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Axial Compressive Strength of Metal Sheet Confined Concrete Cylinders Based on Various Concrete Strengths

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Abstract

This paper investigated effect of concrete strength on axial strength improvement of the metal sheet confined concrete cylinders under axial compression. Totally, 27 concrete specimens were tested based on three different concrete strengths of approximately 13, 32 and 39 MPa. Epoxy was used as a bonding material along interface between concrete and metal sheet. Based on three different concrete strengths, different level of confinement was established by taking one layer and three layers of metal sheet confinement. The experimental results revealed that axial compressive strength of concrete cylinders could be improved by mean of metal sheet wrapping. It was shown that effectiveness of axial strength improvement of metal sheet confined concrete cylinders depended on original unconfined compressive strength of the core concrete. With lower concrete strength, it was found that use of metal sheet confinement could increase the original strength of the columns more effectively than the case of higher concrete strength. Based on existing results, it was observed that strength improvement prediction given by Richart et al. (1928) could be adopted conservatively with exception of very low concrete strength.

Keywords: Concrete Strength; Metal Sheet; Axial Compression; Confinement; Strengthening.

1. Introduction

Metal sheet is commonly used for roofing and cladding in Thai building construction. Despite being thin and lightweight, it possesses mechanical properties of steel. The material is typically coated with Aluminum-Zinc making its surface durable against corrosion. All of these properties indicate a possibility of using the metal sheet in strengthening applications. The metal sheet can be applied on concrete members without changing size and weight of the existing structural members. This is an advantage over the concrete jacketing [1] or the steel jacketing [2]. Compared with the fiber reinforced plastic (FRP) materials, the metal sheet contains some similar properties that are suitable for external strengthening of concrete structures. Despite its relatively lower tensile strength and different rigidity, the metal sheet is however less expensive thus considered here as an attractive choice for alternative economical rehabilitation.

Use of metal sheet as a strengthening material for concrete structures has been new to engineering community .In recent years, applications of metal sheet as a strengthening material for concrete members have been researched, including possible installation on floor panels, beams and columns [3-7]. However, the main focus of the recent research has been on concrete columns, where the metal sheet has been employed as a confining material. It was found in the laboratory experiments [6-7] as well as the numerical analyses [8-10] that the metal sheet confining system could improve axial strength of the concrete specimens. In addition, behavior of the metal sheet confined concrete was found to be somewhat different from the FRP confined concrete. Appearance of local buckling of the metal sheet jacket was

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shown, implying that the jacket resisted tension in the hoop direction (known as confinement effect) and also resisted compression in the axial loading direction along with the concrete core.

Although one could see possibility of using metal sheet to strengthen concrete columns, there have still been some questions regarding parameters relating strength increase of the metal sheet confining system. It has been expected that axial behavior of the metal sheet confined concrete would depend on various factors that also affect corresponding design equations. Results from many studies have indicated that the behavior of the FRP confined concrete depended on fiber type, resin type, fiber orientation, fiber thickness, number of applied layers, cross section shape, concrete strength, and etc. [11-14]. However, only two factors have so far been investigated for the metal sheet confined concrete, i.e. number of applied layers and specimen shapes. It was reported in [6-10] that adding more layers of metal sheet confinement improved axial capacity of the concrete specimens. Regarding the shape of the specimens [15], it was found that circular cross section was the most effective in getting confined by metal sheet. For other shapes, concrete specimens of a smaller aspect ratio were found to be more effective under confinement than those of a larger aspect ratio. Besides these two factors, there are yet many other factors to be explored, such as effect of involving material properties, specimen size effect, or confinement patterns. For this study, we aim to investigate effect of core concrete strength on axial behavior of metal sheet confined concrete. It is interesting to see how the system works for various concrete strengths. Discussion on this matter for the metal sheet confined concrete has never been mentioned in any articles before.

Up till present, there have been a very limited number of research works regarding effect of concrete strength on behavior of metal sheet confined concrete. Some available are of FRP confined concrete. For example, in 2007, there was one investigation on axial compressive behavior of concrete cylinders with six different concrete strengths 47-107 MPa confined with E-glass/epoxy FRP (GFRP) jackets [16]. The results revealed that GFRP confinement improved performance of the unconfined specimens, in terms of both compressive strength and ductility. However, it was found that effect of confinement reduced for higher strength concrete. It was reported in [17] from their experimental results that, for high strength 55-100 MPa and ultra-high strength >100 MPa concrete specimens, highly ductile behaviors were exhibited when confined with the FRP. As the concrete strength increased, axial performance of the confined specimens decreased. The result from [17] was one of the other information used in a newly proposed model [18], applicable to both FRP-confined concrete with concrete strengths up to 120 MPa. Another model was proposed using database from various sources, covering specimens with different concrete strengths between 6.2-169.7 MPa [19]. For higher strength concrete, smaller hoop rupture strain of the FRP shell was observed.

Since the scope of this study is not for high strength concrete but rather normal strength concrete, the concrete strengths in this study were selected up to 40 MPa. This was to be practical since our original goal of using metal sheet confinement system is for strengthening small building structures. In this study, standard cylinders with three concrete strengths, confined with one and three layers of metal sheet, were tested. The experimental results were then discussed, in comparison to the finite element results [15] regarding correlation between the concrete strength and the axial behaviors. Finally, the results were plotted in a normalized relationship and compared to the strength prediction equation by Richart et al.(1928) [20] to see if it could be applicable to the metal sheet confinement system.

