Structural Engineering and Mechanics, *Vol. 70, No. 6 (2019) 781-791*
DOI: https://doi.org/10.12989/sem.2019.70.6.781

Analysis on damage of RC frames retrofitted with buckling-restrained braces based on estimation of damage index

Ruyue Liu*[1,3] and Yong Yang[2a]

[1]*School of Civil Engineering, Fujian University of Technology, Fujian, China, 350118*
[2]*Department of Civil Engineering, Xi'an University of Architecture and Technology, Shaanxi, China, 710055*
[3]*Fujian Provincial Key Laboratory of Advanced Technology and Informatization in Civil Engineering, Fuzhou, China*

(Received January 5, 2019, Revised March 20, 2019, Accepted March 21, 2019)

Abstract. Earthquakes most often induce damage to structures, resulting in the degradation or deterioration of integrity. In this paper, based on the experimental study on 5 RC frames with different span length and different layout of buckling-restrained braces, the seismic damage evaluation law of RC frame with buckling-restrained braces was analyzed, and then the seismic damage for different specimens was calculated using different damage models to study the damage evolution. By analyzing and comparing the observation in test and the calculated results, it could be found that, damage evolution models including Gosain model, Hwang model as well as Ou model could better simulate the development of damage during cyclic loading. Therefore, these 3 models were utilized to analyze the development of damage to better demonstrate the evolution law for structures with different layout of braces and under different axial compression ratios. The results showed that from all layouts of braces studied, the eccentrically braced frame behaved better under larger deformation with the damage growing slowly. It could be deduced that the link beam benefited the seismic performance of structure and alleviated the damage by absorbing high values of energy.

Keywords: buckling-restrained braces; RC frame; damage analysis; damage index; cyclic loading

1. Introduction

Earthquakes typically cause damage on structures, and it is difficult to quantitatively describe the structural damage due to the uncertainty of earthquake action and effects on structures in the seismic analysis and seismic design. However, the prediction of damage during earthquake is important for the structural seismic design and analysis of new-built and existed buildings since that damage is the reflection of deterioration of seismic behavior. Damage changes during the earthquake, therefore, using damage evolution model could help us quantitate the damage of structure and make it clear to determine how damaged the structure was at different critical levels. Therefore, it attracts worldwide attention from researchers on how to calculate the damage of structure, how to set up a reasonable damage model and how to evaluate the seismic performance based on structural damage states.

Seismic damage index is a dimensionless index used to evaluate the damage of a structure or component under earthquake. So far, damage indices are universally classified as either non-cumulative or cumulative (Cao *et al*. 2014). A non-cumulative index indicates the first-time exceedance of maximum response of structure to its ultimate limit, resulting in the failure of structure such as failure in strength, deformation, energy or fatigue failure. Ductility is the most common parameter used in non-cumulative indices, but it only relates to the maximum deformation. However, the degradation or deterioration in stiffness or strength is usually observed and the damage accumulates during earthquake. Therefore, the cumulative indices could more accurately demonstrate the damage development of structure subjected to an earthquake (Rodriguez and Padilla 2009, Kang and Lee 2016), since that it takes the maximum seismic response and effect of cumulative damage into consideration.

Many researchers have conducted a series of studies on structural damage and the description of damage, and proposed different damage index to quantify both local and global damage when subjected to earthquake excitation (Kang and Lee 2016, Massumi and Moshtagh 2013, Gosh *et al*. 2011, Sinha and Shiradhonkar 2012, Andre *et al*. 2015). The damage index was typically normalized within range varying from zero to unity, where zero represents undamaged condition and unity represent collapse state of structures. Several damage models of RC members are widely used, such as Park-Ang model(1985), Banon model(1981), Hwang model(1984), Ou model(1999), and Kratzig model(1989). The Park-Ang model was universally accepted and it was modified by many researchers to obtain more accurate descriptions and evaluation of damage evolution. For example, in order to overcome some shortcomings in Park-Ang model, Wang (2005) introduced the energy-weighted coefficient related with loading path to better understand the effect caused by loading path. Borg (2010) found that the energy and deformation combined

*Corresponding author, Ph.D., Lecturer
E-mail: lry18pig@163.com
[a] Professor

ISSN: 1225-4568 (Print), 1598-6217 (Online)

damage indices scored high ability to quantify damage and could be used to identify the critical damage location.

