Behaviour of Steel Straps-Confined Concrete Column with Lateral Pre-tensioning Stresses under Uniaxial Cyclic Compression

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Abstract: **-** The behaviour of high strength concrete (HSC) under uniaxial cyclic compression load is extremely important to simulate the seismic effect. It is very helpful to the development of high rise building and future demand of HSC. The main problems of HSC are brittle and less ductile. Hence, this project focuses into the brittleness and ductility of HSC column subjected to uniaxial cyclic compression. Eighteen specimens with compressive strength of C60, 100mm in diameter and 200mm in height were tested and analysed under uniaxial cyclic and monotonic compression loads. All the specimens were confined with 2 layers or 4 layers steel straps with pre-tensioning stress at 10mm spacing between straps. The lateral pre-tensioning stresses for 2-layer and 4-layer confinement were fixed to 5bars and 4bars respectively. The results show that SSTT confinement enhances the strength, less brittle and more ductile compare to unconfined specimen. The compressive strength and ductility enhancement are up to 118.5% and 64.5% respectively. The envelope curve of confined HSC tested under uniaxial cyclic loading is almost coincides with the curve of identical specimen tested under uniaxial monotonic load. The graphs of plastic strain confined with 2-layer and 4-layer confinement show the different in gradient. This indicates that plastic strain of SSTT confined HSC depends on the layers of confinement and level of pre-tensioning stress.

***Keywords:* -** *high strength concrete, steel strapping tensioning technique, ductility, cyclic compression, lateral confinement, stress-strain behaviour*

I. INTRODUCTION

Nowadays, technology is always improves and never stop down. HSC is a great invention in construction due to its compressive strength properties. More high-rise buildings and bridges were built with HSC due to lower unit weight. Besides, it provides strength with potential seismic advantages, reduced dimension and reinforcement of members, and more economy to construction.

Although HSC provides so great compressive strength, the weaknesses and main problems are brittle and less ductile compare to normal strength concrete. According to Razvi and Saatcioglu (1992), ductility was a major problem regarding to deformability of structural elements. So, it is a need to have some confinement methods to minimize the problem such as external steel jacketing, steel tube and fiber-reinforced polymer (FRP) (Harries and Kharel, 2002). FRP was used to cover this problem few years ago. However, the existing methods could not delay the deformation and failure of HSC promisingly. The behaviour of low lateral dilation of HSC might unable to activate the confinement material. Lastly, the concrete columns still will fail at sudden (Esfahani and Kianoush, 2004). In addition, FRP and others existing strengthening techniques were expensive and time consuming (Moghaddam et al., 2008).

Therefore, a new technique was introduced by Kypros Pilakoutas using standard strapping machine uses in packaging industry to do post-tensioning metal strips around the column. However, there are some weaknesses in this technique. The two ends of the strip are tightened with sealed clamps to maintain the pre-stress force in the strip. It produced the permanent lock at connection and suspected could not provide layering effect and promising lateral pre-tensioning stress of the confinement of the concrete. Therefore, SSTT was proposed in UTM where it does not apply any notching to the connection clip but secured by bended the extra confinement steel strap. By the way, it did not cause any damage to the concrete surface and easy to handle. On top of that, there is a study on optimum pre-tensioning stress in our research group. Hence, this study will validate the envelope curve for cyclic loading with optimum pre-tensioning stress confinement.

There are many researches done on uniaxial compression test (Sharma et al., 2005; Esfahani and Kianoush, 2004; Yu and You, 2010; Sharma et al., 2007; Thomas et al., 1998) but rare on uniaxial cyclic loading (Lam et al., 2006; Varma et al., 2009; Tasnimi and Lavasani, 2011). There are some uncertainties in some issues such as validity of envelope curve and plastic strain on stress-strain curve especially for HSC. There was also no research done on the metal strips column subjected to uniaxial cyclic compression. Therefore, a study on confinement HSC column is required for future to repair, rehabilitate or strengthen the structure and might be a great knowledge for material enhancement.

This paper presents the test results of a study on behaviour of SSTT confined HSC column which subjected to optimum lateral pre-tensioning stress under uniaxial cyclic compression load. The study obtained the stress-strain relationship between unconfined and confined HSC column under uniaxial cyclic load. Test results obtained are presented and examined.