2. Experimental Study

The test specimens in this study were cylindrical and were of the size $\phi 15 \times 30$ cm. Since effect of core concrete strength on behavior of metal sheet confined specimens was to be explored, three different core concrete strengths were selected and correspondingly categorized into three groups. As shown in Table 1, the specimens in Group A, B, C were made from three different concrete strengths, which were described in this paper as “lowest strength”, “middle strength”, and “highest strength” concrete, respectively. Proportions of three concrete batches were designed to reach three specified compressive strengths following ACI Standard 211.1 [21]. The plain concrete specimens were cured for 28 days. The samples from each batch were collected for the standard compression test at 28 days. The specimens were cleaned and left until their surfaces were completely dry before being wrapped by metal sheet. Installation of each metal sheet layer required an overlap length to be one-fourth of the specimen’s perimeter. Epoxy resin was applied as a bonding material. The jacketed specimens were left for 7 days to let the resin set before testing.

Table 1. Axial compressive strength of concrete following ASTM C39-12 [22]

Specimen Group	Designation	Concrete strength (f'_c) [MPa]
A	Lowest strength	12.7
B	Middle strength	32.2
C	Highest strength	39.1

To study behavior of confined concrete, Zinc-Alum metal sheet was selected as a confining material. The thickness of each sheet was 0.25 mm. According to the test ASTM E8/E8M-11 [23], the yield stress and the tensile strength of the sheet were 550 and 760 MPa, respectively. Two-part adhesive, based on combination of epoxy resins and special fillers, was used as a bonding material between the metal sheet and the specimen’s surface. Thickness of each adhesive layer was controlled to be uniform.

In each group, nine concrete specimens having the same concrete strength were prepared; three of which were unconfined, another three were wrapped with one layer of metal sheet, and another three were wrapped with three layers of metal sheet. In summary, the total 27 specimens were prepared for the test. Ending spaces of 5-mm each were left at the uppermost and the lowermost parts of the confined specimens to make sure that the loading was not directly applied on the metal sheet jacket, as shown in Figure 1.

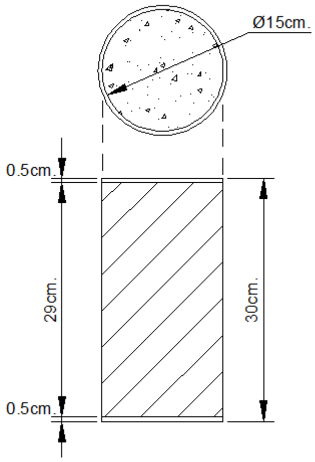
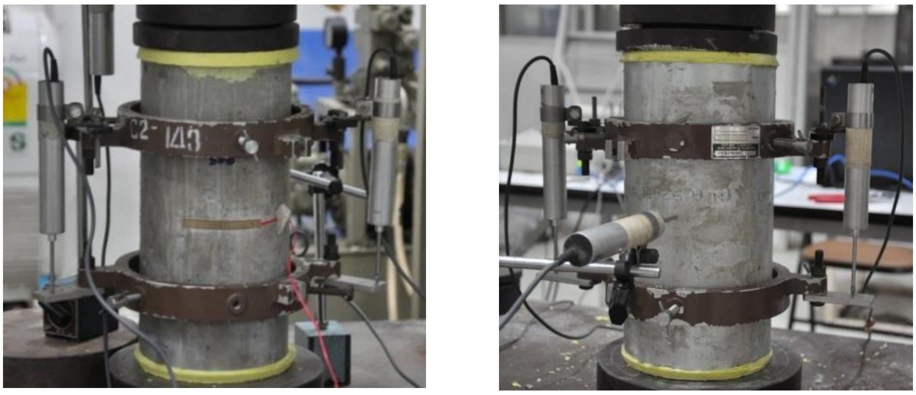


Figure 1. Size of the confined specimens

The experimental set up for the test is shown in Figure 2. Each specimen was placed in the universal testing machine. Two linear variable differential transducers (LVDT) were installed in the middle part of the specimen using the compressometer, for evaluating axial deformation of the specimen during the compression loading. The gauge length was set to be 20 cm. At the middle of the height, another LDVT was aligned horizontally to measure lateral expansion and a strain gauge was attached to measure lateral deformation in the circumferential (hoop) direction.



