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Seismic behaviour of HSC beam-column joints with high-yield strength steel reinforcement

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ABSTRACT: The use of high-yield strength steel reinforcement in RC buildings is a common practice nowadays due to its potential benefits, including reduced steel congestion, less quantity of required steel and a shorter construction time. The purpose of the current study is to find out the seismic behaviour of frame structures in the case of using high-strength material. The experimental findings of high-strength concrete (HSC) interior beam-column joints reinforced with high-strength steel longitudinal bars under zero column axial compressive loading are presented in this paper. Four full-scale interior beam-column joints with varying degrees of reinforcement detailing and different combinations of material grades were subjected to quasi-static horizontal cyclic load. Seismic behaviour of the high-strength and normal-strength specimens is compared in terms of lateral loading capacity, failure modes, strain profiles in the beam and column steel reinforcements and curvature distribution in beams. ACI 318 code provisions regarding utilizing high-strength concrete and high-yield strength reinforcements are reviewed and its validity is investigated based on experimental results.

1 INTRODUCTION

Coupled with the rapid urbanization and development of the world, we have seen the erection of high-rise buildings across the world and the use of high-strength concrete (HSC) in construction has also become more widespread. The definition of high-strength concrete adopted for this study is a workable concrete with the compressive strength of greater than 60 MPa and the age at which this strength is achieved can be more than 28 days.

A number of buildings have been constructed utilizing high-strength concrete with the compressive strength ranging from 60 MPa to 110 MPa. The use of high-strength concrete in building structures offers numerous advantages such as achieving greater heights by reducing the mass of the required concrete and by reducing the size of column cross section. The smaller size of cross sections is also economically favourable due to the increase in rentable floor space. Its high modulus of elasticity which will cause a reduction in deflections and creep deformations has also been pointed as one of its prominent strengths. High-strength concrete is also much more resistant to chemical deterioration as it contains high cement content and low water over cement ratio.

With the increased utilization of high-strength concrete for different structural components, many have voiced concern over whether the current code provisions are adequate and accurate enough for the design of high-strength concrete members. As a result, some related committees such as a committee of the American Concrete Institute (ACI Committee 363) have worked on the behaviour of high-strength concrete and they have published multiple reports according to their research.

Prior to 1990, majority of reinforced concrete structures was constructed using steel reinforcement with the yield strength of 420 MPa. The usage of reinforcement with higher yield strength is more attractive in some countries, especially for beam-column joints in special moment resisting frames; and that acted as the driving motivation for researchers to conduct numerous experiments on beam-column joints with high-yield strength reinforcement (Lee and Hwang 2013; Xin et al. 1992).

To-date, numerous investigations related to the shear, bond, and anchorage behaviour at the joint core of beam-column joints under seismic loading have been carried out (Hakuto et al. 1995; Kurose et al.1988; Pessiki et al. 1990; Alaee et al. 2015). In the current study, the structural performance of the specimens constructed with different grade of materials including concrete and steel reinforcement was evaluated.

2 EXPERIMENTAL PROGRAM

2.1 Test program

Four specimens with the same dimensions but different reinforcement details and different strengths of materials were prepared as shown in **Fig1** for testing typical interior beam-column joints in RC building structures. The specimens were designated as IN80, IH80, IN100 and IH100. The specimens were designed based on the strong column-weak beam requirement and detailing requirements of ACI318-12 and ACI-ASCE Committee 352 report. These four specimens were tested to investigate the possible advantages of using high-yield strength reinforcements incorporated in high-strength concrete material to increase its joint performance. Test results can be compared to previous research on the normal strength concrete (NSC) specimens with normal-strength reinforcements tested in New Zealand and HSC specimens tested by Li and Leong 2014. The target concrete compressive strength of the specimens was 80 and 100 MPa.

