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Concrete columns with discrete confinement by metal sheets subjected to uniaxial compression: derivation toward design rule

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Abstract

This paper applied a nonlinear finite element model to study the effect of discrete metal sheet confinement on the uniaxial compressive strength of concrete columns. The columns in this study had circular cross sections with a diameter of 15 cm and a height of 75 cm. Concrete columns with various discrete wrap patterns were computationally simulated and found to be consistent with available experimental results. The results from the three-dimensional finite element modelling showed the effect of the bi-axial response of the metal sheet when it acted as confining material. An analytical procedure outlined in this study was used to determine the effective confining pressure in concrete. This work demonstrates that the development of the strength of a concrete column with discrete metal sheet confinement depends on its size, spacing and the number of the applied metal sheet layers. Strength prediction equations for study columns were derived as an example adaptable to formulate necessary design rules.

Keywords: Concrete, Metal sheet, Axial compression, Finite element analysis, Confinement

1. Introduction

Confinement is one of the methods widely used for strengthening concrete columns. Use of different types of fiber-reinforced plastic (FRP) composites [1-6] has been very popular, due to its ability to improve the load-carrying capacity of columns while generating minimal additional weight and maintaining the size of the existing columns. The technology of applying the FRP material in column strengthening has been advanced and applied for many years. Some other materials have also been developed, such as post-tensioned high strength metal strips [7-8], which has proven its ability to increase axial capacity as well as ductility of concrete columns. Yet, not many alternative materials have been investigated.

In recent years, researchers at Khon Kaen University have tried to find an alternative material to FRP for use in strengthening concrete members. This alternative material should be light-weight, thin and reasonably resistant to corrosion. Metal sheets, whose applications are mainly for roofing and cladding, have attracted attention, as they are available in almost every construction market and have the required properties. They contain the properties of steel, with some advantages due to very light weight, small thickness and resistance to corrosion on their galvanized surfaces. Many experiments have been conducted for surveying possible applications to strengthen concrete members. To understand the behavior of metal sheet confined concrete columns, metal sheet material has been investigated both experimentally [9-13] and numerically [14-15]. It was found in laboratory experiments that using metal sheet as a confining material can increase axial compressive strength as well as ductility of the confined concrete columns. However, applying one large piece of metal sheet to wrap to the full height of the columns revealed the appearance of some wrinkles on the metal sheet jacket due to a partial loss of bonding between the concrete and the metal sheet [9, 11]. It was additionally found that confining columns using metal sheet strips instead of one-piece full confinement (cf. Figure 1) could reduce wrinkling of metal sheets normally found during loading [10, 12-13]. Applying small strips to wrap around the concrete columns also facilitated the installation process, and simplified quality control. As a result, higher confinement effectiveness could be achieved.

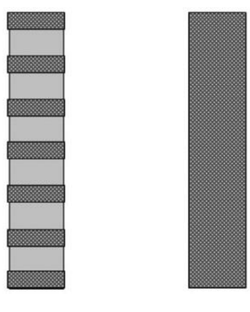

Figure 1 Discrete confinement (left) VS one-piece full confinement (right).

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In addition to the experimental research, finite element models were proposed for modeling concrete columns confined with metal sheets both in the form of a continuous sheet [14] and as discrete strips [15]. The numerical results agreed well with the experimental results and could explain confinement mechanisms. In this paper, more detailed analyses are conducted to demonstrate a possibility of formulating an appropriate design-rule for this confinement technique.

2. Finite element modeling

In this study, the 3D nonlinear finite element model suggested in the work of Boonpichetvong et al. [15] was applied. The confined column model consisted of three materials, concrete, metal sheets and interfacial (bonding) material. The detailed constitutive models for each of the materials are given as follows in this section. The analysis was performed using finite element analysis software MSC.Marc [16].