It is required that the structure should not collapse during earthquake for the safety of life, but repairable damage of members is generally accepted in seismic design. For example, it is required that the design of structure in China should meet the requirement in present seismic design code (GB 50010-2010) where different performance objectives are specified corresponding to no damage, repairable damage state and no collapse of structure. These are associated with frequent, design and rare earthquake action representations. However, the design methods may not comprehensively reflect the damage accumulation during earthquake. Under strong ground motion, although the development of concrete cracking could absorb high values of energy, it also led to serious plastic deformation and degradation of resistance capacity (Yu *et al*. 2011, Fu *et al*. 2013, Liu *et al*. 2008, Wang 2010). Seismic behavior deteriorated with accumulated damage and structures might fail in the end due to excessive deformation or hysteresis energy. As a result, it is considered that deformation and energy-dissipation could better evaluate the damage development of structure under earthquake.

Buckling-restrained braced frame has been gradually applied in practical engineering, whatever in newly constructed buildings or in retrofitting of existing buildings. Compared with other retrofit technologies (Zhang *et al*. 2015, Duran *et al*. 2018, Akbar *et al*. 2018), it has higher lateral stiffness, excellent energy-dissipation capacity and good ductility, and the buckling-restrained braces could improve the seismic performance of structures. But there are still some problems with buckling-restrained braced frame, for example, the segment where the brace connected with beam or column is in complex stress condition and might develop unfavorable failure modes. Besides, the application of buckling-restrained braces changes the stress mechanism of original structure, and it might lead to more damage on main structure if without appropriate design.

So far, the researches on buckling-restrained braced frame mostly focus on the steel frame for the easy connection and the good cooperation between brace and steel frame. However, the reinforced concrete frame (RC frame) accounts for large proportion of buildings in China, and the buckling-restrained braces has been accepted as an effective method in retrofitting RC frame. Rare studies were conducted on RC frame with buckling-restrained brace, leading to the lack of understanding on the seismic performance and how the damage developed under dynamic or repeated load. Therefore, it is of great significance to study the damage evolution of RC frame with buckling-restrained braces, and to set up damage model to evaluate the damage development and deepen the understanding of nonlinear behavior during earthquake.

Consequently, in order to better understand the seismic performance and damage development of RC frame with buckling-restrained braces, experimental study on RC frame with different layout of buckling-restrained braces was performed, aiming to investigate the influence of the brace on the damage. Furthermore, it is expected that the study could provide basis for the safety assessment and reliability analysis of structure with buckling-restrained braces.

Symbols and definitions

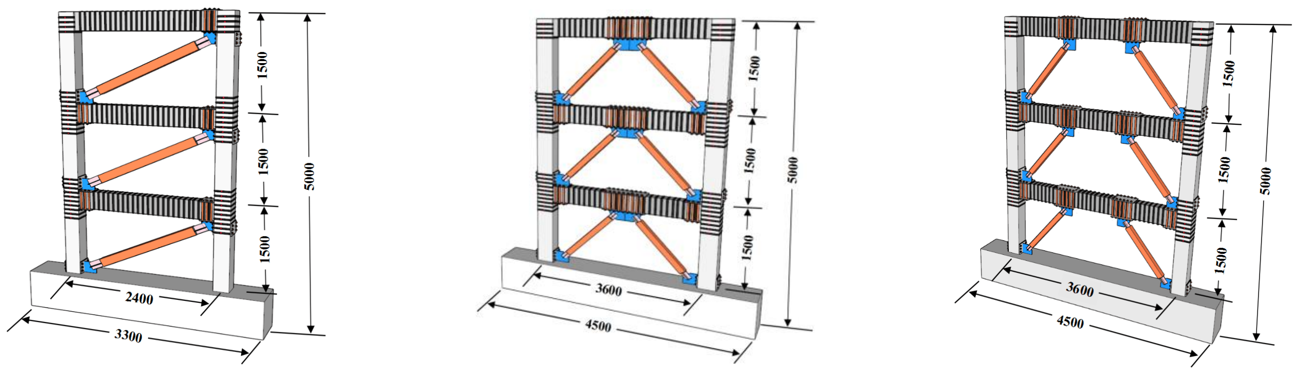
δ_i	maximum displacement at i^{th} half loading cycle	P_i	the strength corresponding to δ_i
δ_{yi}	yielding displacement at i^{th} half loading cycle	P_{yi}	the strength corresponding to δ_y
λ_{ij}	strength degradation coefficient responding to the jth loading cycle at i^{th} loading level	λ_i	capacity degradation coefficient at ith loading level
μ_{si}	static ductility ratio at i^{th} loading level	P_{ji}	the load responding to the i^{th} loading cycle at j^{th} loading level
δ_y	yielding displacement	P_{j1}	the load responding to the 1st loading cycle at j^{th} load level
δ_u	ultimate displacement	P_y	yielding strength corresponding to δ_y
δ_m	maximum displacement	E_i	dissipated energy for i^{th} half loading cycle
δ_{res}	residual deformation	E_u	ultimate dissipated energy under monotonic loading
δ_{rec}	recoverable deformation	E_h	total dissipated energy under cyclic loading

