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APPLICATION OF HIGHLY-FLOWABLE STRAIN HARDENING FIBER REINFORCED CONCRETE (HF-SHFRC) IN NEW RC COLUMNS

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Abstract

The concept of New RC, which is upgrade of concrete and reinforcement strength, was proposed in Japan in 1989. The purpose of New RC project was aimed to reduce the member section sizes and increase the available space of high rise buildings by using high strength concrete (f'_c > 70 MPa) and high strength rebars (f_y > 685 MPa). However, the nature of brittleness of high strength concrete may be obstacles for further application. Addition of steel fibers provides more confinement and shear capacity to enhance the ductility, particularly under high axial loading demands. Highly flowable strain hardening fiber reinforced concrete (HF-SHFRC) has good workability in the fresh state and exhibits the strain-hardening and multiple cracking characteristics of high performance fiber reinforced cementitious composites (HPFRCC) in the hardened state. This study presents the improvement of mechanical properties and confinement efficiency of high strength concrete by adding high strength steel fibers in New RC columns. Three 60×60×180cm New RC columns made of HF-SHFRC were subjected to cyclic loading to verify the enhancement of confinement and shear capacity. The test result shows that great deformation capacity is developed even stirrups spacing is increased to d/2 in New RC columns with 1.5% fiber volume fraction. The feasibility of steel fibers as a substitute for transverse reinforcement is further confirmed. Application of HF-SHFRC in New RC columns offers opportunities to significantly simplify the design and construction of columns, while ensuring adequate ductility and damage tolerance.

Keywords: New RC; HF-SHFRC; HFPRCC; strain hardening; cyclic loading

1. Introduction

The concept of New RC, which is upgrade of concrete and reinforcement strength, was proposed in Japan in 1989. The objective of New RC project was aimed to reduce the member section sizes and increase the available space of high rise buildings by using high strength concrete (f'_c > 70 MPa) and high strength rebars (f_y > 685 MPa). However, the brittle behavior of high strength reinforced concrete during fracturing is still a primary concern despite wide application in the construction industry. Unlike normal strength concrete, as high strength concrete fractures, the fracture plane passes directly through the coarse aggregate and mortar causing an immediate drop in strength once the ultimate strength is reached and catastrophic failure. This failure behavior can be disastrous for societies like Taiwan, which is located in the Pacific Rim seismic belt. Earthquakes are frequent and unpredictable and consequently, structures must be constructed to meet minimum ductility requirements.

Traditional manners to increase the ductility of reinforced concrete columns have relied on increasing the amount and number of lateral stirrups in columns. However, by increasing the amount of stirrups, constructability decreases. Resultantly, new materials are being applied to traditional reinforced concrete structures in hopes of creating a reinforced concrete that has increased mechanical properties without associated losses in constructability. Past studies have shown that adding steel fibers to high strength concrete increases concrete toughness and shear strength [1]. Additionally, the steel fibers serve a bridging role to resist crack propagation in the matrix. This behavior not only inhibits brittle failure, it also distributes stress to other regions of the concrete. Resultantly, the fibers reduce early spalling of concrete cover and help prevent sudden failure.

Highly flowable strain hardening fiber reinforced concrete (HF-SHFRC) has good workability in the fresh state and exhibits the strain-hardening and multiple cracking characteristics of high performance fiber reinforced cementitious composites (HPFRCC) in the hardened state. More information regarding HF-SHFRC can be found in the literatures [2, 3]. As mentioned earlier, higher amounts of transverse reinforcements are required in high strength concrete columns for confinement concerns. This study examines the behavior of high-strength reinforced concrete and HF-SHFRC columns that are subjected to cyclic loading, and discusses the feasibility of replacing stirrups with steel fibers. Additionally, the loading and fracture characteristics of HF-SHFRC and traditional high strength reinforced concrete are discussed.

