Experimental Study on the Failure Traits of Frames with High-Strength Reinforcements

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

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

* Corresponding author. Tel.: +47 67 23 87 45; email: mahdik@oslomet.no

Manuscript submitted March 14, 2020; accepted December 12, 2020.
doi: 10.17706/ijmse.2021.9.1.8-14.

Abstract: Using high-strength reinforcements (HSRs) has several benefits in terms of financial and execution considerations. However, possible effects of HSR application on structural behavior such as ductility, energy dissipation, and damage process are not fully known for the researchers. In this study, firstly the HSR effects on the cyclic behavior, cracking process, and damage indices of special moment frames were experimentally studied under cyclic loading. Four special moment frames with HSRs (with the yield strengths of 500 and 580 MPa) were designed based on the special seismic provisions of ACI 318-19. These frames were subjected to cyclic loading and their responses were acquired. 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 [8].) were applied based on the experimental results. Concerning damage indices, it was observed that using HSRs generally resulted in increased damage indices of the specimens.

Keywords: Special moment frames, failure process, damage indices.

1. Introduction

There are many studies that have focused on the behavior of individual- and dual-lateral resisting systems in reinforced concrete (RC) frames [1]-[4]. The performance of reinforced concrete as a material for designing frames exposed to severe environmental conditions was improved by the development of high-performance concrete (HPC) and High-strength reinforcement (HSR) [5], [6]. HSR application has several benefits, such as decreasing the labor and material costs, peripheral expenses (like the transportation and overhead expenses), reducing construction time, and facilitating the construction procedure. However, there are considerable impediments against the HSR application, such as increasing the crack width under service loads, the brittle failure phenomenon, the difficulties of the HSR production with proper ductility [7]. Then, the application of HSRs is restricted in the special moment frames and shear walls by codes. This restriction to some extent is because of the lack of information and experimental data about the possible effects of HSR application in the frames and shear walls. Accordingly, it is essential to study HSR effects on them.

The damage process and even stiffness degradation of reinforced-concrete (RC) members can be monitored by using damage indices (DIs). The damage indices can have either cumulative or non-cumulative nature. Promis *et al.* [8] carried out seismic damage analysis for RC buildings. They proposed formulations for damage indices based on the different parameters such as energy and displacement. It must be mentioned that there are analytical approaches to study the damage indices like incremental dynamic analysis (IDA) and endurance time (ET) method. In these methods, structures are subjected to incremental cyclic records and their responses are recorded until the damage indices reach specific amounts. Arshadi (2016) overviewed the concepts and methodologies of the IDA with single and multiple records [9]. Additionally, Arshadi *et al.* compared the IDA and ET methods in the structures rehabilitated by base isolators [10]. As for the HSRs application, several researchers studied their application; however, a few of them studied the HSR application in the RC members under seismic loading, where most of them investigated their behavior under monotonic loading. Kheyroddin *et al.* [11] investigated the effect of HSR 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. Arshadi *et al.* [7], [12] experimentally studied the performance of frames and beam-column connections with HSRs subjected to cyclic loading. They concentrated on different parameters such as energy absorption, stiffness degradation, and cracking patterns in their experiments. Arshadi *et al.* [13] experimentally investigated the damage indices of beam-column joints with HSR bars.

In this study, the effects of HSRs on the failure mechanism of four RC frames were investigated based on the different types of damage indices. These frames were designed based on the special seismic provisions of ACI318-19 [14]. Several structural systems can resist lateral forces such as shear walls, moment frames, etc. These systems have restrictions in terms of the height of structures, in which they are applied [15], [16]. Besides, the application of HSR in the special moment frames and shear walls is challenging [17], [18]. Studying the HSR effects on the seismic performance of special moment frames is essential and recommended by several technical sources, see [9]. With regard to these facts, four special moment frames, which had the same geometric characteristics and equivalent amounts of longitudinal and transverse reinforcements, but with discrepant yield strengths (500 and 580 MPa) were constructed. The specimens were tested under cyclic loading and their responses were recorded. Then, the damage indices introduced by Promis *et al.* [8] were calculated in this study. One of these methods is based on displacements and the other method is based on energy absorption. The results indicated that using HSR increased the width and depth of the cracks in the specimens. It must be reminded that the slope of damage diagrams shows the velocity of damage distribution. The results of 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 specimens. Furthermore, applying HSRs as longitudinal reinforcements decreased the velocity of damage propagation in comparison to applying them as just the stirrups.

