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# Strength and Ductility of High-Strength Concrete Cylinders Externally Confined with Steel Strapping Tensioning Technique (SSTT)

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**Graphical abstract**

## Abstract

This research study is to introduce and investigate an effective technique of external pre-tensioning using steel strapping (SSTT) to reduce the brittleness and enhance the ductility of high-strength concrete cylinders. Fifteen cylinders with dimension of 150 mm and 300 mm in diameter and height respectively were casted, pre-tensioned with two and four layers of steel strapping and tested to failure under uniaxial monotonic and cyclic compression. The behaviour of SSTT confined cylinders was studied through their stress-strain relationship upon the longitudinal deflection, transverse strain, mode of failure, confinement ratio, and existence of an envelope curve. It is experimentally proved that SSTT confinement do helps in controlling the brittleness problem of high-strength concrete and at the same time, enhancing both the concrete ductility and compressive strength up to 46.2 % and 112.5 % respectively. The envelope curve of uniaxial cyclic loading also coincides with the corresponding monotonic loading curve, regardless of any loading activity. The observed stress-strain relationship of confined cylinders with different confining ratios are compared with existing strength and strain models and a stress-strain prediction model, the result showed a linear relationship between the compressive strength and strain enhancement and confining ratio, with acceptable agreement between the prediction model.

*Keywords*: High-strength concrete; lateral confinement; pre-tensioning steel straps; ductility; uniaxial monotonic and cyclic compression load

## Abstrak

Kajian penyelidikan ini bertujuan memperkenalkan dan mengkaji keberkesanan teknik pra-tegangan menggunakan lilitan sisi keluli (SSTT) untuk mengurangkan kerapuhan dan meningkatkan kemuluran konkrit kekuatan tinggi. Lima belas spesimen konkrit kekuatan tinggi berdiameter 150 mm dan berketinggian 300 mm disediakan, dipra-tegang dengan dua dan empat lapisan lilitan keluli dan diuji dengan beban mampatan paksi *monotonic* dan beban mampatan paksi *cyclic* sehingga spesimen mengalami kegagalan. Kajian tingkah laku spesimen konkrit kekuatan tinggi ini dinilai melalui hubungan tegasan-terikan pada tegasan membujur, terikan melintang, mod kegagalan, bilangan lapisan lilitan sisi keluli, dan kewujudan lengkung liputan. Keputusan kajian ini telah membuktikan bahawa SSTT mempunyai prestasi yang lebih baik dalam mengawal masalah kerapuhan konkrit kekuatan tinggi dan pada masa yang sama, meningkatkan kedua-dua kemuluran konkrit dan kekuatan mampatan sehingga 46.2% dan 112.5% masing-masing. Lengkung liputan bagi beban mampatan paksi *cyclic* berlaku pada lengkungan graf tegasan-terikan bagi beban mampatan paksi *monotonic*, tanpa dipengaruhi sebarang aktiviti mampatan. Selain itu, hubungan beberapa model tegasan, model terikan dan satu model ramalan tegasan-terikan dibandingkan dengan keputusan experiment ini, dan perbandingan tersebut menunjukan satu hubugan linear antara kekuatan mampatan dan terikan dengan bilangan lapisan lilitan kurungan keluli. Keputusan tegasan-terikan experiment ini juga menunjukkan satu hubungan yang baik antara model ramalan tegasan-terikan.

*Kata kunci*: Konkrit kekuatan tinggi; lilitan sisi keluli; pra-tegangan dengan lilitan keluli; kemuluran; beban mampatan paksi *monotonic* dan *cyclic*

## ■1.0 INTRODUCTION

In recent years, the demand of high-strength concrete has increased in the construction industry. The acceptance of high-strength concrete in related industry is due to several reasons, which include the fact that such concrete gives lower unit weight compared to normal-strength concrete for a given identical load carrying capacity with potential seismic advantages, reduces member dimension and reinforcement required, improved mechanical properties such as modulus of elasticity and tensile strength, and is more economical and time-saving [1-4]. A research carried out by Breitenbiicher [5] found that high-strength concrete is able to reduce member dimension and reinforcement required for about 36 % and 70 % respectively by comparing it with normal-strength concrete. However, there is a major problem with high-strength concrete. Although it gives high compressive strength, it is generally more brittle and less ductile than normal-strength concrete [1, 2, 6, 7, 8, 9]. In order to cater this inadequacy, comprehensive research works has been done by many researchers [9-17] and found that high-strength concrete can be effectively confined with lateral confinement to preserve a flat descending region of stress-strain curve beyond the peak ultimate capacity, restraining the brittleness increment, increasing the concrete compressive strength, and at the same time enhancing the ductility behaviour of concrete to a significant level. So, it is important to ensure that the minimum level of ductility is provided during design of high-strength concrete as to cater the brittleness and low ductility problem.

Inadequate design of ductility can cause critical damages to reinforced concrete structures during earthquake excitation, for instance, shear anchorage, splice failure and buckling of longitudinal reinforcement [18]. Due to the unsatisfactory design of the requirements to current earthquake design codes, many of the existing reinforced concrete structures in high seismic zone required immediate rehabilitation [19]. But, the existing rehabilitation and strengthening techniques are too costly to be carried out. The high total cost of rehabilitation of the vulnerable structures have revealed a need to develop cheaper but effective retrofitting and strengthening technique so to extend the life of expectancy of existing structures. As to study the fundamental behaviour of compression members subjected to seismic excitation, uniaxial cyclic compression load test with prescribed uniaxial unloading/reloading cycles should be examined [20, 21], and its envelope curve should be validated by the relative stress-strain curve tested under uniaxial compression load test.