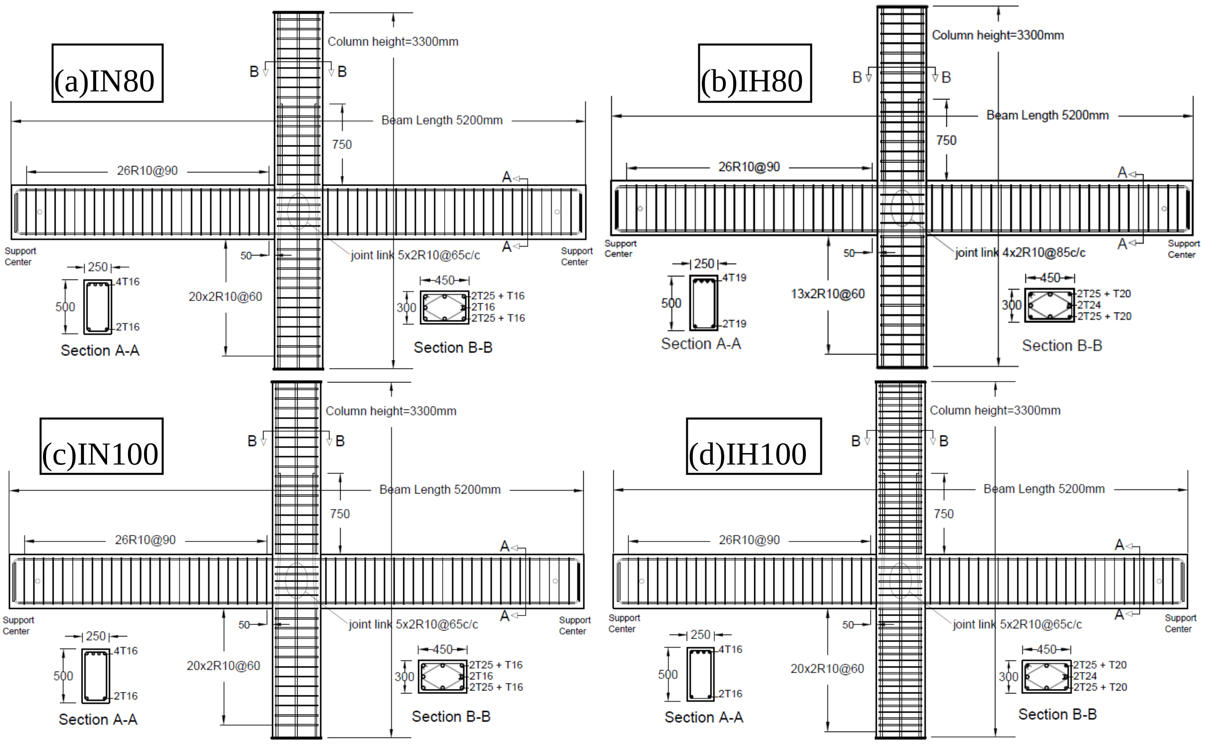


Fig. 1. Reinforcement detailing of tested specimens

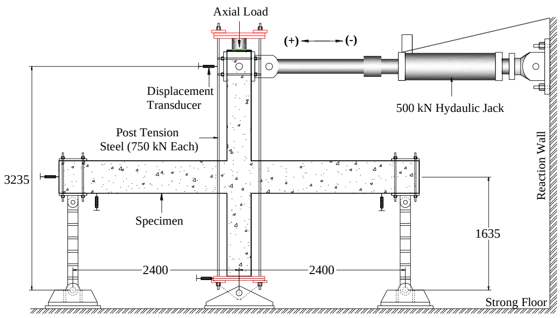
Deformed steel bars of yield strength *fy*=460MPa and *fy*=700MPa were utilized as longitudinal reinforcement of beams and columns in normal-strength and high-strength specimens respectively. The transverse reinforcement utilized in beams and columns included R10 mild steel bars with *fy*=360MPa and *fy*=800MPa for normal-strength and high-strength specimens. The reinforcing bars were tested under uniaxial tension and the measured parameters of the steel bars are mentioned in **Table 1**. The reported values of yield strength and ultimate strength of reinforcing bars are the average values of three tested bars.