2. Test Program

2.1. Material Specifications

The RC frames were cast using the C30 grade concrete with the average compressive strength of 30.52 MPa at 28 days. The concrete had normal weight aggregates with a nominal maximum size of 25.4 mm. In this research, two types of HSRs with yield strengths of 500 and 580 MPa were used.

2.2. Description of Specimens

In this research, four special moment frames (nearly, a third scale of real one) with the same geometric and concrete properties, but with the different types of longitudinal and transverse reinforcements were built (according to the ACI318-19 special seismic provisions [14]). Firstly, the reference frame (whose both transverse and longitudinal reinforcements had the yield strength of 500 MPa) were designed and then the other frames with the equivalent amount of steel with the yield strength of 580 MPa (as the longitudinal and transverse reinforcements) were designed [9]. Table 1 shows the names and specifications of these models.

Table 1. Specifications of the Steel Reinforcements Used in the Frames

Models	Yield strength of longitudinal reinforcements, f_{yl} (MPa)	Yield strength of transverse reinforcements, f_{yt} (MPa)
FL500S500	500	500
FL500S580	500	580
FL580S500	580	500
FL580S580	580	580

2.3. Experimental Procedure

A strong frame and rigid floor were built in the lab to test the specimens. The hydraulic horizontal jack was fixed to the columns of the strong frame. Moreover, a steel box was built and joined to the beam of the strong floor to contain the vertical hydraulic jack in itself. This vertical hydraulic jack imposed a constant axial load equal to 315 kN (for each column) to the top of the columns of frames before applying the lateral load. A stiffened steel plate-girder was utilized to transfer the axial load from the jack to the columns. The lateral load was applied to the top side of the frames by a hydraulic jack with the loading capacities of 2000 kN in compression and 1000 kN in tension. A device with two steel plates at both sides of the frames which were joined to each other by two ultra-high-strength rods was utilized to join them to the horizontal jack [7]. The detail of the test setup is indicated in Fig. 1. The frames were subjected to cyclic lateral loading. This loading protocol was displacement control and based on the ACI-374 provisions.

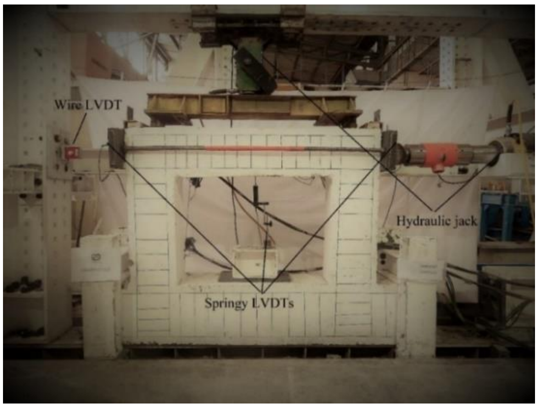

Fig. 1. Test setup detail of the frames.

3. Results

3.1. Cracking Patterns and Failure Mechanism

It is necessary to monitor the generation and distribution progress of the cracks because they are the major source of material nonlinearity. In these experiments, the specimens began to crack by increasing the lateral loads. The observations showed that the moment cracks were formed on both sides of the beams and the lower ends of the columns. The force related to the first cracks was 52.51 kN (equivalent to 0.13% drift level) for the reference specimen (FL500S500) [7]. As for the other specimens, such as the FL500S580, FL580S500, and FL580S580 specimens, the forces corresponding to the first cracks diminished to 51.79, 38.11, and 38.34 kN, respectively. Then, more shear and moment cracks were formed by increasing the loads. Generally, it was observed that by utilizing the HSRs, the crack widths and depths increased.