Generally, there are two common types of lateral confinement-internal confinement and external confinement. Internal confinement takes the form of conventional internal reinforcing steel while external confinement is in the form of external steel jacketing, steel tube, and fiber-reinforced polymer (FRP) composite jackets. [22]. However, majority of the existing lateral confinement techniques are high cost, complexity, time consuming, require the interruption of the use of structure during application and highly dependent and sensitive to the experience labours. Intentionally, pre-tensioning of low cost steel strapping around the concrete cylinder, fully utilizing technique from packaging industry was used and successfully proved that this confining technique able to significantly enhance the ultimate compressive strength and ductility of the confined concrete specimen [18, 19, 23, 24, 25]. Nevertheless, the efficiency of the lateral pre-tensioned stress securing method using sealer to punch notches on the connection clips and steel strapping, composing the layers of straps into one thick layer of steel strapping, has been issued by Awang *et al*., [26, 27]. Consequently, the lateral pre-tensioning stress securing method of this technique was then effectively modified by Awang *et al.*, emphasizing on multi-layer confining effect of the confinement technique to enhance the strength and ductility of high-strength concrete specimens, and namely SSTT.

Previously, many studies have examined the uniaxial monotonic stress-strain behaviour of unconfined and confined concrete [8, 18, 19, 23, 24, 25, 28, 29, 30, 31], but study concerning the confined high-strength concrete, especially with the SSTT external confinement technique, is rare. For one thing, there are still many uncertainties, including the practicability in enhancing the compressive strength and ductility of high-strength concrete, the exact behaviour of externally confined high-strength concrete, and effect of confinement volumetric ratio. Yet, there is no research has been carried out to investigate the current external confinement with high-strength concrete under uniaxial cyclic compression load test. The validity of envelope curve for confined high-strength concrete in comparison with the case of monotonic compression should be determined.

This paper presents the result of an experimental study on the behaviour of the pre-tensioned of different volumetric ratio of steel strappings to high-strength concrete cylinders under uniaxial monotonic compression load and uniaxial cyclic compression load. The behaviour of these specimens was then studied through their stress-strain relationship upon the longitudinal deflection, transverse strain, mode of failure, level of confinement, and its envelope curve. Test results obtained are presented and examined as follow.

## 2.0 EXPERIMENTAL PROGRAM

### 2.1 SSTT Description and Steel Strapping

The SSTT confinement was designed at the Universiti Teknologi Malaysia, which implicates lateral pre-tensioning of steel strapping in multiple layers around the concrete cylinder and subsequently securing the lateral pre-tensioning stress with self-regulated connection clips by bending and tighten the surplus strapping with ties (Figure 1 and Figure 2). It is an external confinement method used to enhance the compressive strength and ductility of concrete, especially for high-strength concrete which naturally possesses small lateral dilation when loaded. The secured lateral pre-tensioning stress would rapidly mobilize the confining material prior to loading, guaranteeing the utilization of the capacity of steel strapping. In contrary to existing confinement technique, which is provided with passive confinement before loading and needs internal microcracks and adequate dilation of concrete to be activated [19], the SSTT confinement with lateral pre-tensioning stress exerted before loading, granted to enhance the overall performance of confined high-strength concrete. In this study, SSTT confinement with two different layers of steel strapping was laterally pre-tensioned by manually operated tensioner around the high-strength concrete cylinder. The behaviour of compressive strength and ductility performance of the confined cylinders to the volumetric ratio was obtained and discussed in this study.

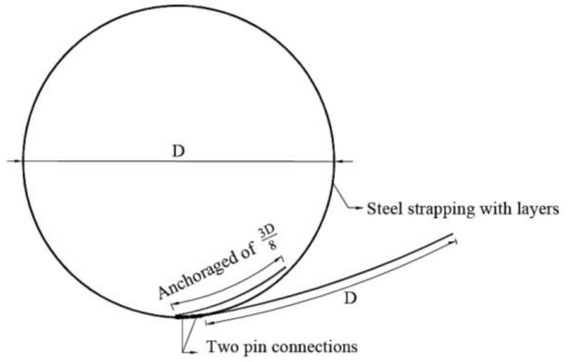

**Figure 1** Schematic diagram of steel strapping for SSTT confinement

Several types of strapping that are available in the packaging industry were chosen for tensile testing investigation, which included steel strapping, galvanized strapping, and polypropylene strapping. Among the tested strappings, “Blue tempered waxed coated steel strapping” of average width and thickness of 15.85 mm and 0.55 mm respectively was selected as the main confining material due its high average ultimate stress (828 N/mm$^2$), lower cost, ease to shape, tensioner compatibility and availability in the packaging industry. The result of tensile test using 250 kN Universal Testing Machine, based on standard test of BS EN 10 002-1:1990, is shown in Figure 3. Similar to Hasan's [19] recommendation, it is suggested to laterally pre-tension the steel strapping to about 30% of its tensile yield strength as to apply an effective lateral stress to the cylindrical specimens from the initial state of loading application.

**Figure 2** Steel strapping with two connection clips

## 2.2 Cylinder Properties and Materials

A set of fifteen high-strength concrete cylinders having diameter of 150 mm in circular sections and height fixed at 300 mm were prepared. The testing parameters primarily dealt with the number of steel strappings layers externally confined on the nine cylinders (plain, two layers and four layers of steel strapping), which were all tested under uniaxial monotonic compression load to failure. To validate the performance of SSTT confinement on high-strength concrete under uniaxial monotonic compression load, uniaxial cyclic compression load was carried out on another six confined cylinders (two layers and four layers of steel strapping). Each of the cylinders were not reinforced longitudinally with steel bar. For all SSTT confined cylinders, the spacing of the steel strappings were fixed at 15 mm along the center of cylinder and 7.5 mm in the two end regions to provide sufficient confinement. This would reduce the possibility of failure at the two end sections of the cylinders (see Figure 4).

Table 1 shows the mixture proportion used to cast high-strength concrete in this study. The high-strength concrete cubes and cylinders were undergone 28 days curing in water before confined with steel straping. The cubes compressive strength ($f'_c$) of high-strength concrete on the 7th and 28th day after casting were tested accordingly.

After 28 days, as the curing process was stopped, all high-strength concrete cylinders were laterally pre-tensioned with prescribed layers of steel strappings, except for control cylinders. The external confinement method implemented was fully followed the SSTT confinement as described in previous section, using manual operated tensioner.

During the study, the fifteen cylinders were assigned into five groups with the notation and specimen's condition as shown in Table 2. The notation of x indicated the sequence of the cylinder testing and "15" indicated the spacing between straps. To ensure that the cylinders were uniformly loaded during testing, it is important to make sure that the top and bottom surface of the cylinder were paralleled. So, the cylinders had to be cast horizontally on a levelled surface.