Table. 1. Summary of specimens' properties

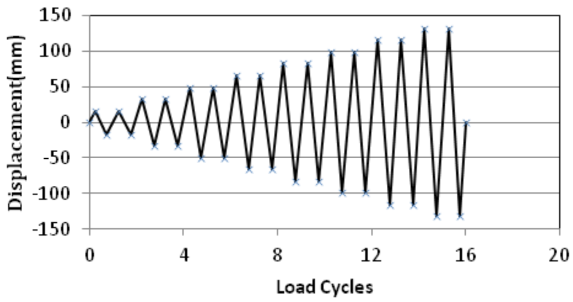
Specimen	Concrete grade (Mpa)	Beam Reinforcement		Column Reinforcement		Joint hoops
		Top	Bottom	Side	Centre	
IN80	80	T16(460MPa)	T16(460MPa)	T25(460MPa)	T16(460MPa)	5R10(460MPa)
IH80	80	T19(700MPa)	T19(700MPa)	T25(700MPa)	T20(460MPa)	4R10(700MPa)
IN100	100	T16(460MPa)	T16(460MPa)	T25(460MPa)	T16(460MPa)	5R10(700MPa)
IH100	100	T16(700MPa)	T16(700MPa)	T25(700MPa)	T20(460MPa)	5R10(700MPa)

2.2 **Test setup**

The test setup is shown in **Fig 2(a)**. The bottom of the column is pinned to the strong floor and beam ends are connected to the strong floor using two vertical links which only restrain the beams vertical movements. Each test specimen was subjected to quasi-static reversed cyclic simulated earthquake loading as shown in **Fig 2(b)**. The horizontal loading is applied to the top of the column using a 500KN hydraulic actuator. No axial load was applied to the specimens.



(a)Test Setup



(b) Loading Pattern

Fig. 2. Loading apparatus

All the test specimens were equipped with numbers of strain gauges and linear displacement transducers (LVDTs) in order to measure strain values in selected points on reinforcing steel bars, and the deformations of different parts of the specimen. Strain gauges were installed on both longitudinal and transverse reinforcements within and around the joint region. LVDTs were used within the joint region to measure flexural and shear deformations, and on top of the column to find the horizontal displacements. As a result of such measurements, hysteresis loop of specimens which shows the relationship between the storey shear and horizontal displacements, and also the strain data can be reported. The mentioned findings are used to analyze the structural behaviour of HSC beam-column joints reinforced with high-strength steel.

3 **EXPERIMENTAL RESULTS**

3.1 **Lateral load-story drift relationship**

Fig 3 shows the lateral load versus the story drift relationship for the specimens. Story drift was calculated based on the value of horizontal displacement of the column's top divided by the column height and the lateral load value was determined based on the amount of force required to achieve the displacement value in each loading step. In Specimens IN80 and IN100 with normal strength steel reinforcements, the maximum strengths occurred at approximately 2% story drift ratio. However, In Specimens IH80 and IH100 with high-yield strength reinforcements, the maximum lateral loading strengths happened at a larger drift ratio of 2.5%. In Specimens IN80, IH80 and IN100 the load carrying capacity gradually decreased after the maximum strength, while Specimen IH100 showed a higher drift capacity and a higher ductility. Bond-slip of the beam longitudinal bars occurred in the joint panel, which resulted in a pinching load-story drift relationship. It is observed that a severe pinching effect was observed in Specimens IN80 and IH100 with high-yield strength steel reinforcements.