II. EXPERIMENTAL PROGRAM

2.1 SPECIMEN PREPARATION

Total of 18 circular specimens were prepared with diameter of 100mm and 200mm height. The testing was carried out by uniaxial monotonic and uniaxial cyclic compression. The test parameter was the volumetric ratio of steel straps confined externally with optimum lateral pre-tensioning stress on the column. The entire cylinder columns were not reinforced internally with steel bar. The width of steel strapping was 16mm and the spacing was fixed to 10mm. The spacing of steel straps at two ends region was reduced to half as to avoid pre-mature failure of the specimens. Figure 1 shows that the detailed of confined specimen and position of strain gauges.

Nine concrete cube of size 100mmx100mmx100mm were prepared together to get the actual strength for the concrete. All the specimens and cubes were cast together by use the mixture proportions as shown in Table 1.

After that, specimens were grinded to ensure the flat surface before steel straps were pre-tensioned on all the specimens except the controls. There were 6 control specimens without steel strap, 12 specimens were wrapped with 2-layer and 4-layer of steel straps respectively.

The optimum tensioning force used was referred from the others` experimental result from the same research group. Figure 2 shows the graph of calibration result for 2 layers and 4 layers of steel strap. From the graph, it shows that 5bars of air pressure provide the maximum pre-tensioning force for 2 layers steel strap. Meanwhile, the optimum air pressure for 4-layer steel strap was 6bars followed by 4bars. However, it is not practical to pre-tension with 6bars of air pressure. Therefore, air pressure of 5bars and 4bars was applied on 2-layer and 4-layer steel strap respectively as the optimum tensioning force.

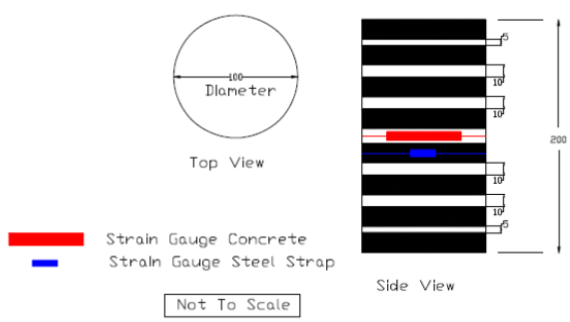


Figure 1: Detailed of specimen size and strain gauge position. (Unit in mm)

Table 1: Concrete mixture proportions for 60MPa concrete

Material	**Type**	**Quantity**
Cement	Ordinary Portland cement	550 (kg/m^3)
Aggregate	Fine aggregate (sand)	885 (kg/m^3)
Aggregate	Course aggregate (max12mm)	957 (kg/m^3)
Water	Pipe water	190 (kg/m^3)
Superplasticizer (mL)	Glenium ACE388 (RM)	0.75% L/ 1000kg cement
Water/ Cement ratio		0.35

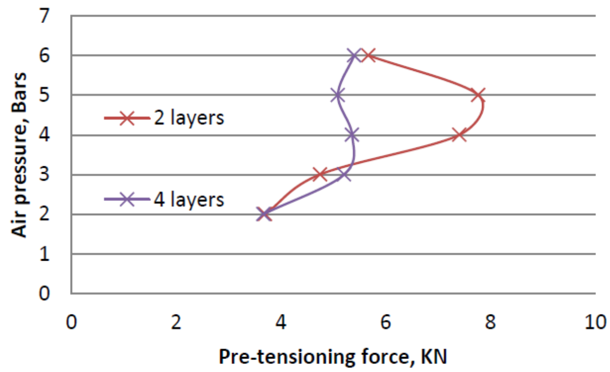


Figure 2: Calibration Result for 2-layer and 4-layer steel strap

2.2 STRAIN GAUGE AND LVDT INSTRUMENT

To measure the transverse deformation of concrete and steel strap, four strain gauges were located on each specimen as shown in Figure 3. The strain gauges were measured by the data logger which connected to the computer. The overall axial deformations of specimens were measured by three linear variable differential transducers (LVDTs) that located at the top part of load cell. On the other hand, three LVDTs were located in the longitudinal LVDT rig holder to measure the centre deformation of specimens. Besides, the lateral deformation of the specimens also measured by using two LVDTs that set in the transverse LVDT rig holder at the centre of specimens. The test was carried out by using TINUS OLSEN SUPER “L” Universal Testing Machine which capacity up to 3MN with rate of 0.4mm/min. The applied loads and all the measurement parameters were connected to computer.