2. Experimental Program

2.1 Material

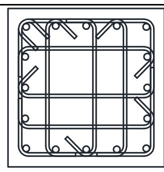
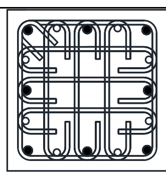
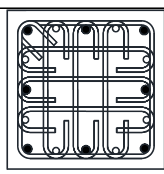
The cementitious materials used in this study were ASTM Type I Portland cement, ground granulated blast furnace slag and class C fly ash. The coarse aggregate had a maximum size of 9.5 mm and consisted of solid crushed limestone from a local source, with a density of about 2.70 g/cm^3. A polycarboxylate-based superplasticizer was used in the mixture. Hooked steel fiber with circular cross-section was used, with normal tensile strength of 2300 MPa and aspect ratio of 79.

The concrete compressive strengths were determined in accordance with ASTM C-39 standard compressive tests on at least six 100 x 200 mm cylinders. The concrete specified compressive strengths were 70 and 100 MPa. The slump flow of HF-SHFRC used in this study is 580mm so that the workability is not the issue during fabrication. Four different sizes of reinforcing bars were used: D29 (6.47 cm^2) and D25 (5.07 cm^2) with yield stress of 685 MPa, and D13 (1.27 cm^2), D16 (1.99 cm^2) with yield stress of 785 MPa. The baseline tensile test for a single control reinforcing bar to determine yield strength, ultimate strength and bar strain at yield stress in accordance with ASTM E8/E8M and ASTM A370.

2.2 Specimen Design

The seismic performance of high strength steel fiber reinforced concrete is assessed by applying a double curvature, cyclic lateral loading experiment. Three columns have been tested in this study. The columns had a clear height of 1800 mm with a square cross-section of 600x600 mm. There are three parameters: transverse reinforcement ratio, axial loading ratio and fiber volume fraction. The label of each specimen begins with an S and the numbers following the S denote the stirrup spacing, measured in millimeters. The final numbers in the label refer to the steel fiber volume fraction, measured in %. For example the name S140-1-5 represents a specimen having a stirrup spacing of 140mm and steel fiber volume fraction of 1.5%. The design parameters of specimens are summarized in Table 1.

Table 1 Design parameters of HF-SHFRC columns

ID	**Cross Section**	**f'_c (MPa)**	**Longitudinal Bar SD685**		**Transverse Bar SD785**			**$P/(A_g.f'_c)$**
			$n\text{-}d_{bl}$	**ρ_l (%)**	**d_{bt}**	**Spacing (mm)**	**ρ_t (%)**	
S140-1.5		70 (V_f=1.5%)	16-D25	2.25	D13	140	0.76	0.57
S260-1.5		70 (V_f=1.5%)	8-D29 8-D25	2.56	D16	260	0.64	0.42
S130-1.0		100 (V_f=1.0%)	8-D29 8-D25	2.56	D16	130	1.28	0.42

2.3 Test Setup

The test of the specimens performed in National Center for Research on Earthquake Engineering (NCREE) using Multi-Axial Resting System (MATS) that built in 2007. The MATS conducted double-curvature cyclic deformation. The maximum axial and lateral load that can be applied by MATS is 60 MN and 7MN, respectively. The lateral force was set from the hydraulic actuator that placed in the bottom as shown in Fig. 1(a) and the loading protocol is shown in Fig. 1(b). For each cycle of each loading phase, once target drift was reached, loading was temporarily stopped and the crack patterns were marked and recorded. The experiment was continued until a significant loss in axial loading capacity of column was observed. Significant loss in axial loading capacity was interpreted using the following guidelines: rapid reduction in axial loading capacity; or sudden MATS loading stroke greater than or equal to 20 mm. It is worth mentioning that a qualified column should satisfy the seismic performance criteria, which is the drift capacity at 80% of maximum lateral load should not less than 3%.