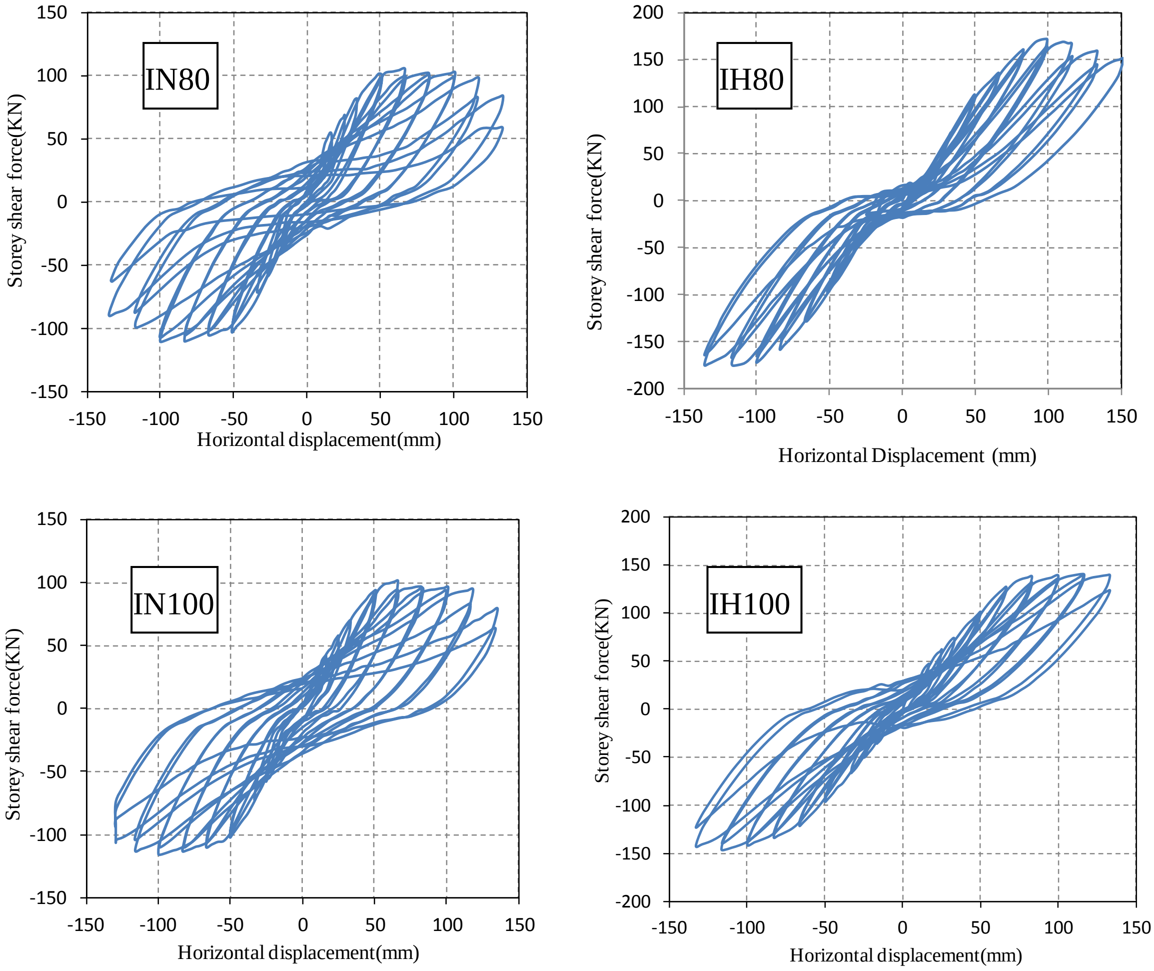


Fig. 3. Storey shears versus horizontal displacements

3.2 Failure modes

It was observed that in Specimens IN80, IN100 and IH100, the damage mode was flexural yielding of beams and the bond-slip of beam flexural bars. However, Specimen IH80 experienced a damage mode of diagonal cracking at the joint which is due to the larger beam bar diameter in this specimen. Concrete crushing occurred at the interface of beam ends and the joint region in all the specimens. Concrete crushing happened in the bottom area of beam ends specifically. The reason is the large compressive stress developed in the bottom part of beams due to the large amount of top reinforcement area in the beam cross section.

3.3 Strain of flexural reinforcing bars in the joint region

Fig 4 shows the strains of the beam top and bottom steel bars in the centre of the joint region. The strain value at “B6” shows the strain value at the centre of the beam bottom bar while “T6” shows the strain value at the centre of top beam bars. The beam top and bottom bars are T16 for Specimens IN80, IN100 and IH100 while T19 was used for Specimen IH80. It was observed that initial yielding happened outside the joint region at fist in all of the specimens and the strain value of the reinforcement within the joint region was always less than its value in the plastic hinge region of the beams. However, it was observed that the strain value in the joint region in Specimen IH80 with large diameter beam bars did not increase significantly due to its bond-slip.

