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SEISMIC PERFORMANCE OF NEW RC EXTERIOR BEAM-COLUMN JOINT MADE OF HIGHLY-FLOWABLE STRAIN HARDENING FIBER REINFORCED CONCRETE

W.-C. Liao(1), W.-R. Su(2), K.-Y. Chang(3)

(1) *Associate professor, National Taiwan University, wcliao@ntu.edu.tw*
(2) *Graduate student, National Taiwan University, suweiru810824@gmail.com*
(3) *Graduate student, National Taiwan University, r04521245@ntu.edu.tw*

Abstract

The New RC Project conducted by Japan in 1988 mainly used high strength materials to reduce the section sizes of members and to save the consumption of materials. However, the brittle nature of high strength concrete should be considered compared to ductile response of normal strength concrete. Therefore, ACI 318-14 requires denser transverse reinforcement while using high strength concrete (fc'≥70MPa) in column members to assure its toughness.

For special moment frames, beam-column joint is a key element to transfer shear and moment forces. Nevertheless, beam-column is an intersection of longitudinal reinforcement of beams and columns along with transverse reinforcement of columns. The heavy reinforcement arrangement may result in construction difficulty and poor construction quality. This issue could be severer in New RC members since their section sizes are smaller. Highly flowable strain hardening fiber reinforced concrete (HF-SHFRC) has excellent workability in the fresh state and exhibits the strain-hardening and multiple cracking characteristics of high performance fiber reinforced cementitious composites (HPFRCC) in their hardened state. Application of HF-SHFRC to beam column joints may be an alternative to transverse reinforcement since its validity has been verified in columns.

This study investigates the seismic performances of high strength fiber reinforced exterior beam-column joints. Estimation of shear strengths and quantification of confinement efficiency are also discussed. Five full scale New RC exterior beam-column joints, including three made of HF-SHFRC with 1.5% volume fraction steel fibers, were subjected cyclic loading under low and high axial loading levels. The high axial load specimen was designed to verify the fiber confinement efficiency in terms of toughness ratio. The test results show not only toughness ratio can properly quantify fiber confinement efficiency, but 75% of transverse reinforcement can be eliminated owing to steel fibers under high axial loading. One specimen was designed to obtain its shear capacity under low axial loading level by joint shear failure. The test results show that its shear strength is 1.91 times of that suggested in ACI 318, even there is no any transverse reinforcement in the joint. Additionally, the specimen ends up with shear failure, but it still can keep the good shape and satisfy all the criterions of a qualified beam-column joints required in ACI 374. In summary, application of high strength fiber reinforced concrete in New RC beam-column joints offers opportunities to significantly simplify the design and construction work, while ensuring adequate ductility and damage tolerance.

Keywords: high strength concrete, fiber reinforced concrete, beam-column joint, strain hardening, shear strength

1. Introduction

The purpose of New RC project was aimed to reduce the member sections and increase the available space of high rise buildings by using high strength concrete (f'c > 70 MPa) and high strength rebars (fy > 685 MPa). Material consumptions and member sections can be further reduced owing to the upgrade of strength. However, the nature of brittleness of high strength may also cause early cover spalling and other ductility issues. Addition of steel fibers is an alternative as transverse reinforcement. Highly flowable strain hardening fiber reinforced concrete (HF-SHFRC) has excellent workability in the fresh state and exhibits the strain-hardening and multiple cracking characteristics of high performance fiber reinforced cementitious composites (HPFRCC) in their hardened state.

A beam-column joint takes an important role in the force transferring mechanism in a special moment resisting frame. Thus, severe damage within a joint panel may cause deterioration in overall seismic performance of the frame. As a joint is subjected to high shear strength, code recommendations suggest arranging closely hoop transverse reinforcement to prevent joins from shear failure, which leads congested joints and results in difficult construction works. With high tensile strength and good toughness behavior, applying HF-SHFRC in joint panels is expected to reduce the amount of transverse reinforcement. The objective of this study is to investigate the feasibility of implementing HF-SHFRC in beam-column joints of New RC building systems, as an alternative of transverse reinforcements.