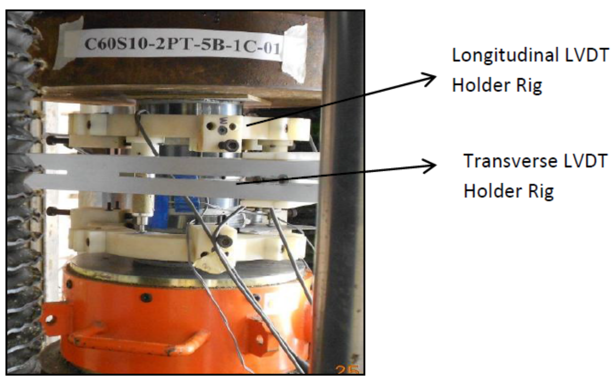


Figure 3: The specimen was fixed in the machine and ready to be tested

2.3 COMPRESSION TESTS

Two types of load testing were carried out in this study, uniaxial monotonic compression and uniaxial cyclic compression. All the testing was done by TINIUS OLSEN super “L” Universal Testing Machine. There were total 18 specimens, 9 specimens were tested under monotonic compression while the other 9 specimens were tested under cyclic compression. For each type of testing, there were 3 unconfined columns (control) and 6 steel strap confined columns with 2L5B and 4L4B confinement respectively. For monotonic compression, the specimens were directly loaded by increasing displacement until failure. For cyclic compression, the process of testing involved unloading and reloading. First, the numbers and values of prescribed load are fixed according to ultimate strength from monotonic compression. The cycles of unloading and reloading were applied at 5 prescribed unloading load until failure. In the test, the load was applied by increasing the axial load to the prescribed value (max. 5) and then unloaded to load level of 1kN to 5kN. So, the process was repeated until specimen was fail. All the loading patterns, loading, displacement, strains and LVDTs were recorded and stored in computer

III. TEST RESULTS AND DISCUSSIONS

3.1 FAILURE MODE

From the testing result, the failures occurred were not much different between monotonic loading and cyclic loading. So, the failure mode can be categorized according to the confined and unconfined specimen. In general, the unconfined specimen failed in collapse condition and deep diagonal shear failure. For confined specimen, the concrete failed in diagonal shear, small crack, and deep diagonal shear. Three specimens which were used to discuss are unconfined concrete (control), 2-layer steel strap specimen, and 4-layer steel strap specimen respectively.

For unconfined specimen, the condition of concrete failed in the way as shown in Figure 4(a). From the figure, it shows that the concrete was crushed along the concrete and deep diagonal failure was observed. Almost all unconfined specimens exploded when reach the ultimate load and the sample collapsed. The ultimate compressive load that obtained from the sample is 72.77MPa and average compressive load is 67.31MPa.

For confined specimen with 2-layer steel strap, the condition of failure was shown in the Figure 4(b), specimen C60S16-2PT-5B-1C-02. The sample was undergone diagonal shear cracking and some minor crack surrounding the concrete. When it reached the ultimate capacity, the explosion happened but the specimen did not collapse. The diagonal shear crack started occurred and followed by breaking of steel strap. From this observation, it shows that the steel straps help to prevent the concrete from collapse and increase the ductility behaviour of concrete. The peak load that can be sustained was increase from 72.77MPa to 120.73MPa and the average incensement is 67.31MPa to 109.49MPa, 62.67% compare to peak unconfined concrete.

For 4-layer steel strap confinement specimen, it is represented by specimen C60S16-4PT-4B-1C-03 as shown in figure 4(c). The concrete was failed in the way such as the 2 layers confined concrete, diagonal shear cracking and minor crush along the specimen. Explosion also occurred when reaches the ultimate load but concrete did not collapsed. This indicates that the 4 layers steel strap prevent the specimens from collapsed. When compare with 2 layers confinement, 4 layers confinement shows that the specimens behave more ductile and can sustained the load up to 154.95MPa, the overall improvement was 118.54% compare to unconfined concrete.

