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Influence of Gusset Plate Stiffeners on the Seismic Performance of Concentrically Braced Frame

B. Mohebi, N. Asadi, F. Kazemi

***Abstract*—**Inelastic deformation of the brace in Special Concentrically Braced Frame (SCBF) creates inelastic damages on gusset plate connections such as buckling at edges. In this study, to improve the seismic performance of SCBFs connections, an analytical study was undertaken. Using edge's stiffeners is one of the main solutions of this study to improve the gusset plate connections' behavior. For this purpose, in order to examine edge's stiffeners effect on gusset plate connections, two groups of modeling with and without considering edge's stiffener and different types of braces were modeled using ABAQUS software. The results show that considering the edge's stiffener reduces the equivalent plastic strain values at a connection region of gusset plate with beam and column, which can improve the seismic performance of gusset plate. Furthermore, considering the edge's stiffeners significantly decreases the strain concentration at regions where gusset plates have been connected to beam and column. Moreover, considering $2t_{pl}$ distance causes reduction in the plastic strain.

***Keywords*—**Special concentrically braced frame, gusset plate, edge's stiffener, seismic performance.

I. Introduction

EXACT study on connection performance in a SCBF is important because gusset plate connections are subjected to forces from frame action and by deforming the braced frame, the connection will be deformed and lead to damage in connections. Therefore, in the design and implementation of gusset plate connections, the effect of such frame action, in addition of the brace axial load, should be considered. It is conventional that the steel bracing members are considered as a dissipative element and should be designed to yield before connections failure. Therefore, the gusset plate connections must be designed to have a greater resistance than the bracing members. Based on recent studies, most of the destructions in the SCBFs have been reported due to poor connection performance. For secure and economical design, it is essential to have a correct understanding of connections behavior and suitable awareness of energy dissipation members [1]. Gusset plates, which have a different seismic performance, play an essential role in the SCBFs with converting and transferring the lateral load of ground motion records from brace to beam and column. Existence of variable boundary conditions such as different failure modes and various connections to beam and column causes to create a complex behavior in the gusset plates. Recently, in order to examine of gusset plate behavior, numerous numerical and experimental studies have been performed. The most important experimental studies were done by Whitmore [2]. Most of the studies have been referred to Whitmore's experiments, and his results have been used as initial assumptions. The results of his study showed that the maximum tensile and compressive stress with good accuracy and a close approximation were concentrated at the end of the effective zone, considering that the force in diagonal members is uniformly distributed. The earliest cyclic tests were performed by Astaneh-Asl et al. [3]. These tests consist of 17 bracing members having gusset plate that were subjected to cyclic loading. The results showed that the cyclic behavior of gusset plate in SCBFs was strongly depended on the direction of bracing member's buckling. When the gusset plate had an out-of-plane buckling, and the plastic hinge was formed, in order to the assurance of free rotation, it was necessary that the linked member (continues bracing member in gusset plate) terminated at least $2t_{pl}$ distance away from the end of gusset plate, where t_{pl} is the thickness of gusset plate. Nast et al. [4] performed some numerical and experimental studies on the edge's stiffeners effect on gusset plates and also interaction of bracing members under cyclic loading. The results indicated that the edge's stiffener did not have a considerable effect on buckling stress of gusset plates, but it helped to the stability of gusset plates in the post-buckling zone. Moreover, using edge's stiffener did not have an effect on tensile stress. The tested stiffeners increased energy dissipation by a set of gusset plates and bracing member, but they had a little effect on tensile cyclic. Yoo et al. [5] studied the improving of seismic behavior of gusset plate connections. In this research, 13 models with different $2t_{pl}$ distances were investigated. Also, in order to verify the experimental work, Yoo et al. [6] used a finite element model in ANSYS software based on the prepared experimental one. They considered the non-elastic performance of structural elements, measuring softness of frame and also the concentration of equivalent plastic strain, which have a rupture or break potential of the weld. Nascimbene et al. [7] investigated gusset plate connections with HSS brace section subjected to quasi-static cyclic loading based. The main purpose of their study was a comparison of different $2t_{pl}$ distance. In their research, a numerical interval for the concentration of equivalent plastic strain in the central point of brace and intersection between gusset plate with beam and column was mentioned. A comprehensive study on the behavior of gusset plate-T0-CCFT connections with different configurations was done by Hassan et al. [8]. The results