(a) Front **(b) Back**

Figure 2. The experimental set up

3. Laboratory Results

3.1. Axial Compressive Strength of Confined Columns

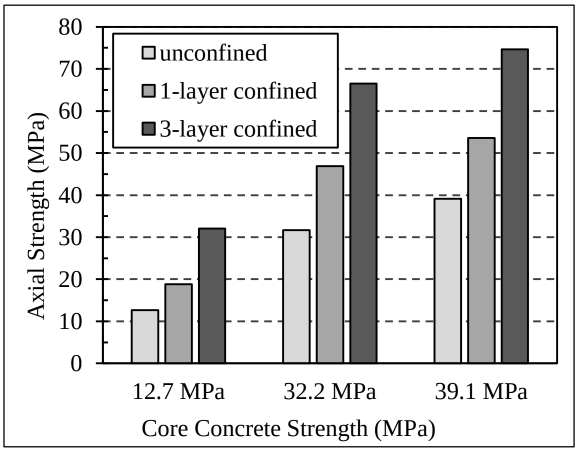
From the laboratory experiment, the axial compressive strengths of the specimens in each group are collected in Table 2. It could be seen that the metal sheet confinement system could improve strength of all the unconfined specimens, from 1.4 to 2.5 times the unconfined strength. The level of improvement depended on the applied layers of metal sheet; the more layers provided higher axial compressive strength of the specimens. However, the strength increases were not exactly in a linear relation to the number of applied layers.

Axial compressive strength of the core concrete was found to be a factor influencing compressive strength increase of the specimens. The results of axial strength increase as compared with the unconfined specimens are also shown in Table 2. The lowest percentage of the strength increase was obtained in Group C specimens with one layer of confinement, and the highest percentage of the strength increase was obtained in Group A specimens with three layers of confinement. It was observed that the specimens with higher core concrete strength tended to provide lower strength increase than the specimens with lower core concrete strengths. With one-layer confinement, the axial strength of the concrete specimens in Group A was 48.4% improved, whereas the specimens in Group B and C showed 45.7% and 37.1% respectively. Similarly, the strength increase of the three-layer confined concrete gave the same trend; axial strength of the specimens in Group A could be improved to 153% of the confined concrete, whereas the specimens in

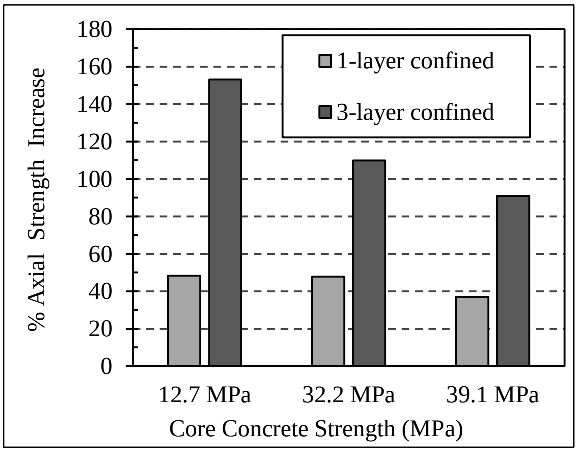
Group B and C could be improved to 106.8 % and 91% respectively. With the same volume of confinement, the metal sheet confinement system was found to be less effective in enhancing axial capacity of the specimens with a higher core concrete strength. It could be mentioned that samples with lower concrete strength were more sensitive to confinement provided by metal sheet wrapping than the samples with higher concrete strength. Figure 3a and 3b show two illustrative comparisons of all the specimens, in terms of the axial strength and the axial strength increase, respectively.

Table 2. Axial compressive strength of the specimens in each group

Specimen Group	Axial Compressive Strength (MPa)			Axial Strength Increase (%)	
	Unconfined	1-layer confined	3-layer confined	1-layer confined	3-layer confined
A	12.7	18.8	32.1	48.4	153.1
B	32.2	46.9	66.5	45.7	106.8
C	39.1	53.6	74.7	37.1	91.0



(a)



(b)

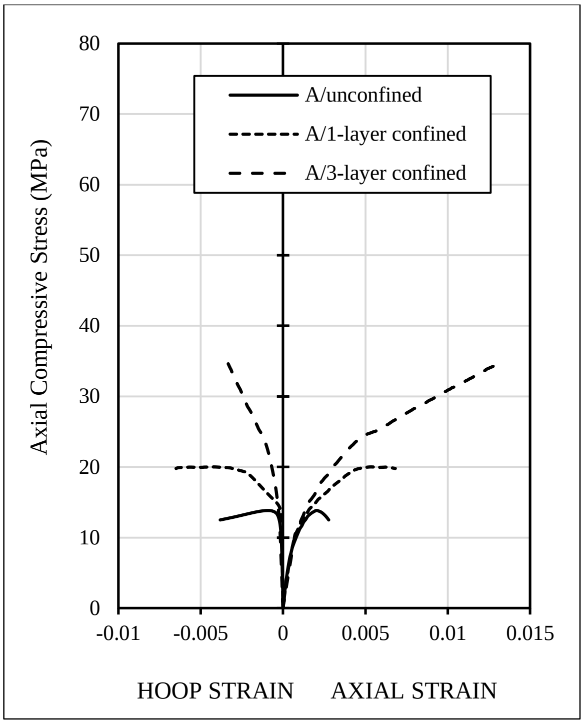
Figure 3. a) Axial strength and b) Axial strength increase of the metal sheet confined specimens in comparison with the unconfined specimens

