

FINITE ELEMENT MODELING OF CONCRETE SPECIMENS CONFINED WITH METAL SHEET STRIPS

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ABSTRACT

This paper introduced a nonlinear finite element model using Msc.MARC to study behavior of concrete columns partially confined with metal sheet strips under uniaxial compression. The concrete and the metal sheet parts were modeled using the linear Mohr-Coulomb yield criterion and the Von-Mises yield criterion, respectively. Behaviors of the interface (bonding) material, both in the normal direction and the parallel direction to the interface, were modeled as a bilinear function based on the cohesive energy and the crack widths. The columns in this study had circular cross sections with the diameter of 15 cm and the height of 75 cm, wrapped around by 5 cm metal sheet strips. The results from 3D finite element modeling were analyzed for internally induced stresses and strains. The predicted column behavior was compatible with observed experimental data. The detailed mechanisms that were difficult to visualize during the laboratory experiments could be obtained from the analysis. It was revealed that the area of confinement and the number of applied metal sheet layers were important factors to the strength increase. The discrete confinement system was shown to be a promising alternative to the one-piece full-wrap system.

Keywords: Column; Concrete; Confinement; Finite element analysis; Metal sheet

1. INTRODUCTION

At present, there are many techniques to strengthen concrete columns. One popular technique is to use a high strength thin sheet material, such as fiber-reinforced polymer (FRP), to wrap around the columns (Mirmiran & Shahawy, 1997; Mirmiran et al., 1998; Wu et al., 2006; Ozbakkaloglu et al., 2013) to provide lateral confinement to the columns. This external strengthening technique can improve axial capacity effectively while still keeping architectural dimensions of the existing core columns.

However, special materials like the FRP can be costly and also need some specialists for installation, some researchers have been trying to find alternatives. At the Department of Civil Engineering, Khon Kaen University, metal sheet was put under investigation for use as a confining material, alternatively to the FRP. Being thin, light-weighted and available almost everywhere in Thailand, the metal sheet was expected to be an interesting material to strengthen the concrete columns. So far, there have been studies on axial strength increase and behavior of of the strengthened columns in the laboratory (Khamthong et al., 2011; Wangsa et al., 2011; Boonyarat et al., 2012; Korbkeu et al., 2013; Positong & Pannachet, 2014), as well as in the finite element modeling (Hongsinlark et al., 2014). The experimental and numerical results

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agreed that confining columns with metal sheet could increase the axial load carrying capacity of the columns when applied with a sufficient amount of metal sheet via a suitable technique. Similar to the use of the FRP, the metal sheet confinement could help resisting lateral expansion of the columns, correspondingly increasing the load carrying capacity. In addition, it was observed that the metal sheet also helped carrying the axial load through a shear transfer mechanism at interface between the core concrete and the metal sheet jacket (Khamthong et al., 2011; Boonyarat et al., 2012). The evidence was that, at the column failure, wrinkle and tearing of the metal sheet could be seen. When wrinkles appeared, implying that the metal sheet tried to resist axial load along with the concrete core, the bonding of the metal sheet and the concrete around the wrinkles was lost, creating a weak zone at the interface before the column had completely failed. Besides the wrinkling problems, wrapping large metal sheet around columns was found to be a tedious task, also requiring very careful attention on quality control of the interfacial bonding.

To seek a better solution, a series of metal sheet strips was applied instead of using one large piece of metal sheet (known as full confinement) (Wangsa et al., 2011; Korbkeu et al., 2013; Positong & Pannachet, 2014). It was found in the laboratory experiment that the discrete confinement using strips of metal sheet could ease the installation process of metal sheet on the concrete columns, and could also reduce the wrinkling effect (and thus, the unbonding problem) of the metal sheet (Figure 1). The discrete confinement system also showed more efficiency than the full confinement system; therefore, with the same amount of metal sheet used in the application, the columns with discrete confinement could gain more strength than the ones with one-piece full confinement (Korbkeu et al., 2013; Positong & Pannachet, 2014).