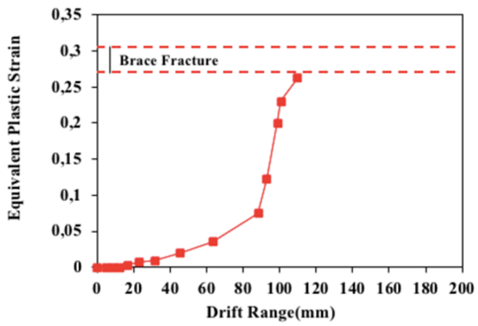
B. Mohebi is with the Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran (phone: +982833901118, PO Box 34149-16818, e-mail: mohebi@eng.ikiu.ac.ir).
N. Asadi is with the Department of Civil Engineering, Islamic Azad University, Qazvin branch, Iran (e-mail: n.asadi@qiau.ac.ir).
F. Kazemi is with the Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran (e-mail: farzin.kazemi@edu.ikiu.ac.ir).

clearly showed that the local buckling the gusset plates were found to be a dominant failure mode for connections, where the gusset plates are directly welded to the steel tube. Ryan et al. [9] used an integrated experimental and numerical approach to investigate the performance of SCBFs subjected to the seismic action of varying intensity. The results showed that model performance was sensitive to the initial camber applied to the brace members. Consequently, the recommended modelling techniques can be employed to achieve optimum performance in future modelling.

The purpose of this study is to evaluate edge's stiffener effects on the gusset plate behavior. It should be noted that satisfactory performance under out-of-plane buckling of single gusset plate can be ensured by allowing the gusset plate to develop restraint-free plastic rotations. In this research to evaluate edge's stiffeners influence on the seismic performance of gusset plate, the gusset plates used in SCBFs includes with and without edge's stiffener. According to results, $2t_{pl}$ distance is recommended to be equal to two times of the plate thickness and the $2t_{pl}$ distance should be considered the minimum offset distance. Numerical results indicate that considering edge's stiffeners has a significant effect on gusset plates performance compared to neglecting them, and considering $2t_{pl}$ distance leads to acceptable results for gusset plates with and without stiffeners.

II. Description and Validation of Analytical Models

In this study, to validate models with finite element software, results obtained on inelastic performance and equivalent plastic strain as a function of drift range were compared with those of an experimental performed by Yoo et al. [6]. In order to compare results of modeling, Fig. 1 presents results of equivalent plastic strain at the middle of a brace from the numerical model which was compared with those from the experimental simulated frame. Furthermore, the equivalent plastic strain as a function of drift range at the intersection of gusset plate with beam and column obtained from the numerical modeling and experimental case has been presented in Fig. 2 and Fig. 3. It can be seen that the values of the equivalent plastic strain curve from the numerical and the experimental model have a good agreement, which proves the accuracy of the finite element model used.



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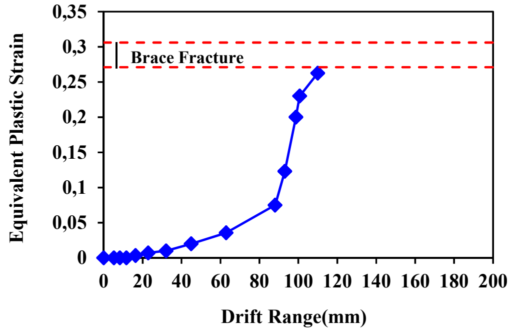

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Fig. 1 Equivalent plastic strain as a function of drift range at the middle of brace, (a) experimental model [6], and (b) finite element model

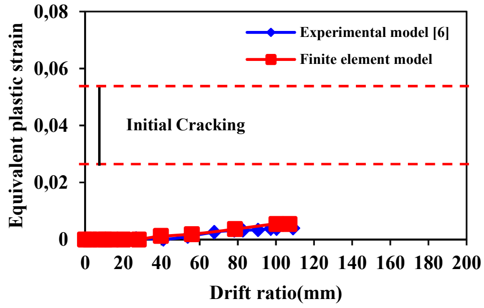


Fig. 2 Equivalent plastic strain as a function of drift range at the intersection of gusset plate and beam, (a) experimental model [6], and (b) finite element model