2. Experiment of buckling-restrained braced frame

2.1 Design summary

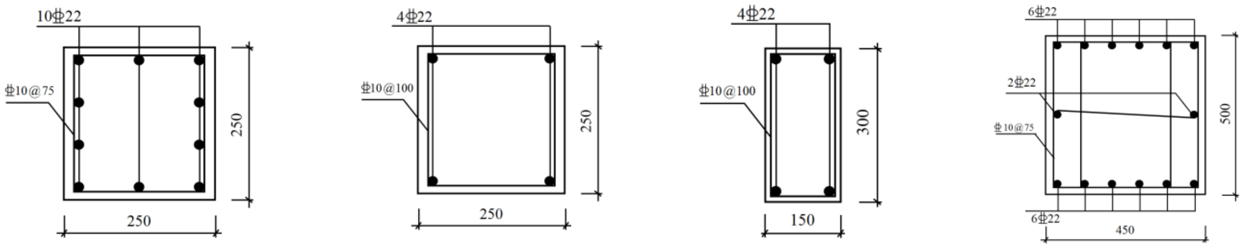
According to present seismic design code (GB 50010-2010), several buckling-restrained braced frames in the region of 8 fortification intensity were designed for the tests, including diagonally braced frame(abbreviated as DBRBF), chevron braced frame(abbreviated as CBRBF) and eccentrically-braced frame(abbreviated as EBRBF). The half-scaled specimens were subjected to pseudo-static test to study the influence of buckling-restrained braces on seismic performance. Besides, two bare RC frames were also tested as comparison. Fig.1demonstrated the design details of the tested specimens and the geometric configurations of braced frame, respectively. For RC-1 and DBRBF, the span was 2.4m while for RC-2, CBRBF and EBRBF, the span was 3.6m. Fig. 2 showed the reinforcing configuration of the main RC frame.

In term of the connection between the buckling-restrained braces and RC frame, the bolted connection, welded connection and pin-joints connection are usually applied. In the test, in order to reduce the effect on bending moment of the brace behavior as much as possible, the connection of bolted connection and welded connection was adopted to connect the brace to the beams and columns (Fig. 3). The design of bolt and weld should meet the requirement of present code(GB 50010-2010) and to ensure the safety and normal working condition of connections, the force acting on the weld and bolt which transferred from braces would be amplified for 2 times when design the connection. Besides, brace and the framing members should intersect at one point to avoid the additional moment on structural members.