2.1 Constitutive models

In modeling of the concrete part, three dimensional 8-node solid brick elements were selected. The tri-axial compression behavior of the confined concrete columns was modeled using the linear Mohr-Coulomb yield criterion:

$$F = \alpha I_1 + \sqrt{J_2} - \kappa \quad (1)$$

where F is the linear Mohr-Coulomb yield function, I_1 is the first stress invariant, J_2 is the second deviatoric stress invariant, α is the frictional parameter, and κ is the softening function of concrete following:

$$\kappa = \sigma_c \left(\frac{1}{\sqrt{3}} - \alpha \right) \quad (2)$$

The variable σ_c in Eq. (2) denotes the stress in concrete following the stress-strain relationship under uniaxial compression as given in the work of Popovics [17].

In modeling the softening behavior of concrete under compression, we adopted a softening function based on the post-peak regime of the stress-strain curve under uniaxial compression [17]:

$$\frac{f_c}{f'_c} = \frac{n\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)}{(n-1) + \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^n} \quad (3)$$

where ε_{co} is the concrete strain at the concrete peak stress f'_c, which was selected as 0.002 herein. The variable n depends on the peak stress and is given by:

$$n = 0.4 \times 10^{-3} f'_c + 1.0 \quad (4)$$

It should be noted that when using Eq. (4), the concrete strength f'_c must be in psi units. The concept of compressive fracture energy (G_{fc}) suggested in [18] was adopted as the model parameter to mitigate the problem of mesh objectivity [19]. The uni-axial stress-strain curve, according to the work of Popovics [17], is illustrated in Figure 2. As for concrete under tension, the mechanical properties of concrete were taken in accordance with ACI318-11 [20] and the standard smeared crack model [19] was employed.

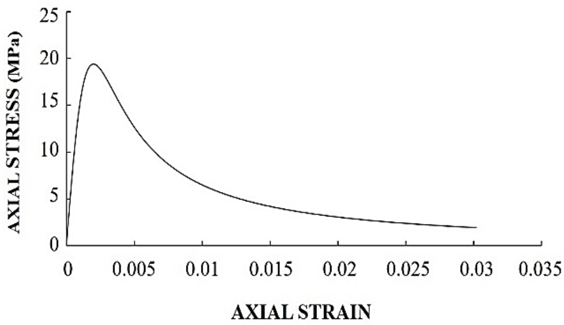


Figure 2 Uniaxial stress-strain curve of concrete under compression following [17].

For the modeling of the metal sheet, three dimensional 8-node solid brick elements were used as well. The tension and compression behavior of the metal sheet was modelled using the Von-Mises yield criterion. An elastic-perfect plastic material behavior was assumed.

For the interfacial part, which represented a layer of epoxy resin, again three-dimensional 8-node interface elements were chosen to model delamination and slip of the bonding material. The normal and shear behavior of the interfacial material was modelled using bi-linear functions, as shown in Figure 3. The input parameters included the cohesive energy (G_{fc}), crack opening width at the peak stress (v_c) and crack opening width at the zero stress transfer (v_m), depended on the specifications given by the manufacturer [21].

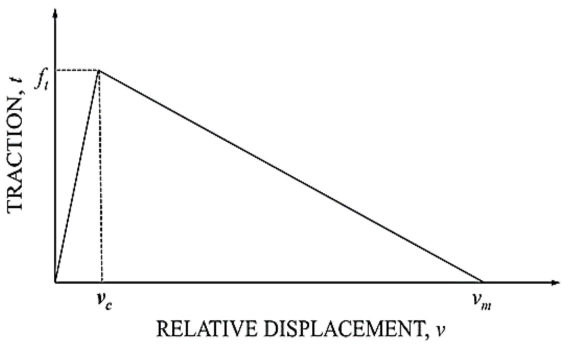


Figure 3 Bilinear material behavior at the interface.

2.2 Geometrical modeling and boundary conditions

To reduce computational effort used in the finite element analysis, only one-quarter of the column was modelled. The boundary conditions were set to preserve geometric symmetry of the columns and the loading. The forces were applied using so-called displacement control. The vertical displacements of the nodes on the top plane were set to be equal, and the vertical displacements of the nodes on the bottom plane were fully restrained. These boundary conditions are illustrated in Figure 4.