3.2. Stress-Strain Relations

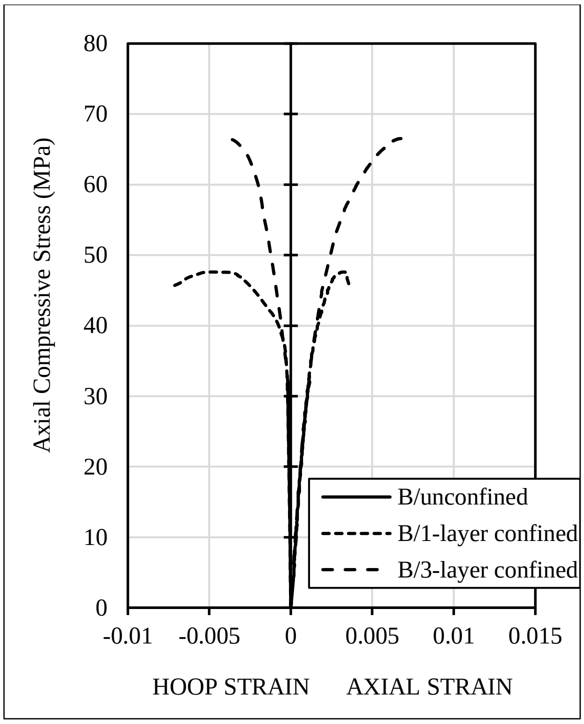
Figure 4 shows plots of axial compressive stress versus hoop strain and axial strain for each group of the specimens. It should be noted that a positive value of the axial strain is referred to shortening of the specimen in the axial direction, while a negative value of the hoop strain is referred to the lateral (circumferential) expansion. The curves show both types of relationships using two sides of the x-axis.

From Figure 4 two factors influencing axial compressive behavior of the metal sheet confinement system could be observed; the first was the number of confinement layer and the second was strength of the concrete core. It could be seen that confining the specimens with more metal sheet layers provided significant effect on axial compressive behavior of the specimens. The curves might be seen as bilinear shapes. For unconfined specimens, a descending branch was observed. As for more confined specimens, the branch was gradually changed to be ascending instead. Our experimental results confirmed the similar behaviors reported in previous studies for specimens with circular cross sections [6, 8, 15]. However, in Figure 4 we could notice the descending branch in the unconfined specimens in Group A, but not clearly in Group B and Group C, which might be due to our experimental limitation. Although we had problems tracing the tail of the response of the unconfined specimens in Group B and C, it could be seen that the response of the specimens with higher confinement level had tendency to change to more ascending tails eventually. All the three-layer confined specimens (from all the three groups) revealed hardening behaviors at the later stage of loading.

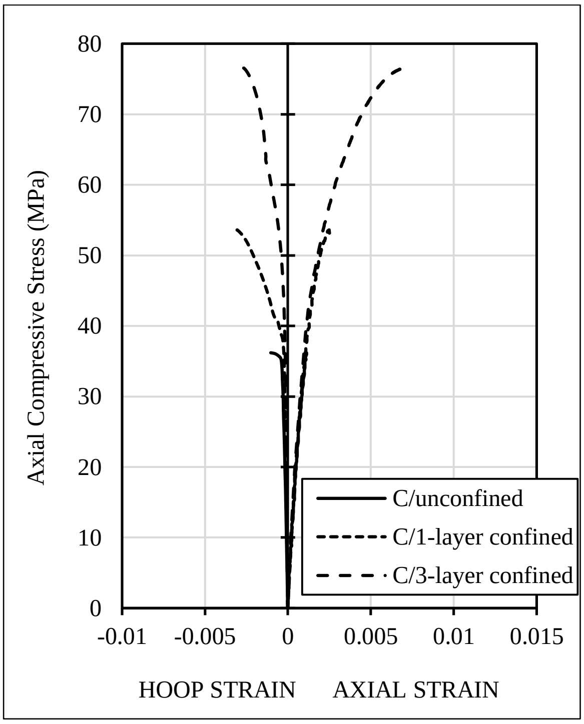
Comparing between Figure 4a, 4b and 4c, it could be seen that specimens of different core concrete strengths revealed different axial compressive behaviors for both unconfined and confined samples. The specimens with a higher core concrete strength showed higher stiffnesses in both axial and radial directions at the earlier stage of loading. At this early stage, stiffness of the confined and unconfined specimens with the same concrete strength were similar and did not alter upon increasing number of metal sheet layers. Obviously, the system showed the improved behavior due to passive confinement, where differences between the confined and unconfined specimens were exhibited at a slightly later stage.