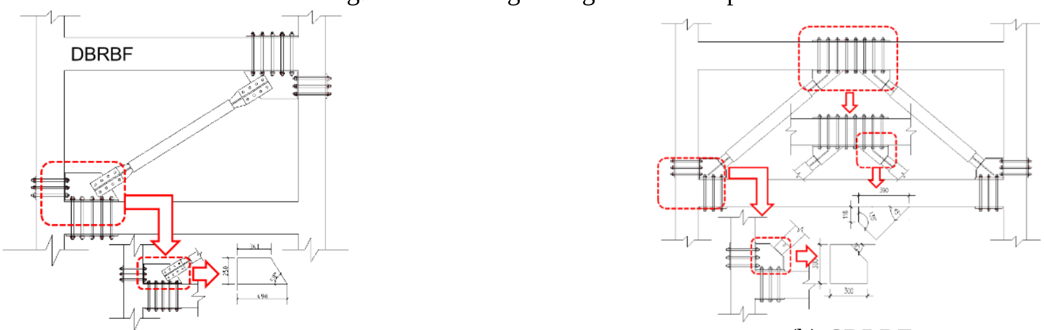
(a) DBRBF (b) CBRBF (c) EBRBF

Fig. 1 Geometric configurations of specimens

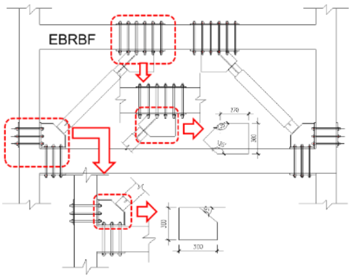


(a) 1st column (b) 2nd and 3rd column (c) beam (d) ground beam

Fig. 2 Reinforcing configurations of specimens



(a) DBRBF (b) CBRBF



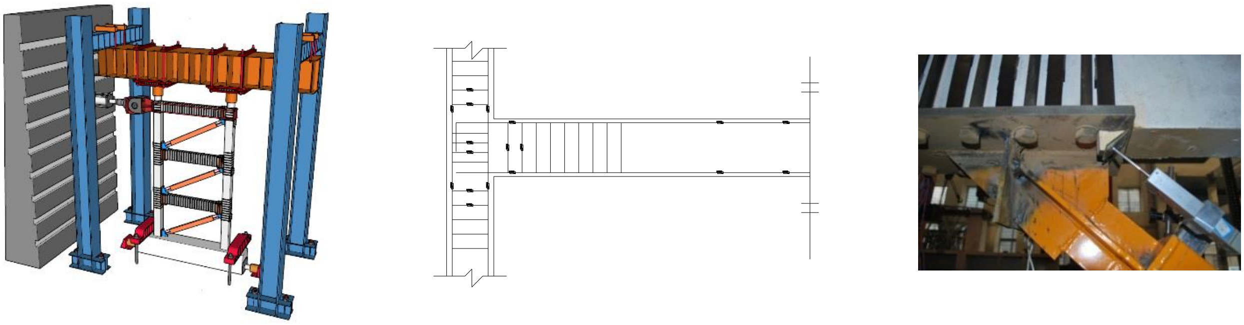
(c) EBRBF

Fig. 3 Connection details for braced frame

2.2 Experiment procedure

The experiments were carried out in *Structural Engineering Key Laboratory at Xi'an University of Architecture and Technology*. All the specimens were tested under cyclic load by MTS electro-hydraulic servo actuators, and during tests, the specimens remained fixed at bottom. The loading protocol was based on the Specification for seismic test of building (JGJ 101-2015), and loading scheme was controlled by force before yielding and displacement after yielding. In order to better capture the seismic performance, smaller displacement increment of 5mm was used and every loading level was repeated three times. The experiments terminate when the load dropped down to 85% of peak load.

During the test, the strains of different elements such as concrete, reinforcement bars and braces, the displacement or drift of every story and the axial deformation of braces were recorded. As shown in Fig.4(c), displacement transducers were fixed on both ends of braces to obtain the



(a) schematic diagram (b) layout of stain gauge (c) measurement of brace

Fig. 4 Test set-up

(a)cracking at beam end (b) cracking at column (c) cracking at joint core (c) concrete collapse

Fig. 5 Failure mode of RC frames

axial deformation. The strains of the core steel of brace (located both at quarter point and the midpoint) were also measured as well. The strain gages were located in the bars of expected plastic hinge zones, such as the beam-ends, column-ends, and the joint core areas (Fig.4b).

2.3 Experimental phenomenon

(a) Failure mode of specimen RC-1and RC-2

For bare reinforced concrete frame, during the experiment, it was found that serious cracking and damage occurred at beam on second story and the bottom of column on top story. The yield mechanism of RC satisfied the beam yield mechanism. Fig.5 demonstrated partial damage modes of the specimens and some conclusions could be summarized as followings:

(1) Flexural cracking at beam end of second story was found at 30kN, and then the cracking propagated and extended to the mid-span of beam. The roof drift was 1/288 in positive direction and 1/236 in negative direction when specimen yielded for RC-1, while 1/303 and 1/237 for RC-2. But the maximum inter-story drift was equally up to 1/202 for both rare RC frames.

(2) With load increase, cracking emerged in other stories and previous cracking gradually developed with damage accumulation. In the order of 1/90 of top drift, some vertical cracking ran through beam depth at ends and almost no new cracking occurred anymore, indicating the complete evolution of beam yield mechanism. Besides, visible shear cracking occurred at the joint core.

(3) At peak load, concrete crushed a bit at top story and all beam developed yield mechanism. Previous cracking developed completely and did not widen anymore. With load increasing, damage accumulated and the joint was damaged seriously; load began to decrease with concrete on column top collapsing.