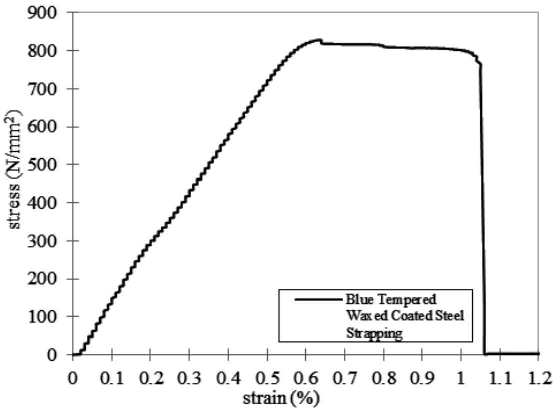

**Figure 3** Graph of stress-strain relationship for steel strapping from direct tensile test

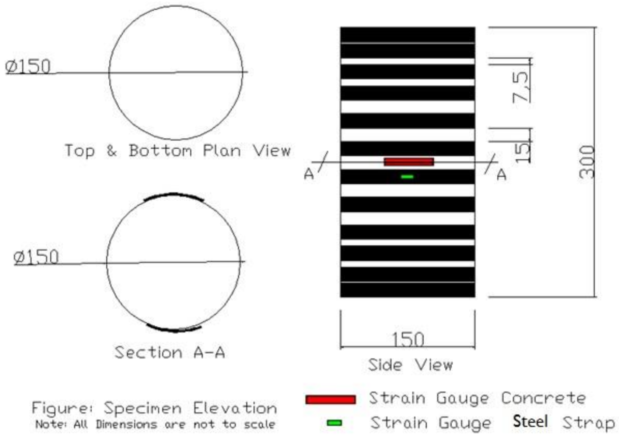

**Figure 4** Details of SSTT confined cylinder

**Table 1** Concrete mixture proportions for 60 MPa concrete

| MATERIALS | TYPE | QUANTITY |
|---|---|---|
| Cement (kg/m$^3$) | Type I OPC | 550 |
| Sand (kg/m$^3$) | River sand | 885 |
| Aggregate (kg/m$^3$) | Maximum size 12mm | 957 |
| Superplasticizer (mL) | Glenium ACE388 (RM) | 0.75% of 100 kg cement |
| Water (kg/m$^3$) | Pipe water | 190 |
| Water/Cement ratio | - | 0.35 |

**Table 2** The arrangement of unconfined and confined cylinders and the designed mode of testing

| GROUP | SSTT CONDITION | MODE OF TESTING |
|---|---|---|
| C60-C-x | Control | Monotonic |
| C60S15-2FT-x | 2Layers of steel straps | Monotonic |
| C60S15-4FT-x | 4Layers of steel straps | Monotonic |
| C60S15-2FT-1C-x | 2Layers of steel straps | Cyclic |
| C60S15-4FT-1C-x | 4Layers of steel straps | Cyclic |

### 2.3 Test Setup and Strain Measuring Instrumentations

The load tests were conducted using TINIUS OLSEN Super "L" Universal Testing Machine which has the capacity of 3 MN in Geotechnics Laboratory, Faculty of Civil Engineering and the load tests were based on displacement-controlled loading with constant loading rate of 0.4 mm/min. The overall view of the cylinder set up and diagram for the loading machine and measuring equipment are as shown in Figure 5 and Figure 6.

The overall longitudinal axial deformations of the cylinders were obtained using the three linear variable differential transducers (LVDTs) located at the top part of the load cell machine, while another three LVDTs were in the Longitudinal LVDT holder rig at the center, measured the relative axial displacement over the 100 mm height of the cylinders. The transverse deformations of the cylinders were obtained using two LVDTs in the Transverse LVDT holder rig located at the center, by wrapping a steel ties around the cylinder. The LVDTs with gage length of 25 mm were used and attached at the shaft of the machine. The overall concrete longitudinal strains were presented as the average value of LVDTs divided by the particular measured length.

On top of that, as shown in Figure 5, the transverse deformations for concrete and steel strapping were obtained using two sets of strain gauges located at the center of the cylinder in diametrically direction. All the strains were measured using the data logger to record the values of load, displacement, and strain. Any cracking pattern, buckling, and deformation, were recorded during testing. The compressive strength of cylinder was tested according to ASTM C39/C39M-11.

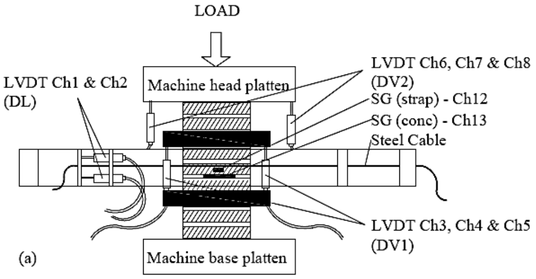

**Figure 5** LVDT holder rig and strain gauges position

**Figure 6** Diagram for strain measuring equipment and the loading device (TINIUS OLSEN Super "L" Universal Testing Machine)

### 2.4 Compression Tests

For the three control cylinders and SSTT confined cylinders assigned for uniaxial monotonic compression load, the tests were performed with monotonically increasing displacement of rate 0.4 mm/min until significant strength dropped to more than 50% of the respective ultimate strength capacity, indicates failure of the cylinders. While for the remaining six SSTT confined cylinders, uniaxial cyclic compression involving unloading and reloading cycles with similar displacement control rate was implemented at several prescribed unloading load values, until cylinders failure were indicated. In other words, the confined cylinder was loaded by increasing the uniaxial load to a prescribed value, and it was next unloaded by reducing the uniaxial load to a target load level (about 1-3 kN). Then the cylinder was loaded to the next prescribed load value for cyclic loading until it was failed.

## ■3.0 OBSERVED BEHAVIOUR AND EXPERIMENTAL RESULT

### 3.1 Mode of Failure

This section discusses the failure mode of each cylinder unconfined, confined with two layers of steel strap, and confined with four layers of steel strap, for both uniaxial compression load and cyclic load tests. Table 3 and Table 4 below show the test result of unconfined and confined cylinders respectively.