a) Group A



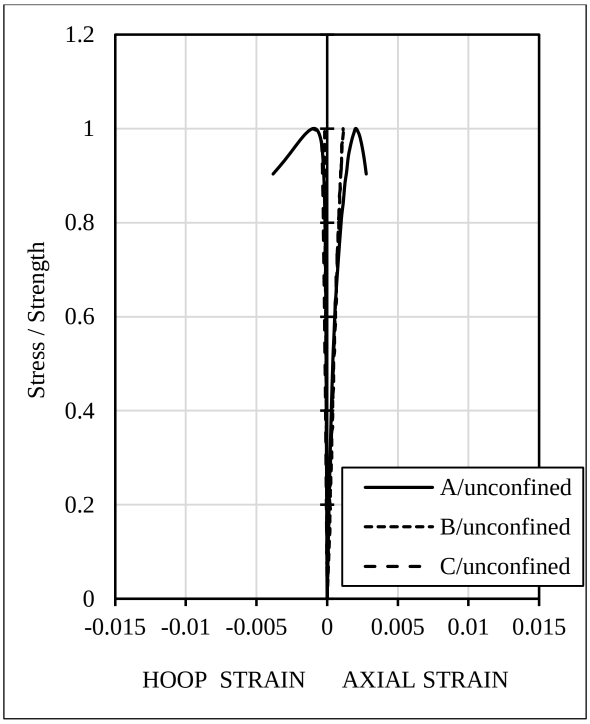
b) Group B



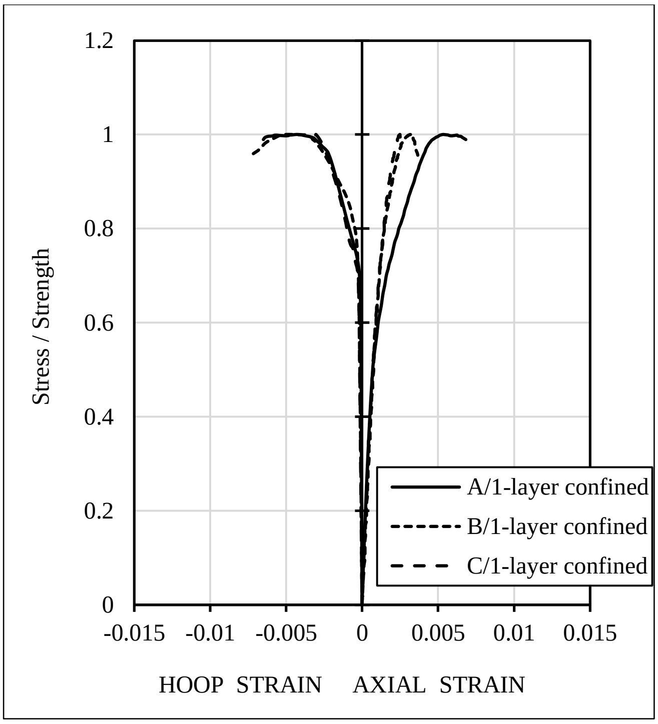
c) Group C

Figure 4. Stress-strain relationship of the specimens for different concrete strength

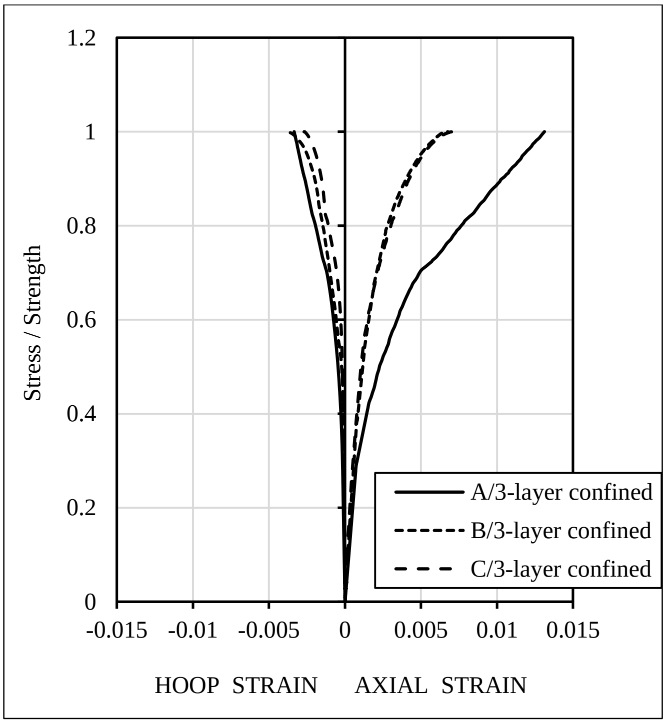
Figure 5, plots of normalized axial stress to axial strength (peak stress) versus hoop strain and axial strain are illustrated. Some common relations among specimens containing different peak stresses were observed. It was shown that the relations at the hoop direction for the specimens in all groups were very close for the same level of confinement, although it could be seen that the lower strength specimens expanded slightly more. For the axial direction, relations obtained from the specimens in Group B and Group C were similar, while the specimens in Group A gave considerably different relations that seem to diverge when adding more layers of confinement.



