SEISMIC EXPERIMENTAL STUDY ON HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE BEAM-COLUMN JOINTS

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Abstract

In order to investigate seismic performance of high-performance fiber-reinforced concrete (HPFRC) beam-column joints, quasi-static test of eight HPFRC beam-column joints were conducted. The influence of parameters on seismic performance was discussed, and the parameters include yield strength of reinforcement, stirrup ratio in joint regions, waist rebar in beam, and non-corner vertical reinforcement in columns. Test results indicate that the application of Grade 600 longitudinal reinforcement in beam improves stiffness degeneration and energy dissipating of joint specimen. The cumulative energy consumption and shear load-carrying capacity of the specimen increases with the increase of stirrup ratio in a certain range. The waist rebar in beam and the non-corner rebar in the column increase the shear load-carrying capacity of joint specimens, and improve strength reduction and energy dissipation capacity to some extent.

Keywords: HPFRC beam–column joints, seismic performance, quasi-static tests

1. Introduction

The beam-column joint is the important element in reinforced concrete (RC) frame structure, which is susceptible to shear failure.[1, 2]. A high percentage of transverse stirrups is usually required in beam-column joint for avoiding shear failure [3-5]. This may lead to congestion of reinforcing bars in joint and difficulty in casting concrete [6-8]. Fiber RC may be a feasible solution to reduce the congestion of stirrups in the beam-column joint core [9, 10]. The main objective of this research is to determine the effect of HPFRC with ultra-high toughness on the shear behaviors of beam-column joints.

High Performance Fiber-Reinforced Concrete (HPFRC), a new type of cement-based composite material [11-13], which possess excellent mechanical properties. Compared with normal concrete, the superiority of HPFRC used in beam-column joints is mainly manifested in three aspects: (1) High ultimate tensile strain of HPFRC can enhance the deformability of joint, thus enhance ductility of the nodes; (2) The application of HPFRC with ultra-high compressive strength can reduce the dosage of concrete, make the joints lighter and lead to a small seismic inertia force. (3) The addition of steel fiber can improve the failure mode of joints and increase toughness of beam-column joints under earthquake load. Moreover, HPFRC has great advantages in durability, [14-16] which is beneficial to improve the service life of the structure. In order to verify the feasibility of HPFRC as a replacement of normal concrete used in reinforced concrete frame structure, we investigate seismic performance of HPFRC beam-column joints through quasi-static test, and study the effect of yield strength of reinforcement, stirrup ratio in joint regions, waist rebar in beam, and non-corner vertical reinforcement in columns on the seismic performance of HPFRC beam-column joints.

2. Description of test program

2.1 Specimen details

The HPFRC beam-column joint specimens described here were approximately 3/4 scale of what can be found in a building. The cross section of all columns was 300×300mm, and the cross section of all beams was 250×350mm. The variables in specimens include yield strength of reinforcement, stirrup ratio in joint regions, waist rebar in beam, and non-corner vertical reinforcement in columns. Fig.1 and Table 1 show illustrates the details of specimens. The longitudinal reinforcement of beam and column of specimen LJ-1, LJ-6, LJ-7 and LJ-8 are deformed steel bars of grade 400, and that of specimen LJ-2, LJ-3, LJ-4 and LJ-5 are deform steel bars of grade 600. All stirrups in beams, columns and connection are plain bars of grade 300. Specimen LJ-6 is equipped with 2 waist rebar with diameters of 14mm through the connection, see in Fig. 1. There are 4 waist rebar with diameters of 14mm through the connection in beam of specimen LJ-7. Specimen LJ-8 is equipped with 2 non-corner vertical reinforcements with diameters of 20mm through connection. The other parameters of specimen LJ-6, LJ-7 and LJ-8 are the same as that of the specimen LJ-1.