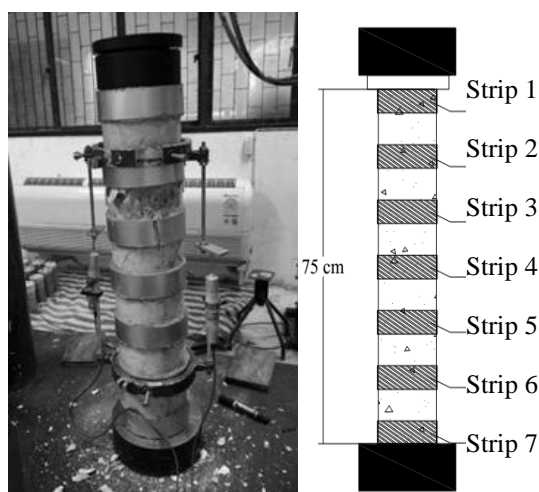


Figure 1 Metal sheet discrete confinement system (Positong & Pannachet, 2014)

Besides the laboratory experiments, numerical modeling of the confined concrete columns is necessary. In many occasions, the laboratory results cannot be explained because some physical mechanisms and stress distribution are hard to visualize during the experiment. So far, there have been attempts of modeling the FRP-confined concrete columns using 3D nonlinear finite element analysis (Mirmiran et al., 2000; Shahawy et al., 2000; Teng et al., 2007; Koksall et al., 2009; Yu et al., 2010) The results from the proposed models agreed well with the experiments and could be used for strength prediction.

Unlike the FRP, which resists only tension, metal sheet can resist both tension and compression. As a pioneering work, a finite element model of the concrete specimens confined with full metal sheet wrap was proposed (Hongsinlark et al., 2014). The results from the model

gave information of what happened during axial compression loading of the columns. However, as the previous study did not cover application of columns confined with metal sheet strips, a finite element model for the discrete system of confinement will be presented in this paper and verified with the experimental results from Korbkeu et al. (2013). The result will also be compared with the results from the full-wrap system, so that interested researchers and engineers can understand the detailed mechanisms of this strengthening system and provide further development in the future.

2. COMPUTATIONAL MODELING

In this study, we performed some nonlinear finite element analyses using the software MSC.Marc (MSC Software Corporation, 2010). The model consists of three materials (concrete, metal sheet and interface bonding materials), each of which exhibits different material behaviors. Details of the modeling are described as follows.

2.1. The Geometric Model and the Boundary Conditions

In this study, our specimens are concrete columns having the diameter of 15 cm and the height of 75 cm, confined by 7 metal sheet strips of 5 cm. Both materials are bonded using Sikadur®-31 CF Normal epoxy resin (Sika Thailand Company Ltd., 2011). Due to two-plane symmetry of the cross section, only a quarter is modeled. The boundary conditions include restraints in the normal direction to both cut planes. Uniform load is gradually applied under displacement control in the vertical direction at the top plane, as shown in Figure 2.

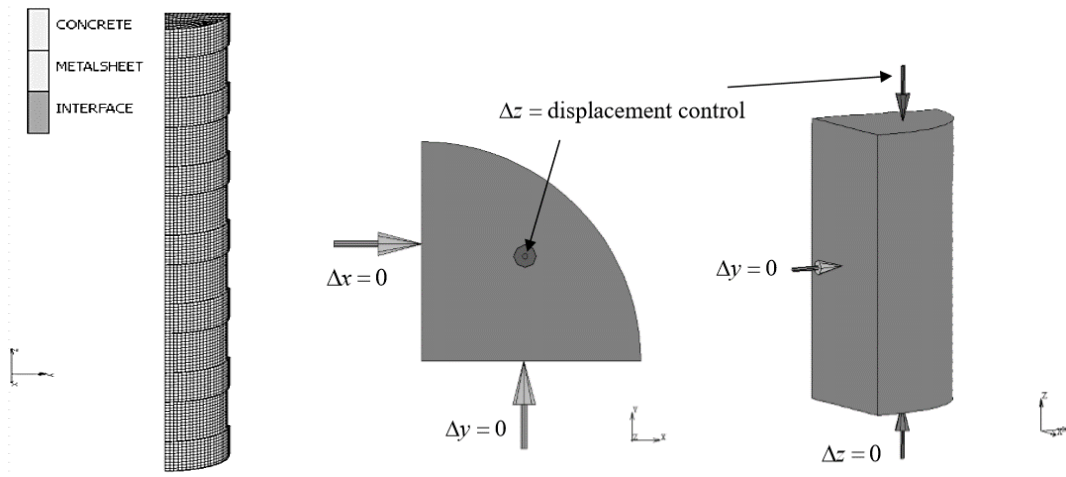


Figure 2 The discretized model and the boundary conditions

2.2. The Concrete Model

In this study, eight-noded solid brick elements (See Figure 3) are chosen for modeling of the concrete part. The tri-axial compression behavior is modeled by using linear Mohr-Coulomb yield criterion. The yield function is defined as shown in Equation 1 below:

$$F = \alpha J_1 + \sqrt{J_2} - \kappa \quad (1)$$

where the first stress invariant (J_1), the second deviatoric stress invariant (J_2) and the softening function (κ) are as shown in Equations 2, 3, and 4:

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (2)$$

$$J_2 = \frac{1}{6} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2] \quad (3)$$

$$\kappa = \sigma_c (1/\sqrt{3} - \alpha) \tag{4}$$

In Equation 4, σ_c is the stress in concrete under uniaxial compression and α is a friction parameter, which in this paper selected as 0.2934.