a) Unconfined



b) One-layer confined



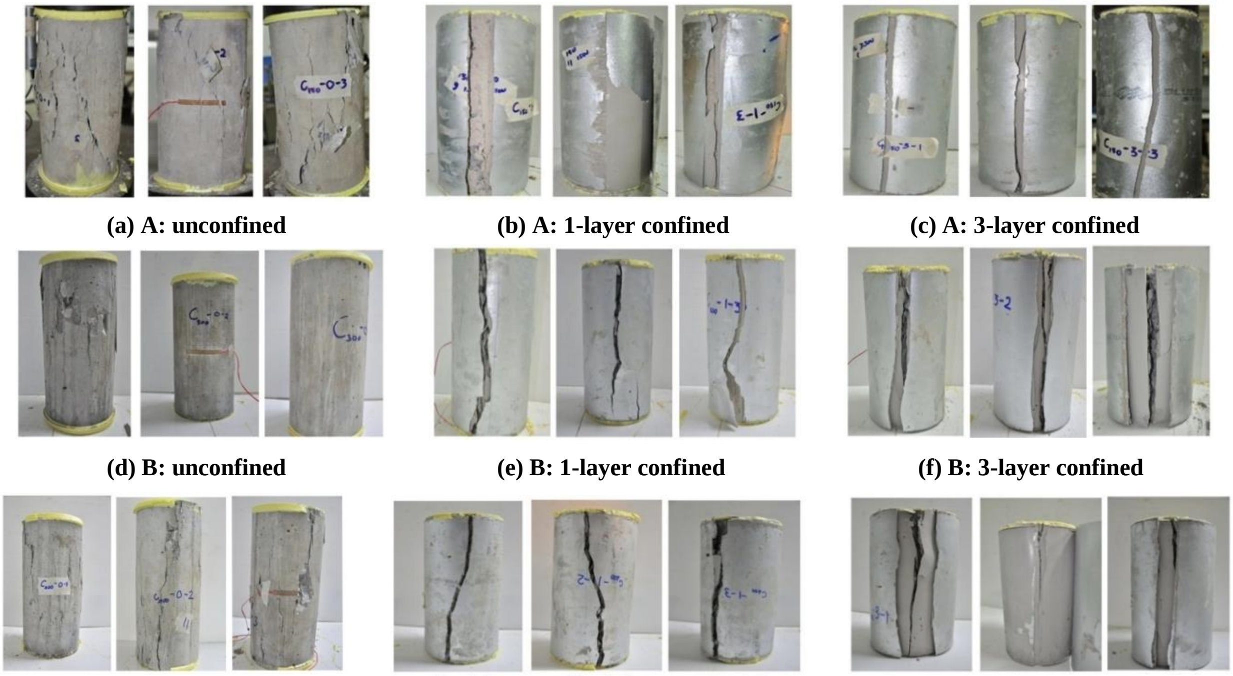
(c) Three-layer confined

Figure 5. Relationship between normalized axial stress and strains of the specimens for different confinement levels

3.3. Failure Patterns

Failure patterns of all the test specimens were shown in Figure 6. Most of the confined specimens in Group A, B and C failed rather immediately by fracture of the metal sheet. The fracture occurred abruptly along the axial direction when the confined specimens reached their ultimate capacities. However, some snapping sounds were still heard before the fracture.

It was previously reported in some of our experiments that two types of failure could be found for the metal sheet confined concrete; the first type was the metal sheet fracture and the second type was the metal sheet opening (delamination at the overlapped part). The failure patterns found in this set of experiment were of the first type for most of the confined specimens, except for two specimens; one out of three specimens in Group A with one layer of confinement (cf. Figure 5 (b)–middle specimen) showed failure with opening of metal sheet at the overlapped part, and one out of three specimens in Group C with three layers of confinement showed failure with opening at the outermost layer of the metal sheet (cf. Figure 5 (i)–middle specimen). For the first type of failure, the tearing off, of the metal sheet appeared at various weak positions on the metal sheet jacket, i.e. not on the overlapped regions. For these specimens, it seemed that the overlapped region of the metal sheet was sufficient that the delamination between the overlapping regions did not occur before failure. It was also observed that the metal sheet and the epoxy worked together as a jacketing system to the concrete core. Bonding between the metal sheet jacket and the concrete core seemed to be sufficient that, at failure, some concrete on surface of the specimen came off together with the inner-layer jacket. For three-layer confined specimens, the fracture on the jacket appeared on all the layers before the specimens failed for most of the specimens. There was only one specimen that the outermost layer showed opening of the overlapped part, whereas fracture was noticed at the inner layers (cf. Figure 5 (i)–middle specimen). It was hard to identify which layer of the material failed first during the laboratory experiment.