2.3 Test procedure

Fig. 2 is the test setup. A constant axial compressive load is applied on the column by a 2 000kN hydraulic jack. The bottom and top of the column is a hinged support. Cyclic loads were applied to the beam tips using two 500kN electro-hydraulic servo actuators. According the china code, earthquake action is applied in two phases, including a load-controlled phase and a displacement-controlled phase[17]. At the beginning of test, cyclic loading with load control was applied, and one cycle of each load level is imposed. When it reaches the crack strength of joint or longitudinal reinforcements in beam reaches their yield strain, the loading process was switched to displacement control, the corresponding displacement of beam tip is defined as Δ_y. This phase comprises of three identical displacement cycles for each displacement level. The left and right beam tips are subjected to reverse loading with an equal rate, simultaneously.

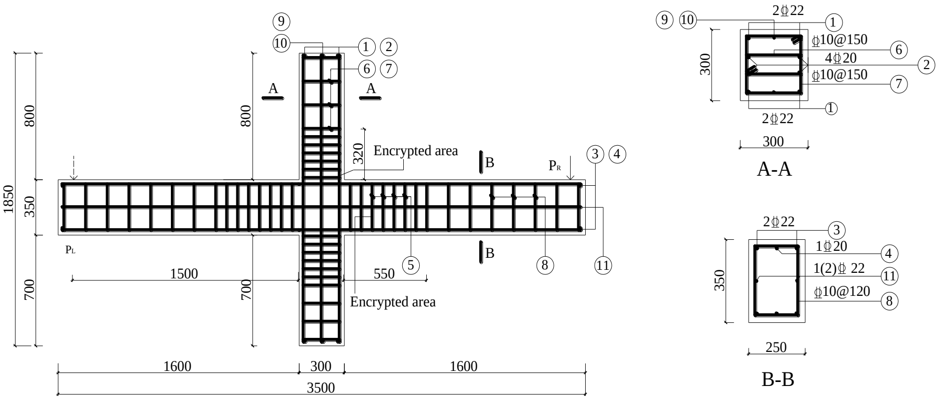


Fig. 1 – Details of geometry and reinforcement of the specimens

Table 1 – Specimen parameters

Specimen	**Compressive strength of HPFRC, MPa**	**Longitudinal reinforcement unilateral column**	**Longitudinal reinforcement unilateral Beam**	**Stirrups in joint core**
LJ-1	107.6	2Φ22+2Φ20	2Φ22+1Φ20	– –
LJ-2	115.0	2Φ22+2Φ20	2Φ22+1Φ20	– –
LJ-3	110.4	2Φ22+2Φ20	2Φ22+1Φ20	1Φ10,4 legs hoop
LJ-4	91.2	2Φ22+2Φ20	2Φ22+1Φ20	3Φ10,4 legs hoop
LJ-5	107.6	2Φ22+2Φ20	2Φ22+1Φ20	5Φ10,4 legs hoop
LJ-6	108.8	2Φ22+2Φ20	2Φ22+1Φ20	1Φ14,waist rebar
LJ-7	124.0	2Φ22+2Φ20	2Φ22+1Φ20	2Φ14,waist rebar
LJ-8	108.6	2Φ22+2Φ20	2Φ22+1Φ20	1Φ20,vertical rebar

