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Experimental Investigation on SSTT Confined Concrete with Low Lateral Pre-tensioning Stresses

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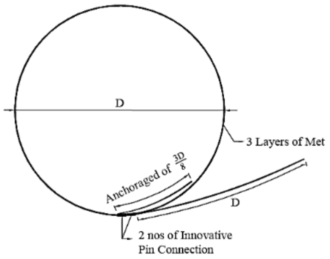
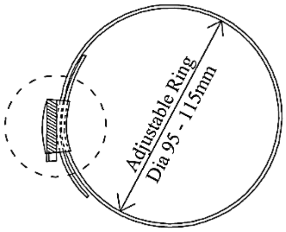
Graphical abstract



SSTT(SS)



SSTT(HC)

Abstract

An experimental and analytical study on the application of Steel Strapping Tensioning Technique (SSTT) confinement on twelve high-strength concrete cylinder specimens with dimension of 100 mm and 200 mm in diameter and height respectively has been studied and presented throughout this paper. The specimens were volumetric-identically confined with two different confining materials of different mechanical properties and lateral pre-tensioning stresses, namely SSTT(HC) and SSTT(SS). All concrete specimens were tested under uniaxial compression load. The performance of SSTT-type confined specimens were studied through their stress-strain relationship upon the longitudinal and transverse deformation, mode of failure, level of lateral pre-tensioning stress, and dilatancy behaviour. The results show that high-strength concretes confined with SSTT would significantly reduce the brittleness problem and at the same time, enhancing both ultimate compressive strength and ductility up to 65% and 344%, 36% and 269% for both SSTT(HC) and SSTT(SS), respectively. Those specimens confined with higher lateral pre-tensioning stress exhibits smaller radial expansion and higher rate of axial strain, able to slow down the dilation of confined specimens under loading and thus, helps in enhancing the compressive capacity and ductility. In addition, an analytical comparison between SSTT-type confinement and conventional confinement models have been presented and the results show a linear relationship between the compressive strength enhancement and confinement ratio. Current experimental results were also validated by comparing the observed stress-strain relationship proposed by Mander.

Keywords: Lateral confinement; steel strapping tensioning technique (SSTT); high-strength concrete; lateral pre-tensioning stress; strength and ductility improvement

■1.0 INTRODUCTION

The low ductile behaviour of high-strength concrete at its post-peak capacity is indicated by the immediate failure with a steep stress-strain curve under uniaxial compression load, in company with severe cracking and explosive failure manner [1, 2, 3, 4, 5, 6]. In order to cater this inadequacy, a lot of research works has been done by many researchers [6, 7, 8, 9, 10, 11, 12, 13, 14] and found out that concrete can be effectively confined with lateral confinement to retain a flat descending region beyond the ultimate capacity in stress-strain curve, restraining the concrete brittleness, increasing the concrete compressive strength, and at the same time enhancing the ductility performance of concrete to a significant level. Better ductility results in safer structures as it will slow down the strength loss beyond the peak load and result in concrete failure at a very much higher ultimate strain, complete with ample warning of failure.

However, the two common type of confinements; i.e., internal confinement (conventional internal tie reinforcement steel) and external confinement (RC jacketing, steel jacketing, glued steel bands, FRP jacketing, post-tensioned cables, ferrocement jacketing, etc) have disadvantages such as high cost, complexity, time consuming, require the interruption of the use of structure during application and highly dependent and sensitive to the experience labours. To solve this problem, pre-tensioning of low cost steel strapping around the concrete specimen, utilizing technique from packaging industry is introduced and some researches have successfully proven that this technique able to significantly enhance the ultimate compressive strength and ductility of concrete specimen [15, 17, 18, 19, 20]. Then, the lateral pre-tensioning stress securing method of this technique was then effectively modified by Awang, *et al*. [24, 25], emphasizing on multi-layer confining effect of these confinement method to enhance the strength and ductility of high-strength concrete specimens, and the technique has been named as SSTT.

A number of experimental works of steel straps confinement has been basically investigated by Hasan, *et al*. and Awang, *et al*. on the clear spacing, confinement volumetric ratios and effect of shape factor to the steel strapping confinement technique, with fixed lateral pre-tensioning stress confined on the steel strapping [15, 16, 17, 18, 19, 20, 24, 25]. However, the focus on the effect of various lateral pre-tensioning stress is yet been studied. This parameter is suspected becomes more significant when dealing with low dilate high-strength concrete under compression. It is also predicted that higher strength concrete needs higher lateral pre-tensioning stress so to optimally utilize the confining steel strapping.