(a) A: unconfined **(b) A: 1-layer confined** **(c) A: 3-layer confined**

(d) B: unconfined **(e) B: 1-layer confined** **(f) B: 3-layer confined**

(g) C: unconfined **(h) C: 1-layer confined** **(i) C: 3-layer confined**

Figure 6. Failure patterns of the test specimens

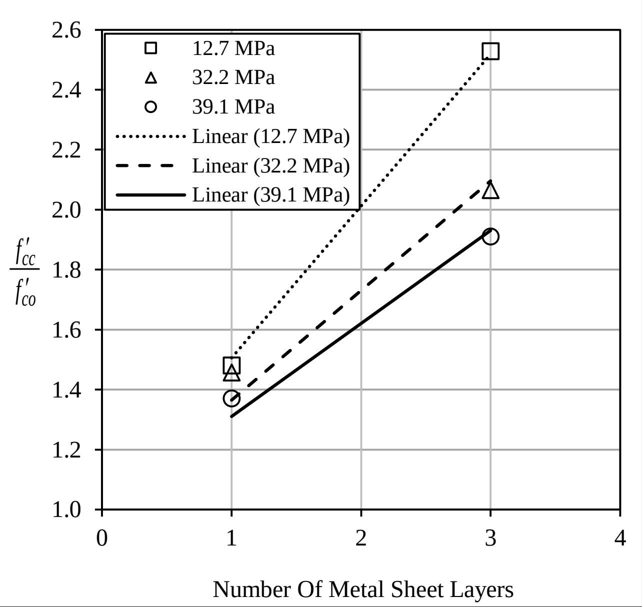
4. Further Discussions

4.1. Comparison to the Past Finite Element Results

It could be seen from the laboratory results that compressive strength of the core concrete had some effects on the axial strength increase of the metal sheet confined concrete specimens. Effectiveness of the metal sheet confinement could be considered by the normalized axial strength, i.e. the ratio between the axial strength of a confined specimen (f'_{cc}) and its original axial strength (unconfined strength) (f'_{co}). In Figure 7 (left), relationships between the normalized strength (f'_{cc}/f'_{co}) and the number of layers were plotted using the information from the laboratory. Linear relations were presented; the corresponding trend lines were fitted to pass through the value f'_{cc}/f'_{co} = 1, which was reasonable as the axial strength of the specimens should be equal to f'_{co} for unconfined specimens, i.e. specimens with zero layer of confinement. All the results suggested that adding layers of metal sheet confinement led to improvement of the axial capacity of the concrete specimens. However, with the same amount of metal sheet application, it was observed that the concrete specimens with low concrete strength were enhanced relatively to their unconfined strength in a greater percentage than the concrete specimens with higher concrete strength.

The finding was also observed in the past finite element analyses by Hongsinlark [15], in which some parametric studies were conducted. Some observations herein are made to connect the similar findings in the past computational study to the present experimental study with emphasis on the effect of concrete strength. Size of the cylindrical specimens in [15] was the same as the standard cylinders, i.e. with 15 cm diameter and 30 cm height. In the past work, three concrete strengths were 22, 32 and 42 MPa, and the yield stress of the metal sheet was 550 MPa as specified from the manufacturer. It should be noted that these properties were different from the properties of our test specimens in this paper, despite having the same size. The finite element analysis was based on modeling the metal sheet confined specimens using three materials; concrete was modeled using Drucker-Prager yield criterion, the metal sheet was modeled based on Von Mises yield criterion, and the epoxy resin was modeled using interface elements with bi-linear softening relation. Details of the model was described in [15].

In Figure 7 (right), relationships between the normalized strength (f'_{cc}/f'_{co}) and the number of layers were plotted using the past results from the finite element analysis. Comparing to our laboratory results, the same information was obtained; the lower concrete strength specimens had higher percent strength increase when confined with the same amount of metal sheet. Both the experimental and numerical results showed that compressive strength of the core concrete had an effect on axial compression behavior of the confined specimens. The increase of stiffness in axial direction also related to the increase of stiffness in lateral (radial) direction of the concrete specimens. With a higher lateral stiffness, the lateral expansion of the higher strength concrete specimen was less. Relatively less efficiency in axial strength increase could be obtained. The similar observations were found in case of the FRP confined concrete [16-18, 24-25].



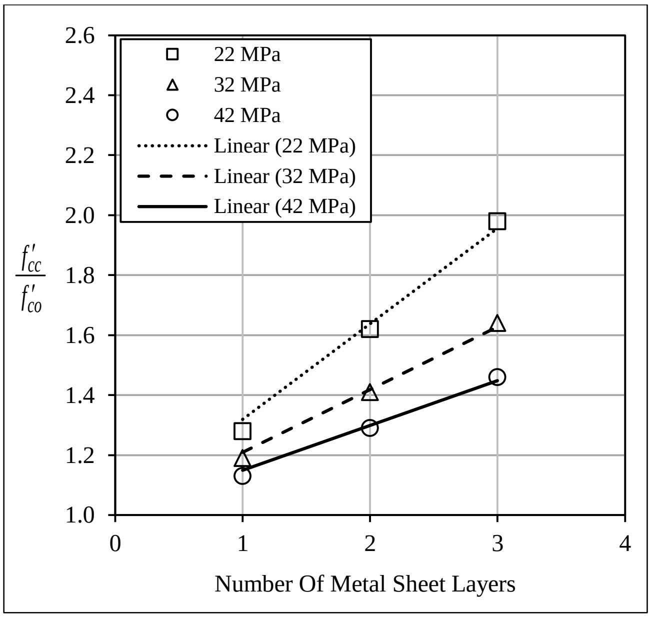


Figure 7. Comparison of the normalized strengths from the experiment (left) and the finite element modeling (right)

4.2. Comparison to the Strength Improvement Equation

Among many strength improvement equations proposed in many previous literatures, it was mentioned in the work of Hongsinlark (2013) [15] that the strength equation by Richart et al. (1928) [20] could give a reasonable strength prediction for the metal sheet confined cylinders. For tri-axially loaded concrete, strength of the confined concrete can be described using the following equation:

$$\frac{f'_{cc}}{f'_{co}} = 1 + k\frac{f_l}{f'_{co}} \tag{1}$$

Where f'_{cc} and f'_{co} refer to axial strengths (peak stresses) of confined concrete specimen and axial strength of unconfined concrete specimens, respectively. The variable f_l denotes the confining pressure which can be formulated using equilibrium condition to relate to the stress in the confining material as:

$$f_l = \frac{2ntf_m}{D} \tag{2}$$

Where D the diameter of the cylindrical specimen, n is the number of layers of metal sheet confinement, t the thickness of each metal sheet layer, and f_m is here taken as the yield stress of the metal sheet. The normalized strength f'_{cc}/f'_{co} is known as the confinement effectiveness and the normalized confining pressure f_l/f'_{co} is also known as the confinement ratio. Plots of these two nominal variables are typically used to maintain comparable relations among specimens having different parameters. For uniform confining pressure, the confinement effectiveness coefficient k could be expressed as 4.1 [21].