For the unconfined cylinder (control cylinder and represented by cylinder C60-C-02), as shown in Figure 7(a), most of the top portion failed and collapsed in several deep diagonal shear modes. Thus, it is clear that the unconfined cylinders underwent serious crushing along the cylinder. All the unconfined cylinders failed with explosive behaviour when reaching the ultimate load. The sustainable average compressive load for unconfined cylinders ($f_{c0}$) was 59.18 MPa.

For the SSTT confined cylinders which were externally pre-tensioned with two and four layers of steel strapping and tested under uniaxial compression load test (represented by C60S15-2FT-07 and C60S15-4FT-11), as shown in Figure 7(b) and 7(c), the cylinders had diagonal shear crack and minor crushing along the cylinders. When the loading approaches the ultimate load of the cylinders, there was a significant cracking but the confined cylinders did not collapsed. At the same time, further diagonal shear cracks developed. The only explanation to this scenario is due to the function of pre-tensioned steel strap in preventing the confined cylinders to collapse. All the confined cylinders exhibit more ductile behaviour compared to the unconfined cylinders. Thus, it can be justified that the pre-tensioning of steel strap helps in improving the ductility of the high-strength concrete cylinders. The respective average ultimate compressive load and ductility ratio that can be sustained by SSTT confined cylinders pre-tensioned with two layers of steel strapping was 101.04 MPa and 70.7% increment compared to unconfined cylinders. While the respective average ultimate compressive load and ductility ratio of such confinement with four layers of steel strapping was 125.75 MPa and 112.5% increment compared to unconfined cylinders.

In addition, similar failure mode observation can be noticed for SSTT confined cylinders which tested under uniaxial cyclic compression load test for both two and four layers of steel strappings (represented by C60S15-2FT-1C-14 and C60S15-4FT-1C-17), as shown in Figure 7(d) and 7(e). The average highest compressive load that can be sustained by such confined cylinder under several prescribed loading/unloading cycles was 100.29 MPa and 121.00 MPa, a 65.0% and 99.0% increment compared to unconfined concrete, for both confined cylinder with two and four layers of steel strappings, respectively. Although minor deduction of average ultimate compressive capacity obtained for those confined cylinders tested with uniaxial cyclic compression, the sustainability of the SSTT confinement to the several prescribed loading/unloading cycles was significantly feasible, with obvious compressive strength and ductility enhancement.

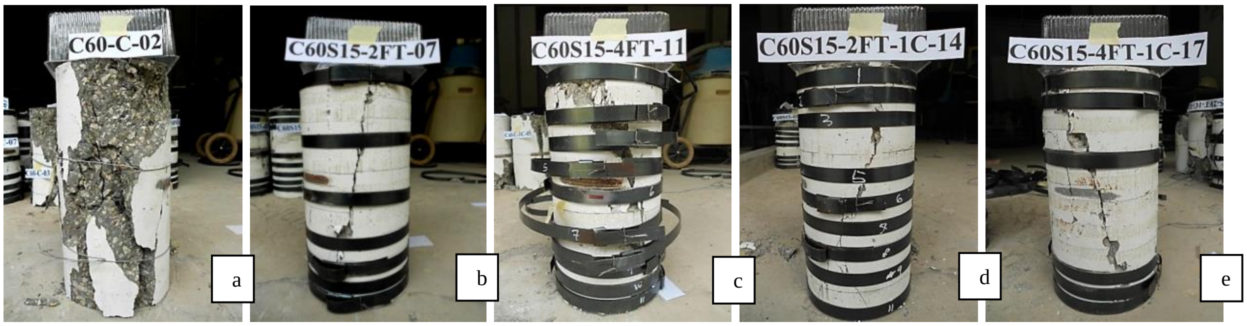

**Figure 7** The cracking pattern of (a) unconfined concrete, (b & c) two layers and four layers SSTT confined concrete subjected to uniaxial monotonic compression load, respectively; (d & e) two layers and four layers SSTT confined concrete subjected to uniaxial cyclic compression load

**Table 3** Average test result of unconfined concrete cylinders

| **Specimen Notation** | $f'_c$ (MPa) | $f_{c0}$ (MPa) | $\varepsilon_{c0}$ | $\varepsilon_{85}$ | $\varepsilon_{50}$ | $f_{c0}/f'_c$ |
|---|---|---|---|---|---|---|
| C60-C | 70.40 | 59.18 | 0.0070 | - | - | 0.841 |

**Table 4** Average test results of confined concrete cylinders

| **Specimen Notation** | $f_{cc}$ (MPa) | $\varepsilon_{cc}$ | $\varepsilon_{85}$ | $\varepsilon_{50}$ | $f_{cc}/f_{c0}$ | $\varepsilon_{85}/\varepsilon_{cc}$ | $\varepsilon_{50}/\varepsilon_{cc}$ |
|---|---|---|---|---|---|---|---|
| C60S15-2FT | 101.04 | 0.0114 | 0.0129 | 0.0157 | 1.707 | 1.132 | 1.377 |
| C60S15-4FT | 125.75 | 0.0177 | 0.0213 | 0.0250 | 2.125 | 1.203 | 1.412 |
| C60S15-2FT-1C | 100.29 | 0.0100 | 0.0117 | 0.0145 | 1.695 | 1.170 | 1.450 |
| C60S15-4FT-1C | 121.00 | 0.0130 | 0.0164 | 0.0190 | 2.045 | 1.262 | 1.462 |

## 3.2 Discussion of Experimental Result

Table 3 and Table 4 show the average test results of the unconfined and confined cylinders for both uniaxial monotonic and cyclic compression load test, respectively. In between these two tables, $f_{c0}$ and $\varepsilon_{c0}$ are the peak compression strength in MPa and strain at the peak compressive strength in the unconfined cylinders, respectively. $f_{cc}$ and $\varepsilon_{cc}$ are the peak compression strength and the strain at peak strength in the confined cylinders (cylinders pre-tensioned with two layers of steel strap and four layers of steel strap) respectively. $\varepsilon_{85}$ and $\varepsilon_{50}$ are the strains at 85 % and 50 % of the peak compression strength after the full peak compression strength, respectively.