3.2. Displacement-Based Damage Indices

The first damage index used in this research which is based on the displacement was proposed by Promis *et al.* [8]. This index which shows the linear accumulation of the damage is calculated as follows:

Firstly, the cumulative term β_ω is calculated:

$$\beta_\omega = C\sum_i \frac{\delta i}{\delta f} \tag{1}$$

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:

$$DI = \frac{e^{n\beta\omega} - 1}{e^{n} - 1} \tag{2}$$

where *n* is regarded 1 for the strongly reinforced nodes, otherwise, $n = -1$, see [8].

The displacement damage indices of the specimens calculated by this definition are shown in Fig. 2. The slope of damage diagrams shows the velocity of damage distribution. In the frames, the damage diagram slope of the FL500S500 specimen was the least among the other specimens, which means that this specimen had the least damage propagation velocity. On the other hand, the slope of the damage diagram of the FL580S500 specimen was greater than the other specimens, which showed its swift failure. Moreover, the damage diagram slope of the FL580S580 was less than the FL500S80 specimen and greater than the FL500S500 specimen. In conclusion, the FL500S500 specimen had the best performance in terms of the damage propagation, and the FL580S500 specimen had the worst one among the specimens.

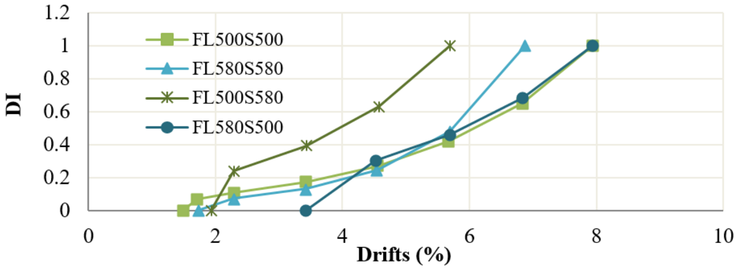

Fig. 2. Displacement-based damage indices of the frames.

3.3. Energy-Based Damage Indices

The damage indices based on the absorbed energy have cumulative types. Promis *et al.* [8] proposed a formulation for damage index based on the dissipated energy of the RC structures [8]. This formulation relies on the dissipated energy, but only during cycles for which the force of displacement is higher than that of the one related to the steel yielding. This means that only the cycles, where $\frac{Fi}{Fy} \geq 0.75$ are considered, in which F_i is the force reached during cycle *i* and F_y is the yield force of the RC structures. The formulation to calculate the damage index is demonstrated below:

$$DI = \sum_i \frac{Fi\delta i}{Fy\delta y} \tag{3}$$

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 must be reminded that the formulation to calculate dissipated energy, according to the surfaces of the hysteresis loops is as follows:

$$\int dE = \int F(\delta)d\delta = \int M(\phi)d\phi \tag{4}$$

where *E* is the dissipated energy, $M(\phi)$ & ϕ are the moment and its corresponding rotation, $F(\delta)$ & δ are the force and its corresponding displacement. Fig. 3 indicates the evolution of the damage index in the frames. The damage index of the FL580S500 specimen was lower than that of other specimens. As shown in the figure below, the FL500S500 specimen had the highest damage capacity among all the specimens. Moreover, it was observed that the damage progression was rather linear, but there were differences in their slope and intensity. Regarding the results of this damage index formulation, it can be concluded that a similar trend to the displacement-based damage index was seen, i.e., the FL500S500 had the best performance in terms of the damage distribution.

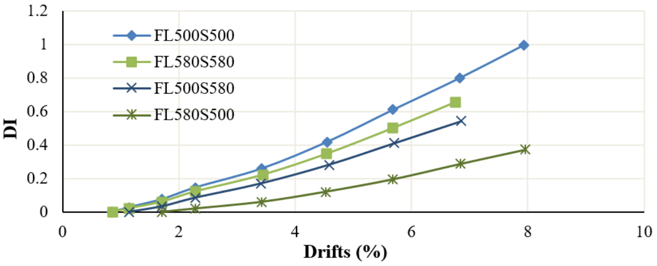

Fig. 3. Energy-based damage indices of the frames.