This paper presents the result of an experimental study on the behaviour of SSTT confinement using two different confining materials confined with different lateral pre-tensioning stresses on high-strength concrete specimens, and tested under uniaxial compression load. The overall behaviour of these confined high-strength concrete specimens was then studied through their stress-strain relationship upon the longitudinal deflection, transverse strain, mode of failure, lateral pre-tensioning stress, dilatancy behavior, etc. Test results obtained are presented and examined as follow.

■2.0 DESCRIPTION OF CONFINEMENT TECHNIQUE

2.1 SSTT Description

The SSTT confinement apply in this study for strengthening the high-strength concrete columns was basically been disclosed at the Universiti Teknologi Malaysia. It is an external confinement technique use to enhance the strength and ductility of concrete column with prescribed lateral pre-tensioning stress, especially for high-strength concrete which naturally possesses small lateral dilation when loaded. Basically SSTT are made up of strapping materials (such as steel strapping, galvanized strapping or zinc strapping) circulated around the concrete column and pre-tension it by using tensioning equipment. A special connection clip was fabricated to secure the pre-tensioning stress during and after tensioning application. In this experimental study, two different types of strapping were investigated and compared its confinement performance, i.e. steel strapping and zinc plated hose clip, designed as SSTT(SS) and SSTT(HC), respectively.

The SSTT(HC) utilises the zinc plated hose clip straps (HC) to laterally pre-tension them around the high-strength concrete column and subsequently securing them in place by screwing the clip, as illustrated in Figure 1. The lateral pre-tensioning stress exerted by SSTT(HC) is preserved by the screw holding on the treaded frame. The market available HC straps have diameters of 9-281mm and thicknesses of 0.1mm. In terms of mechanical properties, HC straps with tensile strength in excess of 500 N/mm^2, and elongation of 3.0% are available in the market. However, the lateral pre-tensioning stress exerted by SSTT(HC) is limited to only a fixed stress, and the secured stress is relying on the stiffness of clip and screw. The HC straps were laterally pre-tensioned to about 26% of it material’s yield stress, to ensure the early mobilization of the capacity of the confined HC straps before testing. This pre-tensioning works can avoid the early premature crushing of the confined concrete during testing.

While SSTT(SS) involves lateral pre-tensioning of steel strappings by using tensioner around the high-strength concrete column and securing them with self-regulated connection clips without applying sealing notch on the clip, as illustrated in Figure 2 [24, 25]. Manually operated tensioner was used in this study to tighten the SS straps around the concrete specimens. It is recommended to laterally pre-tension the SS strap to about 30% of its yield strength as to apply an effective lateral stress to the high-strength concrete specimens from the initial state of loading application. By implementing SSTT as external confinement method, it is predicted to have a full mobilization of strapping material upon loading application, and also would able to enhance the strength and ductility of the confined high-strength concrete columns.

2.2 Properties of Confining Materials

One of the significant parameter in this experimental study was to compare the confinement performance of two different type of strapping by using SSTT, in term of strength and ductility. Hence, two distinctive strapping materials with different strengths and elongations were used for strengthening the high-strength concrete column. The first series of specimens were laterally pre-tensioned with 12.0mm*1.0mm HC straps and the second series were pre-tensioned with 15.85mm*0.55 mm SS straps. Tensile tests were carried out to investigate the tensile strength and elongation of HC straps and SS strap using 250 kN Universal Testing Machine, in compliance with BS EN 10 002-1:1990. The tensile strength of HC straps and SS straps were averagely about 465 N/mm^2 and 916 N/mm^2, while average maximum elongations were about 3.0% and 0.8%, respectively, as illustrated in Figure 3. Hence, a comprehensive comparison of confinement performance between both low tensile strength and high ductile strappings (HC), and high tensile strength but low ductile strappings (SS) were carried out in this study.