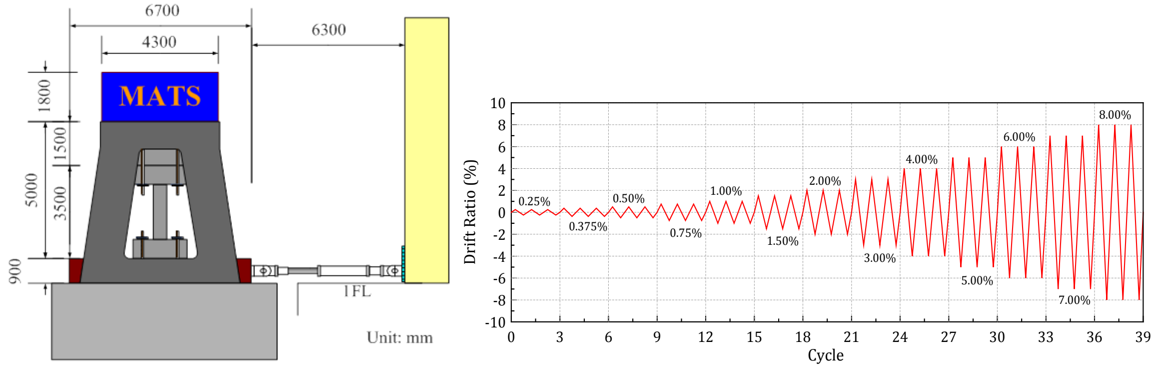


Fig. 1 – (a) Test setup with MATS; (b) loading protocol

Experiments in this study were conducted under high axial forces, resultantly the P-Δ effect was noticable, and consequently, correction was required. Correction methodology is detailed in Fig. 2 and calibrated complete hysteresis loop for the column specimen can be modified accordingly.

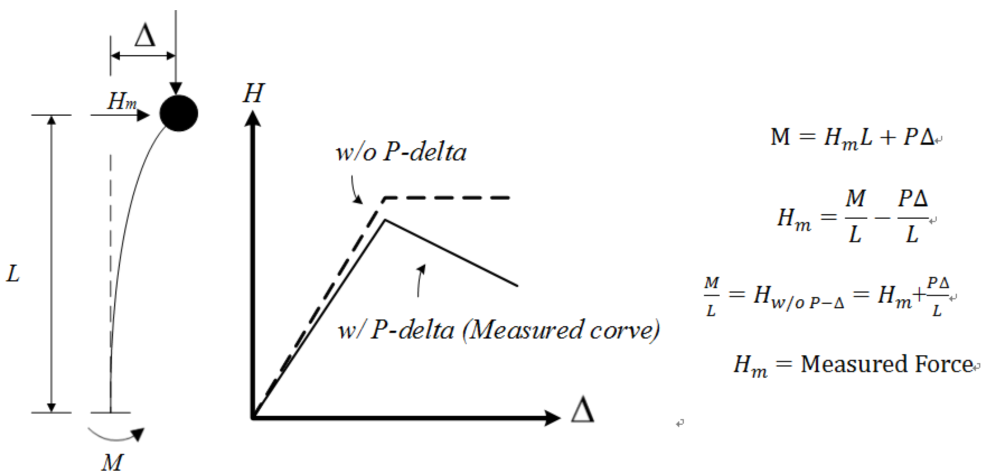


Fig. 2 Methodology of P-Δ effect correction

3. Test Result

3.1 Specimen S140-1.5

The S140-1.5 HF-SHFRC specimen is compared to specimen B5 reported by Chang in 2010 [4]. It is noted that the B5 was designed to comply with the transverse reinforcement requirement of ACI 318-11, which did not explicitly account for higher confinement demanding due to high strength concrete and high axial loading level. Both specimens have the same cross-section design, including longitudinal and transverse reinforcement layout. Stirrup and cross-ties have hooked ends bent at 90°and 135° respectively. They were tested under high axial loading ratio of 0.57. The hysteresis loops for both specimens are plotted in Fig. 3. The ultimate drift (drift corresponding to 80% maximum lateral capacity) for S140-1.5 was 3.23%, which is greater than the criteria of 3%. For specimen B5, before lateral strength reached 80% of the ultimate strength, it failed suddenly due to poor confinement. The drift ratio corresponding to failure was only 1.25%, a level far from the requirements to meet standards.