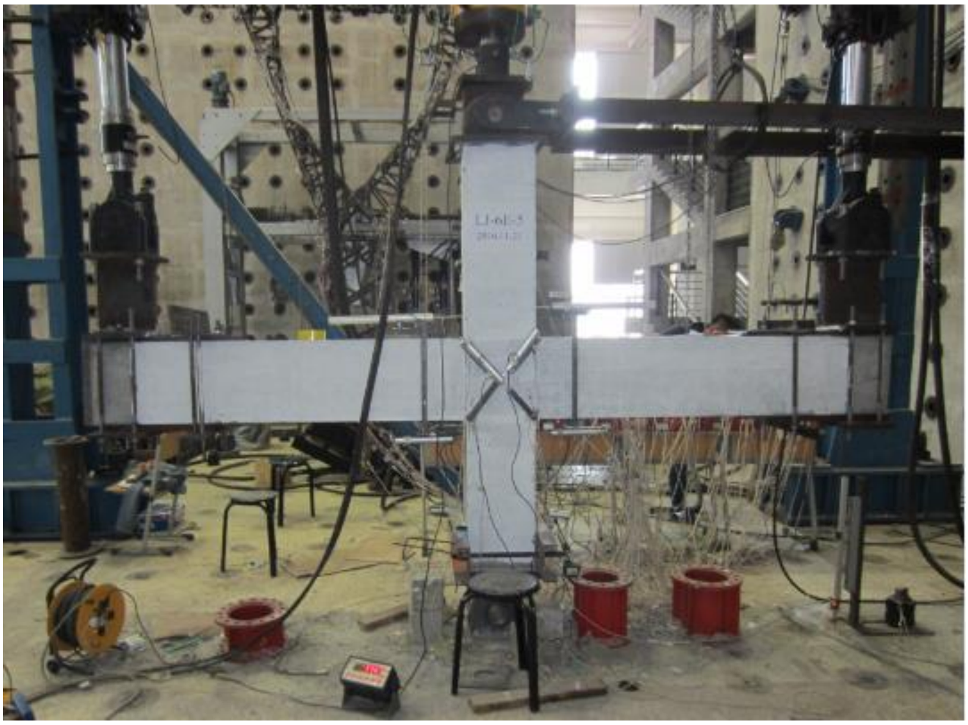


Fig. 2 – Loading apparatus

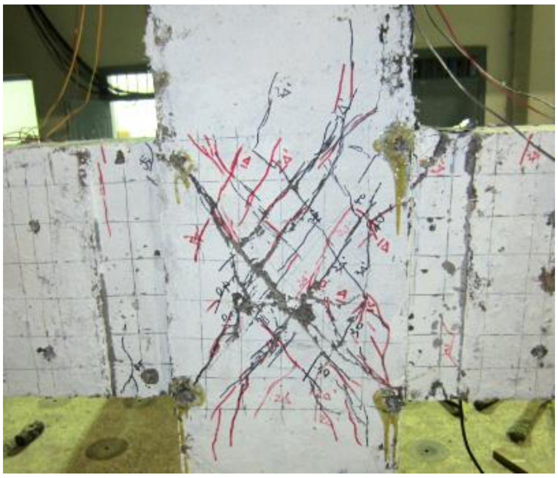
3. Results and discussion

The seismic performance of HPFRC beam–column joint specimens is analyzed; the analysis includes failure patterns, hysteresis performance, and energy dissipation capacity. The results indicate that the load–deformation relationship and the energy dissipation performance of HPFRC beam–column joints are affected by different parameters. These parameters are the quantity of stirrups at the joint core region, the strength of longitudinal reinforcement bars in the beam and column, inner waist reinforcement of beam and non-angular vertical reinforcement in column.