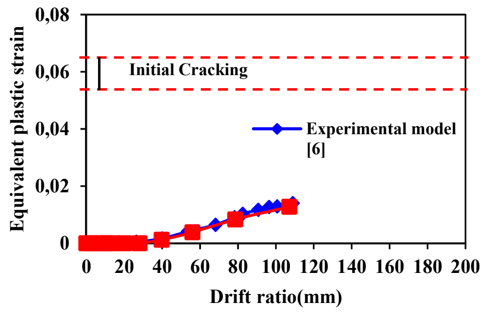


Fig. 3 Equivalent plastic strain as a function of drift range at the intersection of gusset plate and column, (a) experimental model [6], and (b) finite element model

In this study, six models included a brace (2UNP), two beams (typically W16x45 sections) at above and below the brace, two columns (W12x72) and gusset plate connections at each end of the brace were modeled to complete the single bay frame modeling using ABAQUS software [10], which is shown in Fig. 4. The centerline measurements of the models were 3.67 m by 3.67 m (12 ft by 12 ft). Models have been divided into two groups including with and without stiffener.

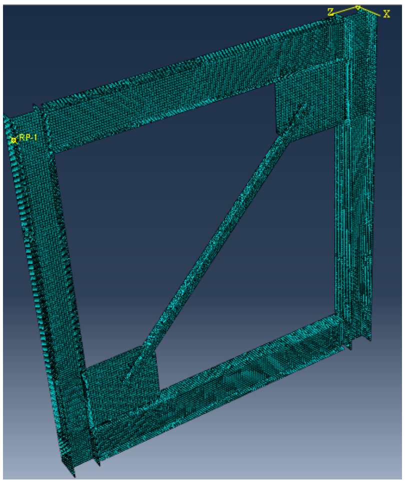


Fig. 4 Finite element model

In all sampled models, a type of material properties named as ST37 steel was used in the analyses (Table I). It can be noted that the plastic behavior in the web was neglected. The geometrical characteristics of the gusset plates with and without edge's stiffener for different brace sections are presented in Table II. For brace sections, double channels as 180, 200 and 220 were used. The stiffeners were designed according to Iranian Steel Design [11]. Also, the incremental loading pattern that used for simulation is based on Lehman et al. [12], where it starts from 5 mm and continues up to 110 mm by 80 stages.

TABLE I
MATERIAL PROPERTIES OF ST37 STEEL

Modulus of elasticity E (kg/cm^2)	Yield stress (kg/cm^2)	Ultimate stress (kg/cm^2)
2×10^6	2400	3700

TABLE II
CHARACTERISTIC OF THE GUSSET PLATE DIMENSIONS WITH AND WITHOUT EDGE'S STIFFENER FOR DIFFERENT BRACE SECTIONS

brace section	gusset plate dimension with edge's stiffener					
	a	b	c	t	L*	S*
2UNP 180	26	11.8	150	300	500	500
2UNP 200	30	15	150	300	500	500
2UNP 220	31	10	150	400	600	600

brace section	gusset plate dimension without edge's stiffener			
	a	b	c	t
2UNP 180	26	400	620	641
2UNP 200	30	500	720	740
2UNP 220	31	650	830	860

*L and S are the width and weld size of the gusset plate connection, and units are the same as mm.

In the models with edge's stiffener gusset plate, the distance from the free line of bending axis is equal to $2t_{pl}$. To investigate connections behavior in braced frames and considering the interception points of beam and column to gusset plate, the frame behavior should not cause the brace buckling and gusset plate distortion.