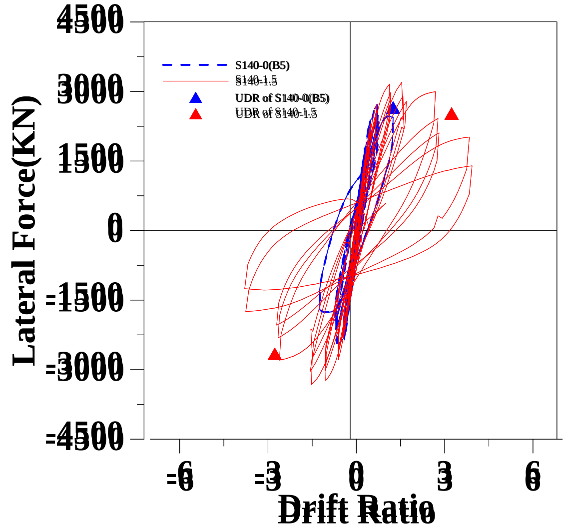


Fig. 3 The hysteresis loops for S140-1.5 and B5 reported by Chang in 2010 [4]

The ultimate strength of specimen S140-1.5 was 11% (314kN) higher than that of specimen B5. Additionally, specimen S140-1.5 exhibited a fuller hysteresis loop, which presented stable platform while yielding of longitudinal bar fully developed. Before the drift ratio of 0.75%, both specimens remained elastic, and the lateral stiffness remained constant. At the drift ratio of 1%, the S140-1.5 specimen still mainly remained elastic; in contrast, the severe cover spalling was observed and lateral strength dropped in specimen B5 and its ultimate strength was also reached. At the drift ratio of 1.5%, the lateral stiffness of specimen S140-1.5 began to decay, but lateral strength continued to increase. Under the same conditions, the lateral strength of specimen B5 was significantly loss. Before the second cycle could be applied, B5 had failed. Once a 2% drift ratio was reached, specimen S140-1.5 reached its ultimate strength, but continued to keep its capacity up to 4% drift.

As mentioned, ACI 318-11 did not consider confinement effectiveness in determining the required amount of confinement. It instead assumed constant confinement effectiveness independent of how the reinforcement is distributed. Thus, the confinement requirements for columns have been significantly modified in ACI 318-14. The experiment result of B5 also shows that the confinement requirement in ACI 318-11 is not adequate for high strength concrete columns under high axial loading level.

Experiment results of specimen S140-1.5 and B5 demonstrate that if the confinement is inadequate, which may be the case for columns that have been constructed using wide stirrup spacing and thin cross ties, adding steel fibers to the concrete can enhance the confinement efficiency and further meet the ductility requirements.

3.2 Specimen S260-1.5

The design cross section and longitudinal reinforcement ratio of S260-1.5 HF-SHFRC specimen is the same as the T100-1 made by Hwang in 2013 [5]. The axial load ratio applied to both specimens was 0.42. The main difference is that the transverse reinforcement of T100-1 was designed in accordance with ACI 318-14 [6], which requires notable transverse reinforcement amount for high strength concrete or columns under axial loading ratio higher than 0.3. In this case, transverse reinforcement required by ACI 318-14 is 40% higher than that required by ACI 318-11. By contrast, in S260-1.5, the spacing between stirrups is the maximum value specified by ACI 318-14 for shear resisting purpose, an half of the effective depth (d/2). The transverse reinforcement ratio of S260-1.5 and T100-1 was 0.64% and 1.67%, respectively. The hysteresis loops for both specimens are plotted in Fig. 4.