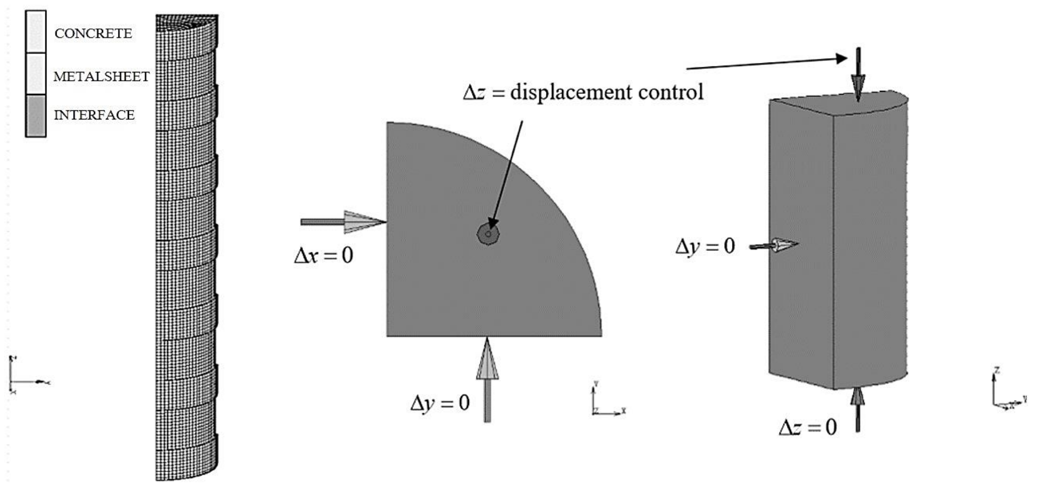


Figure 4 Boundary conditions.

Table 1 Details of the columns used in this study.

Group	Column	Width of Strip (cm)	Number of Strips	Number of layers	Remarks
C0	C0-0-0	n/a	n/a	n/a	No confinement
C5	C5-7-1	5	7	1	Discrete confinement
	C5-7-2	5	7	2	
	C5-7-3	5	7	3	
C7.5	C7.5-7-1	7.5	7	1	
	C7.5-7-2	7.5	7	2	
	C7.5-7-3	7.5	7	3	
C10	C10-7-1	10	7	1	
	C10-7-2	10	7	2	
	C10-7-3	10	7	3	
C75	C75-1-1	75	1	1	Continuous confinement
	C75-1-2	75	1	2	
	C75-1-3	75	1	3	

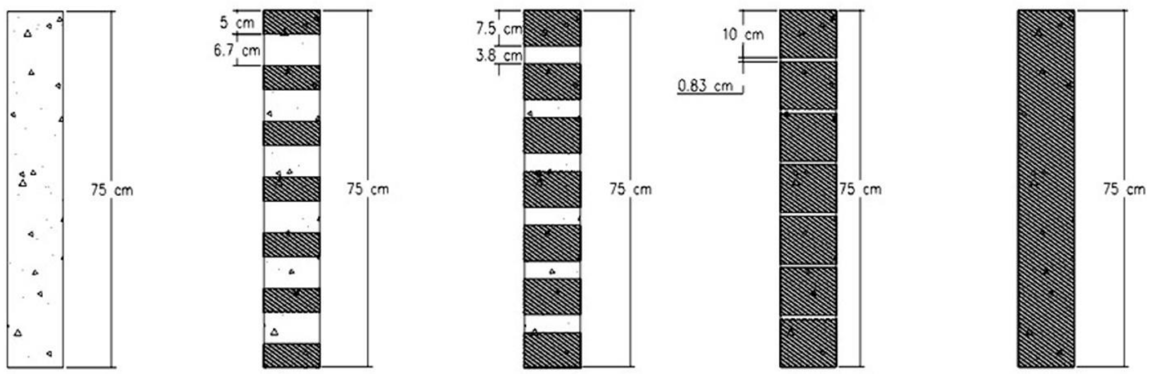


Figure 5 Setup of the columns in this study.

3. Columns in the analyses

In this study, 13 cylindrical concrete columns, 15 cm diameter and 75 cm height, were selected for the finite element analyses. As a reference, one of the columns did not have any confinement. The next nine columns were confined discretely with seven strips of three varying sizes and layers. The remaining three columns were fully confined with one continuous piece of metal sheet, with various layers of confinement. Detailed information is given in Table 1. The setup of columns are schematically shown in Figure 5.