It is observed that the strain value of the beam bottom bars is less than that in the beam top bars in Specimens IN80 and IH80 with the concrete grade of 80MPa. This observation clarifies that the bond-slip occurred at the beam bottom bars.

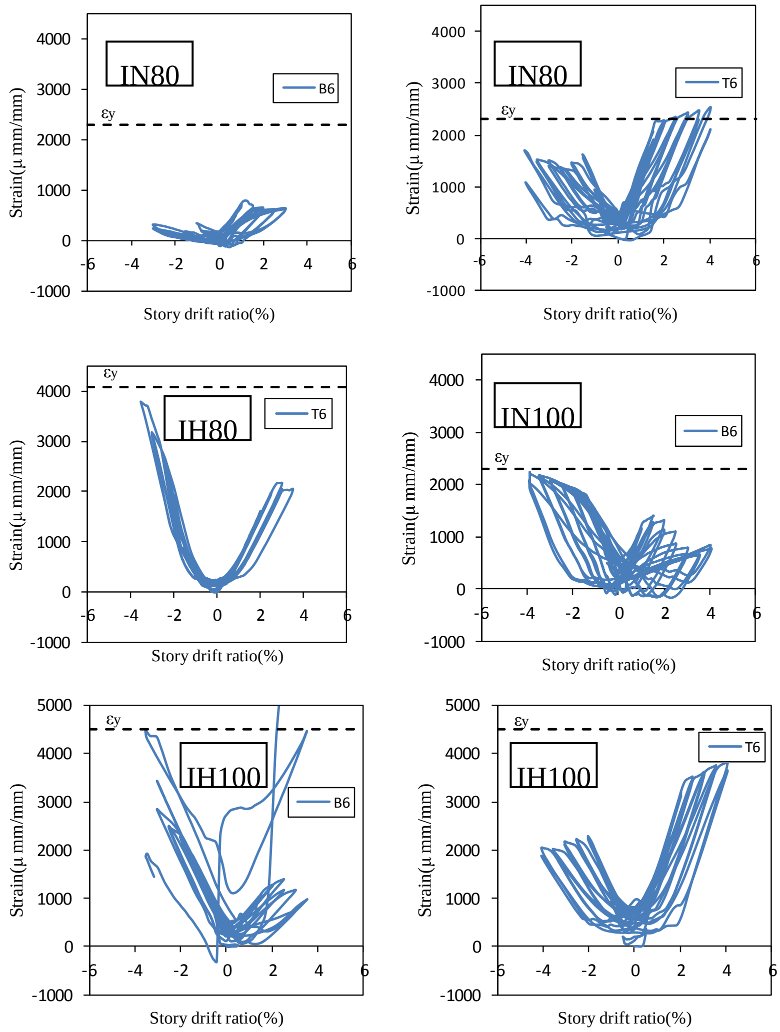
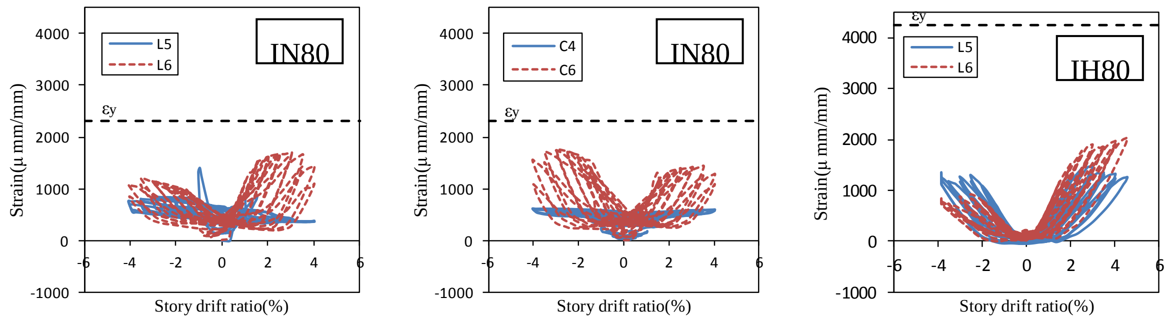


Fig. 4. Strain of beam top and bottom reinforcing bars

3.4 **Strain of longitudinal reinforcing bars in the column**

Fig 5 shows the strains of side bar and central bar of columns in all the specimens.L5 and C5 represent the strain value in the centre of the side bar and the central bar in the column, while L6 and C6 represent the strain value of the column side bar and centre bar in the level of beam bottom bars. Generally the strains increased gradually, although they did not reach the yield strain. From the top beam face to the bottom beam face, the column reinforcement experienced tension. The central column bars experienced lower stress compared to the side column bars in general. The column remained elastic at the end of the test.