Five full scale New RC exterior beam-column joints, including three made of HF-SHFRC with 1.5% volume fraction steel fibers, were subjected cyclic loading under low and high axial loading levels. The high axial load specimen was designed to verify the fiber confinement efficiency in terms of toughness ratio. The test results show not only toughness ratio can properly quantify fiber confinement efficiency, but 75% of transverse reinforcement can be eliminated owing to steel fibers under high axial loading. One specimen was designed to obtain its shear capacity under low axial loading level by joint shear failure. The test results show that its shear strength is 1.91 times of that suggested in ACI 318, even there is no any transverse reinforcement in the joint. Additionally, the specimen ends up with shear failure, but it still can keep the good shape and satisfy all the criterions of a qualified beam-column joints required in ACI 374. In summary, application of high strength fiber reinforced concrete in New RC beam-column joints offers opportunities to significantly simplify the design and construction work, while ensuring adequate ductility and damage tolerance.

2. Highly flowable strain hardening fiber reinforced concrete (HF-SHFRC)

Self-consolidating concrete (SCC) has a high flowability and a moderate viscosity, and has no blocking by the reinforcement during flow. The concept of SCC was proposed first by Okamura in 1986. The development of SCC can be deemed as one of the most important breakthrough in concrete technology in the decades. Not only SCC, considerable attention has also been paid to fiber reinforced concrete/cement composites (FRCC) in recent years. In order to classify FRCC based on their tensile performance, Naaman [1][2] proposed a new class of FRCC, referred to high performance fiber reinforced cement composites (HPFRCC). The idea behind this new classification of FRCC was to distinguish between the typical tensile performance obtained with traditional FRCC, characterized by a softened response after first cracking, and the tensile strain-hardening response with multiple cracking exhibited by HPFRCC. Typical tensile stress-strain responses of FRCC and HPFRCC are illustrated in Fig. 1.

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 characteristics of HF-SHFRC, such as mix design, mixing procedure, fresh properties, tensile strain hardening behavior, resistance of crack propagation and structural applications, can be found in the literatures by Liao et al. [3][4][5]

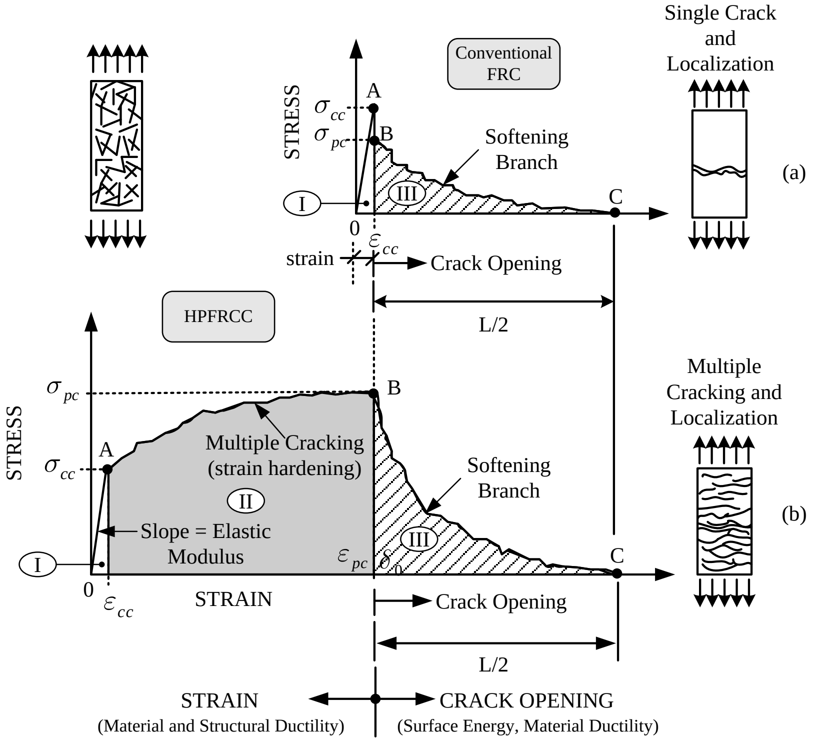


Fig. 1 – Stress-strain response of conventional FRC and HPFRCC [1]