4. Conclusion

In this study, the effects of using HSRs on the failure mechanism of special moment frames were experimentally investigated. Four special moment frames were designed and constructed based on the special seismic provisions of ACI 318-19 [14]. These frames had the same geometric characteristics and equivalent amounts of the longitudinal reinforcements and stirrups, but with different yield strengths of 500 and 580 MPa. The frames were tested under cyclic loading and their responses were obtained. The observations showed that the width and depth of cracks increased by using HSRs. Moreover, the cracking load of the specimens decreased by HSRs. Then, the damage indices of the specimens proposed by Promis *et al.* [8] based on the energy and displacement were calculated. The damage indices demonstrated the velocity of the damage propagation. The results showed that the lower the steel grade, the better the failure behavior (FL500S500). Moreover, the energy-based damage indices showed that the failure process in the case of using HSRs as both the longitudinal and transverse reinforcements happened sooner (and in lower drift ratios) than the other specimens. However, the displacement-based damage indices showed that the frame with high-strength reinforcements as just the transverse bars failed sooner. On the other hand, applying HSRs as longitudinal reinforcements decreased the velocity of damage propagation in comparison to applying them as just the stirrups (i.e. this specimen failed in a higher drift ratio).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Arshadi and Kheyroddin conducted the experimental research; Arshadi and Kioumarsi analyzed the data; Naderpour supervised the experimental and analytical program, Arshadi and Kioumarsi wrote the paper; all authors had approved the final version.

Acknowledgment

The first author thanks the Semnan University for supporting and facilitating the experimental program. The first author would also like to show his gratitude to Mohammad Haji, Ph.D. candidate, University of Tehran for sharing his pearls of wisdom with us during this research.

References

[1] Bypour, M., Gholhaki, M., Kioumarsi, M., & Kioumarsi, B. (2019). Nonlinear analysis to investigate effect

of connection type on behavior of steel plate shear wall in RC frame. *Engineering Structures, 179*, 611-624.

[2] Kioumarsi, B., Gholhaki, M., Kheyroddin, A., & Kioumarsi, M. (2016). Analytical study of building height effects over steel plate shear wall behavior. *International Journal of Engineering and Technology Innovation, 6(4)*, 255.

[3] Bypour, M., Kioumarsi, B., & Kioumarsi, M. (2019). Investigation of failure mechanism of thin steel plate shear wall in RC frame. *Key Engineering Materials*, *803*, 314-321.

[4] Kheyroddin, A., Kioumarsi, M., Kioumarsi, B., & Faraei, A. (2018). Effect of lateral structural systems of adjacent buildings on pounding force. *Earthquakes and Structures*, *14(3)*, 229-239.

[5] Kioumarsi, M., Tajfar, M., Kheyroddin, A., & Kioumarsi, B. (2016). Investigation of the seismic response of reinforced concrete column-beam connections using high performance fibre reinforced cementitious composites (HPFRCC). *Nordic Concrete*, *36*.

[6] Kheyroddin, A., Arshadi, H., & Khedri, J. (2021). The resistance of fiber-reinforced concrete with steel fibers and CFRP to drop-weight impact. *Periodica Polytechnica Civil Engineering*, *65(2)*, 666-676.

[7] Arshadi, H., Kheyroddin, A., & Naderpour, H. (2019). High-strength reinforcement effects on the seismic behaviour of beam-column joints. *Proceeding Institute of Civil Engineering - Structures and Buildings*.

[8] Arshadi, H., Kheyroddin, A., Naderpour, H., & Haji, M. (2021). Study on The Damage Indices of Concrete Members Reinforced with High-Strength Steel (HSS). *Proceedings of the Institution of Civil Engineers-Structures and Buildings* (pp. 1-35).

[9] Arshadi, H. (2016). An overview on the concepts and methodologies of incremental dynamic analysis IDA (with a single record and multiple records). *Proceedings of the 2016 Structures Congress (ASEM). Jeju Island, Korea*.

[10] Arshadi, H., Izadifard, R. A., & Estekanchi, H. (2014). The comparison of the IDA and ET on steel structures rehabilitated by isolators. *Journal of Rehabilitation in Civil Engineering, 2(2), 46-62*.

[11] Kheyroddin, A., Arshadi, H., & Binaipur, F. (2017). An overview of the effects of high-strength reinforcement (HSR) on the intermediate moment-resisting frames. *AUT Journal of Civil Engineering*.