2.3 Exerted Lateral Pre-tensioning Stress

SSTT(HC) and SSTT(SS) in this study employing two different type of pre-tensioning techniques, where the formal uses screw to tighten the straps and the later uses tensioner to exert pre-tensioning stress to the straps. As the inequitable lateral pre-tensioning stresses applied by both techniques are of the comparing parameter, hence, a set up as proposed by Hasan, *et al.* [15], with improving modification were used to measure the lateral pre-tensioning stress, as shown in Figure 4. A load cell was placed between two semi-circular steel frameworks, and the lateral pre-tensioning stresses of each respective technique were monitored during tensioning work on the set-up. In this case of study, one layer of confining strap was examined and the corresponding lateral pre-tensioning stresses were recorded by means of a data acquisition unit, as shown in Table 1. The lateral pre-tensioning stresses implemented in this study are considered as low lateral pre-tensioning stress (about 25% and 40% of the corresponding tensile strength of confining materials, for HC and SS respectively).

■3.0 EXPERIMENTAL PROGRAM

3.1 Preparation of Confined Concrete Specimen

Twelve high-strength concrete cylinder column specimens with diameter of 100 mm in circular sections and height of 200mm were prepared. The testing parameters primarily dealt with the two distinctive lateral pre-tensioning stresses to the effect of SSTT confinement on high-strength concrete columns using two different tensioning techniques and different mechanical properties of straps, as mentioned in previous section. All unconfined and SSTT confined specimens were tested under uniaxial compression load to failure. In this case of study, internal confinement was not implemented. For SSTT confined specimens, the spacing between straps were fixed at 10mm along the center of column and were wrapped with only one layer of strap. The spacing for both end sections was reduced to about 7.5mm to provide sufficient confinement. This would reduce the possibility of failure at the two end sections of the specimens. Figure 5 shows the SSTT confined specimens for both series of confinement.

Two different batches of high-strength concrete mix proportions, designed as Batch A and Batch B as given in Table 2 were used in this study. Different compressive strength for each series of specimens was needed to obtain an identical effective mechanical volumetric ratio of 0.10. All specimens and cubes were removed from the formworks and moulds right after 24 hours of casting and went through moist curing. The curing process was stopped at 28 days and the high-strength concrete specimens were externally pre-tensioned with SSTT(HC) and SSTT(SS) accordingly. It is important to make sure the specimens were uniformly loaded during testing by paralleled the top and bottom surface of the specimens with grinding machine.

3.2 Strain Measuring Instrumentation

All the unconfined and SSTT confined specimens were tested under uniaxial compression load using TINIUS OLSEN Super "L" Universal Testing Machine which occupied capacity of 3MN. A constant load rate of 0.4 mm/min was used. The details of the specimen size and strain gauge position of confined specimen, the specimen set up and diagram for strain measuring instrumentations are as shown in Figure 6 and Figure 7. The overall displacement of longitudinal axial deformations of specimens were obtained using three linear variable differential transducers (LVDTs) positioned at the top plate of loading machine, while another three LVDTs were installed in Longitudinal LVDT holder rig to measure the specimens' center deformation (100mm). The lateral deformation of concrete specimens were obtained using two LVDTs in the Transverse LVDT holder rig located at the center, by wrapping a steel ties around the specimen. On top of that, the transverse deformations for specific concrete surface and straps were obtained using strain gauges located at the center of specimen in diametrically direction as shown in Figure 6. All stresses and strains attained were measured and recorded using data acquisition unit. Any physical deformation, i.e. cracking pattern, buckling, explosion, etc., was recorded during testing. The uniaxial compression load test was performed in compliance with ASTM C39/C39M-11.