The unconfined uniaxial compressive strength of the concrete used in this study was 19.4 MPa. The modulus of elasticity and Poisson's ratio were computed following the standard of ACI Committee 318 [20]. Properties of the metal sheets were the manufacturer specifications [22]: the tensile strength was 550 MPa, the thickness was 0.23mm, the modulus of elasticity was 200 GPa, and Poisson's ratio was 0.3. The input for the bonding material (epoxy resin) included a cohesive strength of 17 MPa, and moduli of elasticity of 5000 MPa and 4600 MPa for tension and for compression, respectively. These input parameters were based on information given by the manufacturer [21].

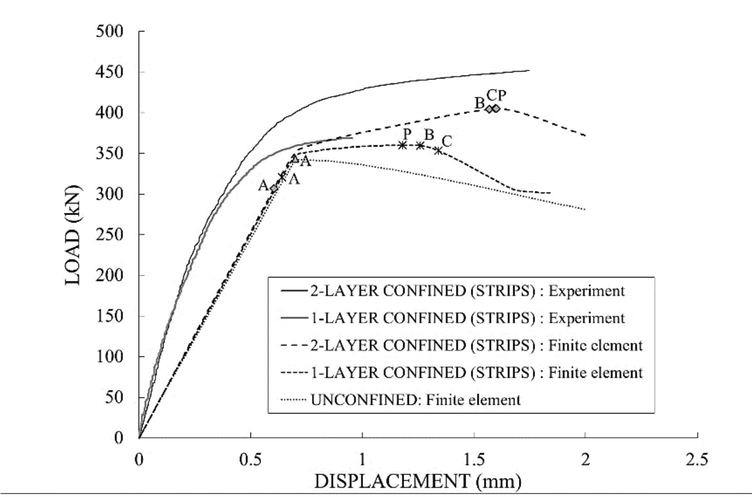


Figure 6 Axial load-displacement relationship of the columns confined with 1-layer and 2-layers of metal sheet strips.

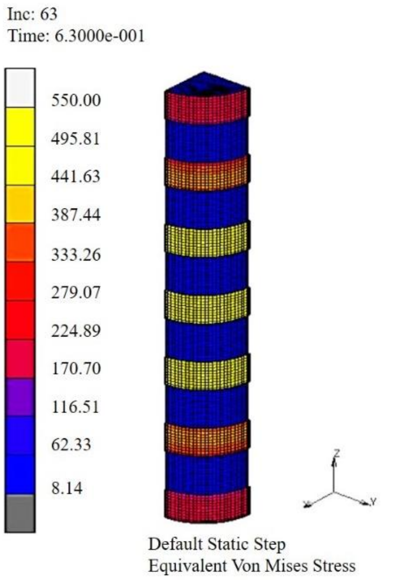


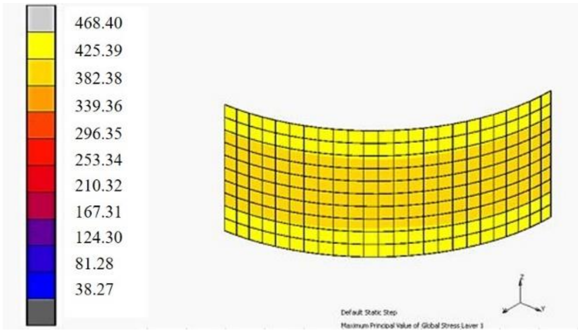
Figure 7 Distribution of equivalent Von Mises stress along the height of the confined column C5-7-1.

