Circular HSC Columns Confined with Pre-tensioned Steel Straps

Ma Chau Khun, Abdullah Zawawi Awang, Wahid Omar, Maybelle Liang

Abstract— Steel-straps tensioning technique (SSTT) has been proven to be an effective mean to confined High-strength concrete (HSC). The pre-tensioned force offered by this confining method can significantly restrain the small lateral dilation of HSC. However, most of the design guidelines only concerned with FRP-confined columns subjected to concentric compression. The direct application of these design guidelines on the SSTT-confined HSC column is being questioned due to different material and confining method adopted. Hence, a numerical study was carried out to compare the proposed model with the previous studies. The comparison between experiment results and previous studies has proven that external confinement using steel strap is comparable to others external confinement method. However, there is no definitive conclusion regarding the effectiveness of different confinement method as the geometry of the specimen is different.

Index Terms— Steel straps, confinement, theoretical model, design equation, high-strength concrete, short column, flexural capacities.

1 INTRODUCTION

Lateral confinement of concrete columns has been proven to be very effective in increasing both ultimate strength and ductility [1]. However, conventional confinement methods are less effective in confining high-strength concrete (HSC) due to smaller lateral dilation compared to normal-strength concrete (NSC) [2, 3, 4, 5]. Under-utilization of the confining materials used in confining HSC was reported due to the sudden failure of HSC before it was fully dilated under compression. This has led to the uneconomical use of such confining method for HSC structure [6].

For HSC column confined with steel-straps tensioning technique (SSTT), the low-cost steel-straps which is normally seen in the packaging industry were used (Figure 1). The steel-straps were pre-tensioned around the column by using the pneumatic tensioner prior to the loading. Different from the conventional confining method where confining effect is initiated by the dilation of concrete itself, the pre-tensioned force provides by SSTT can ensure the structure was perfectly confined even before dilation. Figure 2 shows the pneumatic tensioner used in pre-tensioning the steel-straps.

SSTT in HSC columns has several functions. They are to confine the concrete core and to restrain the longitudinal reinforcement from buckling. All of these functions contributed to the improvement of flexural strength and ductility of the columns. It should be noted that the flexural strength and moment capacity for SSTT-confined short HSC column under eccentric loads will increase with the increasing confinement volumetric ratio. However, no design equation is available to determine the actual flexural capacity of such a column.

In this paper, the development of an analytical model such a column is presented. A parametric study was conducted to investigate all parameters affecting the ultimate capacity of SSTT-confined HSC Columns. The proposed design equation to calculate the flexural strength and moment capacity is expected to be a very useful design aid for structural engineers in the design of SSTT-confined HSC columns.

2 ANALYTICAL MODEL

2.1 Stress-strain Model

The stress-strain model proposed by Awang [6] for SSTT-confined HSC is chosen in this study. The parameters considered in this stress-strain model are SSTT-confinement ratio, $\rho_s$. 
and unconfined concrete strength, \( f'_{co} \) respectively. The proposed stress-strain model is as below:

\[
\frac{f'_{cc}}{f'_{co}} = 2.62 \left( \rho_s \frac{f_s}{f'_{co}} \right)^{0.4} \quad \text{and} \quad \rho_s = \frac{v_s}{v_c}
\]

where

\( f'_{co} = \text{unconfined concrete strength} \)
\( \rho_s = \text{SSTT-confining volumetric ratio} \)

The peak strain \( \varepsilon'_{cc} \) is calculated as below:

\[
\frac{\varepsilon_{cc}}{\varepsilon'_{co}} = 11.60 \left( \rho_s \frac{f_s}{f'_{co}} \right)
\]

where

\( \varepsilon'_{co} = \text{concrete axial strain for unconfined concrete strength} f'_{co} \)