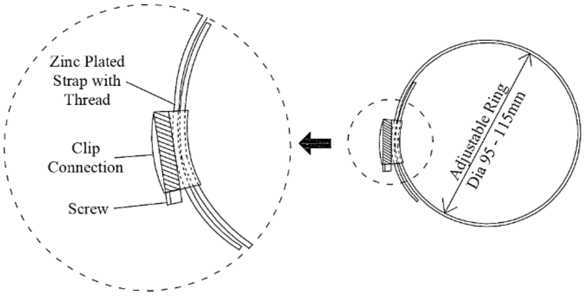


Figure 1 Schematic diagram of SSTT(HC) strap and clip connection

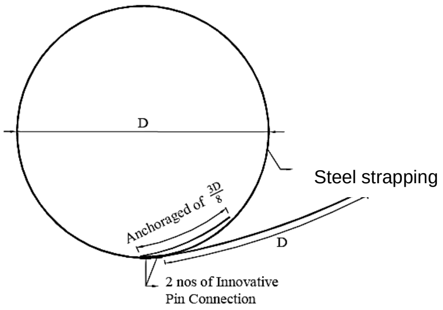


Figure 2 Schematic diagram of SSTT(SS) strap and clip connection

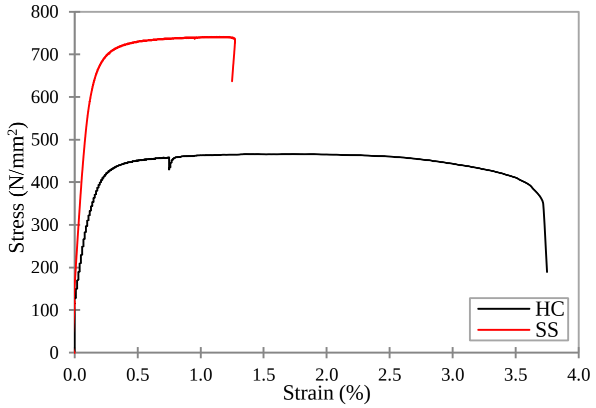


Figure 3 Graph of stress-strain relationship for HC and SS strap from direct tensile test

Figure 4 Set up to measure the lateral pre-tensioning stress of confined strap

Table 1 Lateral pre-tensioning stress for SSTT(HC) and SSTT(SS)

SSTT-Type	Average Pre-tensioning Stress (kN)
SSTT(HC)	1.40
SSTT(SS)	3.20

Figure 5 SSTT(HC) (left) and SSTT(SS) (right) confined high-strength concrete specimens

Table 2 Concrete Mixture Proportion for Batch A and Batch B

Material	Type	Batch A	Batch B
Cement (kg/m^3)	Composite cement	575	480
Silica fume (kg/m^3)		-	30
Sand (kg/m^3)	River sand, norminal size 2.36 mm	705	757
Aggregate (kg/m^3)	Crushed aggregate, maximum size 12.5 mm	860	1011
High-range Superplasticizer (ml/m^3)	Glenium ACE 388(RM) Suretec	-	5300
Water (kg/m^3)	Pipe water	230	153
Compressive strength at 28 days of moist curing (MPa)	Cube/cylinder	50/47	80/68

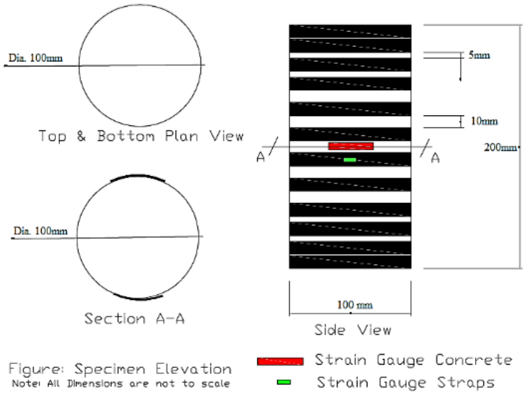


Figure 6 Detail of specimen size and the strain gauge position

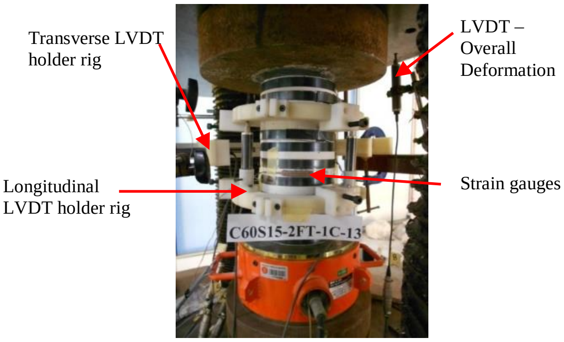


Figure 7 Diagram of strain measuring instrumentations

■4.0 OBSERVED BEHAVIOUR AND TEST RESULT

4.1 Mode of Failure

This section discusses the mode of failure of unconfined and confined specimens wrapped with two different lateral pre-tensioning stresses, SSTT(HC) and SSTT(SS). Figure 8(a1), 8(a2), 8(b1) and 8(b2) show the failure mode for unconfined and confined specimens for SSTT(HC) and SSTT(SS), respectively.

For unconfined specimens of both batches of concrete, almost all tested specimens started to fail at the top portion and consequently collapsed in several deep diagonal shear mode as shown in Figure 8(a1) and 8(b1). All unconfined high-strength concrete for both batches underwent extreme crushing along the column and collapsed with explosive sound, right after reaching its ultimate capacity.