The strength enhancement ratio of a confined cylinder, defined as the ratio of the compression strengths $f_{c0}$ and $f_{cc}$ (i.e., $f_{cc}$ / $f_{c0}$ > 1.0), is one of the confinement enhancing effect measurements as shown in Table 4. According to the result two layers of steel strap was 1.707, while that of SSTT confined cylinder pre-tensioned with four layers of steel strap was 2.125. Throughout this study, the compressive strength enhancement ratio for confined cylinders pre-tensioned with four layers of steel strap performed better than the confined cylinder pre-tensioned with two layers of steel strap. The effect of four layers pre-tensioned steel strap showed more consolidate result compared to the effect of two layers pre-tensioned steel strap. However, it is recommended to have more set of results with more layers of steel strap in order to prove this result.

The ductility ratio of a confined cylinder, defined as the ratio of two strains $\varepsilon_{50}$ and $\varepsilon_{cc}$ (i.e., $\varepsilon_{50}$ / $\varepsilon_{cc}$ > 1.0), is one of the ductility measurement parameters shown in the Table 4. According to the test result, the average ductility ratio of SSTT confined cylinders pre-tensioned with two layers of steel strap was 1.377, while that of SSTT confined cylinders pre-tensioned with four layers of steel strap was 1.412. From this study, it has been proved that the confined cylinder with four layers of pre-tensioned steel straps have higher ductility ratio than confined cylinder pre-tensioned with two layers of steel strap by 2.5 %. In addition, the plasticity ratio of a confined cylinder, defined as the ratio of $\varepsilon_{85}$ and $\varepsilon_{cc}$ (i.e., $\varepsilon_{85}$ / $\varepsilon_{cc}$ > 1.0), showed an improvement up to 13.2 % for confined cylinder pre-tensioned with two layer of steel strap and 20.3 % for confined cylinder pre-tensioned with four layers of steel strap.

While for SSTT confined cylinders tested under uniaxial cyclic compression load, the average strength enhancement ratio for confined cylinders pre-tensioned with two and four layers of steep strappings were 1.695 and 2.045 respectively. Compared to those SSTT confined cylinders tested under uniaxial monotonic compression load, the strength enhancement ratio for uniaxial-cyclised SSTT confined cylinders dropped about 0.7% and 3.8% for cylinders with two and four layers of steel strapping, respectively. Besides, plasticity and ductility ratio for such confined cylinders pre-tensioned with two layers of steel strapping showed an increment of 17% and 45% respectively; and 26% and 46% of that increment for confined cylinders with four layers of steel strapping. Basically there were no major disparities between the confined cylinders with equivalent layers of steel strapping, tested under both uniaxial compression load tests, in term of strength enhancement ratio, plasticity ratio and ductility ratio. The effect of loading/unloading cycles of such confined cylinders appeared to be unaffected to the investigating ratios, holding significant compressive strength and ductility enhancement.

### 3.3 Stress-Strain Behaviour of SSTT Confined High-Strength Concrete

Figure 8 and Figure 9 show the analysis graph in longitudinal and transverse direction for unconfined and confined concrete respectively. From Figure 8, the obvious observation is that the cylinders pre-tensioned with steel strappings provided more compressive strength sustainability, with higher ultimate strain and ductility than the unconfined cylinders. The compressive strength for unconfined cylinders dropped tremendously with explosive behaviour right reaching the ultimate compressive capacity; once again the natural characteristic of high-strength concrete, i.e. brittle and low ductile behaviour, was proven. Besides, it is proven that the confined cylinders strengthened with four layers of steel strapping had higher compressive strength than cylinders strengthened with two layers of steel strapping. The correlation between the ultimate compressive strength, ultimate strain and ductility has been proved to be directly proportional to the confinement ratio of steel strapping, i.e. as the steel strapping confinement ratio increases, the ultimate compressive strength, ultimate strain and ductility of the cylinders also increases.

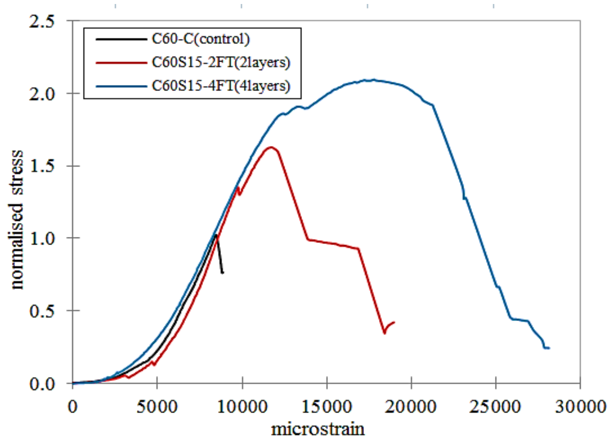

**Figure 8** Graph of stress-strain relationship in longitudinal direction

From Figure 9, it is experimentally proved high-strength concrete with SSTT confinement able to sustain more lateral dilation compared to the control cylinders which failed at specimen's ultimate capacity. It also correlates that confined cylinders with higher confinement ratio able to sustain higher lateral ultimate strain than those counterpart cylinders.

Figure 10 shows the graph of average stress-strain relationship of steel strap for both cylinders strengthened with two layers and four layers of steel strap. C60S15-2FT shows greater ultimate strain before failure than C60S15-4FT because the later cylinder can sustain heavier load. Simply to say, the effect of steel strap confinement for C60S15-4FT was not as efficient as C60S15-2FT due to the difficulty in tensioning for high volumetric ratio confinement.