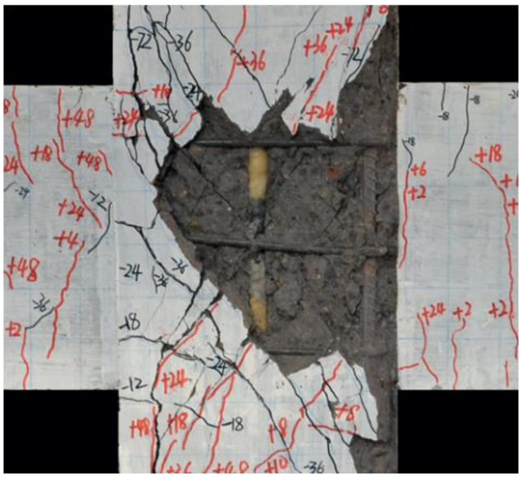
3.1 Failure patterns

The bending failure occurred in the beam end of specimen LJ-5, while the other specimens were shearing failure in the core area. The failure process of the HPFRC beam-column joints can be divided into three stages: initial crack stage, through crack stage and failure stage. In the initial phase, there were no cracks at the end of the beam or in the core area before the load reached 30kN. Initial cracks appeared at the left and right end of the beam when about 30% of the peak load is applied, but the core area is still not cracked. When about 40% of the peak load is applied, the initial oblique crack begins to appear in the diagonal of the core area, and diagonal cracks appear on the other diagonal of the core area when reverse loading is applied. The cracking load of all the core areas is mostly distributed in 35~40kN, which indicates that the strength of the longitudinal reinforcement and the ratio of the stirrup in the core area have little effect on the crack load, and the actual effect is the tensile strength of HPFRC. The experimental results indicate that the strain of stirrups in the core area measured by strain gauges is very small, which also proves that stirrups have little effect at the initial crack stage. According to references 3 and 4, when the load was about 14kN, the first crack of ordinary concrete beam-column joints appeared, while the cracks of the HPFRC joints appeared above the loading 30kN. This actually reflects that the tensile strength of HPFRC is better than that of ordinary concrete. Subsequently, with the increase of displacement and continuous cyclic loading, the crack width of the main diagonal line in the core area increases. In the stage of displacement control, there are almost no new cracks in the $1\Delta_y$ loading stage. During the loading stage of $2\Delta_y$ and $3\Delta_y$, there are more cracks in beam ends and core area of joint. Even in the $4\Delta_y$ loading stage, the crack width was increasing and accompanied by bared sound, which was the sound of the steel fiber being pulled out. At this time, the width of the main diagonal crack in the core area is increasing, and the width of the crack varies between 0.4mm~0.6mm. The specimen was in the through crack stage. At the failure stage, the width of cracks increases, and the development speed of cracks is significantly accelerated, and the phenomenon of spalling begins to appear in the core area concrete and at this point, some of the steel fibers in the core area can be found to be pulled out. The core area of joints was broken into many blocks and concrete spalling occurred at the crack at the loading end, but the joint maintained a good integrity, see in Fig.5 a). The failure pattern of HPFRC joints is different from that of normal concrete joints (see in Fig. 5b)). when the joints of the ordinary concrete beams and columns are destroyed, large amount of concrete exfoliation, the number of tiny cracks is small, and the integrity of the joints is poor.

We can see from Fig. 5a) that the crack direction in the core area of the HPFRC interior beam-column specimen is close to the diagonal direction. It can be seen from Fig. 5a) that a small amount of crushed HPFRC falls out of the main oblique crack and the edge of the oblique crack is skinned. This due to the fact that there is no coarse aggregate in HPFRC and the bite force between aggregates is not strong. However, due to the existence of steel fiber, there is a greater bond between HPFRC and steel fiber. Even if the stirrups yield at the later loading stage, the steel fiber can also play a very good connection role, so that the HPFRC beam-column joints retain greater integrity.



a) HPFRC beam-column joints



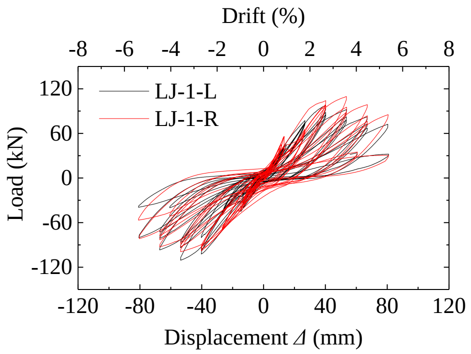
b) Normal strength concrete beam-column joint[18]

Fig. 3 – Failure patterns of beam–column joint.