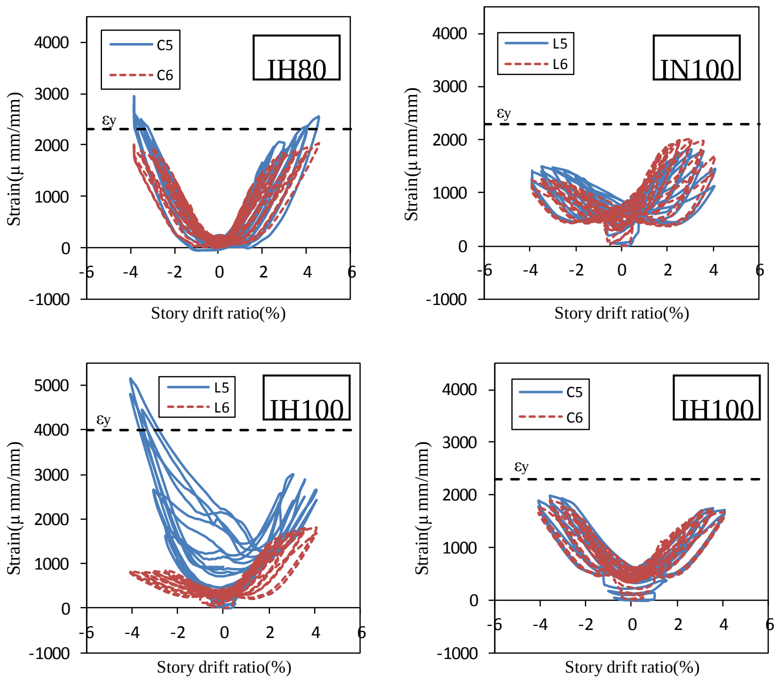


Fig. 5. Strain of column reinforcing bars

3.5 Strain of ties

Fig 6 shows the strains of the tie bars in the joint region. H1 represents the lowest tie in the joint panel and H3 is the tie in the centre of the joint. The maximum strain value was 0.0012, 0.0014 and 0.002 in Specimens IN80, IN100 and IH100. The maximum strain was less than the yield strain in all the specimens and no yielding of joint hoops was observed.

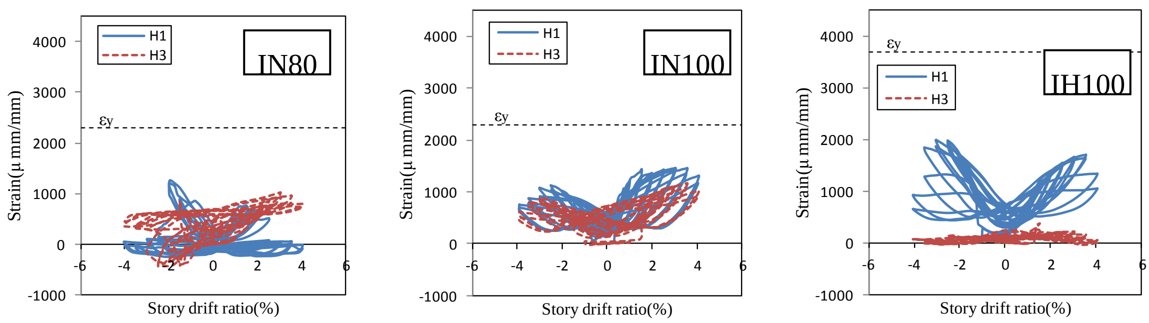


Fig. 6. Strain of tie bars in the joint region

3.6 Beam curvatures

Fig 7 shows the beam curvature distributions estimated from the experimental results and instruments readings. Curvature values are presented for drift ratios of DR=1% and DR=3% in the positive and negative loading directions.