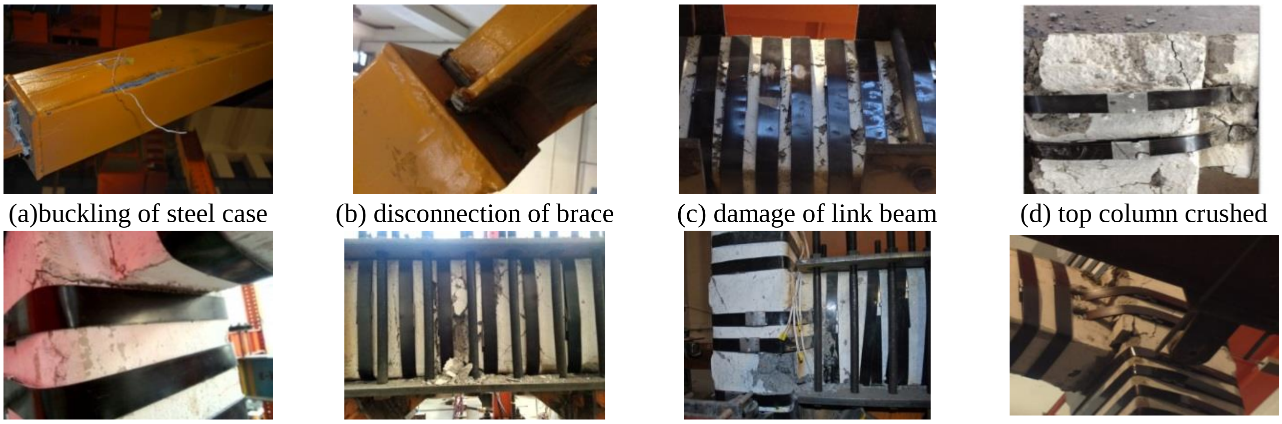
(b) Failure mode of specimen RC frame with buckling-restrained braces

For the other 3 buckling-restrained braced frames, the deformation and damage development were similar. Before brace yielded, the deformation was minor and all framing components were in good condition. The buckling-restrained braces began to dissipate energy after yielding in core and the with deformation increasing, concrete cracked and reinforcing bar yielded. Cracking and deformation development could be described as following:

(1) For DBRBF, the roof drift was less than 1/643 before load increased to 120kN, but obvious cracking at beam end was found when load was 240kN, besides, brace developed yield strain. Then the cracking extended and widened as test went on, the strain at brace core grew quickly and the initiation of disconnection of the brace core from outer constraint segment occurred. When top displacement increased to 77mm (about 1/58.5), the inter-story drift achieved 1/55 and beam cracked seriously. In the order of 91mm, the deformation of brace was about 40mm, and the concrete started to collapse locally. The maximum capacity was 464kN at 124mm and the inter-story drift at peak was 1/25.

(2) For CBRBF, brace deformed slightly before 200kN and the visible cracking at beam end was found at 240kN when brace yielded. In the order of 60mm, the location where the brace connected with beam was observed with obvious shear cracking and it developed quickly. At 90mm, the inter-story drift of second story was about 1/50 and the beam was damaged seriously at mid-span, large amount of concrete crushed and bending deformation was observed in gusset plates. The peak load achieved 500kN and the maximum inter-story drift was about 1/35.

(3) For EBRBF, the damage development was similar with CBRBF. However, with link beam, the force mechanism was improved. After brace yielded, deformation grew greatly, and the link beam yielded prior to ordinary framing elements. At 44mm, the cracking at link beam was significant, and the concrete crushed with inner



(a)buckling of steel case (b) disconnection of brace (c) damage of link beam (d) top column crushed

(e) cracking at joint core of CBRBF (f) beam failure of CBRBF (g) joint failure of CBRBF (h) concrete collasped at joint of EBRBF

Fig. 6 Failure modes of braced frame

reinforcement exposure when roof drift increased up to 1/61 and the maximum inter-story drift was 1/48. Axial deformation of brace was significant with disconnection between brace core and outer segment. The peak load was 603kN corresponding with roof drift of 1/46 and then load decreased with concrete collapsing seriously, but the inter-story deformation capacity could approach to 1/33 finally. More details of the seismic behavior of EBRBF could be obtain in Yang *et al*. (2017).

The major failure modes could be seen from Fig. 6.

3. Research review of damage model

Many different parameters which could reflect the resistance, deformation and energy-dissipation are used as damage index to describe the damage of structure, such as ductility ratio μ_{si}, strength degradation coefficient λ_{ij}, capacity degradation λ_i and hysteresis energy-dissipation factor α_i. These damage parameters could be calculated by:

$$\mu_{si}=\left|\frac{\delta_i}{\delta_y}\right|,\quad \lambda_{ij}=P_{ji}/P_{j1},$$

$$\lambda_i=P_i/P_y,\quad \alpha_i=\frac{E_i}{P_y\delta_y}$$

Current available damage models generally use one or more damage indices mentioned above to describe the evolution of structural damage and evaluate the structural seismic performance. In the followings, some commonly used damage models are summarized, and it should be noted that the denominator D_0 in formula for different damage model means the maximum value of numerator when the structure or member totally failed. In addition, some modified damage models are given.