4. Results and discussion

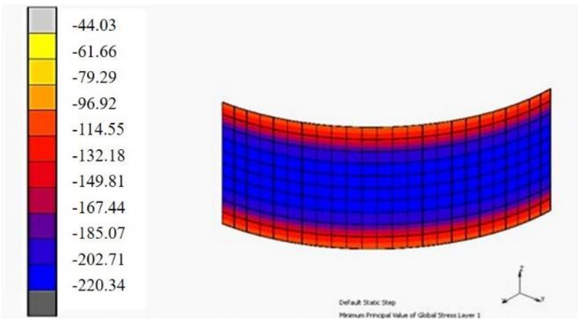
4.1 Behavior of concrete columns with stripped metal sheet confinement

To understand the behavior of concrete columns confined with strips of metal sheet, the specimens C5-7-1 and C5-7-2 confined with 5-cm metal sheet strips were chosen for general explanation. A four step mechanism revealed by the finite element analysis was plotted together with the experiment results from [12] as shown in Figure 6. Point A is when the stress at a point in any concrete element reaches its yield surface in compression. Point P is when the column reaches its peak axial load. Point B is when the metal sheet at middle strip yields, and Point C is when the metal sheet strip adjacent to the middle strip yields.

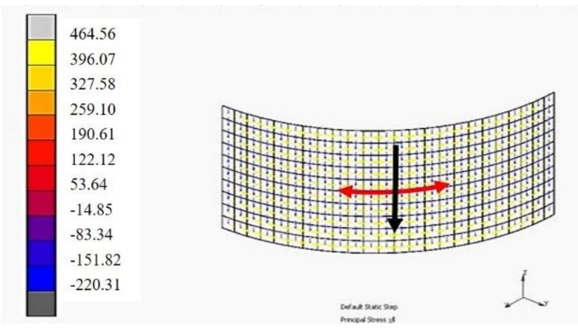
At Point B, distribution of the stress along the height of the column C5-7-1 is plotted in Figure 7. It was found that the stress state at a point in the fourth strip (the middle strip) reached the Von-Mises yield criterion at 550 MPa, thus implying that the strip yielded. However, when considering



(a) Stress distribution of the metal sheet strip in the circumferential direction



(b) Stress distribution of the metal sheet strip in the axial direction



(c) Vector of stresses in the metal sheet strip

Figure 8 Stress distribution at the middle (the fourth) metal sheet strip.

Table 2 Comparison of the confined compressive strength (f'_{cc}) obtained from finite element analysis and laboratory experiments [12].

Column.	Number of layers	Confinement area (%)	Experiment f'_{cc} (MPa)	Finite element f'_{cc} (MPa)
C0-0-0	0	0.00	19.40	19.41
C5-7-1	1	46.67	21.52	20.37
C5-7-2	2	46.67	24.62	22.90
C5-7-3	3	46.67	25.92	24.55
C7.5-7-1	1	70.00	23.44	21.82
C7.5-7-2	2	70.00	29.10	25.69
C7.5-7-3	3	70.00	35.51	29.70

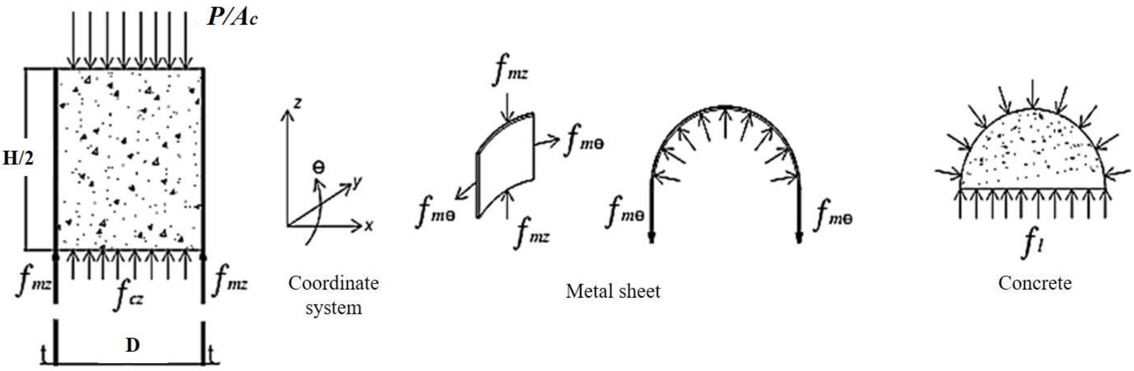


Figure 9 Free-body diagram of a cylindrical concrete column confined by a metal sheet.