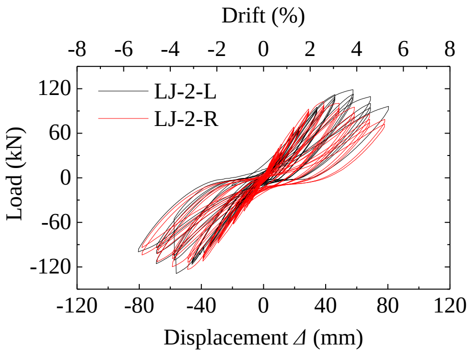
3.2 Hysteresis behavior

Fig. 4 shows the load–displacement hysteretic curve of four test specimens, where “L” and “R” represent the left and right beams, respectively. The hysteretic curve of reinforced HPFRC beam–column joint is characterized by the following.

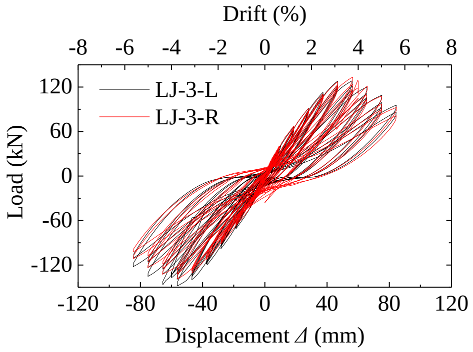
(1) At the initial stage, the horizontal displacement of the beam tips is small, and the positive and negative loading and unloading curves change linearly. The unloading curve returns through the original path. During unloading, the residual deformation is minimal, which indicates that the