With the positive beam moment during DR 1%, the beam curvature measured near the column face reached the theoretical yield curvature. Rapid increase of the curvature was observed in the subsequent loading cycles. This was due mainly to the plastic hinges forming in the beam end. A similar situation was also observed in the negative loading cycles. Beam curvature increases rapidly after DR 3%.

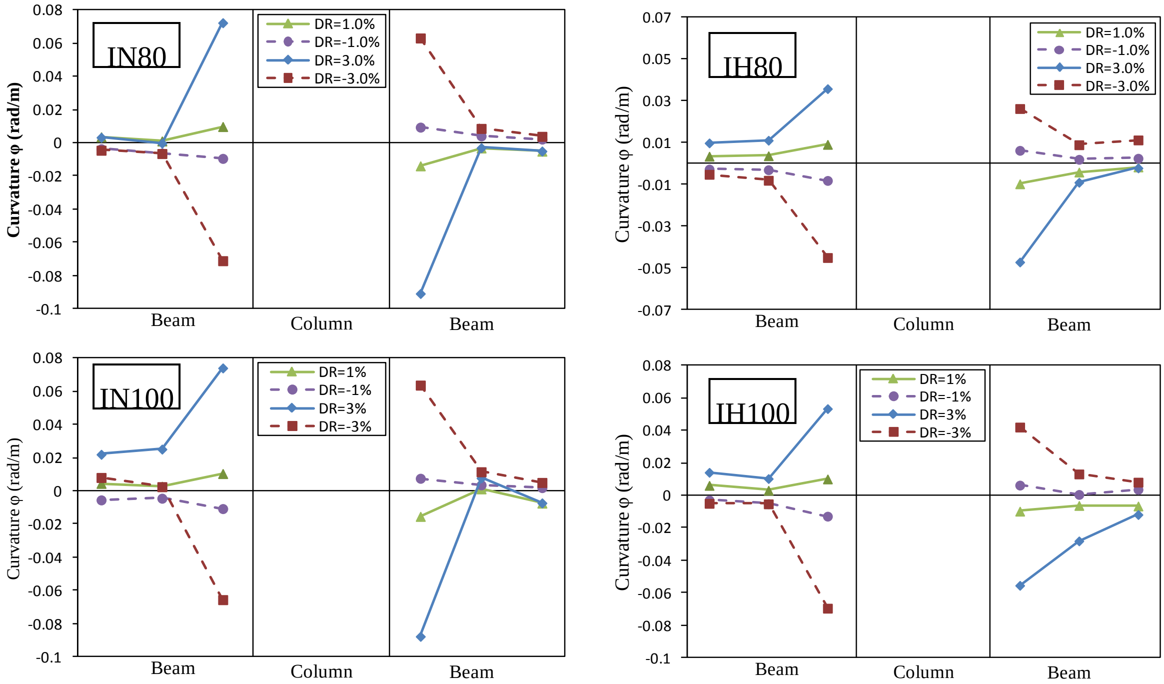


Fig. 7. Curvature distribution of the beams

4 CONCLUSIONS

A study was carried out on the seismic performance of HSC beam column joints reinforced with high-yield strength steel reinforcement. In order to evaluate the structural performance, four interior specimens using grade 80 and 100MPa concrete were designed as part of special moment frame according to the provisions of ACI 318-12 (Building Code Requirements for Structural Concrete) and ACI 352R-02 (Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures) for the seismic design of reinforced concrete structures. The following conclusions are summarized:

1- Utilizing high grade steel reinforcement will improve the load-carrying capacity of the specimens. However, a more pinching hysteresis response is observed, which is due to the bond-slip of the beam top and bottom steel reinforcements.

2- Flexural failure mode in the beam plastic hinge regions was observed at the end of each test which implies the validity of ACI 318-08 code provisions for the design of high strength beam-column joints.

3- The strain profiles of steel reinforcements showed that column rebars and joint hoops remained elastic during the test and yielding occurred in beam top and bottom rebars which is desirable according to the contemporary structural design philosophy.

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