Figure 4: Failure mode of specimen for (a) control, (b) 2-layer confinement and (c) 4-layer confinement

3.2 DISCUSSION OF TEST RESULT

Tables 2 and 3 show the average test results of the unconfined and confined specimens under monotonic and cyclic uniaxial compression. Besides, fco (MPa) is the peak compression strength for unconfined specimen and Ɛco (mm/mm) is the strain of unconfined concrete during peak compression. fcc (MPa) and Ɛcc (mm/mm) are the peak compression strength and its strain for confined specimen. Ɛ85 (mm/mm) and Ɛ50 (mm/mm) are the strains at 85% and 50% of the peak compression strength after concrete failed.

Table 2: Average test results of unconfined concrete specimens

Specimen Notation	fco (MPa)	Ɛco (microstrain)
C60-C	81.63	10433.3
C60-C-1C*	67.31	9991.67

Table 3: Average test results of confined concrete specimens

Specimen Notation	fcc (MPa)	Ɛcc (Microstrain)	ε85 (Microstrain)	ε50 (Microstrain)	fcc/fco	ε85/εcc	ε50/εcc
C60S16-2PT-5B	106.87	17308.33	2013.33	24220.83	1.309	1.162	1.404
C60S16-2PT-5B-1C*	109.49	13283.33	15075.00	19466.67	1.627	1.149	1.640
C60S16-4PT-4B	140.70	17666.67	25233.33	30816.67	1.724	1.465	1.793
C60S16-4PT-4B-1C*	147.11	19150.00	24050.00	27800.00	2.186	1.262	1.465

After the analysis of the overall data, the confined concrete specimens show improvement on the result compare to unconfined concrete specimens with subjected to optimum lateral pre-tensioning stress under uniaxial cyclic load.

The enhancement ratio of the confined concrete is 62.7% for 2 layers steel strap and 118.6% for 4 layers steel strap. Enhancement ratio defined as the comparison of compressive strength on unconfined specimen (fco) and confined specimen (fcc). Four layers confinement show the higher ratio compare to 2 layers. This shows that 4 layers of confinement perform better and the result might vary due to the layers of steel strap. Therefore, more data should be produced by investigate on more layers of steel strap to get the evidence on this statement.

Other than compressive strength, ductility was an important parameter in this experiment. Table 3 shows the data for the ductility measurement in the ratio of two strains when the 50% of peak compressive strength after concrete failed (Ɛ50) to the peak compressive strength (Ɛcc). The average ductility of confined concrete was higher than unconfined concrete. The ductility ratio for 2 layers steel strap was increase 64% while 4 layers steel strap increase 46.5%. This shows that the 4 layers steel strap produces lower ratios due to the larger strain at peak compressive strength. However, the ductility of 4 layers steel straps specimen was higher than the 2 layers specimens.

The plasticity ratio was defined as the ratio of strain at 85% of peak compressive strength after concrete failed (Ɛ50) to the peak compressive strength (Ɛcc). The results show that the 2 layers confinement plasticity ratio was 1.149 and 4 layers confinement was 1.262. The plasticity ratio increase 9.83% from 2 layers confinement to 4 layers confinement.

3.3 ENVELOPE CURVE

According to Varma et al. (2009), there is a good fit exist between the envelope of cyclic stress-strain curve and the stress-strain curve of corresponding monotonic test. The envelope curve is made up by three branches. First, it is an almost linear slope that depends basically on the RC properties. Second, it is followed by a transition branch of pronounced non-linearity. Third, it ends with an almost linear branch of a slope that mainly depends on the confinement properties. The envelope curve for confined and unconfined concrete is approximately same as the stress-strain curve for the same concrete under monotonic loading. (Lam et al., 2006; Shah et al., 1983)

According to Figure 5 and Figure 6, the envelope curve that can be obtained from cyclic stress-strain curve was approximately same as the monotonic stress-strain curve. The graphs shown were quite small and difficult to differentiate the envelope curve from stress-strain curve from the corresponding monotonic loading test due to the both curve are almost coinciding. This shows that the envelope curve is valid for HSC confined with steel strapping. By the way, the unconfined concrete strengths were slightly different under the monotonic and cyclic loading due to the fatigue effect.