For SSTT-type confined specimens with one layer of strapping (Figure 8(a2) and Figure 8(b2), both batch of specimens had obvious shear cracks or crushing spots along the column. However, the SSTT-type confined specimens does not collapse or explode right after reaching its ultimate capacity but further sustain the compressive stress and deformation. The testing was terminated after the compressive strength was decreased 50% lesser than its particular confined ultimate strength. The mobilization of pre-tensioned straps to certain amount of stresses do enhance the ductility behaviour of high-strength concrete column which having low rate of lateral dilation, and hence preventing the concrete to collapse.

Yet, by comparing the confinement with different lateral pre-tensioning stresses, it can be observed that SSTT(HC) confined specimens possess serious shear cracking than SSTT(SS). The sustainability of SSTT-type confinement at the ultimate greatly depending on the lateral pre-tensioning stress, where specimen with higher pre-tensioning stress (SSTT(SS)) would cause minor devastation to the high-strength concrete specimen. But, experimental work with current lateral pre-tensioning stresses only is not enough to establish the SSTT-type confinement. It is believe that there is an optimum lateral pre-tensioning stress and confinement volumetric ratio to be used in this technique to optimally enhance the strength and ductility of confined specimen, needed to be figure out in future.

4.2 Discussion of Test Results

Table 3 and Table 4 show the average test results of the unconfined specimens and SSTT-type confined specimens respectively. In between these two tables, f_{c0} and ε_{c0} are the peak compression strength in MPa and strain at the peak compressive strength for the unconfined specimens, respectively. f_{cc} and ε_{cc} are the peak compression strength and the strain at peak strength for the confined specimens, respectively. ε_{85} and ε_{50} are the strains at 85 % and 50 % of the peak compression strength after the ultimate compression strength, respectively.

By referring to Table 4, the strength enhancement ratio (f_{cc} / f_{c0}) for SSTT(HC) was 1.65, while that of SSTT(SS) was 1.36. Throughout this comparison, the strength enhancement ratio for SSTT(HC), which with lower lateral pre-tensioning stress and material yield strength but higher confining material’s elongation, performed better than the SSTT(SS) confinement by 21.3%. However, it is recommended to have more set of results with different type of confining material in order to prove this result.

On the other hand, the plasticity ratio of SSTT-type confined specimen (ε_{85} / ε_{cc}) showed an improvement up to 8% for SSTT(HC) confined specimen and 233% for SSTT(SS) confined specimen. It was a reversed enhancement comparing to strength enhancement ratio, where confinement with lower elongation but higher lateral pre-tensioning stress and material yield strength perform greater and able to sustain more deformation. Adversely, while for ductility ratio (ε_{50} / ε_{cc}), the confined specimen with SSTT(HC) does performed much greater than its companions by 20.3% (ductility ratio of 4.44 and 3.69 for SSTT(HC) and SSTT(SS) respectively). This result makes the SSTT(HC) confined specimens undergone a steep decrement right after the ultimate strength, while SSTT(SS) method would able to sustain and slow down the strength loss beyond the peak load at higher strain value, without rendering major concrete failure (Figure 9 and Figure 10). This happened due to the confining material of SSTT(SS) was pre-mobilized with higher lateral pre-tensioning stresses and effectively pra-tightened by the low lateral dilation of high-strength concrete, and hence slow down the sudden strength loss after the ultimate capacity to a more safer region.

4.3 Stress-Strain Behaviour

Figure 9 shows the analysis graph in longitudinal and lateral direction for concrete core. From Figure 9, it can be observed that high-strength concrete with SSTT-type confinement able to provide more ductility and sustain higher ultimate strain than the plain control high-strength concrete columns. The compressive strength for control specimens dropped tremendously right after reaching the ultimate compressive capacity.