The capacity of SSTT-confined HSC sections can be calculated if the stress-strain model for such a concrete is known. However, strain gradient exists for column subjected to eccentricity loading and it is general practice to assume that this effect is negligible. The axial load, \( P \) and bending moment, \( M_x \) is found based on the equations below:

\[
P = \int_{\lambda_c = R - x_n}^{R} \sigma_c b d\lambda_c + \sum_{i=1}^{n} (\sigma_{si} - \sigma_c) A_{si}
\]

\[
M_x = \int_{\lambda_c = R - x_n}^{R} \sigma_c b \lambda_c d\lambda_c + \sum_{i=1}^{n} (\sigma_{si} - \sigma_c) A_{si} (R - d_{si})
\]

Where \( R \) is radius, \( b \) is the length of the segmented layer from the location of \( \lambda_c \), \( \sigma_{si} \) is the steel stress within that particular layer, and \( A_{si} \) is the cross-sectional area of the steel.

The reference column used in this study is circular with diameter \( D = 150 \) mm. The concrete characteristic cube strength is 60 MPa. 4 steel bars are distributed around the column evenly. The characteristic yield strength of the steel is 460 MPa with elastic modulus, \( E_s = 200 \) GPa.

This analysis equally divided the column section into 50 layers with each thickness of 3 mm. In order to ensure accuracy, the calculation is stopped when difference between the resultant load and assumed load exceeded \( 10^{-6} \) N. This theoretical model assumed the columns should have deflected in half-sine shape. Checking on the force equilibrium is only needed at the mid-height of the column where failure normally takes place. However, the model is limited to the modeling of column subjected to equal eccentricities. The present method of analysis has been used in several past studies and the reliability of this method has been proven [7, 8, 9]. Nevertheless some of the existing design codes are based on this method of analysis [10, 11].

It is assumed that the deflected shape of columns can be closely approximated using a half-sine shape. It is easily expressed mathematically as [7, 8, 9]:

\[
\delta = -\delta_{mid} \sin \left( \frac{\pi}{l} x \right)
\]

where \( \delta_{mid} \) is the displacement at the critical section and \( x \) is the distance from the origin. By differentiate Equation 5 twice, the equation for curvature is obtained as below.

\[
\phi = \delta_{mid} \frac{\pi^2}{l^2} \sin \left( \frac{\pi}{l} x \right)
\]

When \( x \) is occurred at the mid-height of the column, hence

\[
\delta_{mid} = \frac{l^2}{\pi^2} \phi_{mid}
\]

The moment of acting on the critical section thus can be found. However, this moment and stress at the critical section have to be in equilibrium state. Hence, strain value for outmost compression segment has to be assumed to check the axial load and moment for each value of \( \phi_{mid} \). The correct \( \delta_{mid} \) is found when the axial force divided by moment is equal to the \( \delta_{mid} \) for a particular \( \phi_{mid} \). The complete load-deflection curve can then be drawn for incremental value of \( \phi_{mid} \).

\[\text{Fig. 3. Typical train and stresses diagram over the circular confined column}\]

2.2 Moment-Curvature Interaction Diagram

A series of theoretical moment-curvature curves is generated based on the stress-strain model discussed on the previous section. Assumptions were made in generating the moment-curvature curves:

(i) Linear strain is assumed across the column section.
(ii) Tensile strength of concrete is assumed negligible.

(iii) The ultimate unconfined concrete strain is 0.004

(iv) The initial tangent modulus of concrete, $E_c$, is equivalent to $4230 \sqrt{f_{cu}}$

Figure 5 shows a series of moment-curvature curves for different axial load. It should be noted that the axial load level is defined by $P/A_{f'c}$, where $P$ is the axial load, $A$ is the cross-sectional area of the column and $f'_{cc}$ is the confined concrete strength. In Figure 5, it is clearly seen that the ductility of moment-curvature curves reduced gradually as the axial load increases. In low axial load level, the curves resembled to the elasto-plastic shape. For higher axial load level, the maximum moment degrades rapidly.