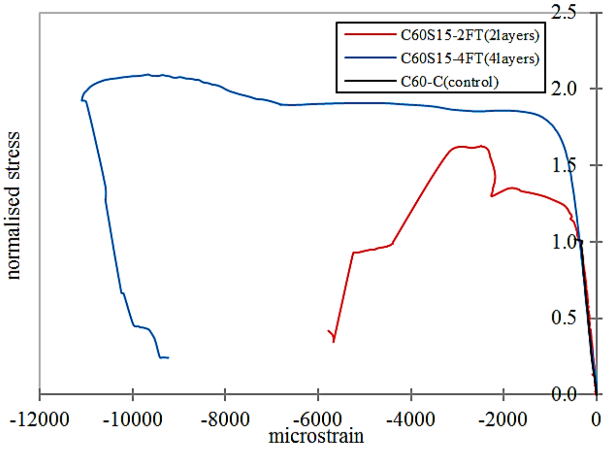

**Figure 9** Graph of stress-strain relationship in transverse direction

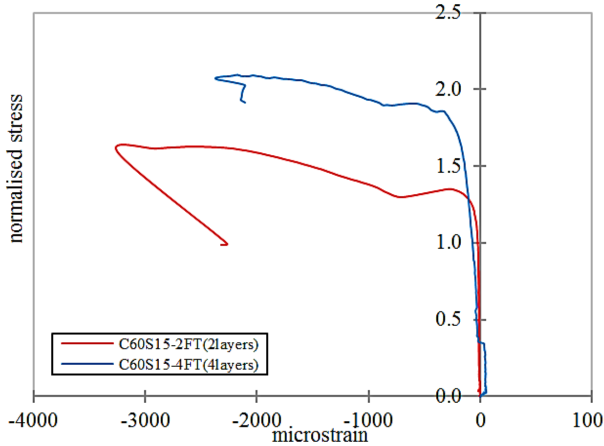

**Figure 10** Graph of stress-strain relationship for steel strapping

### 3.4 Validation of Envelope Curve for Uniaxial Cyclic Compression Load Test

The concept of an envelope curve for unconfined and confined concrete was defined as the curve joining the resulting broken curves or the loading branches between each cycles and the monotonic stress-strain curve simultaneously estimated will falls between the envelope curves under constantly increasing strain [39]. Envelope curve also can be considered as an upper boundary response of unconfined and confined concrete subjected to any loading history in the stress-strain domain [40]. However, there exists controversy regarding the crossing point of envelope curve and the monotonic stress-strain curve for confined concrete among the researchers. Some researchers suggested that the monotonic stress-strain curve for confined concrete may stay below the envelope curve [20, 42], while other researchers suggested a coincidence of both monotonic and envelope curve may observed for confined concrete [40, 43].

As to compare both uniaxial monotonic and cyclic stress-strain curves of SSTT confined cylinders, the envelope curves from Figure 11 and Figure 12 (concrete pre-tensioned with two and four layers of steel strapping, respectively) were be easily obtained by connecting all the initial unloading points on the stress-strain curve within the uniaxial cyclic loading history. It is clearly observed that the initial unloading/reloading cycles at each prescribed axial load coincided with the monotonic stress-strain curve, while after the ultimate compressive stress, the envelope curves stayed below the monotonic stress-strain curves. Hence, this observation proved that the basic hypothesis of envelope curve is valid for SSTT confined high-strength concrete. The envelope curve coincides with the monotonic stress-strain curve for the initial unloading points until the ultimate compressive load, while the subsequent envelope curve is staying below the monotonic curve.

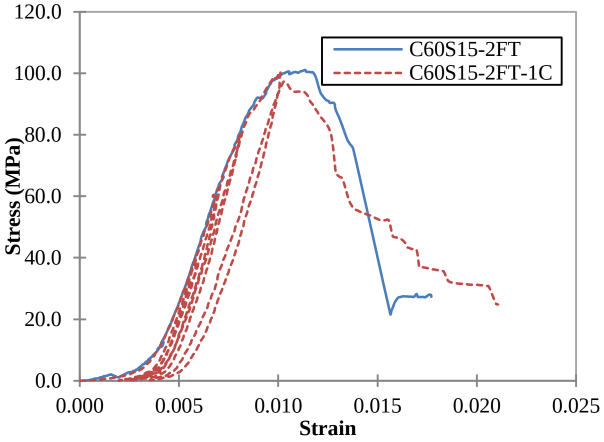

**Figure 11** Uniaxial cyclic stress-strain curves of concrete confined with two layers of steel strapping in comparison with monotonic stress-strain curves of corresponding confined concrete

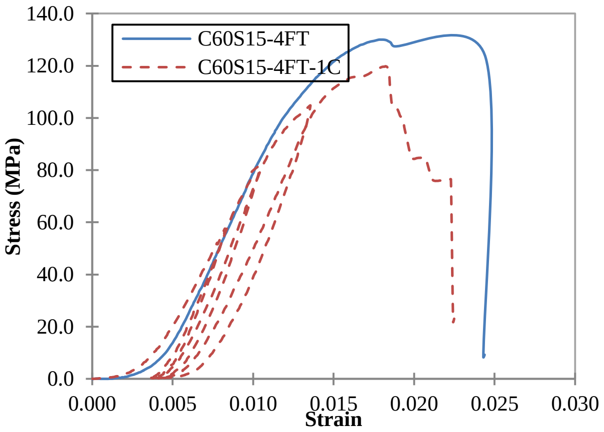

**Figure 12** Uniaxial cyclic stress-strain curves of concrete confined with four layers of steel strapping in comparison with monotonic stress-strain curves of corresponding confined concrete

## ■4.0 ANALYTICAL ASSESSMENT OF THE EXPERIMENTAL RESULT

### 4.1 Ultimate Uniaxial Compressive Strength Evaluation

Many of the existing ultimate uniaxial compressive strength models for confined concrete take the following terms:

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

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 *et al.* [41] for actively confined concrete. This form of Eqn. (1) is also suggested eligible for steel strap confined concrete.

In order to design the ultimate compressive strength enhancement of confined concrete, it is a necessary to model an equation to calculate the ultimate strength gain of concrete due to steel strap confinement. In this study, seven existing compressive strength models of confined concrete (Table 5) were selected and compared to current experimental results as shown in Figure 13. It should be noted that confining ratio (axis-x) in Figure 13 defined as effective mechanical volumetric ratio of confining steel as defined in EC8 code.