3. Experimental program

Five full-scale exterior New RC beam-column joints, including two specimens with intensive conventional transverse reinforcements and three specimens made of HF-SHFRC without any stirrup, are tested.

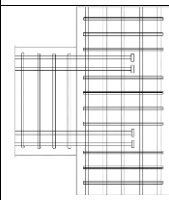
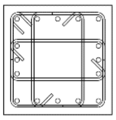
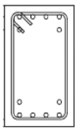
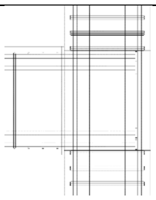
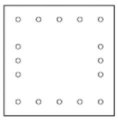
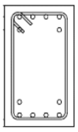
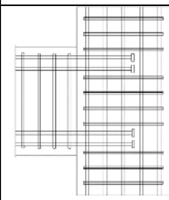
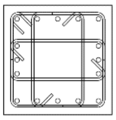
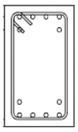
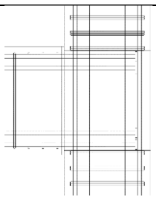
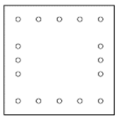
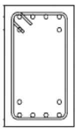
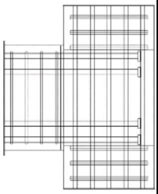
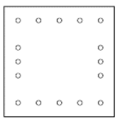
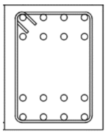
3.1 Specimen design

The seismic performances of exterior beam-column joints are assessed by applying a double curvature, cyclic lateral loading experiment. There are two groups in this experimental program; the first group includes 4 exterior beam-column joints, to investigate the feasibility of application of HF-SHFRC in New RC beam-column joints and to compare their seismic performances with those with intensive conventional transverse reinforcements. The columns have a clear height of 2800 mm with a square cross-section of 600×600 mm. Beam section size is 400×700mm and the net length is 3500mm. These four beam-column joints are labeled as LAMV, HAMV, LAMV_SF and HAMV_SF, respectively. LA represents as low axial load which is equal to 0.1 Ag/f'c; HA represents as high axial load which is equal to 0.45 Ag/f'c. MV represents medium shear ratio which is defined as the ratio of shear demand $V_{jh,u}$ and shear capacity V_n of joints, which is 0.7 in this experimental program, where $V_{jh,u}$ is the total horizontal joint shear force and V_n is the nominal shear strength of joint. LAMV and HAMV are considered as control group [6], and LAMV_SF and HAMV_SF are the experimental group. All these specimens have the identical flexural strength in column and beam section since their reinforcement layouts of beam and column sections are the same. The joints of LAMV and HAMV consist of dense transverse reinforcement to comply with ACI 318-11, while no transverse reinforcement is arranged in joints by using HF-SHFRC instead in LAMV_SF and HAMV_SF.

The second group includes one HF-SHFRC exterior beam-column joint. It is labeled LAHHV_SF to present extremely high shear ratio which is 2.12 and low axial load which is equal to 0.1 Ag/f'c. LAHHV_SF was designed to fail in J-type to obtain the ultimate shear strength of HF-SHFRC beam-column joint. The column of LAHHV_SF has the same size as those in first group, while beam section size is 550×700mm with 2.54% reinforcement ratio to increase the shear ratio.

The design parameters are listed in Table 1.