III. RESULTS AND DISCUSSION

This section compares the results of gusset plates considering different conditions of edge's stiffener. Therefore, three channel sections according to Table II were modeled. The displacement-load curves and equivalent plastic strain as a function of drift range have been presented, which are considered in central point of brace and intersection points of gusset plate with and without edge's stiffener. A region for starting of the crack in the central point of brace and intersection points of gusset plate has been determined based on Nascimbene et al. [7]. Moreover, performance levels including IO and CP (IO: Immediately Occupancy, CP: Collapse prevention), corresponding to drifts 0.5% and 2%, and a region for starting of the crack were considered according to ASCE/SEI 41-13 [13]. The displacement-load curves for the model with 2UNP 180 brace section, with and without edge's stiffener are shown in Fig. 5. With comparing Figs. 5 (a) and (b), it is obvious that two models closely approximated all aspects. Therefore, considering edge's stiffener did not significantly influence the displacement-load curves.

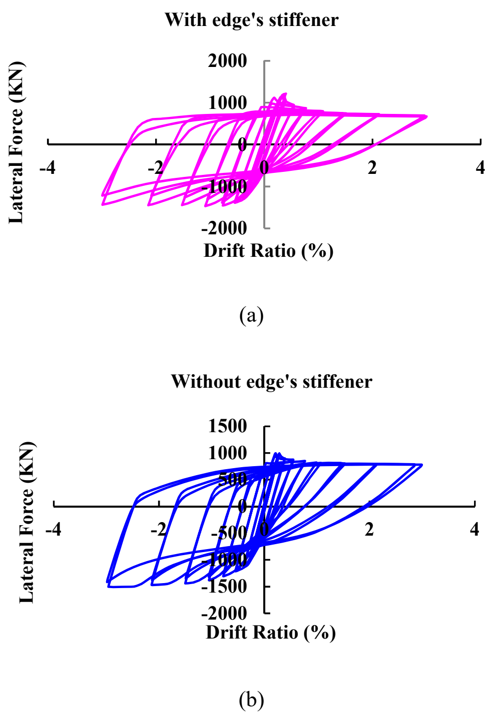
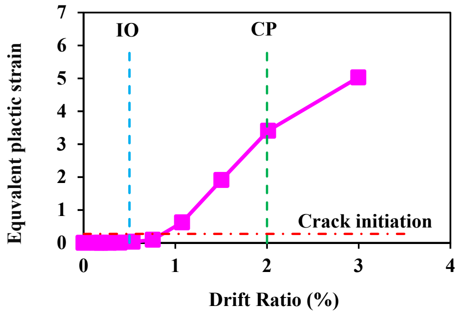


Fig. 5 Displacement-load curve for the model with 2UNP 180 (a) with edge's stiffener (b) without edge's stiffener

To evaluate the potential for the equivalent plastic strain to predict failure modes, the equivalent plastic strains as a function of the drift range for the model with 2UNP 180 at the central point of the brace are illustrated in Fig. 6. With comparing two curves, it is clear that two models, with and without edge's stiffener, have not a substantial difference.



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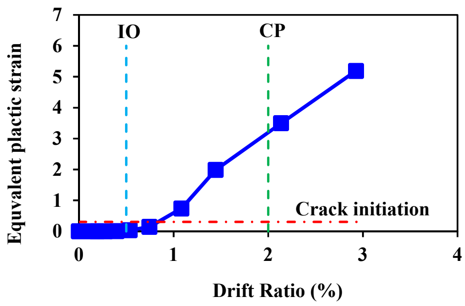
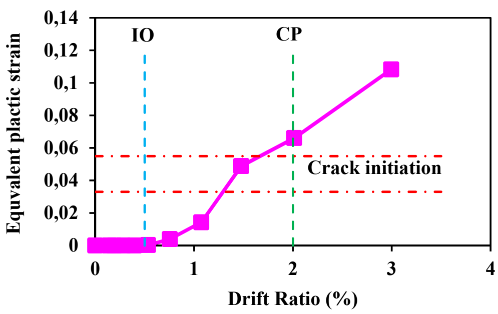


(b)

Fig. 6 Equivalent plastic strain as a function of the drift ratio for the model with 2UNP 180 at the central point of brace (a) with edge's stiffener (b) without edge's stiffener- (IO: Immediately Occupancy, CP: Collapse prevention)

Figs. 7 and 8 illustrate the equivalent plastic strain as a function of the drift range for the model with 2UNP 180 at the intersection point of gusset plate with beam and column, respectively. The results show that, with considering edge's stiffener, the equivalent plastic strain decreased 70% and 61.5% at the intersection point of gusset plate with beam and column, respectively. Therefore, the results indicate that considering edge's stiffener significantly influences the equivalent plastic strain value at the intersection point of gusset plate with members. It is worth mentioning that this reduction led to improving the seismic performance of the gusset plate connections.