[12] Arshadi, H., Kheyroddin, A., & Naderpour, H. (2019). An investigation into the behavior of special Moment frames with high-strength reinforcement Subjected to cyclic loading. *Journal of Building Engineering, 26, 100905*.

[13] Arshadi, H., Kheyroddin, A., Naderpour, H., & Kioumarsi, M. (2020). Experimental investigation into the failure process of exterior beam-column joints with high-strength reinforcements. *Proceedings of 3rd International Conference on Civil Engineering and Architecture*.

[14] American Concrete Institute (ACI). (2019). ACI 318-19: Building code requirements for structural concrete. American Concrete Institute, Farmington Hills, MI, USA.

[15] Arshadi, H. & Kheyroddin, A. (2019). Shear lag phenomenon in the tubular systems with outriggers and belt trusses. *Magazine of Civil Engineering, 86(2), 105–118*.

[16] Bypour, M., Kioumarsi, M., & Yekrangnia, M. (2021). Shear capacity prediction of stiffened steel plate shear walls (SSPSW) with openings using response surface method. *Engineering Structures, 226*, 111340.

[17] Kheyroddin, A., Mirrashid, M., & Arshadi, H. (2017). An investigation on the behavior of concrete cores in suspended tall buildings. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*. *Springer International Publishing, 41(4), 383–388*.

[18] Arshadi, H., Kheyroddin, A., Ahadi, M. R., Taban, G., & Kioumarsi, M. (2021). The impact resistance of Fiber-Reinforced concrete with polypropylene fibers and GFRP wrapping. *Materials Today: Proceedings (in press)*.

Hamed Arshadi lives in Iran. He was born in 1985. He holds a Ph.D. degree in structural engineering, which was graduated from the Semnan University in 2019. He has been post-doctoral research fellow in structural engineering since 2020.

He had many experiences in the domain of design, performing and retrofitting reinforced concrete structures. He also works as a research- and teacher assistant in the Semnan University. His research interests are retrofitting concrete structures, tall buildings, earthquake engineering, and new types of materials.

Dr. Arshadi is the member of Iranian Association of Official Experts, Iranian Concrete Institute (ICI), and Tehran Construction Engineering Construction.

Ali Kheyroddin lives in Iran and born in 1964. He holds a Ph.D. degree in structural engineering which was graduated from the MC Gill University in 1997.

He had many experiences in the domain of design and rehabilitation of reinforced concrete structures. He is a distinguished professor in the Semnan University. His research interests are retrofitting concrete structures, tall buildings, earthquake engineering, damage indices, and health monitoring.

Prof. Kheyroddin is the member of Center of Excellence for Engineering and Management of Civil Infrastructures, Iranian Concrete Institute (ICI), American Concrete Institute, and Semnan Construction Engineering Construction.

Hosein Naderpour lives in Iran and born in 1981. He holds a Ph.D. degree in structural engineering which was graduated from the Semnan University in 2011.

He is an associate professor in the Semnan University. His research interests are soft computation, retrofitting concrete structures, serviceability of structures, earthquake engineering, damage indices, and health monitoring.

Dr. Naderpour is the member of Iranian Concrete Institute (ICI), American Concrete Institute, and Tehran Construction Engineering Construction.

Mahdi Kioumarsi lives in Norway and born in 1982. He did his Ph.D. in structural engineering at Norwegian University of Science and Technology (NTNU) in Trondheim, Norway in 2015. His PhD topic was mainly developed independently concerning the topic of simulation of deteriorated concrete structures.

He is an associate professor at the Department of Civil Engineering and Energy Technology, Oslo Metropolitan University (OsloMet), Oslo, Norway. He has more than eight years' experience with research on deteriorated concrete structures, fiber-reinforced concrete, FE simulation, and computational algorithms and has published in leading international conferences and journals.

Dr. Kioumarsi was awarded a grant by OsloMet to develop numerical and experimental methodology on assessing bond-slip behavior of RC concrete in close collaboration with Niccolò Cusano Universities in Rome. Dr. Kioumarsi has been granted an individual fellowship at Research Talent Development Program by OsloMet for the period 2020-2021. During this one-year program. He is currently the principal participant and work package leader of the H2020-funded project HYPERION; a collaboration between OsloMet and 16 European partners.