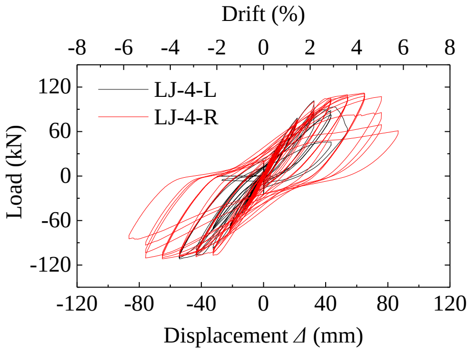
a) LJ-1



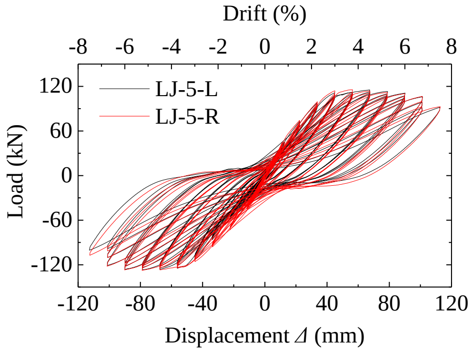
b) LJ-2



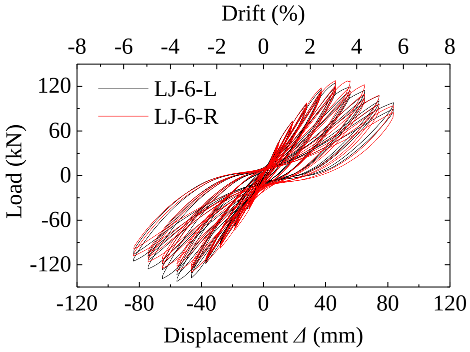
c) LJ-3



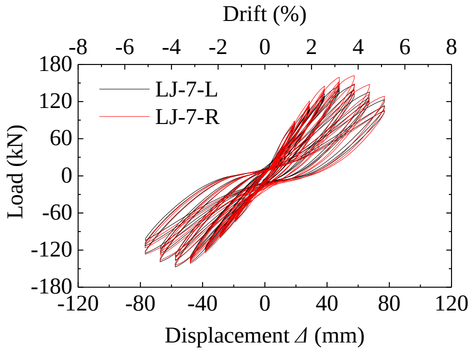
d) LJ-4



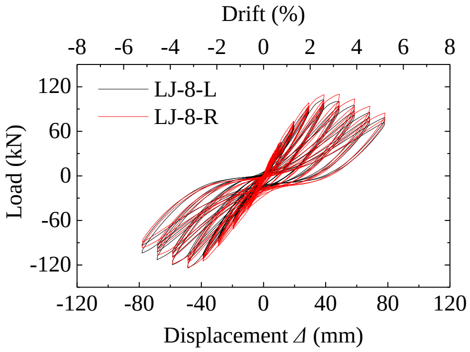
e) LJ-5



f) LJ-6



g) LJ-7



h) LJ-8

Fig. 4 – Hysteretic curve of specimens

specimen is in the elastic stage, and the change in overall stiffness is inconsequential. In contrast, normal concrete joints subjected to cyclic loading generally crack at the early stage of loading and quickly enter the plastic stage. The unloading curve indicates that the stiffness decreases to a certain extent, and an unloading residual deformation occurs.

(2) The load in the beam tips increases with the loading displacement. At this stage, the slope of the hysteresis loop of the specimen gradually becomes smaller, and the load slowly increases. The load in the beam tips ceases to increase linearly with the displacement, and the unloading stiffness is distinctly lower than the loading stiffness; these indicate that the specimen has entered the plastic deformation stage. After unloading, residual deformations are found, and the overall stiffness of the specimen starts to decrease. The area bounded by the hysteretic curve increases and is full; these indicate that the specimen has improved plastic deformation ability and energy dissipation capacity and a good seismic resistance.

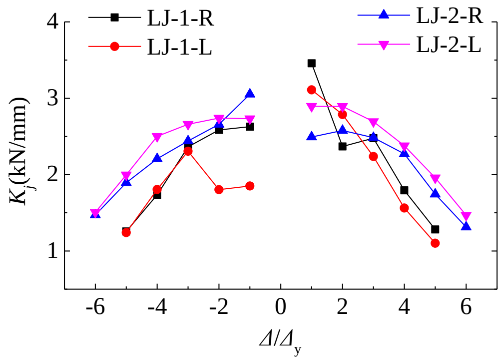
(3) When the peak load is reached, a descending segment in the hysteretic curve is observed, and the shear load-carrying capacity of the joint begins to decrease. This shows that the hysteretic curve has a relatively moderate descent, which is caused by the presence of stirrups and steel fibers. Because the concrete is restrained and connected by stirrups and steel fibers, the brittle failure of concrete is avoided when the concrete cracks. It can be observed that the larger the quantity of stirrups configured, the slower the descent of the hysteretic curve.

(4) The hysteretic curve has a distinct pinch phenomenon. The hysteretic curves at the left and right ends of beams have good symmetry, and the positive and negative symmetries of each hysteretic curve are better.

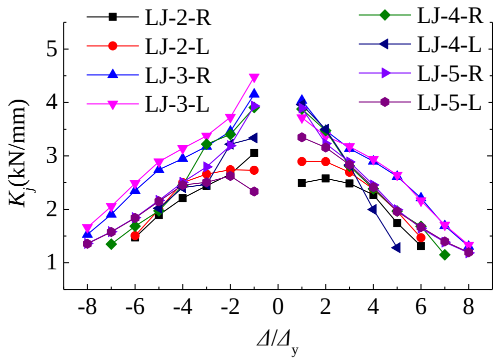
(5) Compare Fig. 4 (a), (f),(g), and (h), it can be found that waist rebar in beam and non-corner vertical reinforcement in columns both significantly improve the load bearing capacity of the HPFRC beam-column joints. This due to that two functions of waist rebar and non-corner vertical reinforcement. Firstly, they can undergoing tension in the direction of reinforcement, secondly, they provide constraints on the HPFRC and increase its strength.