the circumferential stress at a point, it was found that the tensile stress appeared to be only 468.40 MPa (cf. Figure 8(a)). Additionally, the compressive stress in the axial direction (loading direction) at this point appeared to be 220.34 MPa (cf. Figure 8(b)). When considering these two components together, the equivalent von Mises stress indeed reached the yield criterion as specified. From this observation, it was obvious that the metal sheet did not only yield due to increasing tensile stress in the confining direction, but also due to the addition of the increasing compressive stress transferred from the concrete core to the strips. This behavior is considered the result of bi-axial action, which can be shown in the plot of the stress flow vectors in both directions in Figure 8(c). Table 2 shows good agreement between the compressive strength modelled by finite element analyses and the existing experiment results by Korbkeu et al. [12].

4.2 Effective confining stress

Based on the work of Richart et al. [23], the axial strength prediction of confined concrete columns can be written in the form:

$$f'_{cc} = f'_{co} + k\, f_l \tag{5}$$

where f'_{co} and f'_{cc} denote the axial strengths of unconfined and confined concrete columns, respectively. The parameter k is the effectiveness coefficient, and f_l is the lateral confining pressure.

For confined concrete columns, the confining pressure f_l in Eq. (5) is indeed an average confining stress acting on the column and is analytically associated with the stress of the confining material. From [24], it was found that failure of the cylindrical columns confined by FRP occurred when the FRP reached its tensile strength. Since the FRP had merely lateral resistance to tension, but not to axial compression, use of its tensile strength in deriving the resulting confining stress to the concrete core was reasonable. On the other hand, as explained in the previous section, rigid material like a metal sheet does not only have lateral resistance to tension but can also be shown to carry axial compression. According to this view point, the behavior of the metal sheet confined concrete is different from FRP confined concrete. The mathematical formulation should analytically take the existing circumferential stress in the metal sheet to find the true lateral confining stress in the confined concrete column in derivation of the confining stress f_l in Eq. (5).

With the very small cross sectional area of the confining material compared with the cross section of the concrete column, contribution of the metal sheet strips in the axial direction was disregarded in the present study.

Considering the free-body diagram of a cylindrical column shown in Figure 9, when the column is confined, the confining pressure is developed along the circumference of the column. The lateral confining stress of confined concrete (f_l) is defined as:

$$f_l = \frac{2nf_{m\theta}t_m}{D} \tag{6}$$

where t_m, D, n and $f_{m\theta}$ denote thickness of the metal sheet, diameter of the concrete column, number of confining layers, and circumferential tensile stress in the metal sheet, respectively.

From the equilibrium and the deformation compatibility conditions, one of the factors affecting effectiveness of the discrete confinement is the area of effective confinement. It is expected based on the research by Mander et al. [25] that the area of effective confinement of strip-type confined

Table 3 Effective confining stresses obtained from FE analysis at the peak load.

Column	Effective confining stress of concrete (f_l) (MPa)		Average circumferential tensile stress of metal sheet strip ($f_{m\theta}$) (MPa)	Ratio of circumferential stress to yield stress ($f_{m\theta}/f_y$) (MPa)
	FE analysis	Eq.(6)		
C5-7-1	0.50	0.44	333.89	0.61
C5-7-2	0.79	0.83	317.32	0.58
C5-7-3	1.44	1.41	357.56	0.65
C7.5-7-1	0.67	0.76	369.61	0.67
C7.5-7-2	1.42	1.56	382.52	0.70
C7.5-7-3	2.02	1.61	262.05	0.48
C10-7-1	0.92	0.99	351.08	0.64
C10-7-2	1.91	1.58	279.33	0.51
C10-7-3	2.73	2.12	249.19	0.45
C75-1-1	0.97	0.99	324.04	0.59
C75-1-2	1.85	1.84	300.50	0.55
C75-1-3	2.85	2.84	309.02	0.56

columns is less in comparison to full (continuous) confinement, depending on the pattern of the partial confinement. Under a force equilibrium condition, the confining force in the concrete P_c and the tensile force carried by the metal sheet P_m (cf. Figure 10) can be written as:

$$P_c = P_m \tag{7}$$

Given f_c the average compressive stress in concrete in the normal direction to the cut plane, $f_{m\theta}$ the tensile stress in metal sheet in the circumferential direction, t_m the metal sheet thickness, D the column diameter, n number of the metal sheet layers, b the metal sheet strip width, and s' the strip clear spacing measured from edge of particular strip to edge of consecutive strip, the resultant compressive force in concrete can be computed from:

$$P_c = f_c(b + s')D \tag{8}$$

and the tensile force carried by metal sheet can be computed from:

$$P_m = 2 f_{m\theta} ntb \tag{9}$$

Substituting Eq. (8) and Eq. (9) in Eq. (7), we get:

$$f_c = \frac{2 f_{m\theta} ntb}{D(b + s')} \tag{10}$$

Here, f_c is seen as the average effective confining stress. Therefore, the prediction equation formerly proposed by Richart et al. [26] should consider effectiveness of strip-type confinement by redefining the effective confining stress f_l as:

$$f_l = \frac{2 f_{m\theta} ntb}{D(b + s')} \tag{11}$$

From the finite element analyses, the associated stresses at the middle of the column height (z = 375mm) were evaluated where the maximum lateral expansion occurs. At the peak load (Point P in Figure 6), the effective confining stress obtained from the finite element analyses and from Eq. (11) were compared as in Table 3, where it is seen that the confining pressure varied with the number of layers. With the series of columns in this study, it was found that the average circumferential stress induced in the metal sheet ranged from 0.4 to 0.7 times the specified yield strength.

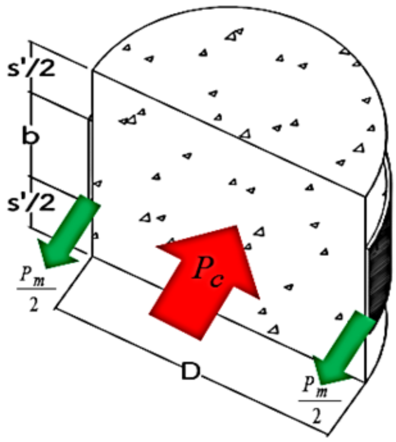


Figure 10 Forces in concrete and in a strip of metal sheet during loading.

4.3 Confinement effectiveness

From the previous section, use of metal sheet confinement showed its ability to strengthen axial capacity of concrete columns. However, efficiency of the technique should be assessed by considering confinement effectiveness, i.e., the ratio of axial strengths of the confined and unconfined columns(f'_{cc}/f'_{co}). From previous work [9-13] and the present research, there are many factors affecting the confinement effectiveness of strengthened concrete columns. These include confinement area, the number of layers of confinement, and the strength of the materials.

To demonstrate the effect of the confinement area to the strength increase of the columns, the response of concrete columns confined with 7 strips of one-layer metal sheet of the following strip sizes, 1.3 cm, 2.5 cm, 5 cm, 7.5 cm, 10 cm were compared with the fully confined situation. This variation of confinement area corresponded to percentages of confinement area of 12.5, 23.3, 46.7, 70, 93.3 and 100, respectively. It is shown in Figure 11 that the confinement effectiveness and the confinement area of the study column showed a nonlinear relation. When the confinement area was

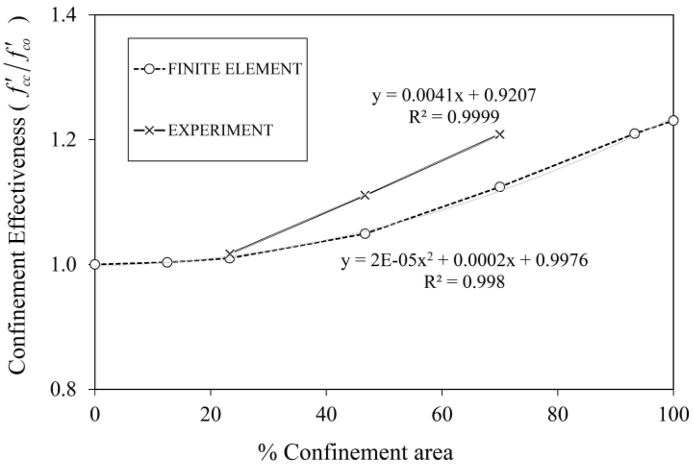


Figure 11 Relationship between confinement effectiveness and percent of confined area.