**Table 5** The existing compressive strength models

| **Source** | **Ultimate Strength models** |
|---|---|
| Karbhari and Gao [32] | $\frac{f_{cc}}{f_{co}} = 1 + 2.1\left(\frac{f_l}{f_{co}}\right)^{0.87}$ |
| Mander er al. [33] | $\frac{f_{cc}}{f_{co}} = -1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f_{co}}} - 2\frac{f_l}{f_{co}}$ |
| Hoshikuma *et al.* [34] | $\frac{f_{cc}}{f_{co}} = 1 + 3.8\frac{f_l}{f_{co}}$ |
| Cusson and Paultre [35] | $\frac{f_{cc}}{f_{co}} = 1 + 2.1\left(\frac{f_l}{f_{co}}\right)^{0.7}$ |
| Kono *et al.* [36] | $\frac{f_{cc}}{f_{co}} = 1 + 0.0572 f_l$ |
| Spoelstra and Monti [37] | $\frac{f_{cc}}{f_{co}} = 0.2 + 3.0\left(\frac{f_l}{f_{co}}\right)^{0.5}$ |
| EC8 | $\frac{f_{cc}}{f_{co}} = 1 + 2.5\frac{f_l}{f_{co}}$ |

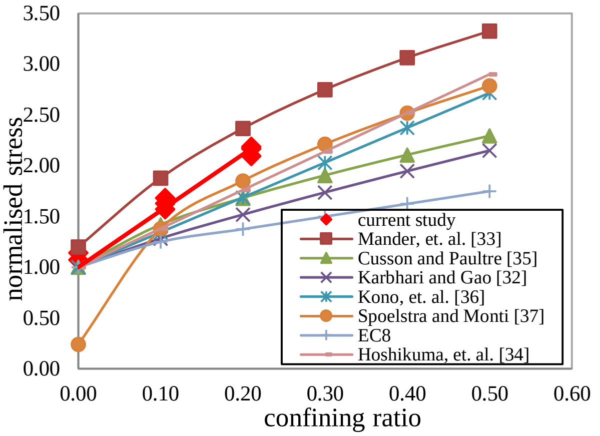

**Figure 13** Comparison of existing compressive strength models with current experimental results

By referring to Figure 13, most of the existing compressive strength models lie in the bottom part of current experimental results. The concrete axial compressive strength of existing models is less than those with SSTT confinement except for Mander *et al.*'s model [33]. The figure shows that none of the models give close predictions to the experimental test results. Of the seven models, Mander *et al.*'s models, which are the most commonly used for steel-confined concrete, are not conservative to current study; all the other six existing models are over-conservative to steel strap confined concrete. The following equation for the compressive strength of SSTT confined concrete was therefore proposed for design use, with correlation coefficient, $R^2$ equal to 0.97:

$$\frac{f_{cc}}{f_{co}} = 1 + 5.57\frac{f_l}{f_{co}} \tag{2}$$

The proposed compressive strength model is linearly related to the lateral confining ratio provided by confined steel strapping. The proposed model is recommended for design use due to its simplicity. Further research endeavor is still needed to justify its reliability.

## 4.2 Ultimate Uniaxial Strain Evaluation

For the ultimate uniaxial strain model evaluation, similar form of equation proposed by Richard *et al*. [41] has been implemented:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + k_2\frac{f_l}{f_{co}} \tag{3}$$

where $\varepsilon_{cc}$ and $\varepsilon_{co}$ are the ultimate compressive strains of the confined and the unconfined concrete respectively, $f_l$ is the lateral confining pressure, $f_{co}$ is the ultimate compressive strength of unconfined concrete and $k_2$ is the strain enhancement coefficient.

A graph of normalised strain ($\varepsilon_{cc}/\varepsilon_{co}$) verses confining ratio of the SSTT confinement has been plotted as shown in Figure 14. Four existing ultimate uniaxial strain models of confined concrete (Table 6) were chosen and compared with the current experimental results. A linear relationship between the strain enhancement and confining ratio provided by SSTT confinement has been proposed. By referring to Figure 14, none of the existing strain models give fully close prediction to the experimental results. Karbhari and Gao's strain model [32] give the closest prediction for the confinement with low confining ratio but over-conservatively divergence for the confinement with higher confining ratio. While the other three strain models lie in the top part of the current experimental results, showing a non-conservation prediction for the SSTT confinement.

**Table 6** The existing ultimate strain models

| **Source** | **Ultimate Strain models** |
|---|---|
| Karbhari and Gao [32] | $\varepsilon_{cc} = 0.01\left(\frac{f_l}{f_{co}}\right) + \varepsilon_{co}$ |
| Mander *et al*. [33] | $\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)$ |
| Miyauchi *et al*. [38] | $\varepsilon_{cc} = 0.002\left[1 + 10.6\left(\frac{f_l}{f_{co}}\right)^{0.373}\right]$ |
| Hoshikuma *et al*. [34] | $\varepsilon_{cc} = 0.002 + 0.066\frac{f_l}{f_{co}}$ |

An equation for the ultimate strain of SSTT confinement was proposed for design use, with correlation coefficient, $R^2$ equal to 0.93:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 6.30\frac{f_l}{f_{co}} \tag{4}$$

For steel-confined concrete investigated by Richard *et al*. (1928), the strain enhancement coefficient ($k_2$) was suggested to be five times higher than the confinement effectiveness coefficient ($k_1$). This suggestion is not ideal for the SSTT confinement, where the ratio between strain enhancement coefficient and confinement effectiveness coefficient ($k_2/k_1$) in this study is just 1.13. However, the concluded coefficients found out in this study were in regards to the testing of the small amount of SSTT confined cylinders, where further research is still needed to justify the reliability of current findings.