Table 1 – Detailed design parameters of beam-column joints

Specimen ID	Elevation	Column section at joint	Beam section	$\frac{A_{sh}}{sb'_c}$ (%)	V_f (%)	ρ column (%)	ρ beam (%)	Shear ratio	$\frac{N}{A_g f'_c}$
LAMV				1.0	0	2.25 (SD685 D25)	1.25 (SD685 D25)	0.7	0.1
LAMV_SF				0	1.5	2.25 (SD685 D25)	1.25 (SD685 D25)	0.7	0.1
HAMV				1.0	0	2.25 (SD685 D25)	1.25 (SD685 D25)	0.7	0.45
HAMV_SF				0	1.5	2.25 (SD685 D25)	1.25 (SD685 D25)	0.7	0.45
LAHHV_ SF				0	1.5	2.25 (SD685 D25)	2.54 (SD685 D25)	**2.12**	0.1

3.2 Specimen design

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. 2 and the loading protocol is shown in Fig. 3. 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. Experiments in this study were conducted under high axial forces, resultantly the P-Δ effect was noticeable.

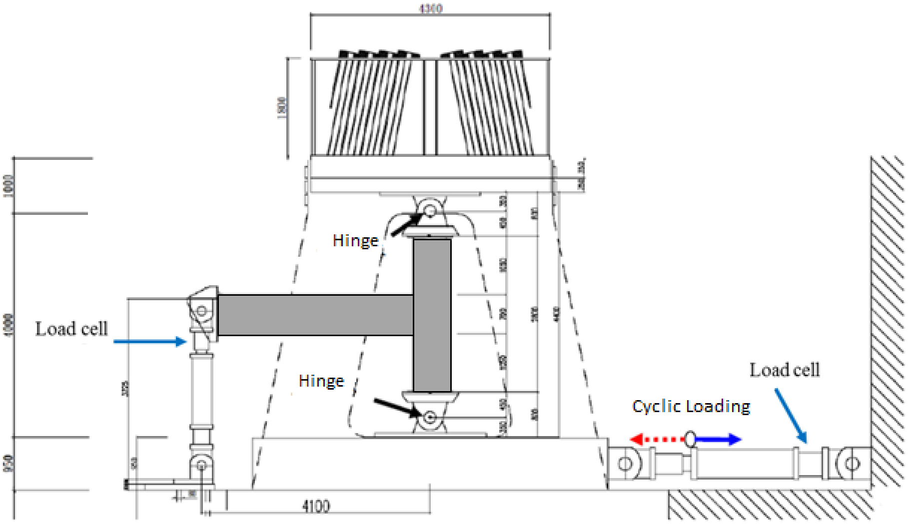


Fig. 2 – Test setup with MATS

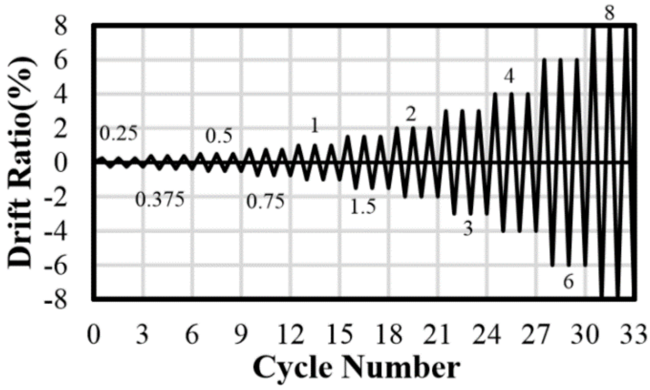


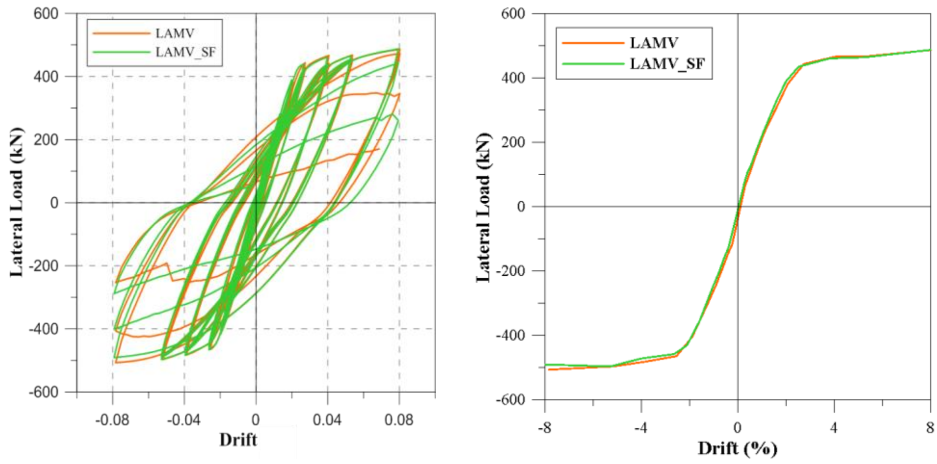
Fig. 3 – Loading protocol

4. Test results

4.1 LAMV and LAMV_SF

