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Experimental investigation into the failure process of exterior beam-column joints with high-strength reinforcements

H Arshadi[1], A Kheyroddin[2], H Naderpour[3], and *M Kioumarsi[4]

[1, 2, and 3] Faculty of Civil Engineering, Semnan University, Semnan, Iran.
[4] Faculty of Technology, Art and Design, Department of Building and Energy Technologies, Oslo Metropolitan University, Oslo, Norway

*mahdik@oslomet.no

Abstract. Although using high-strength reinforcements (HSRs) have economical and execution benefits, their possible negative effects on the performance of structures such as ductility, energy dissipation, and damage process caused them to be restricted by building codes in seismic areas. In this research, the HSR effects on the cyclic behavior, cracking process, and damage indices of exterior beam-column joints were experimentally investigated under cyclic loading. Three exterior beam-column joints with HSRs (with the yield strengths of 500 and 580 MPa) were designed based on the special seismic provisions of ACI 318-19. These specimens were subjected to cyclic loading and their responses were obtained. The results showed that using HSRs led to increasing the width and depth of the cracks. Then, two methods of calculating damage indices (introduced by Promis *et al.*, 2009) were applied based on the experimental results. Considering the damage indices, it was observed that using HSRs increased the damage indices of the specimens and the damage distribution in them.

1. Introduction

Several structural systems resist earthquake-induced forces such as shear walls, moment frames, and dual systems (moment frames with shear walls). Although there are many studies on performance of the lateral resisting systems [1-5], but these systems have some usage limitations such as height of structures, etc. [6]. For instance, special moment frames along with shear walls are earthquake-resisting systems that high-strength reinforcement (HSR)–steel reinforcements with the yield strengths greater than 500 MPa– application is restricted in them due to possible repercussions of HSR application [7,8]. There are considerable challenges against the HSR application such as increasing the crack width, the brittle failure, decreasing the ductility and energy dissipation. On the other hand, HSR application has several benefits, such as diminishing the labor and material costs, reducing construction time and facilitating the construction procedure [6].

Damage indices can be calculated based on different parameters such as strain, stress, displacement, dissipated energies, stiffness, and ductility. Several researchers have proposed Damage indices (DI) for different types of structures during recent years. These indices have been modified and calibrated by passing the time. Promis *et al.* (2009) carried out seismic damage analysis for reinforced-concrete (RC) buildings

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[9]. They proposed and used several damage indices in their study. The damage indices can be studied by analytical methods like incremental dynamic analysis (IDA) and endurance time (ET) method. In these methods, structures are subjected to incremental cyclic loads and their responses are calculated until the damage indices get certain amounts. Arshadi (2016) went over the concepts and methodologies of the IDA with single and multiple records [10]. Also, Arshadi *et al.* (2014) compared these two methods in the frames rehabilitated by base isolators [11]. The initial experiments on the RC members with HSRs did not include cyclic loading. Firstly, cyclical experiments were carried out by Burns and Siess to study the performance of the elements subjected to seismic excitations in the early 1960s [12]. Kheyroddin *et al.* (2017) studied the HSR effects on the cracking, drifts, decreasing steel consumption and effective moment of inertia of beams and columns by nonlinear static and dynamic analyses in the intermediate moment frames [12]. Their research showed that HSR application increased the concrete cracks and decreased the effective stiffness of RC structures. Arshadi *et al.* (2019) experimentally studied the behavior of frames and beam-column joints with HSRs subjected to cyclic loading [6, 13]. They focused on different parameters such as energy absorption, stiffness degradation, cracking and plastic hinge formation in their research. They showed that using HSRs led to a considerable decrease in ductility and energy absorption of the specimens. Dabiri and Kheyroddin (2020) investigated the effects of bars on the behavior of non-seismically detailed RC beam-column joints [14]. Arshadi *et al.* (2020) experimentally investigated the damage indices of special moment frames with HSR bars. They showed that HSRs expedited the failure process of the frames [15].

In this study, the HSR influences on the failure process and damage indices of three exterior beam-column joints were studied. Three beam-column joints were designed based on the special seismic provisions of ACI318-19 [16]. The specimens were constructed with the same geometry and equivalent amounts of the reinforcements. The specimens were tested under cyclic loading. The experimental results showed that the HSR application decreased the cracking forces and increased the crack propagation in the specimensBesides, the damage indices introduced by Promis *et al.* (2009) were used to study the damage behavior of the joints [10]. One of these methods was based on the displacements and the other one was based on the energy absorption. The slope of damage diagrams indicates the velocity of damage distribution in the specimens. The damage indices showed that the velocity of the damage propagation in case of applying HSRs as both the longitudinal and transverse reinforcements was the most among the beam-column joints. Also, applying HSRs as longitudinal reinforcements decreased the velocity of damage propagation in comparison to applying them as just the stirrups.

2. Experimental program

2.1. Material properties

Normal ready-mixed concrete with the water-cement ratio of 0.43 and Portland cement type 2 was used to achieve a compressive strength of 30 MPa and to cast the specimens. As for HSRs, two types of HSRs with the yield strengths of 500 and 580 MPa produced by the Thermex method were used. The Thermex method is just a swift water quenching process that ensures consistent properties over the entire bar length [6].