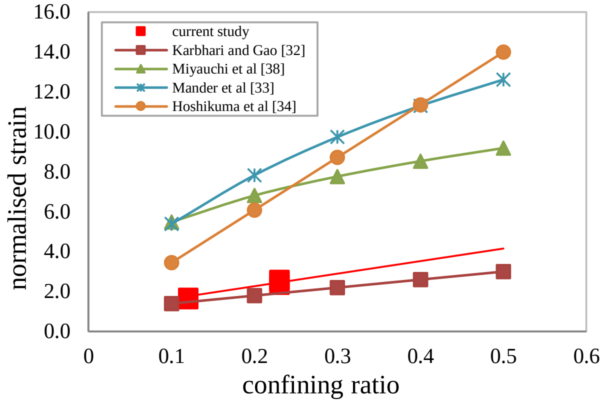

**Figure 14** Comparison of existing strain models with current experimental results

## 4.3 Existing Stress-Strain Curve Comparison

In this study, a well-known stress-strain model proposed by Mander *et al*. [33] is selected and compared to current experimental results. The model proposed was to simulate both ascending and descending branches of the stress-strain curve for transverse reinforced confined cylinder with circular, square and wall-type rectangular sections. The schematic unified stress-strain approach proposed by Mander *et al*. for unconfined and confined concrete under monotonic loading is as illustrated in Figure 15.

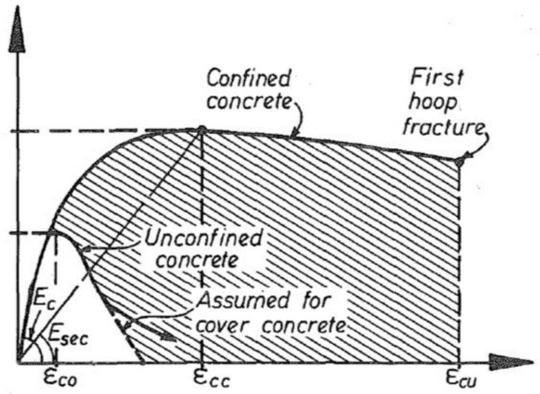

**Figure 15** Schematic diagram of the proposed unconfined and confined concrete model by Mander *et al*. [33]

The proposed existing stress-strain model equations, validity limited to slow static strain rate monotonic loading only, are presented as followed:

$$f_c = \frac{f_{cc}xr}{r-1+x^r} \tag{5}$$

where $x = \frac{\varepsilon_c}{\varepsilon_{cc}}$ in which $\varepsilon_c$ is the longitudinal compressive concrete strain and $f_c$ is the longitudinal compressive concrete stress. The equations of ultimate compressive strength and ultimate longitudinal strain for confined concrete are as described in previous sections, in Table 5 and Table 6 respectively. A logical comparison with equivalent confinement volumetric ratio suited with SSTT confinement for Mander stress-strain curve was plotted (Figure 16) and compared with the observed stress-strain behaviour of current experimental results for the examined pre-tensioned layers of steel strapping.

From the comparison graph illustrated in Figure 16, a satisfactory stress-strain prediction with relatively good agreement between Mander's model and current experimental results has been disclosed. However, the existing prediction model over-estimated the experimental results with steeper slope of elastic increment (higher confined concrete elasticity) in the initial segment of the prediction curve. Overall, the model of Mander *et al*. provides approaching prediction to SSTT confinement.

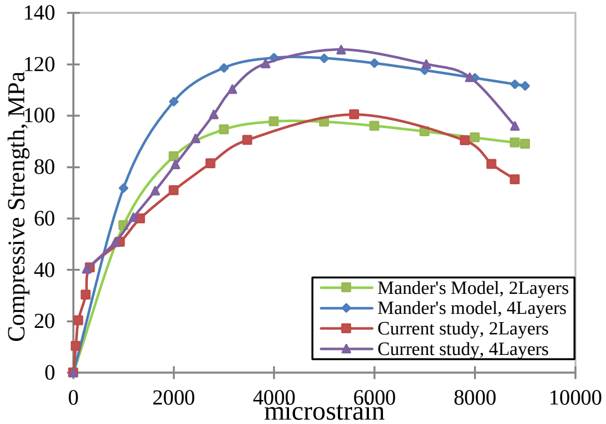

**Figure 16** Experimental stress-strain curve of SSTT confined high-strength concrete compared to Mander *et al*. [33] stress-strain theoretical model

## ■5.0 CONCLUSIONS

1. Concrete naturally become more brittle as the concrete compressive strength increases. Generally, they will fail with explosion right after passing the elastic zone. However, current external confinement of steel strapping is able to dispel the brittle nature of high-strength concrete cylinder, causing them to instead fail gradually after the elastic zone without explosion. Therefore, this study confirmed that SSTT confinement is capable of solving the brittle characteristic of high-strength concrete cylinder and thus is useful for structures in seismic zone.
2. According to this experimental study, for *cylinders* with similar concrete strength, cylinders with more layers of steel strapping give better strength and ductility performance. However, the influence of maximum confinement layers in concrete strength enhancement has not been studied in this research. It is suspected that when a certain limit of layers has been achieved, the position effect 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.
3. While for those SSTT confined high-strength concrete cylinders under uniaxial cyclic compression load with several prescribed unloading/reloading cycles, an increment in ultimate compressive strength of up to 69.5% and 104.5%, and increment of ductility up to 45.0% and 46.2% for the confined cylinders which pre-tensioned with two and four layers of steel strapping respectively, has been obtained. Basically, in term of ultimate compressive strength enhancement ratio, plasticity ratio and ductility ratio, there were no major disparities between corresponding confined cylinders tested under both uniaxial compression load test. Hence, similar relationship of confined cylinder tested under uniaxial monotonic load, between confinement ratio and ultimate strength and ductility can be made.
4. There is a close and linear relationship between the confinement ratios, ultimate strength enhancement and ultimate strain of SSTT confined cylinders. The proposed compressive strength and strain model are linearly related to the lateral confining ratios provided by confined steel strap. The proposed model is recommended for design use only due to its simplicity and unconfirmed reliability.
5. Mandel *et al.*'s prediction model is selected to compare the stress-strain response of SSTT confined high-strength concrete under uniaxial monotonic compression. A satisfactory stress-strain prediction with relatively acceptable agreement has been disclosed. But, the existing prediction model over-estimated the current experimental results with steeper slope of elastic increment in the initial segment of the prediction curve. Overall, the prediction model provides approaching prediction to SSTT confined cylinders' stress-strain curve.

It should be noted that the above conclusions have been reached only in regard to the basis of tests conducted on small-scale cylinders, which are standard cylinder concrete specimens. Dimension and size variability may impose different effects and such effects should be examined using full-scale cylinders in the future.

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