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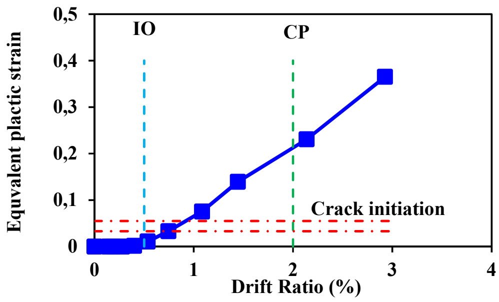

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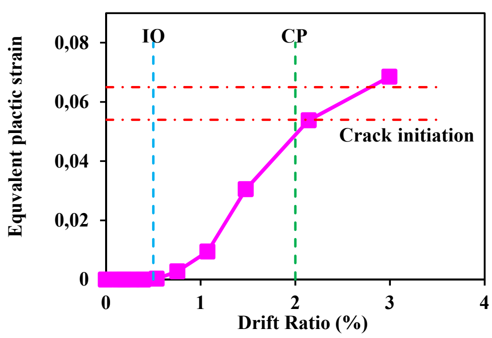
Fig. 7 Equivalent plastic strain as a function of the drift range for the model with 2UNP 180 at the intersection point of gusset plate with beam (a) with edge's stiffener (b) without edge's stiffener- (IO: Immediately Occupancy, CP: Collapse prevention)



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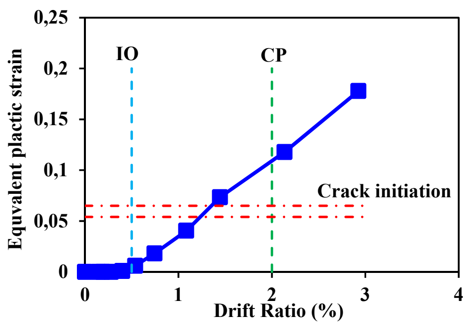
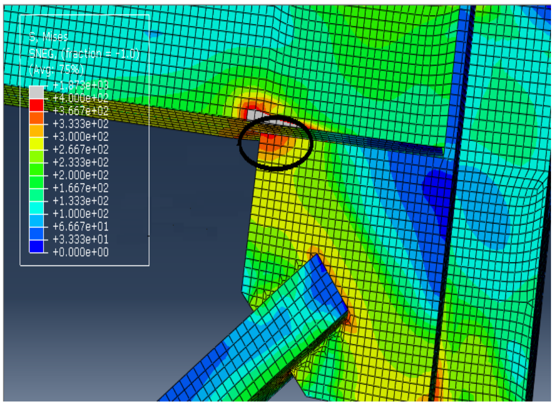


(b)

Fig. 8 Equivalent plastic strain as a function of the drift range for the model with 2UNP 180 at the intersection point of gusset plate with column (a) with edge's stiffener (b) without edge's stiffener- (IO: Immediately Occupancy, CP: Collapse prevention)

Figs. 9 and 10 present strain contour for the model with 2UNP 180 at the intersection point of gusset plate corresponding to beam and column, respectively. According to Figs. 9 and 10, it is concluded that considering the $2t_{pl}$ distance from the free line of bending axis, can cause to a significant reduction in the rate of stress at the critical point. Moreover, the stress contours show that considering the edge's stiffeners causes to create a large stress in the beam and column rather than neglecting them.