(1) Newmark Model

Previously, the damage model was based on the evaluation of deformation, and the ductility ratio at maximum deformation is most often used as the deformation-based index. In order to take the effect of cyclic load into consideration, a new damage index (Newmark *et al*. 1971) was proposed to overcome the shortcoming of ductility ratio in describing structural damage.

$$D=\frac{\dfrac{|\delta_i-\delta_y|}{\delta_y}}{D_0}=\frac{|\mu_i-1|}{D_0} \tag{1}$$

Where, D_0 equals to the maximum of $|\mu_i-1|$ at failure.

(2) Krawinkler Model

To better explain the accumulation effect of plastic deformation under cyclic load, the damage model was proposed based on the accumulation plastic deformation (Krawinkler and Zohrei 1983), that is:

$$D=\frac{\sum_{i=1}^{N}(\mu_{si}-1)^b}{D_0} \tag{2}$$

In the formula, D_0 means the maximum of $\sum_{i=1}^{N}(\mu_{si}-1)^b$ at the failure of the structure or members; the range for b is [1.6,1.8] and it was considered as 1.7 in most cases; N means the half loading cycles numbers; μ_{si} is the ductility at each loading level.

(3) Darwin Model

From the prospective of energy, Darwin and Nmai(1986) proposed "Darwin model" based on energy-dissipation (Darwin and Nmai 1986), that is:

$$D=\frac{\sum_{i=1}^{N}\dfrac{P_i\delta_i}{P_y\delta_y}}{D_0} \tag{3}$$

Where, D_0 equals to the maximum of $\sum_{i=1}^{N}(\mu_{si}-1)\,\lambda_i$ at failure.

(4) Gosain Model

It was considered that the damage not only increased the deformation of structure but also resulted in strength degradation, then the damage model taking static ductility and strength degradation into consideration was proposed by Gosain(1977), the expression was as follows:

$$D=\frac{\sum_{i=1}^{N}(\mu_{si}-1)\lambda_i}{D_0} \tag{4}$$

Where, D_0 equals to the maximum of $\sum_{i=1}^{N}(\mu_{si}-1)\,\lambda_i$ at failure.

(5) Hwang Model

Based on the proposal by Gosain, the energy was introduced to further depict the damage evolution (Hwang and Scribner 1984). The energy-based damage model comprised the Gosain model and the energy-dissipation coefficient, given in:

$$D=\frac{\sum_{i=1}^{N}(\mu_{si}-1)\lambda_i\alpha_i}{D_0} \tag{5}$$

Where, D_0 equals to the maximum of $\sum_{i=1}^{N}(\mu_{si}-1)\,\lambda_i\alpha_i$ at failure.

(6) Park-Ang Model

As a typical two-parameter damage model, it demonstrated the damage calculation principle based on the maximum deformation and hysteresis energy absorption (Park and Ang 1985). The calculated method was quite empirical and proposed on the basis of experimental analysis of reinforced concrete members.

$$D=\frac{\delta_m}{\delta_u}+\beta\frac{\int d\varepsilon}{P_y\delta_u} \tag{6}$$

In which, δ_m and δ_u was the maximum deformation and the ultimate deformation corresponding to peak capacity and ultimate capacity, respectively; β was the energy-dissipation coefficient while the $\int d\varepsilon$ was the cumulative energy-dissipation; $P_y$was the yield capacity corresponding to the yield displacement.

(7) Ou Model

Considering that the Park-Ang model could not reflect the influence of loading path and the hysteresis energy was only determined by the maximum deformation, the precision of the damage calculation based on Park-Ang could not be guaranteed due to its empirical feature. Ou *et al.* (1999) proposed a new damage model, taking the plastic deformation and the cumulative plastic energy dissipation into consideration, and the damage index was described using exponential function of deformation and energy, such as:

$$D=\frac{(\frac{\delta_{i,\max}}{\delta_u})^{\omega}+(\frac{\sum_{i=1}^{N}E_i}{E_u})^{\omega}}{D_0} \tag{7}$$

Where, D_0 equals to the maximum of $\left(\frac{\delta_{i,max}}{\delta_u}\right)^{\omega}+\left(\frac{\sum_{i=1}^{N}E_i}{E_u}\right)^{\omega}$ at failure and ω was recommended as 2.0.

(8) Banon Model

The weight coefficient of deformation and energy was considered by Banon (1981) based on the OU damage model and then the mathematical expression of the damage was given:

$$D=\frac{\sqrt{(\mu_{i,\max}-1)^2+(\sum_{i=1}^{N}h(2\alpha_i)^d)^2}}{D_0} \tag{8}$$

Where, D_0 equals to the maximum of $D=\sqrt{(\mu_{i,max}-1)^2+(\sum_{i=1}^{N}h(2\alpha_i)^d)^2}$ and it was recommended h be 0.38 and d be 1.1.