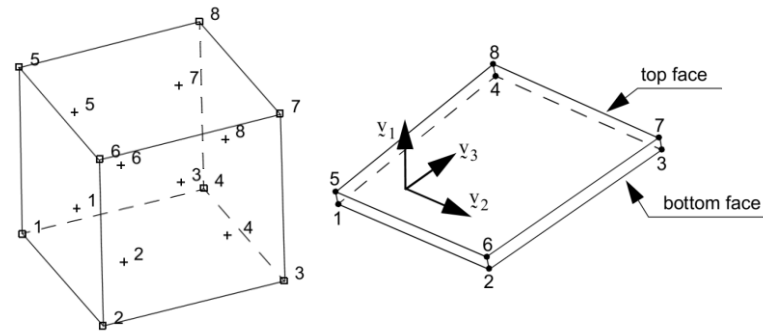


Figure 3 The 8-noded solid brick element (left) and the 8-noded interface element (right)

In the pre-peak modeling, the linear stress-strain relationship based on the axial strength (f'_c) of 19.4 MPa and Young’s modulus formula of the ACI specification is used. Softening behavior of the concrete is modeled using the post peak function of Popovics’ uniaxial stress-strain relationship (Popovics, 1973) as shown in Equations 5 and 6:

$$\frac{f_c}{f'_c} = \frac{n \left(\frac{\epsilon_c}{\epsilon_{co}} \right)}{(n-1) + \left(\frac{\epsilon_c}{\epsilon_{co}} \right)^n} \tag{5}$$

where

$$n = 0.4 \times 10^{-3} f'_c [\text{psi}] + 1.0 \tag{6}$$

and $\epsilon_{co} = 0.002$. The concrete model with the softening function was previously employed in Hongsinlark et al. (2014) and it showed its ability to model concrete behavior with uniform confinement as in Figure 4.

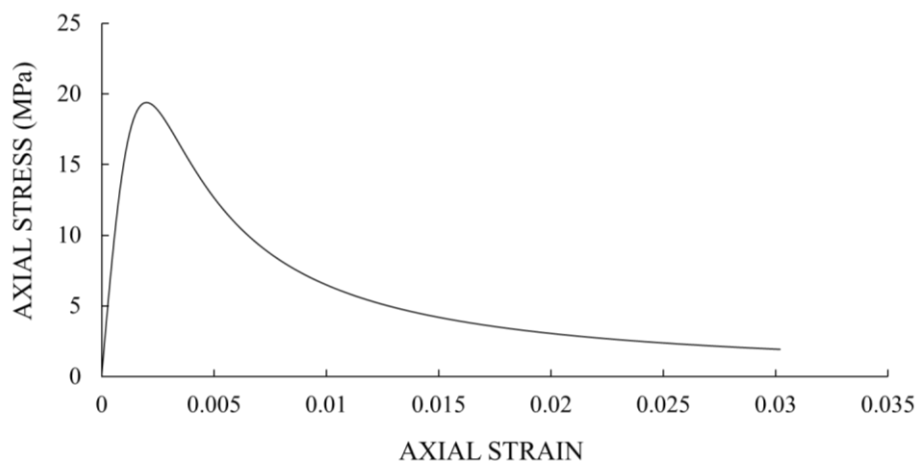


Figure 4 Uniaxial stress-strain curve of concrete, according to the work of Popovics (Popovics, 1973)

To prevent the mesh dependency problem (Rots, 1988) that often occurs in typical concrete modeling, we use the compressive fracture energy (G_{fc}) of concrete as a control parameter, as suggested in Lertsrisakulrat et al. (2001). In our model, tensile cracking is also allowed via the smeared crack concept (Rots, 1988).

2.3. The Metal Sheet Model

In modeling the metal sheet part, eight-noded solid brick elements are also used. The metal sheet is assumed to exhibit an elastic-perfect plastic material behavior, and the Von-Mises yield criterion is employed. The modulus of elasticity, the yield strength and the Poisson's ratio are assigned in the analysis as 200 GPa, 550 MPa and 0.3, respectively.