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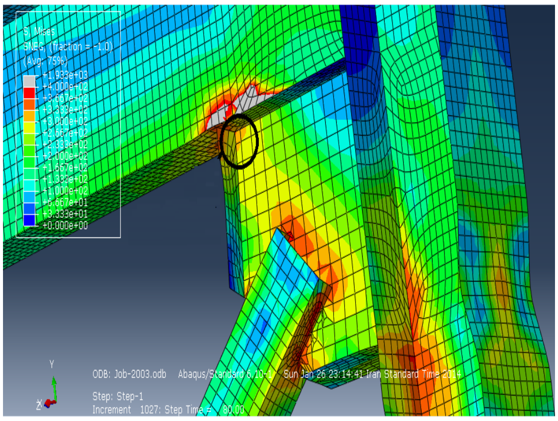
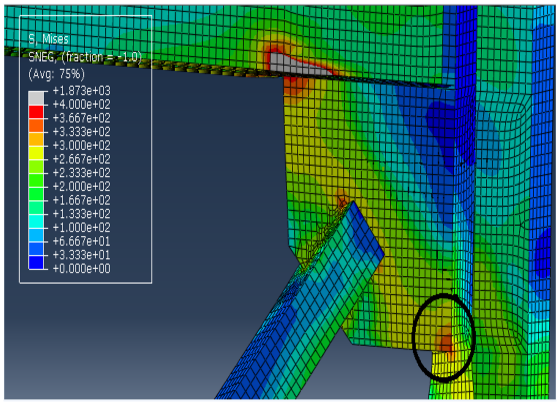


(b)

Fig. 9 Comparison of strain contour for the model with 2UNP 180 at the intersection point of gusset plate with beam (a) without edge's stiffener (b) with edge's stiffener

IV. Conclusion

In this study, in order to evaluation of gusset plate behavior with and without edge's stiffeners, six finite element models were modeled using ABAQUS software subjected to static and cyclic analysis, while a $2t_{pl}$ distance has been considered from the free line of bending axis of gusset plates. It is noted that lateral force in gusset plate can be divided into two parts and frame action can be neglected during brace buckling. Considering the edge's stiffener can improve the seismic performance of gusset plate using reduction of the equivalent plastic strain values at the connection region of gusset plate with beams and columns. The equivalent plastic strain values in models with considering edge's stiffeners for brace sections of 2UNP 180, 2UNP 200, 2UNP 220 at the connection region of gusset plate to beams decreased 70%, 72%, and 74.4%, and at the connection region of gusset plate to columns decreased 61.5%, 82%, and 75.65%, respectively. It should be noted that considering $2t_{pl}$ distance causes to reduce the plastic strains. Furthermore, considering the edge's stiffeners have an important role in decreasing of strain concentration at locations where gusset plates have been connected to beams and columns.



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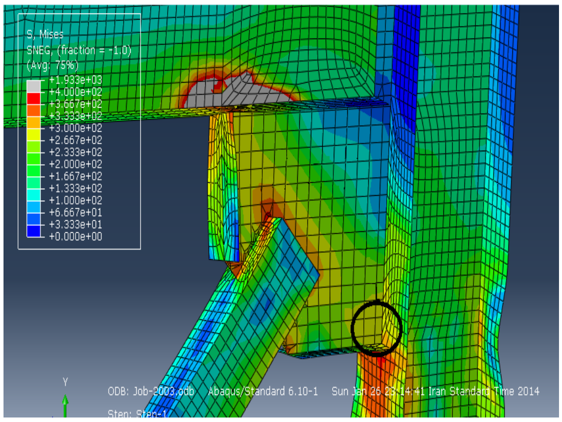

(b)

Fig. 10 Comparison of strain contour for the model with 2UNP 180 at the intersection point of gusset plate with column (a) without edge's stiffener (b) with edge's stiffener

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Benyamin Mohebi received Ph.D. degree in Earthquake Engineering from Iran University of Science and Technology, Tehran, Iran, in 2011. Now, he works as an Assistant Professor at Faculty of Engineering and Technology, Imam Khomeini International University (IKIU), Qazvin, Iran. His research interests include nonlinear analysis of structures, seismic hazard analysis, seismic retrofitting of structures, and optimization in structural engineering.

Nasim Asadi received her M.Sc. in Structural Engineering from Qazvin Islamic Azad University (QIAU), Qazvin, Iran. Her main research areas are structural modelling issues in seismic performance assessment of steel structures.

Farzin Kazemi received his M.Sc. in Earthquake Engineering from Imam Khomeini International University (IKIU), Qazvin, Iran. His main research areas are seismic performance assessment of structures and seismic hazard analysis in earthquake engineering.