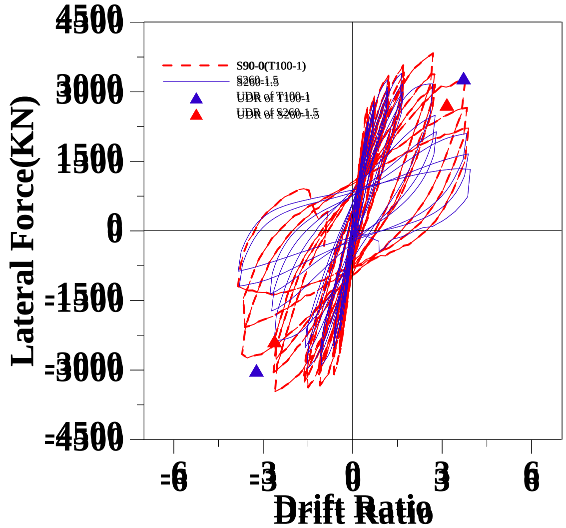


Fig. 4 The hysteresis loops for S260-1.5 and T100-1 reported by Hwang in 2013 [5]

The ultimate drifts and the corresponding lateral strengths for S260-1.5 and T100-1 were 3.16% and 2,715kN, and 3.72% and 3,290 kN, respectively. Both specimens fulfil the seismic criteria. The hysteresis loops for S260-1.5 and T100-1 are almost identical. During initial loading, the behavior of specimens S260-1.5 and T100-1 were very similar; the stiffness of both specimens rapidly deteriorated once the drift ratio reached 1%. Up to 2% drift ratio, the hysteresis loops of both specimens were nearly the same and plot on top of each other in Figure 4. This experiment verified the confinement efficiency provided by steel fibers even with the maximum stirrup spacing (d/2).

3.3 Specimen S130-1.0

The design cross section and longitudinal reinforcement ratio of S130-1.0 HF-SHFRC specimen is the same as the T100-1 made by Hwang in 2013 [5]. The axial load ratio applied to both specimens was 0.42. The stirrup spacing of S130-1.0 is 1/4 of the effective depth (d/4) and fibers of 1.0 % volume fraction are added. The hysteresis loops for both samples are shown in Fig. 5. The ultimate drift ratio for S130-1.0 was 3.78% and that for T100-1 was 3.72%. For both specimens, once the lateral strength was reduced to 80% ultimate strength, the drift ratio was greater than the 3%.

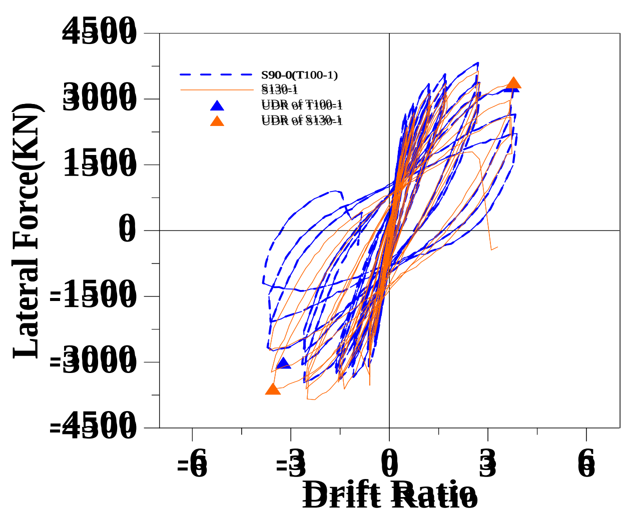


Fig. 5 The hysteresis loops for S130-1.0 and T100-1 reported by Hwang in 2013 [5]

In the first half of the loop, both behave the same; at 1% drift ratio, the stiffness of both specimens began to rapidly decrease. Once a drift ratio of 3% was reached, the ultimate strength of the specimens was reached as well. Notably, at 4% drift ratio, the lateral strength of the specimens rapidly decreased; however, the rate at which specimen T100-1 decreased was far greater than the rate associated with specimen S130-1. In this comparison, the confining efficiency developed by the steel fibers remained relatively constant during repeated lateral loading. Both specimens failed at the 3rd cycle of drift ratio of 4%.