In Figure 8, relationships between the normalized strength and the normalized confining pressure were plotted. Both the experimental results and the numerical results were plotted together. The results from the finite element analysis exhibited close relations to the Richart's Equation for all the concrete strengths. The effect of different concrete strengths on strength equations was hardly noticed. On the other hand, the results from the laboratory experiment provided a slightly different relations from the Richart's Equation; it could be seen that relations from Group B and C were close and both provided trends of higher strength improvement as compared to the predicted relations, implying that confinement effectiveness of the tested specimens in both groups was higher than expected from the Richart's Equation. Based on the past test results from our laboratory [10], the confinement effectiveness coefficients of the cylindrical specimens were likely to be higher than the value given in the Richart's Equation. An exception could be seen in Group A specimens, where the strength improvement trend was lower than the Richart Equation and obviously diverged from the other group specimens. Due to the limited number of specimens in this group, it would be difficult to conclude on this issue at present. Additional laboratory experiments and finite element analysis would be needed.

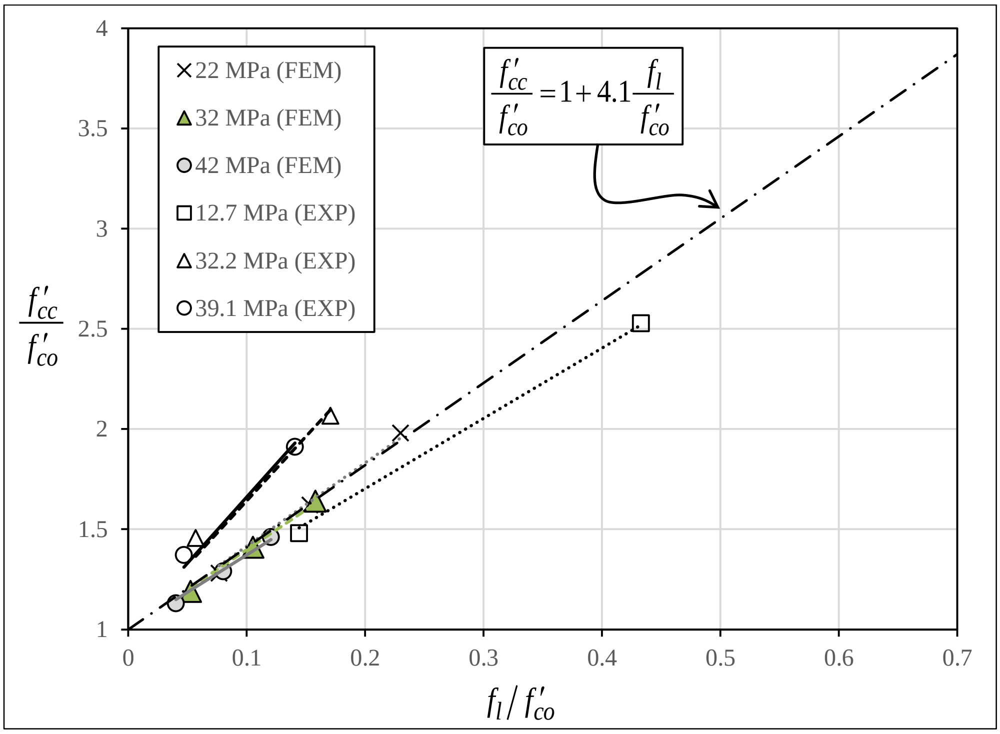


Figure 8. Relationship between the normalized strengths and the normalized lateral confining pressure

5. Conclusions

In this paper**,** effect of concrete strength on axial compressive behavior were studied. The following conclusions can be made:

- Concrete specimens with low concrete strength can be enhanced in a greater percentage relatively to its unconfined strength, as compared to the concrete specimens with higher concrete strength. With lower axial stiffness and lateral stiffness, the metal sheet confinement is more efficient in improving axial compressive capacity of the lower strength concrete specimens.
- For a given concrete strength, adding more layers of metal sheet confinement leads to higher axial compressive strength in a quite linear relation, and also affects axial behavior of confined concrete.
- Confined specimens tend to fail in a quite sudden manner due to tension in the hoop direction, either by fracture of the metal sheet or by delamination. The fracture occurs at various weak positions but not on the overlapped region of the metal sheet jacket when the confined specimens reach their ultimate capacities. Some snapping sounds can be heard before the fracture.
- The existing relation of normalized strength and the normalized confining pressure of metal sheet confined concrete cylinders suggested that the confinement equation given by Richart et al. (1928) might be fairly and conservatively adopted except the case of the specimens with a very low concrete strength.

6. Acknowledgement

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7. Conflicts of Interest

The authors declare no conflict of interest.

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