2.2. Specifications of the specimens

An exterior beam-column joint is a part of a moment frame and achieved by cutting through points of contra-flexure of the beams on both sides of the column and cutting through the column nearly one-half story height above and below the joint. Studying the behavior of beam-column joints with HSRs is recommended by the technical reports [13]. In this paper, three exterior beam-column joints (nearly the two-thirds scale of the real one) with the same geometry and concrete properties were designed based on the special seismic instructions of ACI 318-19 [16]. The specifications of the columns were identical in all the specimens because it was intended that the columns had to remain elastic. These columns which played the role of the foundation for the beams had the same steel bar arrangements and were built with the 500 MPa steel. In the specimens, HSRs were only used in the beams. Firstly, the reference model whose both transverse and longitudinal reinforcements were the 500 MPa steel, was designed. Then, the other two beam-column joints with the equivalent 580 MPa steel as the longitudinal or transverse reinforcements were designed based on the reference specimen [6]. Table 1 shows the names and properties of the test models.

Table 1. Properties of the longitudinal and transverse steel bars in the beam-column joints

Models	Yield stress of longitudinal rebars, f_{yl} (MPa)	Yield stress of transverse rebars, f_{yt} (MPa)
BL500S500	500	500
BL580S500	580	500
BL580S580	580	580

2.3. Test procedure
The lateral cyclic load was applied to the top of the beam by a bidirectional hydraulic jack with the loading capacities of 2000 kN in compression and 1000 kN in tension [6]. The specimens were fixed to the rigid floor by the metal jackets. This actuator was attached to the beams by a system consisted of two plates joined to each other by two ultra-high-strength rods. All the specimens were tested under cyclic lateral loading at the top of the beams. Figure 1 shows the laboratory setup of the specimens. The protocol employed in horizontal cyclic loading was a displacement control one proposed by ACI 374 [13].

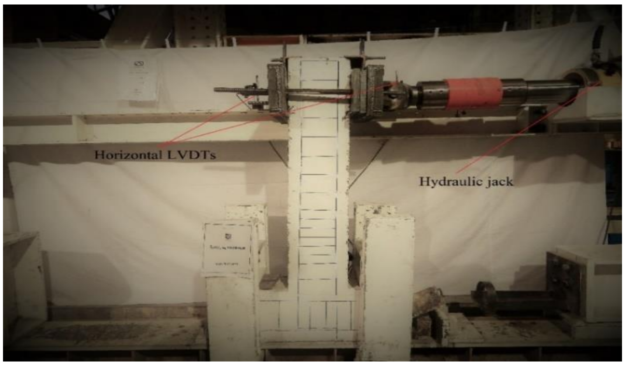

Figure 1. Laboratory setup of the beam-column joints [8]

3. Experimental results

3.1. Crack patterns
The initial cracks were moment ones formed near the end of the beam (close to their joint to the columns). In the BL500S500 and BL580S580 specimens, the initial cracks were formed at the 0.12% drift level and in the BL580S500 specimen, the first cracks were formed at the 0.14% drift level. The number, width, and depth of the shear and moment cracks increased by applying more loading [6]. However, no cracks were formed on the columns, because of the weak beam-strong column rule considered in the designing. The average cracking loads (in tension and compression) for the BL500S500, BL580S500 and BL580S580 specimens are 6, 5.5 and 3.75 kN, respectively. As for the crack distribution, the higher the yield strength of the steel, the wider and deeper the cracks.

3.2. Indices based on displacements
The displacement-based damage indices used in this research were proposed by Promis *et al.* (2009) [9]. This index which indicates the linear accumulation of the damage is calculated as follows:

Firstly, the cumulative term β_ω is calculated:

$$\beta_\omega = C\sum_i \frac{\delta i}{\delta f} \qquad (1)$$

where δ_i is the maximum displacement for cycle i, δ_y is the displacement corresponding to the yield of steels, δ_f is the failure displacement in monotonous loading, and C = 0.1. Then the total damage D is calculated based on β_ω. The values of this damage index function in extreme cases are: f (0) = 0 and f (1) = 1. The definition of DI (damage index) according to β_ω is:

$$DI = \frac{e^{n\beta\omega} - 1}{e^n - 1} \qquad (2)$$

In which: n is considered 1 for the strongly reinforced nodes, otherwise, n = -1 [9]. The displacement damage indices of the specimens calculated by the above definition are shown in Figure 2. It must be mentioned that the slope of damage diagrams shows the velocity of damage distribution. In the beam-column joints, the damage propagation velocity of the BL500S500 specimen (based on its damage diagram slope) was more than the other two specimens. Moreover, the BL580S580 and BL580S500 specimens had similar displacement damage propagation. The BL500S500 specimen also had the highest damage capacity among the beam-column connections. This means that it endured greater amounts of forces and failed later than the other specimens because of less intensity of damage distribution. The BL580S500 had the least damage capacity and failed sooner than the other specimens.

