	329.83	298.83	9.46		2.064	2.010
31.5-N	11.12	24.98	336.9	305.67	9.26	2.617	2.108	2.056
31.5-B	12.20	29.42	441.00	416.78	5.51		2.759	2.803
31.5-M		29.87	441.72	452.86	2.69		2.764	3.046
31.5-B 2	11.12	20.85	403.70	379.45	6.01		2.526	2.552
31.5-B-W	11.12	20.21	402.43	382.78	4.88		2.518	2.575
31.5-B-C		21.32	372.08	342.68	7.74		2.328	2.305
RS		-	159.80	148.65	6.97	-	-	-

Failure Pattern

Samples failed with generation of full and partial depth longitudinal crack as in Fig. 5. Few lateral cracks were generated also. Local failure occurred due to stripping out of concrete at the new and old concrete interface which agrees with [7]. This happens as the jacketed column is unable to maintain strain compatibility at the interface of new and old concrete. Crushing of jacket concrete along with failure of ties were seen. Concrete failed at the corner due to the high concentration of stress which agrees with [9]. Significant increase of axial capacity was found up to 178% depending on compressive strength of jacket. From Table 1 it is seen that, for same area ratio bonding and surface prepared sample had increased capacity ratio from 18-22% than the nonbonding sample.

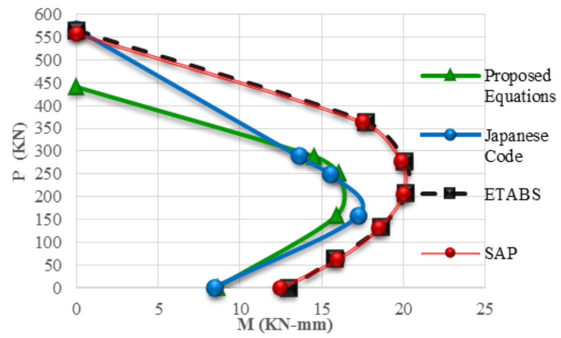


Fig. 3: Comparison of Interaction Diagram.

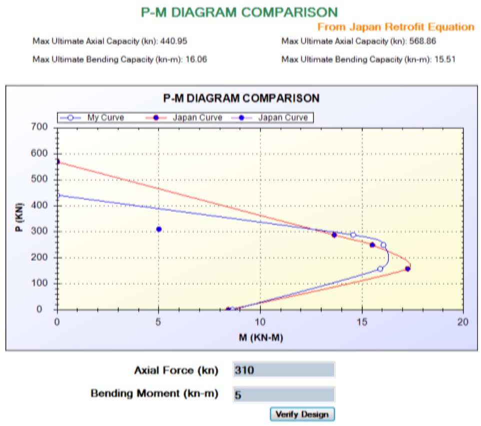


Fig. 4: Developed software output interface

Development of Analysis Software

A software is developed to analyse jacketed column using Eq. (1)-(6) in the programming language of 'Microsoft C#'. Interface takes the input of material properties and dimensions to generate interaction curve both with and without phi. A comparison is also generated with Japanese code in the output interface as shown in Fig. 4. User facility like print, save as image, and zoom options are incorporated. Jacket design verification can be performed using the dynamically generated point.

Stress-strain Behaviour

Maximum loading occurred in an average strain of 0.012-0.013 mm/mm for all the sample as in Fig. 6. However, 25-M, 31.5-M and RS samples had lesser rate of 0.011 and 0.01 respectively. Thus ultimate strain of confined concrete increases due to jacketing as tensile reinforcement undergoes strain hardening well agreed with S. Chun and H.C. Park (2012). 0.3% ductility is achieved in axial loading corresponding to 1.61% increase of size. This approves the seismic effectiveness of jacketing.

25-N 25-B 25-M 31.5-N 31.5-B 31.5-M

Fig. 5: Typical failure pattern of samples

Effect of Surface Preparation, Confinement Stress and Welded Ties

Increase capacity can be achieved without using any bonding agent and surface preparation. However, use of this increased the capacity to 24-30%. A detailed trial method was carried out with different value of CB ranging from 0.85-1 for bonded and 0.60-0.70 for non-bonded. Hence CB in the range 0.85-0.95 is proposed. For perfect bonding the value is 1. Tabulated capacity is calculated with the minimum value of CB as 0.85 and 0.65 for surface prepared and non-prepared sample respectively. Test result verified the analysis with an accuracy of 89 to 96%. For same jacket thickness, clear cover of bars in jacket determines the effective thickness of confinement concrete. Thus the reduction of clear cover will increase the capacity with a ratio varying from 0.45-0.50 and vice versa. For constant clear cover, confinement stress increased due to increase in the thickness and compressive strength of jacket concrete. Welding of ties prevent buckling of main and tie bar in failure with an increase of axial capacity at a range of 1-2.5% only. Thus for construction convenient welded ties may not be applicable except joint.

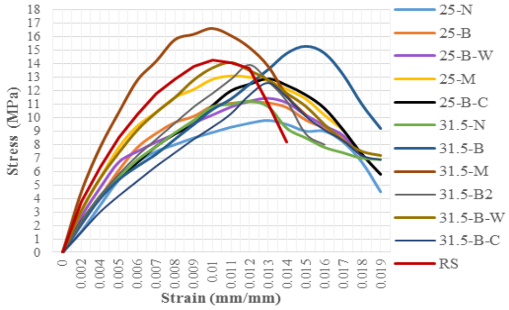


Fig. 6 Stress vs. Strain

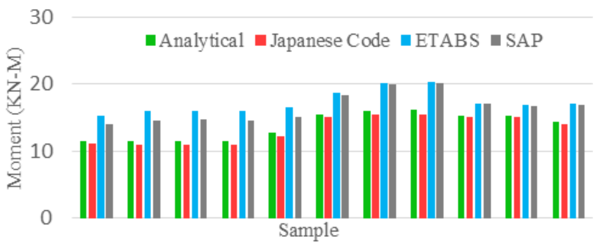


Fig. 7 Maximum bending capacity comparison

CONCLUSIONS

Based on the results and findings presented in the paper, following conclusions can be drawn:

- Capacity enhanced significantly (up to 178% in this research) by RC jacketing depending on compressive strength, clear cover, use of surface treatment and bonding agent. Outer concrete and interface bonding governs the failure pattern.
- Developed compressive stress of RC jacketing can be used instead of weighted average or existing value. Proposed equations can be used for simplified analysis of RC column jacketing.
- Idea of using commercial software (such as ETABS, SAP) in analysing and designing jacketed column is controversial. Engineers should be careful in case of retrofitting column design.
- The developed program can be a useful tool in jacketed column capacity prediction. It can be effectively used by the engineers to analyse and design for simplicity and enhanced time efficiency.
- Proposed CB and bending capacity analysis can further be evaluated for precision by axial and bending test of actual size column.
- This research work may contribute to develop a design guideline for column strengthening using RC jacketing.

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