On the other hand, as to have a logical comparison solely on the lateral pre-tensioning stresses applied by both techniques, an equalised effective mechanical volumetric ratio of 0.10 of confinement was implemented. The analysis correlates that the specimen with lower lateral pre-tensioning stress (SSTT(HC)) sustains higher ultimate compressive strength enhancement than those confined with higher lateral pre-tensioning stress (SSTT(SS)), however it exhibits low initial (85% of post-ultimate compressive strength) ductile behaviour with a steeper slope decrement after the ultimate capacity. The low lateral pre-tensioning stress needs greater lateral dilation exerted from high-strength concrete to optimally mobilize the pre-tensioned confining materials. The confining materials were only then effectively activated when the high-strength concrete deformed to adequate lateral dilation. This phenomenon can be observed with high longitudinal and lateral strains sustained at 50% of post-ultimate compressive strength for SSTT(HC) confined specimens. In the safety aspect, confinement with higher lateral pre-tensioning stress is more appropriate due to the slow rate of strength losses beyond the ultimate, although it exhibits lower ultimate performance.

4.4 Dilatancy Behaviour

In addition to stress-strain behaviour, concrete with confinement under uniaxial compression loading will exhibits volumetric changes. Before the concrete failure under the loading, it exhibits volumetric strain contraction. After all, due to the propagation of microcracking in the material microstructure, the concrete invariably performs a volumetric strain expansion and then concrete failure happens. The volumetric strain contraction of concrete will be more obvious when concrete is confined with prescribed pre-tensioning stress [27, 28], where a steeper curve will be obtained. Volumetric strain, ε_v, is used to illustrate the dilatancy behaviour of confined concrete and can be written as:

$$\varepsilon_v = \varepsilon_c + |2\varepsilon_j|$$

where ε_c and ε_j are the strains in the longitudinal and transverse direction or hoop strain for concrete. Positive value indicates the volumetric strain contraction while negative value indicates the volumetric strain expansion.

Figure 10 illustrates the dilatancy behaviour for SSTT-type confined concrete specimens with different lateral pre-tensioning stress as discussed above, which including unconfined specimens (control), SSTT(HC) and SSTT(SS). The unconfined specimens perform a volumetric contraction in the initial stages of loading. As the imposed uniaxial compression stress increases, the initial volumetric contraction is reversed gradually until zero (at about 50% of unconfined concrete ultimate capacity). Then then unconfined concrete dilate rapidly (volumetric strain expansion) after the stage of zero volumetric strain until failure. While for SSTT-type confined concrete specimens, both the specimens with different lateral pre-tensioning stresses experience higher volumetric strain contraction until concrete's ultimate capacity and gradually failed in volumetric stain expansion region. This phenomenon is due to the laterally pre-tensioned confining materials prior to load application leading to higher axial concrete strain than radial concrete expansion (area strain), thus, SSTT-type confinement can be considered as active confinement rather than passive ones in the initial stages of loading application. It is also observed that the volumetric strain curve for SSTT(SS) confinement (higher lateral pre-tensioning stress) exhibits more steeper than the lower ones (SSTT(HC)), indicates smaller radial expansion due to the higher pre-tensioned lateral confinement. However, the optimum lateral pre-tensioning stress for high strength concrete might need further investigation.

4.5 Analytical Assessment of Experimental Results

Many of the existing compressive strength models for confined-concrete take the following term:

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{f_l}{f_{co}}$$

where f_{cc} and f_{co} are the compressive strengths of the confined and the unconfined concrete respectively, f_l is the lateral confining pressure and k_1 is the confinement effectiveness coefficient. This form of equation was first proposed by Richart [26] for actively confined concrete. This form of model is also suggested eligible for steel strap confined concrete [24].

Previously, a simple compressive strength model following the similar form of confinement model for SSTT(SS) with various volumetric ratios has been proposed by Awang [24], with 5.57 as the confinement effectiveness coefficient. This confinement model will be used to represent the SSTT(SS) confinement in this study. As presented in Figure 11, relationship between ultimate strength enhancement of unconfined and confined specimens and effective mechanical volumetric ratio for SSTT(HC) was modelled. Yet, three correlative existing strength models of confined concrete (Table 5) were compared, as to validate the current experimental results. By referring to the figure, all of the existing strength models including strength model for SSTT(SS), underestimates the SSTT(HC) confinement. Mander *et al*.'s model and SSTT(SS)'s model gives close predictions to the experimental results, while the less are over-conservative for current confinement method. Hence, the following linear strength model for SSTT(HC) was therefore proposed for the use of design and confinement prediction, with correlation coefficient R^2 equal to 0.97:

$$\frac{f_{cc}}{f_{co}} = 1 + 6.36 \frac{f_l}{f_{co}}$$

The strength enhancement of current confinement method has been found to be higher than other existing confinement method counterpart for the equal amount of confinement ratio. The proposed model is recommended for design use due to its simplicity. Further research endeavour is still needed to justify its reliability.