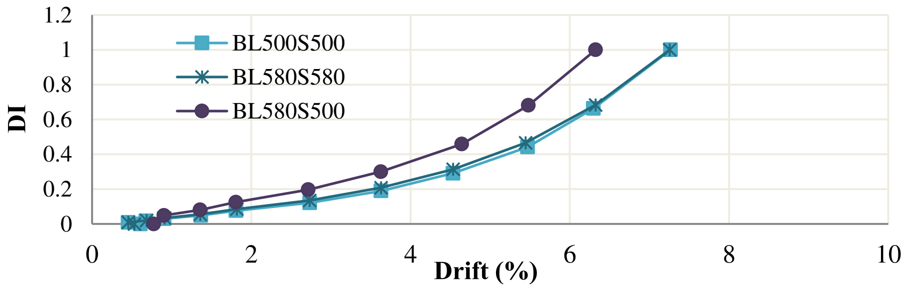

Figure 2. Displacement-based damage indices of the beam-column connections

3.3. Indices based on energy

Promis *et al.* (2009) proposed a formulation for damage index based on the dissipated energy of the RC structures [9]. This formulation depends on the dissipated energy, but just during cycles for which the force of displacement is higher than that of the one related to the steel yielding. This means that just the cycles in which $\frac{Fi}{Fy} \geq 0.75$ are taken into account. In which F_i is the force reached during the cycle i, and F_y is the yield force of the RC structures. The formulation to calculate the damage index is as below:

$$DI = \sum_i \frac{Fi\delta i}{Fy\delta y} \qquad (3)$$

where δ_i & F_i are the maximum displacements and its corresponding forces for cycle i, δ_y & F_y are the displacements related to the steel yielding and its corresponding forces. This definition of damage index depends on the determination of specimen failure, which happens at a 25% decrease in the maximum load of the hysteresis loops. It is worth mentioning that the relation to calculate the dissipated energy, according to the surfaces of the hysteresis loops is as follows:

$$\int dE = \int F(\delta)d\delta = \int M(\phi)d\phi \quad (4)$$

where E is the dissipated energy, M (ϕ) & ϕ are the moment and its corresponding rotation, F (δ) & δ are the force and its corresponding displacement. Figure 3 indicates the damage indices in the beam-column joints. In the beam-column joints, the energetic damage index of the BL580S500 specimen was less than the other specimens. As for this damage index definition, the previous legacy which was shown in the displacement-based damage indices was observed, too. This means that the BL500S500 had the best performance in terms of damage propagation and the BL580S500 had the least damage capacity among the other specimens.

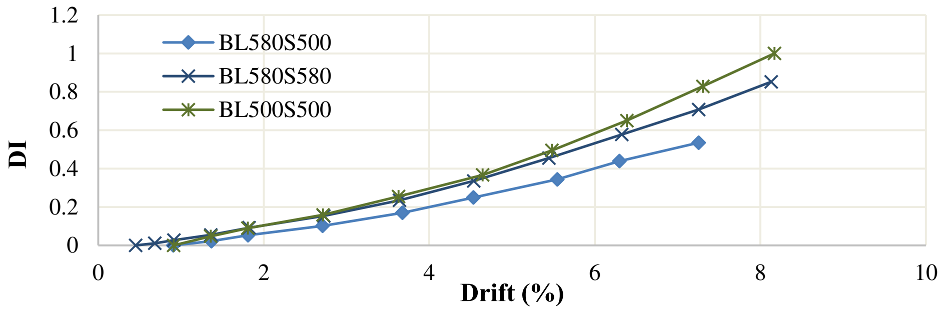

Figure 3. The energetic damage indices of the beam-column connections

4. Conclusion

In this research, the HSR effects on the failure process of three exterior beam-column joints were studied. The beam-column joints are one of the important structural parts that HSR effects on them are not studied sufficiently. Then, three beam-column joints were designed based on the special seismic provisions of ACI318-19 in this research [16]. They were constructed with the same geometry and tantamount amounts of the reinforcements. The specimens were subjected to cyclic loading. The experimental results indicated that the HSR application decreased the cracking forces and increased the crack propagation in the specimens. Then, the damage indices introduced by Promis *et al.* (2009) [9] were applied to investigate the damage behavior of specimens. One of these methods was based on the displacements and the other one was based on the energy absorption. The damage indices showed that the velocity of the damage distribution in the case of applying HSRs as just the longitudinal reinforcements (BL580S500) was the most among the specimens. It must be reminded that the slopes of the damage diagrams show the velocity of damage distribution in the specimens. Moreover, applying HSRs as both the longitudinal and transverse reinforcements (BL580S580) decreased the velocity of damage distribution in comparison to applying them as just the longitudinal ones (BL580S500). This means that higher-strength steel reinforcements as longitudinal and transcerse ones had better interaction with each other than using high-strength and low-strength ones with each other. Finally, the BL500S500 specimen had the best damage performance and failed in a higher drift ratio than the other specimens.

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