(9) Other modified models

To better consider the effect of deformation and energy on the structural damage under earthquakes, new damage models based on existing two-parameter damage model were proposed (Cao *et al*. 2014, Chen *et al*. 2015, Ye *et al*. 2018, Teran-Gilmore *et al*. 2010, Kamaris *et al*. 2013). Following equations demonstrate the expression of the damage calculation

Cao *et al*. (2014)
$$D=\frac{P_y u_{res}}{P_y u_{res}+P_y u_{rec}} \tag{9}$$

Chen *et al*. (2015)
$$D=(1.0\text{-}\eta)\frac{\delta_i-\delta_y}{\delta_u-\delta_y}+\eta\sum_{i=1}^{N}\frac{E_i}{P_y(\delta_u-\delta_y)} \tag{10}$$

Ye *et al*. (2018)
$$D=(1\text{-}\alpha)\frac{\delta_m}{\delta_u}+\alpha(\frac{E_h}{E_u})^{\gamma} \quad (\alpha=0.0879 \quad \gamma=0.0814) \tag{11}$$

Amador *et al. (*2010)
$$D=\frac{aE_h}{r[4(\delta_\mu-\delta_y)P_y)]} \tag{12}$$

Kamaris *et al.* (2013)
$$D=\frac{\sqrt{(M_S-M_A)^2+(N_S-N_A)^2}}{\sqrt{(M_B-M_A)^2+(N_B-N_A)^2}} \tag{13}$$

In Eq. (11), 1-α and α are the contributions from maximum deformation and hysteresis energy, and γ reflects the influence from accumulative fatigue. In Eq. (12), a and r are coefficients for the energy demand the energy capacity, which make the damage index as 1 at collapse. In Eq. (13), all the parameters could be referred in Kamaris *et al*. (2013), and it takes into account the interaction between the bending moment and axial force.

4. Analysis of experimental results

4.1 Experimental results summary

Based on experimental results, the seismic performance

Table1 Result of resistance at feature points

Specimen Load/kN	RC-1		RC-2		DBRBF		CBRBF		EBRBF	
	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
Yield point	84.7	-76.0	83.3	-70.5	167.7	-99.56	257.3	-246.2	313.3	-301.7
Peak point	121.4	-114.5	97.8	-82.3	384.2	-463.9	500.6	-488.9	589.0	-602.9
Ultimate point	106.3	-95.42	88.2	-69.9	311.9	-412.2	425.5	-415.6	475.8	-485.0

Table 2 The ductility of specimen

Specimen Arguments	RC-1		RC-2		DBRBF		CBRBF		EBRBF	
	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
Δ_y /mm	52.8	-51.0	33.5	-33.3	58.9	-55.76	30.7	-38.8	48.94	-46.99
Δ_u /mm	145.9	-143.4	75.6	-75.9	127.9	-125.3	108.8	-116.4	131.3	-124.8
μ	2.76	2.81	2.26	2.28	2.17	2.25	3.54	3.0	2.68	2.66

of 5 specimens was analyzed. Table 1 and table 2 listed some major results including capacity and deformation in term of positive direction and negative direction considering the differences in mechanical behavior of buckling-restrained braces. It could be clearly seen that compared with RC frame, buckling-restrained braces greatly improve the bearing capacity and the ductility of RC frame with buckling-restrained braces was quite good.

4.2 Analysis of seismic performance

Fig. 7 demonstrated the hysteresis behavior for the specimens. As it known to us that the hysteresis curve is an important seismic index to evaluate the seismic performance, and it reflected the bearing capacity, deformation capacity, stiffness degradation, ductility and energy-dissipation capacity, and so on. Based on the hysteresis curve, it could be simplified to get the envelop curve, which could concisely describe the change of stiffness in reloading and unloading, the ductility and the resistance as well. Fig. 8 showed the comparison of skeleton curve specimens according to different specimen span, and it could more clearly illustrate the seismic performance of specimens and the difference caused by braces.

From Fig. 7, it could be seen that for RC frame with buckling-restrained braces, it developed better hysteresis behavior, and hysteresis curve was more “fat”. However, for CBRBF, “pinching” in hysteresis curve still existed, and it was due to the deviation in centering between the buckling-restrained brace and beam during test. It was also found in the test that the damage of beam at mid-span was quite serious, resulting in the crush of concrete and slip of reinforcing. It is undeniable that the effective confining tie between members is important for the seismic performance. But bond-slip was usually induced by the degradation of mechanical behavior of concrete and reinforcement and it changed the damage mechanism of structures (Rizwan *et al.* 2018, Rashid and Ahmad 2017, Ahmad *et al.* 2019). Furthermore, it resulted in the deterioration of the interaction of framing members and led to the reduction of stiffness and ductility (Ahmad *et al*. 2018).