In this study, stress-strain model for round bar confined concrete proposed by Mander [21] is selected and compared with current experimental results. It is an expression proposed by them to simulate both ascending and descending branches of the stress-strain curve for circular, square and wall type rectangular sections. An equivalent confinement volumetric ratio for Mander stress-strain model was plotted. Figure 12 shows the stress-strain relationship comparison between SSTT-type confined cylindrical specimens and Mander model. It can be observed that SSTT-type confinement method could be able to enhance the ultimate compressive strength and ductility of high-strength concrete, but Mander model perform better in ductility section.


(a1) (a2)

(b1) (b2)

Figure 8 The cracking pattern of (a1) unconfined and (a2) SSTT(HC) confined specimens, (b1) unconfined and (b2) SSTT(SS) confined specimens

Table 3 Average test results of unconfined specimens

Batch	f'_c (MPa)	f_{c0} (MPa)	ε_{c0}	ε_{85}	ε_{50}	f_{c0}/f'_c
A	50.34	46.95	0.0044	-	-	0.93
B	60.90	61.10	0.0055	-	-	1.00

Table 4 Average test results of SSTT-type confined specimens

SSTT-no	f_{cc} (MPa)	ε_{cc}	ε_{85}	ε_{50}	f_{cc}/f_{c0}	$\varepsilon_{85}/\varepsilon_{cc}$	$\varepsilon_{50}/\varepsilon_{cc}$
HC(A)	77.57	0.0036	0.0039	0.0160	1.65	1.08	4.44
SS (B)	82.85	0.0042	0.0140	0.0155	1.36	3.33	3.69

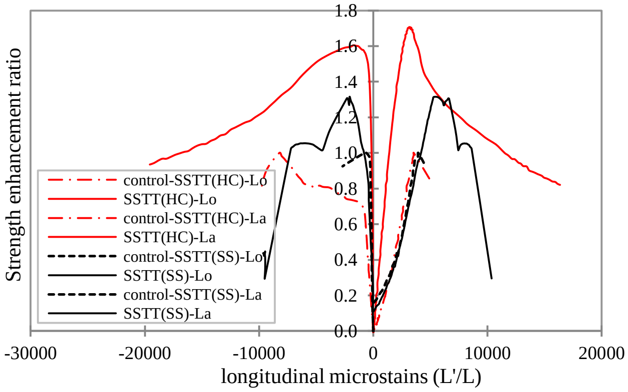


Figure 9 Graph of stress-strain relationship in longitudinal and lateral direction of SSTT(HC) and SSTT(SS)

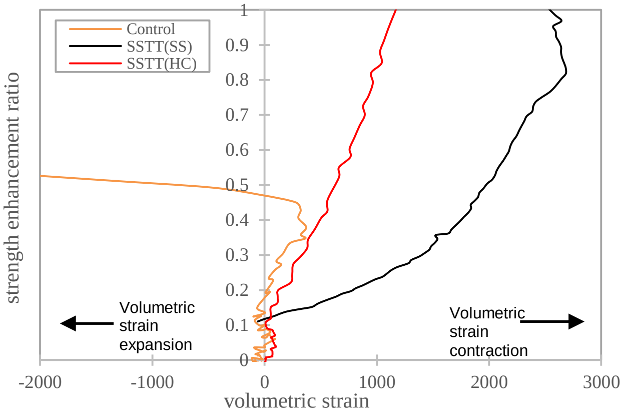


Figure 10 Dilantancy behaviour of specimens for different lateral pre-tensioning stress

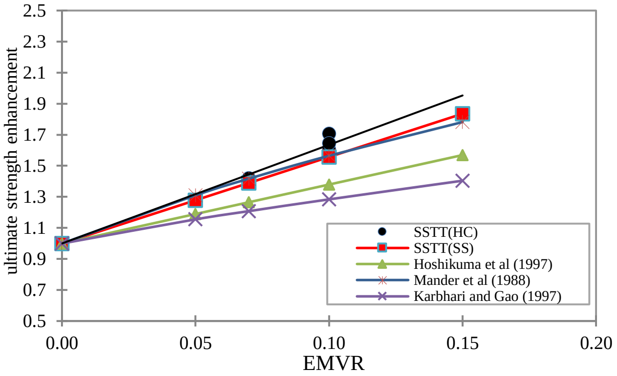


Figure 11 Comparison of existing compressive strength models with SSTT(HC)