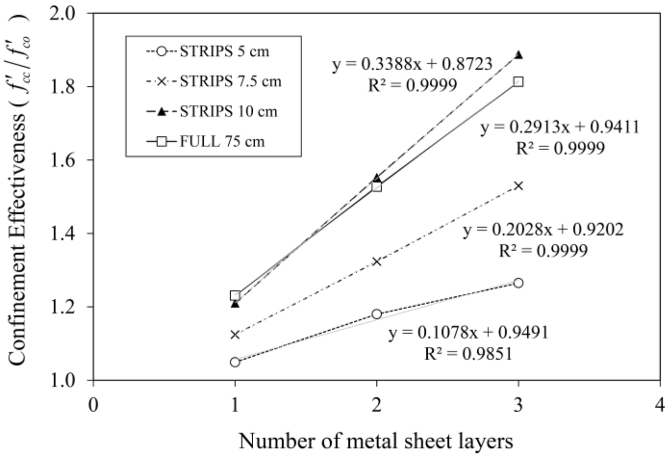


Figure 12 Relationship between confinement effectiveness and number of metal sheet layers.

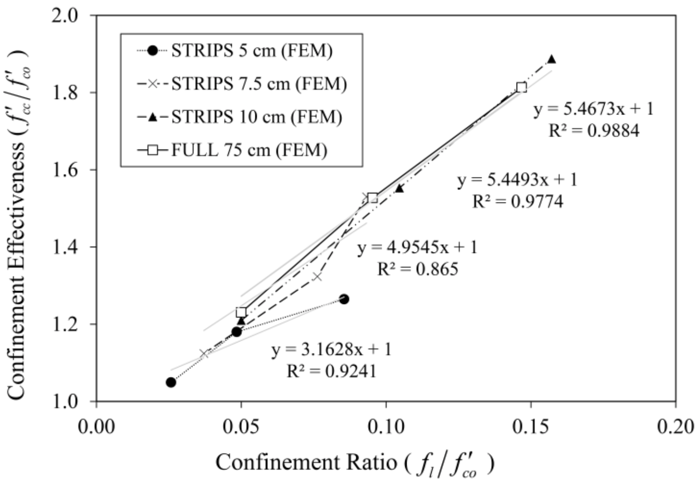


Figure 13 Strength prediction equation for cylindrical concrete columns confined by metal sheet from the FE analysis results.

increased, the confinement effectiveness of the confined columns tended to diverge from that of the unconfined columns. With a larger confined area, higher strength was achieved.

Similar to the confinement area, the axial compression capacity of the columns was increased when adding more layers of the metal sheet confinement, as shown in Figure 12. Both the discrete and the continuous confinement techniques showed similar trends in the strength increase. According to the finite element results, using larger metal sheet strips provided a higher rate of axial strength increase compared to smaller strips with more layers of confinement.

Strength prediction equations, following the form of Eq. (5), could be developed via setting the relationship between the confinement effectiveness (f'_{cc}/f'_{co}) and the confinement ratio (f_l/f'_{co}). Using the lateral confining pressure obtained from the finite element analysis, a set of prediction equations corresponding to each strip size could be created as shown in Figure 13.

5. Conclusions

In this paper, a series of finite element analyses was performed to study the response of concrete columns confined by metal sheet in discrete form. The numerical results showed that, under axial compression, the metal sheet strips could help to confine the concrete columns and increase the compressive strength of the columns. The metal sheet strips exhibited a bi-axial response i.e., resisting the tensile circumferential stress associated with lateral expansion of inner concrete and also absorbing compression transferred axially from the concrete core. This action suggested that the effective confining stress in concrete column must not be analytically derived merely from the theoretical yield strength of the metal sheet in tension. At the peak load of the column, the average effective circumferential tensile stress in the metal sheet was shown to range from 0.4 to 0.7 times the specified yield strength. This paper demonstrates that strength development with the discrete (strip-type) confinement depends on size, spacing and number of layers of the applied metal sheet strips. The procedure from this study can be exercised to create a set of strength prediction equations for general columns in the near future.

6. Acknowledgments

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