2.4. The Interface Model

The interface part between the concrete core and the metal sheet accounts for delamination and slip of the bonding material, i.e. the epoxy in this study. Eight-noded three-dimensional interface elements are used (See Figure 3). Behaviors of the interface material, both in the normal direction and the parallel direction to the interface, are modeled as bilinear functions, as shown in Figure 5 (MSC Software Corporation, 2010). The input parameters, including the cohesive energy (G_c), crack width at the ultimate stress and at the zero stress transfer (v_c and v_m), are computed using information from the manufacturer (Sika Thailand Company Ltd., 2011).

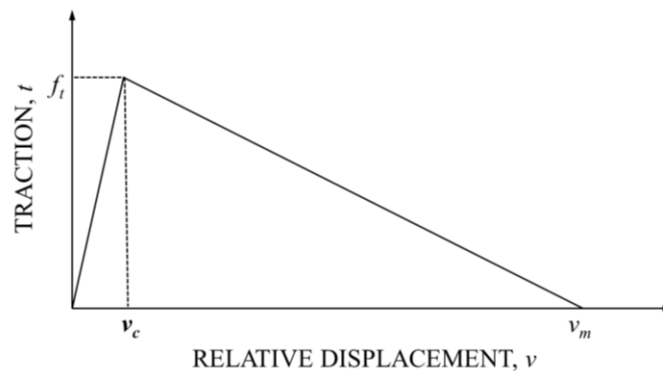


Figure 5 Bilinear material behavior at the interface

3. NUMERICAL RESULTS AND DISCUSSIONS

3.1. Behavior of Concrete Columns Confined with Metal Sheet

From the finite element analysis, the axial compression load-displacement relationship of the columns confined with 1-layer and 2-layer metal sheets are plotted in Figure 6, in comparison with the laboratory experimental results from Korbkeu et al. (2013) and Positong & Pannachet, (2014). Both results agree well. The small difference might be due to lack of sufficient experimental data, such as material properties of metal sheet and epoxy, as described in the experiment (Korbkeu et al. 2013; Positong & Pannachet, 2014).

The results obtained from the finite element analysis can explain some detailed mechanisms that are difficult to visualize during the laboratory experiments. In the load-displacement relationship shown in Figure 6, four critical points can be observed; Point A is where the stress in concrete is at the yielding stage (or at the boundary of the Mohr-Coulomb yield surface), Point P is where the stress is at its ultimate capacity, Point B is where the fourth metal sheet strip (located at the middle of the height) yields, and the yielding of the third and fifth strips (adjacent to the middle strip) occurs at Point C.

In the one-layer metal sheet confined specimens, axial compressive behavior is elastic before

yielding of the concrete. When the specimens are compressed axially, it creates compressive strain in the axial direction as well as expansion in the perpendicular directions, according to the Poisson's effect of the concrete core. With metal sheet confinement, this lateral expansion creates a confining pressure to the metal sheet. When the concrete stress reaches the Mohr-Coulomb yield criterion at Point A, the concrete starts to behave inelastically. At this point, the metal sheet strips try to resist the lateral expansion of the concrete core as well as the axial load, resulting in a hardening behavior starting at Point A. Upon further loading, the confining pressure continues increasing until the column reaches its ultimate load carrying capacity at Point P. The metal sheet strip located at the middle of the height (the fourth strip) is found to yield first at Point B, followed by the adjacent strips (the third and the fifth strips) at Point C. After that, softening behavior occurs, similarly to the unconfined specimen.

Mostly like the above results, the two-layer metal sheet confined specimens; however, show some different behaviors. Yielding of the metal sheet strip at the middle height (the fourth strip) is found to occur only on its outer layer at Point B. The adjacent strips (the third and the fifth strips) then start yielding in a similar manner, i.e. also only at their outer layers, at Point C. Upon the yielding of the outer layers, the inner layer of the strips can still resist the lateral expansion of the concrete core, until the specimen reaches its ultimate load carrying capacity at Point P.