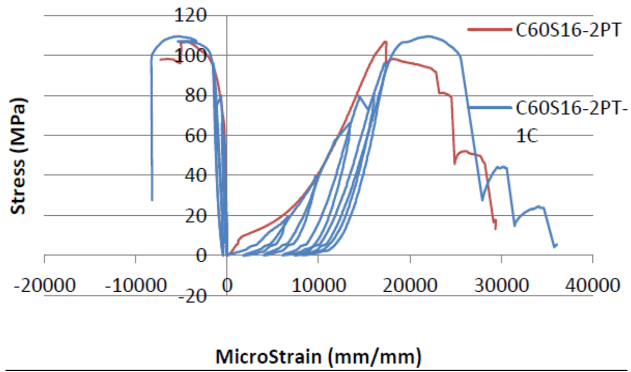


Figure 5: Stress-strain curve of confined concrete under uniaxial cyclic and uniaxial monotonic load for 2 layers steel straps confinement.

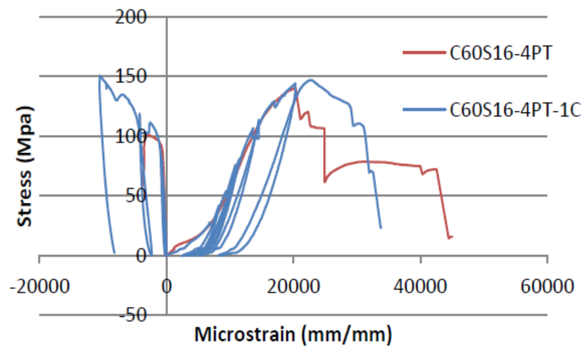


Figure 6: Stress-strain curve of confined concrete under uniaxial cyclic and uniaxial monotonic load for 4 layers steel straps confinement.

3.4 PLASTIC STRAIN

According to Konstantinidis et al. (2007), plastic strain is known as non-recoverable strain (in case of concrete). It is corresponding to zero stress on the compressive unloading or reloading curves and define the strength and stiffness degradation due to cyclic loading. The strain where the stress reach zero is defined as plastic strain on the unloading path (Sakai and Kawashima, 2006). Lam et al., (2006) stated that plastic strain of concrete is defined as the residual axial strain of the concrete when it is unloading to zero stress. Figure 7 shows the relationship of plastic strain versus envelope unloading strain of confined specimen pre-tensioned with two layers and four layers steel straps under uniaxial cyclic compression.

Plastic strain of steel-confined concrete was suggested to use a linear function of the unloading strain, μ for the region of $0.001 \leq \mu \leq 0.0035$ and $\mu \geq 0.0035$ (Sakai and Kawashima, 2006). According to Lam et al. 2006, FRP-confined concrete produce a linear relationship between the plastic strain and the envelope unloading strain with $\mu \geq 0.0035$. In Figure 7, plastic strain versus envelope unloading strain shows linear relationship for SSTT confined HSC with steel straps. The linear trend lines for both series of confinement are no coinciding with gradient 0.5 for 2 layers steel straps and 0.6 for 4 layers steel strap. This shows that the plastic strain of steel strap confined HSC is depend to volumetric ratio. However, more set of data should be obtained for the corresponding confined specimen with variable layers of steel straps or other conditions to prove the result.

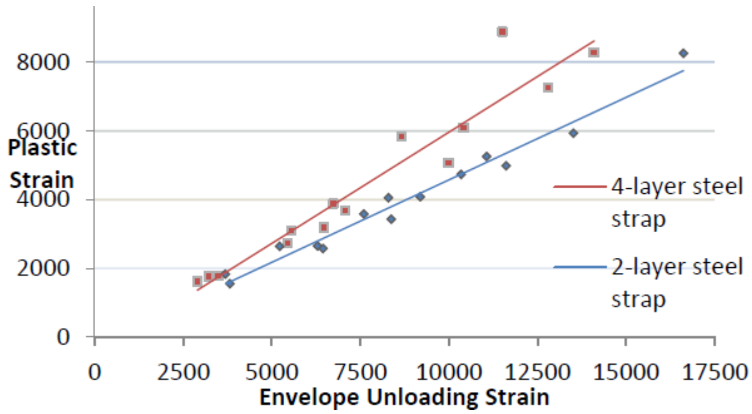
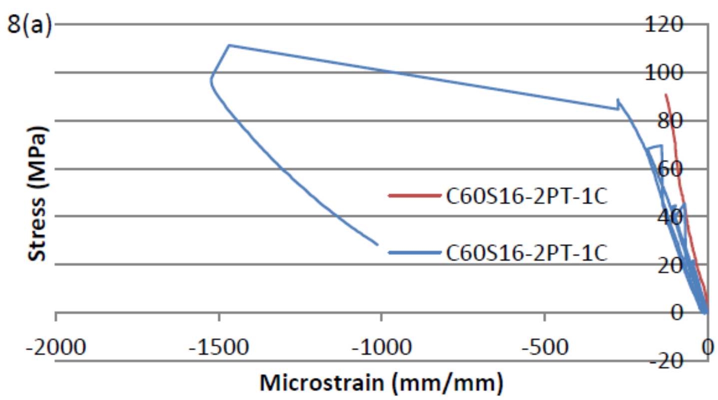