3.3 Stiffness degradation

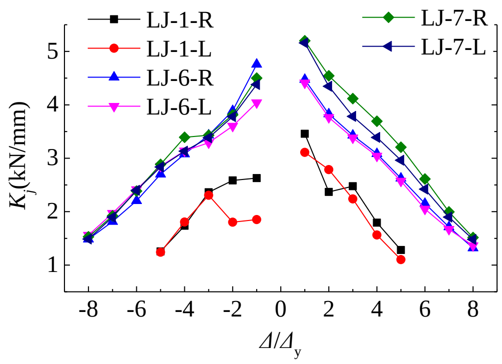
In this study, the secant stiffness method was used to evaluate the stiffness degradation of HPFRC joint specimens[19, 20]. Fig. 5 shows the curve of the stiffness of specimens versus loading displacement level relationship under different influence factors. "L" refers to the left end beam of the joints, and "R" refers to the right end beam of the joints. It can be seen that the law of stiffness degradation of all joint specimens is similar, and the rate of stiffness degradation and the stiffness value of final failure are similar. With the increase of the amplitude of loading displacement and the elastic-plastic deformation of the specimen, the cracking of concrete and the accumulation of steel bar damage, the ring stiffness of all specimens decreases gradually. It can be seen from Fig.5 (a) that there is no effect on the initial stiffness of the joints by using the high strength steel bars in the longitudinal bars of the beams and columns, but the rate of stiffness degradation is slightly slowed down. Fig. 5 (b)shows that in a certain range of stirrups ratio, the stiffness of the joint specimen increases gradually with the increase of stirrups ratio in the core area. However, when the stirrups ratio of core area exceeds a certain range, the increase of joint stiffness is not obvious, and the joint stiffness will even be reduced. It can be seen from the diagram that the stiffness of the specimen LJ-5 is slightly lower than that of the specimen LJ-3. The reason for this phenomenon may be that too many stirrups reduce the compactness of HPFRC in the core area, thus reducing its stiffness under earthquake load. Form Fig.5 (d), we can find that the longitudinal non-angular reinforcement in the column can obviously improve the stiffness of the specimens, especially under the condition of large cyclic displacement. And From Fig.5 (c), the waist reinforcement in the beam can effectively improve the stiffness of the joints. But, with the increase of the amount of waist reinforcement and from the stiffness of the specimen LJ-6 and the specimen LJ-7, it is can be found the increasing speed of stiffness of the specimen slowed down.



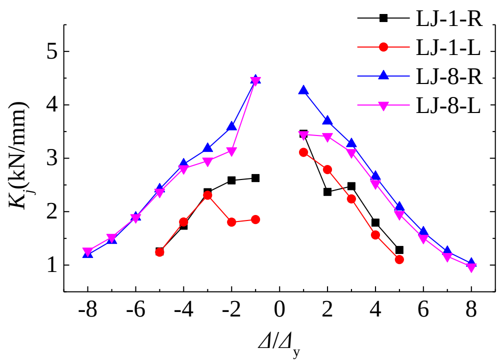
a) Influence of longitudinal reinforcement strength grade



b) Influence of stirrup ratios



c) Influence of the waist rebar in beam



d) Influenceof non-corner reinforcement in column

Fig. 5 – Influence of different factors on stiffness of specimens[20]

3.4 Energy dissipation

Energy dissipation capacity of structural members is an important index of seismic performance. The cumulative energy dissipation (E_{total}) is used to evaluate the actual energy consumption of the HPFRC beam-column joints during loading. The energy dissipation of each cycle is calculated by the area surrounded by hysteresis loops, and the cumulative energy dissipation (E_{total}) of the specimens is the sum of the area of hysteresis loops[20, 21]. Fig.6 is cumulative energy accumulation versus cumulative displacement relation curve. It can be seen from the of Fig.6 that the accumulative energy consumption of each specimen has little difference and is almost not affected by longitudinal reinforcement strength and ratio core area stirrup ratio at the initial loading stage. With the increase of loading displacement and cycle number, the specimen has different failure modes, and the cumulative energy consumption difference increases gradually. Under the same displacement, the energy consumption of LJ-5 is significantly higher than that of other specimens. This can due to the fact that the plastic hinge is formed by the yield of longitudinal reinforcement at the end of LJ-5 beam. The existence of the waist reinforcement in beam and the non-corner reinforcement in column improves the circular displacement, and thus increases the total energy consumption.