Table 5 The existing compressive strength models

Source	Strength models
Karbhari and Gao [22]	$\frac{f_{cc}}{f_{co}} = 1 + 2.1\left(\frac{f_l}{f_{co}}\right)^{0.87}$
Mander *et al.* [21]	$\frac{f_{cc}}{f_{co}} = -1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f_{co}}} - 2\frac{f_l}{f_{co}}$
Hoshikuma *et al.* [23]	$\frac{f_{cc}}{f_{co}} = 1 + 3.8\frac{f_l}{f_{co}}$
Awang *et al.* [24]	$\frac{f_{cc}}{f_{co}} = 1 + 5.57\frac{f_l}{f_{co}}$

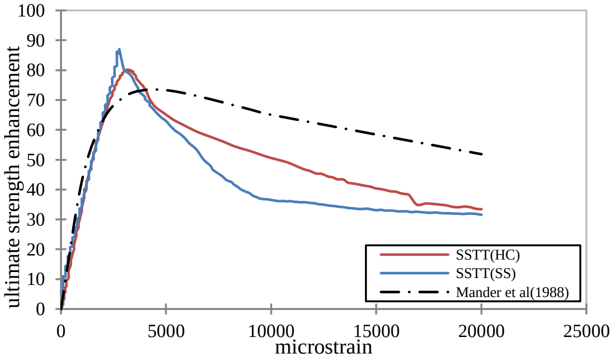


Figure 12 Experimental stress-strain behaviour of SSTT-type confined high-strength concrete compared to Mander *et al.* 1988 theorectical model

■5.0 CONCLUSIONS

This paper deals with the behaviour of high-strength concrete column confined with two different lateral pre-tensioning stresses by SSTT-type confinement, tested under uniaxial compression load test. Results from experimental testing have been presented and discussed in various form of relationship. The experimental test results also have been compared with several existing strength models and one stress-strain model to validate its feasibility. Hence, the following conclusions may be drawn from the current study:

1. The current pre-tensioning techniques can significantly improve the confined performance of high-strength concrete columns, providing an increment in ultimate compressive strength of up to 65% and 36%, and increment of ductility up to 344% and 269% for SSTT(HC) and SSTT(SS) confined specimens, with identical effective mechanical volumetric ratio, respectively. Confinement with higher lateral pre-tensioning stress well performed with its capability to slow down the strength losses beyond the peak compressive strength, providing a slow and safer concrete failure. However, the influence of optimum lateral pre-tensioning stress to the overall performance of confined high-strength concrete has not been studied in this research. It is suspected that when a certain amount of lateral pre-tensioning stress has been achieved, the performance of such confinement will either halt or reduce. Acceptance and clarification of this suspected behaviour must therefore depend on further research outcome to ascertain it.
2. Both the current pre-tensioning techniques are capable to provide considerable increase in strength and ductility of high-strength concrete which is naturally brittle and low ductile. The strength lost beyond the ultimate compressive capacity can be greatly slow down with higher lateral pre-tensioning stress (SSTT(SS)) and hence provide a safer condition when the concrete reaches its peak capacity. Therefore, this finding confirmed that SSTT-type confinement is capable of solving the inadequacies of high-strength concrete and thus is useful for strengthening structures in seismic zone.
3. It can be observed that confinement with higher lateral pre-tensioning stress will slow down the radial strain and increase the rate axial strain of concrete specimen, and tends to go further in the volumetric strain contraction region. It is believe that concrete with low radial strain will enhance the concrete ultimate capacity and ductility of confined concrete.
4. A close and linear relationship between the effective mechanical volumetric ratio and strength enhancement of SSTT(HC) confinement is modelled, with 6.36 as the confinement effectiveness coefficient. The proposed model is recommended for SSTT(HC) confinement design use due to its simplicity and unconfirmed reliability. For a similar layout of lateral confinement, SSTT-type confinement shows an enhancement in ultimate compressive strength compared to Mander model.

It should be noted that the above conclusions have been reached only in regard to the basis of tests conducted on small laboratory scale high-strength concrete cylindrical column specimens only. Dimension and size variability may impose different effects and such effects should be examined using real-scaled specimens in the future.

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