Fig. 4 (a) shows the hysteresis loops of LAMV and LAMV_SF, which are modified with P-Delta effect. Their hysteresis loop envelopes are also shown in Fig. 4 (b). The apparent yielding plateau can be found in both LAMV and LAMV_SF, which stand for the B type failure mode. Their hysteresis loops and envelopes are almost identical since the yielding and failure of beam governs the cyclic behaviors. It is worth mentioning that there is no transverse reinforcement in the joint of LAMV_SF.

Their hysteresis loops present a linear status before the story drift ratio reaches 0.29%; as the story drift ratio exceeds 0.29%, lateral force declines slowly along with the increase of the story drift ratio. The lateral force declines obviously till the second and third cycle of the 8% drift ratio loop. The maximum lateral forces of LAMV and LAMV_SF are 487 kN and 488 kN as reaches 5.38% and 8%respectively. While the experiment progress to the third cycle of 6%, the longitudinal steel bar in the beam occurred local buckling, and failed in the plastic zone as 8%. The experiment ended up in the second cycle of 8%.



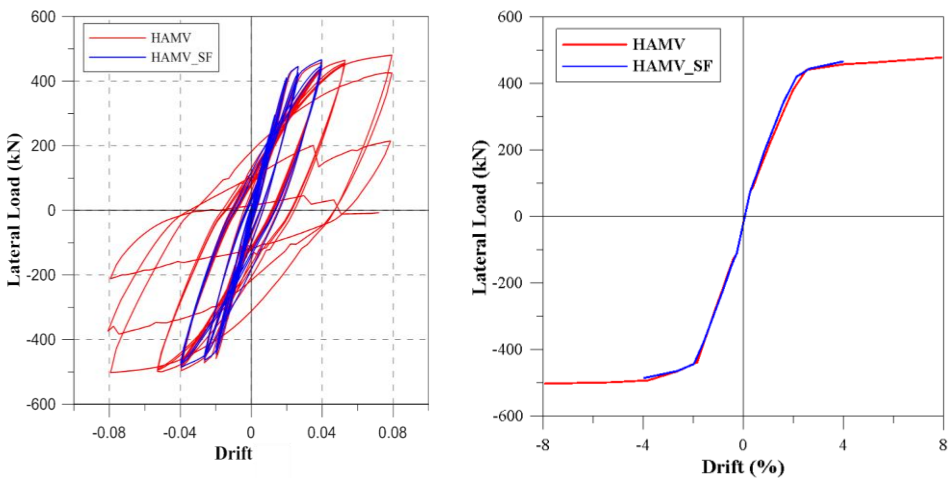
(a) (b)