$$ \text{Axial Load: } N \text{(kN)} $$

$$ \text{Moment: } M \text{(kN.m)} $$

Fig. 6. Load – moment interaction curve

### Table 1

<table>
<thead>
<tr>
<th>Column ID</th>
<th>Eccentricities (mm)</th>
<th>Layers of Confinement</th>
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<tr>
<td>C60-UNC</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C60-2FT</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>C60-4FT</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>C60-UNC-E25</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>C60-2FT-E25</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>C60-4FT-E25</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>C60-UNC-E50</td>
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<td>2</td>
</tr>
<tr>
<td>C60-2FT-E50</td>
<td>50</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 6 shows the corresponding load-moment interaction curve. It is obvious from Figure 6 that moment increases from zero to approximately $3.5 \times 10^5$ N. mm. After this level, the moment decreases as the axial load increases. The maximum moment occurred when the axial load is approximately $1 \times 10^6$ N, which represented the balanced axial load level.

3 Analytical Results & Discussions

Table 1 shows the parameters for the analytical model test. The test results are compared for varies confinement ratio, $\rho_s$, against efficiency ratio, $\rho (%)$ and plasticity ratio, $\rho_{0.85}$. The confinement efficiency ratio, $\rho (%)$ indicates the percentage of strength gained from the confined specimens compared to the unconfined specimen. The plasticity ratio, $\rho_{0.85}$ indicates the ratio of ductility at 85% reduction after peak load. Where $\epsilon_{0.85}$ is the displacement corresponding to 85% of ultimate strength at the descending part of curve, $\epsilon_{max}$ is strain corresponding to ultimate strength.

Table 2 and 3 shows the effects of confinement ratio to concentrically and eccentrically loaded HSC columns, respectively. It can be observed from both tables, the efficiency of external confinement increases with the confinement ratio. The plasticity ratio, which indicating the ductility increment of confined column also was observed to has increased significantly with the confinement ratio. The results suggested that the effect of eccentricities to the efficiency of confinement is negligible.

Table 4 shows the comparison of efficiency ratio between the
experimental results and previous studies. It can be seen that external confinement method can effectively improved the ultimate load capacity of the specimens. By increasing the confinement volumetric ratio, the ultimate load capacity of the specimen was increased.

The percentages of load decrease with different eccentricities were compared with previous studies as shown in Table 5. It is can be observed that similar trend of load reduction with previous studies: the greater the magnitude of eccentricity, the larger the reduction in ultimate load capacity.

### 4 Conclusion

The lacking of ductility in HSC, which has been the major argument against it, is no longer a problem since the confinement can turn its brittle failure into a ductile type of failure. For the approximately constant compressive strength of column, the experiment that we conducted shows that, there is the increment of column ductility and some significance of improvement of the column strength. Steel strapping method is capable to solve the nature brittle characteristic of HSC column. The improvement of the ductility and compressive strength for confined column is depending on confinement volumetric ratio. The ultimate load capacity for concentric loaded column C60S15-2FT and C60S15-4FT increased 21% and 31% respectively as compared to the ultimate load capacity of specimen C60-UNC. For eccentric loaded column C60S15-2FT-E25 and C60S15-4FT-E25, the load capacity increase 17% and 23% compared to unconfined C60-UNC-E25.

The behaviour of the HSC column is significantly affected by the eccentric load. The stress concentrations caused by the eccentric loading further reduce the strength and ductility of HSC. The ultimate load capacity for unconfined column C60-UNC-E25 and C60-UNC-E50 decreased 27 and 69 percent respectively as compared to the ultimate load capacity of specimen C60-UNC. For column that confined with 2 layers steel straps C60S15-2FT-E25 and C60S15-2FT-E50, the load capacity decreased 28 and 63 percent compared to unconfined C60-UNC-E25.
The comparison between experiment result and previous studies had prove that external confinement using steel strap is comparable to others external confinement method. However, there is no definitive conclusion regarding the effectiveness of different confinement method as the geometry of the specimen is different.

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REFERENCES