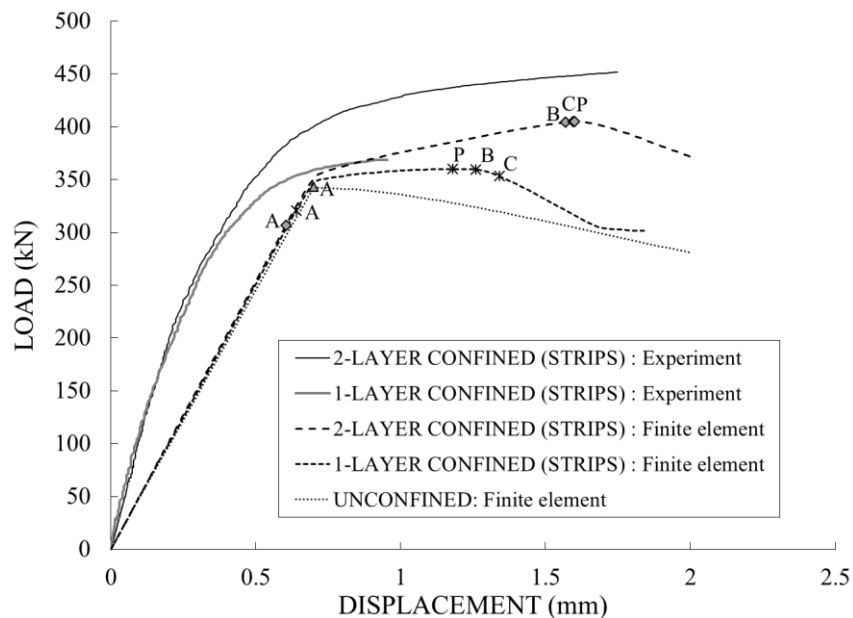


Figure 6 Axial load-displacement relationship of the columns confined with 1-layer and 2-layer metal sheet strips

To verify the numerical results, the results from a laboratory experiment (Positong & Pannachet, 2014) are used for a comparison. Figure 7 shows the stress-strain relationships of the concrete columns confined with one layer of seven 5-cm metal sheet strips. Average numerical results are used. The numerical axial stress is determined by summing up axial forces at the top end of the column, then dividing it by its cross-sectional area. The numerical axial strain is determined by using the shortened length of the columns divided by the column height, and the circumferential strain is measured at the mid-height point, so that it is comparable to the laboratory results. It should be noted here that, in Figure 7, the positive strain refers to the direction of compression, whereas the negative strain refers to the direction of tension.

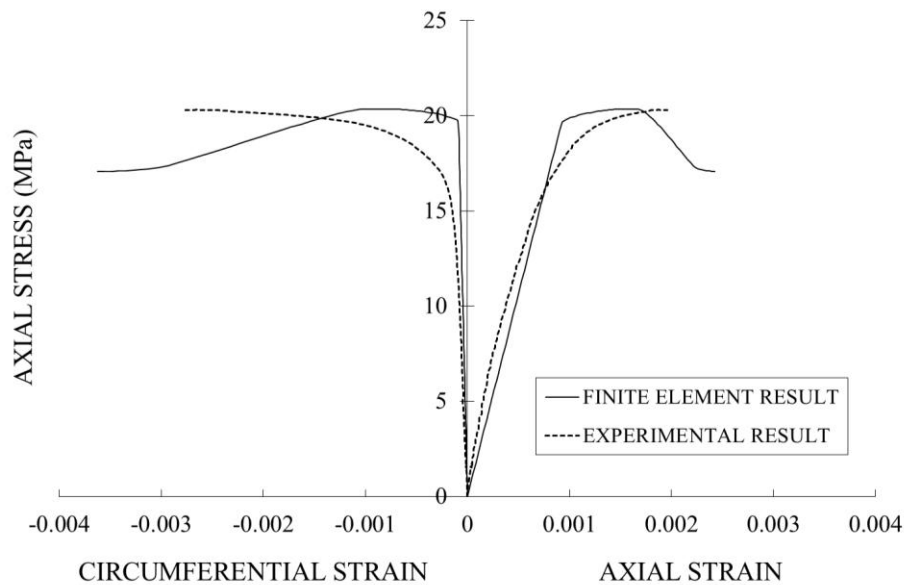


Figure 7 Comparison of the one-layer metal sheet confined specimens between the finite element results and the experimental results

3.2. Full Confinement VS Discrete Confinement

The numerical results of the columns confined with metal sheet strips are similar to the results of using one-piece full wrap metal sheet, i.e. the confined columns have higher axial strength than the unconfined ones. The area of confinement and the number of applied metal sheet layers are also important factors to the strength increase. In Figure 8 and Figure 9, it was found that the columns with 2-layer discrete confinement (strips) can gain strength as comparable to the 1-layer full wrapped columns, despite the fact that the discrete confinement system covers only 46.77% of the side surface area of the columns.