Figure 7: Plastic strain versus envelope unloading strain

3.5 STRESS-STRAIN CURVE FOR STEEL STRAPS

Figure 8 (a) and (b) show the uniaxial cyclic and uniaxial monotonic stress-strain curves of steel strap with 2 layers and 4 layers confinement. Both of the figures show that the steel straps were mobilized when stress acting on the specimen. The HSC was brittle and only allowed very small lateral dilation before failure. Hence, a very high lateral pre-tensioning stress was needed to mobilize the steel straps. With optimum lateral pre-tensioning stress, mobilization of the steel straps started at stress less than 1MPa. This indicates that the specimen was under confining effect and could prevent the specimen to fail immediately or explode as unconfined specimen.



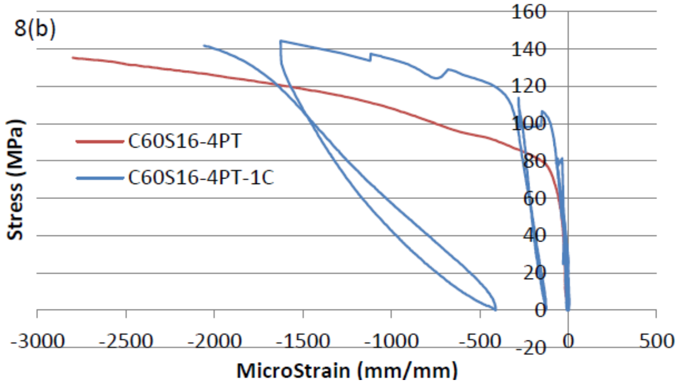


Figure 8: Stress-strain curve for steel straps under uniaxial cyclic and uniaxial monotonic compression for (a) 2-layer steel straps confinement and (b) 4-layer steel straps confinement

IV. CONCLUSIONS

This paper describes the behaviour of SSTT HSC with optimum lateral pre-tensioning stress under uniaxial cyclic loading. Results obtained from monotonic and cyclic compression tests on confined specimens had been analysed and discussed. Hence, the following conclusions can be done from the study:

1. The envelope curves are valid for HSC with 2 layers and 4 layers of steel straps confinement. The stress-strain curve of uniaxial cyclic loading and uniaxial monotonic loading show that the envelope curve is almost coincides.
2. The plastic strain of HSC with steel straps confinement shows a linear relationship to the envelope unloading strain. It is also indicates that the plastic strain is depend to the amount of confinement.
3. Confined specimens show the enhancement on compressive strength. For confined specimen with 2 layers steel strap, the peak load that can be sustained increase from 72.77MPa to 120.73MPa and the average incensement is 62.67% compare to peak unconfined concrete. Meanwhile the 4 layers confinement shows that the specimens can sustain the load up to 154.95MPa and the overall improvement is 118.54% compare to unconfined concrete. It can be conclude that the steel strap confinement can increase the compressive strength of HSC.
4. There is improvement on ductility of the steel strap confined HSC. The ductility ratio for 2 layers steel strap increase 64% while 4 layers steel strap increase 46.5%. The specimens do not show characteristic of brittle and explosive failure but fail gradually after the elastic zone. Therefore, this is a method that capable to solve the brittle characteristic of HSC and useful to the future development.

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