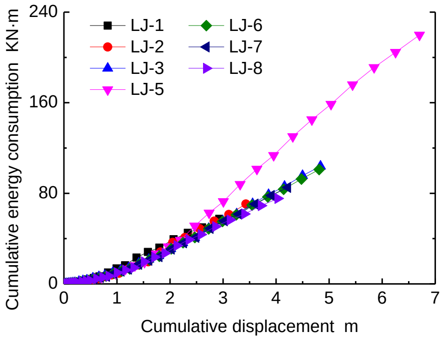


Fig. 6 – Cumulative energy accumulation versus cumulative displacement relation

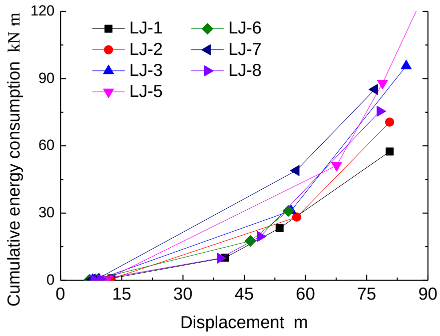


Fig. 7 – Cumulative energy accumulation versus displacement relation

Fig. 7 shows cumulative energy dissipation of corresponding to the crack in the core area of the joints, peak load, and ultimate load. It is obvious that the displacement and cumulative energy consumption of LJ-5 is much larger than that of other specimens when the specimen is about to be destroyed. For the sake of comparison, only the cumulative energy dissipation at peak load point and the trend line of limit load point are given. When the peak load and ultimate load are reached, the displacements of LJ-1 and LJ-2 are close to each other, however, the cumulative energy consumption of LJ-2 is 1.21 times higher than that of LJ-1. This demonstrates that the use of high strength steel bars with greater deformation capacity as longitudinal reinforcement of beams can improve the energy dissipation capacity of specimens. When peak load is reached, the displacement of LJ-2 and LJ-3 is close to each other. The cumulative energy consumption of the specimen increases slightly with the increase of stirrup ratio. When the ultimate load is reached, the cumulative energy consumption of the specimen LJ-3 is 1.35 times that of the specimen LJ-2. The energy dissipation capacity of the specimen can be improved to some extent by the inner waist bar and the non-corner steel bar in the column.

4. Conclusions

(1) The experimental results of eight HPFRC beam-column joints show that the failure of reinforced HPFRC beam-column joints mainly consists of two types: core shear failure and beam end bending failure. The failure process of HPFRC beam-column joints under earthquake load can be divided into three stages: elastic stage, crack stage and failure stage. The cracks develop fully after the cracking, and most of them are small cracks. The integrity of the specimens is better with less exfoliation of HPFRC when they are destroyed. Due to the existence of steel fiber, the specimens are not easily divided into large blocks in the process of failure. Steel fiber and HPFRC have a good bond effect, which can restrain the development of cracks and improve the seismic behavior of joints.

(2) Grade 600 steel bar has higher yield strain and low elastic modulus, the application of Grade 600 in longitudinal reinforcement of beam improves stiffness degeneration and energy dissipating of joint specimen.

HPFRC beam-column joints have good shear load-carrying capacity and ductility under seismic load. The axial compression ratio has influence on seismic behavior of HPFRC joints.

(3) The increase of stirrup ratio in a certain range can improve strength reduction and incrase energy dissipating capacity and shear load-carrying capacity of joint specimens during the failure stages.

(4) The cumulative energy consumption and of the specimen increases with the increase of stirrup ratio. The waist rebar in beam and the non-corner rebar in the column increase shear load-carrying capacity of joint specimens, and improve strength reduction and energy dissipation capacity to some extent.

5. Acknowledgements

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6. Copyrights

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