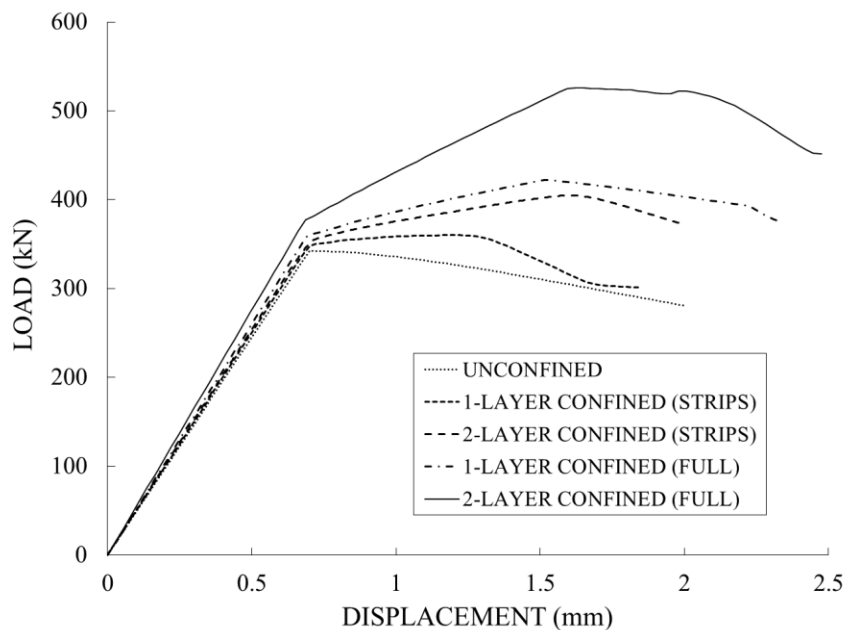


Figure 8 Comparison of the axial behavior between the results from the full confinement and the discrete confinement

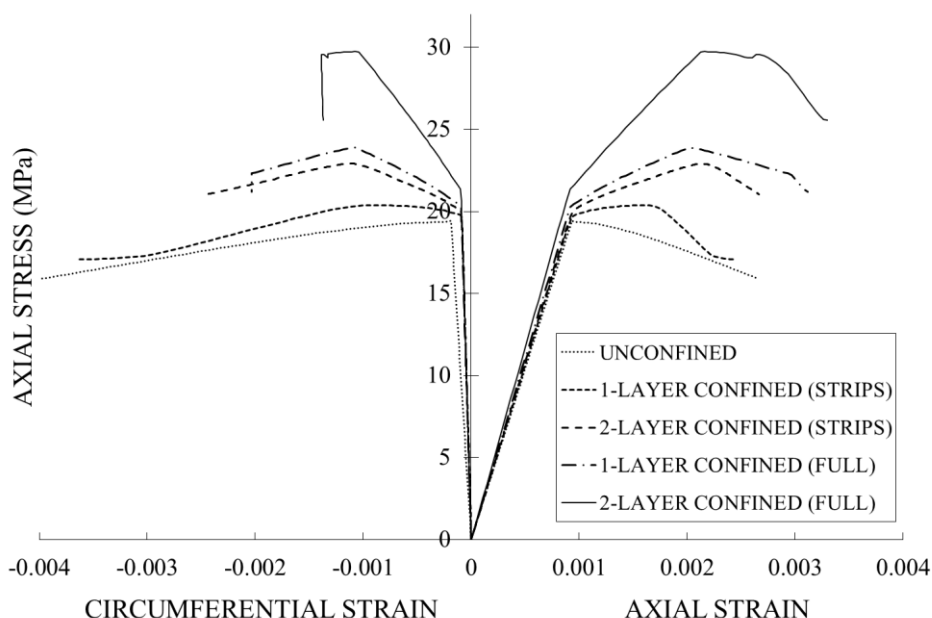


Figure 9 Comparison of the axial and circumferential behaviors between the full confinement results and the discrete confinement results

4. CONCLUSION

The finite element analysis results show that confining the concrete columns with metal sheet strips can enhance its axial compression capacity. The extent of the enhancement depends on the number of applied layers; the more layers, the more strength increase. The results between the 1-layer full wrap and the 2-layer discrete wrap systems are comparative. Applying discrete strips of metal sheets can lead to a more efficient technique than the one-piece full-wrap system, due to its simpler installation. The discrete system can be a good alternative for axial strengthening of concrete columns.

5. ACKNOWLEDGEMENT

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