Fig. 4 – (a) Hysteresis loops; (b) hysteresis loop envelopes of LAMV and LAMV_SF

4.2 HAMV and HAMV_SF

Fig. 5(a) illustrates the hysteresis loops of HAMV and HAMV_SF, which are modified with P-Delta effect as well. Their hysteresis loop envelopes are compared in Fig. 5(b). It is noted that the inversion of the hysteresis loop can be observed before modified with P-Delta effect due to additional lateral force caused by high axial load. Thus, the lateral force of MATS needs to be reversed to get the expected displacement. It is found that there is also a clear yield plateau in HAMV with B type failure mode. The specimen performs as a linear status before the story drift ratio reaches 0.27% and its maximum lateral forces are 478kN as reaches ±7.93%.

Almost identical cyclic behavior of HAMV_SF can be observed before the second cycle of 4% since it suddenly fails. From the photo at specimen failed and the hysteresis loop (Fig. 5(a)), it can be conjectured that the failure of HAMV_SF caused by inadequacy of confinement, rather than insufficiency of shear capacity as BJ type failure. Even though HAMV_SF failed at 4.0% drift ratio, its performance is still qualified as acceptable joint in terms of stiffness, strength and energy dissipation required by ACI 374 [7].



(a) (b)

Fig. 5 – (a) Hysteresis loops; (b) hysteresis loop envelopes of HAMV and HAMV_SF

4.3 LAHHV_SF

The design objective of LAHHV_SF is to obtain the ultimate shear capacity provided by HF-SHFRC placed in the joint, so the target test result is the joint shear failure (J-type). The hysteresis loop of the LAHHV_SF is shown in Figure 6. It is obvious to see that the shear force Q_n does not reach the lateral force corresponding to the maximum probable moment strength of the beam, even though yielding is found at the partial upper and lower reinforcements from the strain gauges. It can determine the failure mode of LAHHV_SF is joint shear failure (J-type) as designated. According to the test results, it is found that the ultimate shear strength of LAHHV_SF is very high and it is contributed from HF-SHFRC.

In LAHHV_SF, all the tranvseverse reinforcement is eliminated and only placed with HF-SHFRC. The ultimate shear strength of LAHHV_SF is 5673 kN, which is $1.91\sqrt{f_c'} \cdot b_j \cdot h_j$ by conveted with f'c in MPa. In ACI 318, the nominal shera strength of exterior joint is $1.00\sqrt{f_c'} \cdot b_j \cdot h_j$, and even that of joint confined by beams on all four faces is $1.67\sqrt{f_c'} \cdot b_j \cdot h_j$. Joints complied with code requirement are reinforced with intensive transverse rebars; however, the nominal joint shear strength is only half of the shear strength provided by HF-SHFRC. Therefore, under low axial loading level, HF-SHFRC not only can replace the transverse reinforcement in the joint, but also the shear capacity of the joint can be significantly improved.