As is seen above, for columns that are made of high strength concrete and/or are subject to high axial loading, the required confinement is now significantly increased. The test results of B5 and T100-1 also show this necessity. The impact of the changed requirements is expected, particularly for constructability. Based on the results of specimens S130-1, S260-1.5 and T100-1, to a certain degree, it has been demonstrated that lateral stirrups can be replaced by steel fiber. As the stirrup spacing is increased, steel fibers increasingly contribute to the ductility of the concrete. Even at the maximum specified stirrup spacing (d/2), HF-SHFRC with 1.5% fiber still meet seismic performance criteria; however, in later loading stages, the strength may drastically decrease, demonstrating that for larger deformation demand, stirrups are still needed to ensure a stable confining effectiveness globally. In summary, with adequate transverse reinforcement, the steel fibers can be an alternative to stirrups and improve the constructability, particularly for high strength concrete columns.

4. Conclusions

This study performed lateral cyclic loading tests on HF-SHFRC columns to examine its confinement efficiency and the effect of steel fibers on stirrup spacing. Based on experimental observations, the following conclusions were reached:

[1] The performance of high strength concrete columns was enhanced by adding steel fibers. In situations where the stirrups are inadequate, the contribution by the steel fibers to confining effectiveness and toughness is most apparent.

[2] The ultimate strength of specimen S140-1.5 was reached once the longitudinal reinforcement yielded, demonstrating that flexural strength was fully developed and that a significant shear capacity provided by fibers maintained. Even with the maximum specified stirrup spacing (d/2), the ultimate drift ratio of 3% was still met.

[3] Steel fibers can be used to substitute some stirrups but not all. A comparison of specimens S130-1.0 and T100-1 was performed. Despite the stirrup spacing of specimen S130-1 being 44% (40mm) greater than specimen S90-1, the overall behavior of the two specimens was nearly identical.

[4] The stirrup spacing used on specimen S260-1.5 is the maximum spacing specified (d/2) and the criterion of an ultimate drift ratio of 3% was fulfilled. However, during later loading stages, the stirrups provided most of the confining strength, demonstrating that even with the addition of steel fibers; stirrup specifications must still be followed.

[5] The feasibility of steel fibers as a substitute for transverse reinforcement is further confirmed. Application of HF-SHFRC in New RC columns offers opportunities to significantly simplify the design and construction of columns, while ensuring adequate ductility and damage tolerance.

5. Acknowledgements

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6. Copyrights

7. References

[1] Sugano, S., Kimura, H., and Shirai, K. (2007): Study of New RC Structures Using Ultra-High-Strength Fiber-Reinforced Concrete (UFC)-The Challenge of Applying 200MPa UFC to Earthquake Resistant Building Structures. *Journal of advanced concrete technology*, **5**(2), 133-147.

[2] Liao W.-C., Chao, S.-H., and Naaman, A. E. (2010): Experience with Self-Consolidating High Performance Fiber Reinforced Mortar and Concrete. *ACI Journal*, Special Publication No. 247: *Fiber Reinforced Self-Consolidating Concrete - Research and Applications*. 79-94.

[3] Liao, W.-C., and Chao, S. H. (2014): Crack Opening Evaluation and Sustainability Potential of Highly Flowable Strain-hardening, Fiber-reinforced Concrete (HF-SHFRC). *Journal of Testing and Evaluation*, **43(**2), 343-360.

[4] Chang, Feng-Chan (2010): *Study on the Confining Effect of Reinforced Concrete Columns Using High Strength Materials*. Master Thesis, National Taiwan University, 286 pp.

[5] Hwang, Guann-Jye (2013): *Design of Seismic Confinement of RC Columns.* Master Thesis, National Taiwan University, 270 pp.

[6] ACI Committee, 318 (2014): Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary. *American Concrete Institute*, Farmington Hills, Mich.

[7] Ahmed, O., Van Gemert, D. and Vandewalle, L. (2001): Improved model for plate-end shear of CFRP strengthened RC beams. *Cement and Concrete Composites*, **23**, 3-19.

[8] Sezen, H., and Moehle,J. P. (2004): Shear Strength Model for Lightly Reinforced Concrete Columns. *Journal of Structural Engineering*, ASCE.