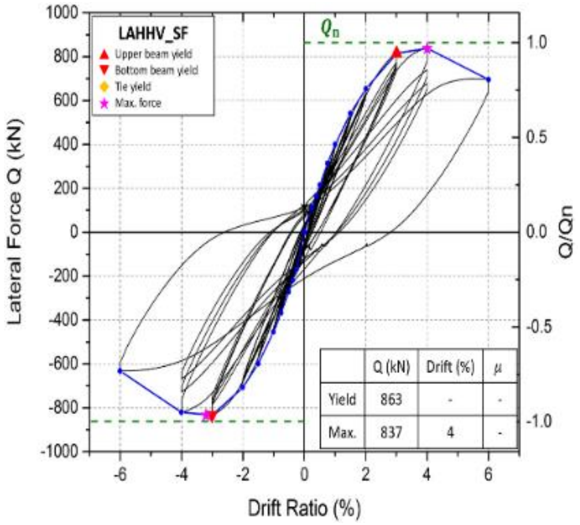


Fig. 6 –Hysteresis loop of LAHHV_SF

The first crack of LAHHV_SF occurred at + 0.35%, which is a flexural crack of the beam, and the shear crack in the joint appeared later than + 1.5%. The overall crack development is more focused on the joint area. The design objective of t LAHHV_SF is joint shear failure (J-type), so beam members and column members are expected to be non-failed. In terms of the crack development, the first crack of the beam is very small from the beginning to the end of the test. The larger crack only appears at the top and bottom of the beam. It is caused by the bending moment when the displacement and drift ratio are large. At the end of the test, the crack width of the beam was only 1.6mm, and the number of cracks was few. The shear cracks in the joint area developed mainly with 45 ° diagonal after the first crack occurred. At first, the shear crack width was within 1.5mm. Along with the increasing number of cracks, the cracks became more obvious after reaching + 4%. The final shear crack width was 19mm, and the specimen did not have serious damage results such as spalling of the concrete. Therefore, although the joint was subjected to joint shear failure, it was found that the overall integrity was maintained, as shown in Fig. 7.

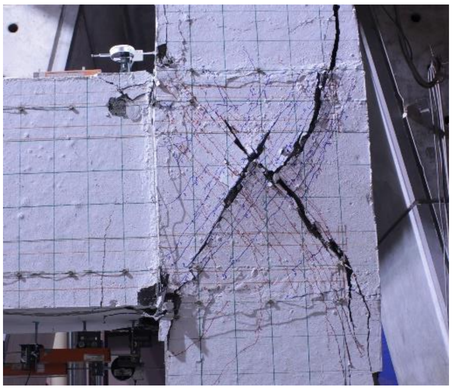


Fig. 7 – Final failure and crack patterns of LAHHV_SF

In general, joint failed in J-type loses its strength very quickly after reaching the shear capacity. Poor energy dissipation and severe stiffness degradation can be also observed. It is worth mentioning that even LAHHV_SF failed in J-type but it still complies with all requirement as a qualified beam-column joint per ACI 374[7]. ACI 374.1-05 provides the standard for evaluating the seismic performances of beam-column joints. These criteria for a qualified beam-column joint can be roughly divided into three categories: strength, energy dissipation, and stiffness degradation. The detailed criteria and performances of LAHHV_SF both in positive and negative directions are listed in Table 2. LAHHV_SF meets all the requirements in ACI 374 thanks to high damage tolerance of HF-SHFRC.

Table 2 – Seismic performances of LAHHV_SF per ACI 374 [7]

		Strength	**Energy**	**Stiffness**
		$Q\ 3^{rd}/Q_{max} \geq 0.75$	$K_0/K_i \geq 0.05$	$\beta = E_D/E_{PP} \geq 0.125$
LAHHV_SF	Positive	0.81	0.25	0.22
	Negative	0.80	0.16	

5. Conclusions

This study presents lateral cyclic loading tests on HF-SHFRC beam-column joints to examine its adequacy to substitute transverse reinforcement in the joint region under different axial loading levels. The following conclusions can be drawn:

(1) LAMV_SF and LAMV have similar or even better cyclic behaviors, which implies HF-SHFRC can fully replace transverse reinforcement under low axial load.

(2) According to the test results of HAMV_SF, it shows that proper transverse reinforcement should be applied for confinement purpose in the case of high axial load for global confinement purposes, even though shear capacity of HF-SHFRC is sufficient.

(3) In LAHHV_SF, all the tranvseverse reinforcement is eliminated and only placed with HF-SHFRC. The ultimate shear strength of LAHHV_SF even higher than that of joint joint confined by beams on all four faces. Joints complied with code requirement are reinforced with intensive transverse rebars; however, the nominal joint shear strength is only half of the shear strength provided by HF-SHFRC.

(4) HF-SHFRC specimens perform as well as specimens with intensive transverse reinforcements regarding failure mode, ductility, energy dissipation and crack width control. Application of HF-SHFRC to New RC building systems can assuring construction qualities and further diminish labor work and give infrastructure longer service life, and eventually lower the life-cycle cost.

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