The skeleton curves in Fig.8 visually depicted the initial stiffness, peak capacity and the deformation. By comparison, it could be seen that the bearing capacity and the stiffness of RC frame with buckling-restrained braces were improved significantly but the stiffness decreased with brace yielding. The development of RC-1 and RC-2 was similar since that they were moment-resisting structure and the capacity was contributed by beam and column members while for the other specimens, the buckling-restrained braces as lateral resisting system could provide large resistance.

Difference in the behavior in compression and tension was observed for RC frame with buckling-restrained braces, especially for DBRBF with only diagonal brace. The frictional effect between core brace and outer constraint segment mainly accounts for the difference in behavior, since that the brace would contact with constraint segment in compression, leading to higher capacity of brace. The residual deformation of braced frame was larger than that of RC frame under larger deformation and the residual deformation of brace was obvious. This implied that after brace yielded, the energy was mostly dissipated by the plastic deformation of buckling-restrained braces. During the test, it was observed that the core brace disconnected with the outer segment under large deformation.

Both the hysteresis behavior and the capacity of EBRBF was better that CBRBF, therefore, it could be implied that the link beam improved the seismic behavior of RC frame furthermore. The dissipated energy was enhanced notably with the link beam dissipating energy with plastic deformation, however, the capacity of the structure was not impaired even though part of the link beam was damaged. Consequently, the combination of buckling-restrained brace and link beam could be considered as a better method for improving the seismic performance as well as protecting the main frame.

4.3 Analysis of damage

4.3.1 Comparison of damage calculation for specimens

The ductility could well reflect the deformation capacity after yielding and it was closely related with the energy-dissipation. Moreover, in order to take the dynamic characteristics of ground motion into consideration, the cumulative ductility was adopted. Therefore, based on the existing damage model, the relationship of damage index and cumulative ductility, which was defined as the summary of ductility at different loading level, was used to describe the damage development of all specimens.

Fig. 9 demonstrated the calculated damage result corresponding to cumulative ductility. At the beginning, the damage was given as zero(undamaged hypothesized) and when the load capacity decreased to 85% of peak load, the damage was taken as unity.

From the damage result, it was stated that for all specimens, the damage developed with the increase of ductility. However, there was still some difference in the development of damage, for example, the calculated damage result based on Banon damage model was the largest while the Krawinkler-damage-model-based result

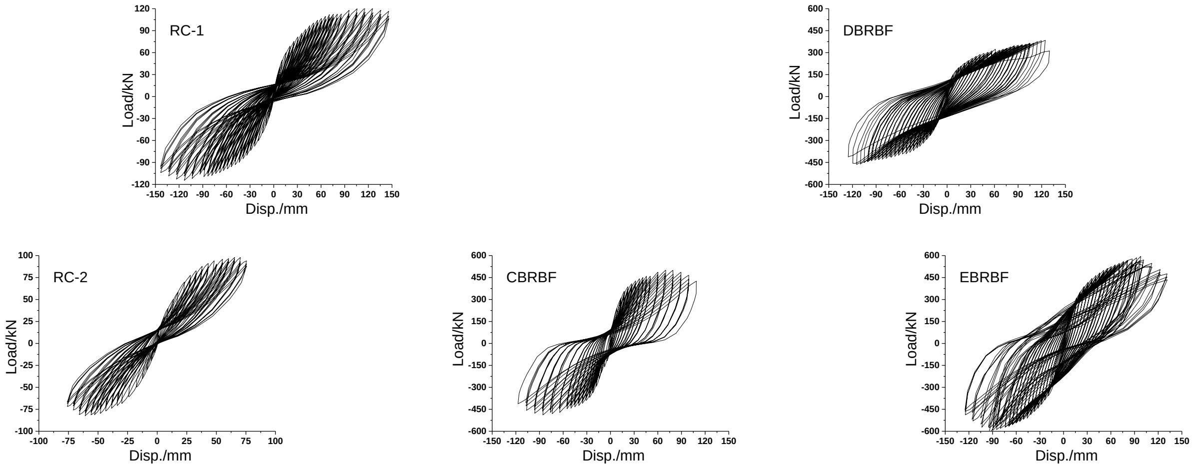


Fig. 7 Hysteresis curves

Fig. 8 Skeleton curves

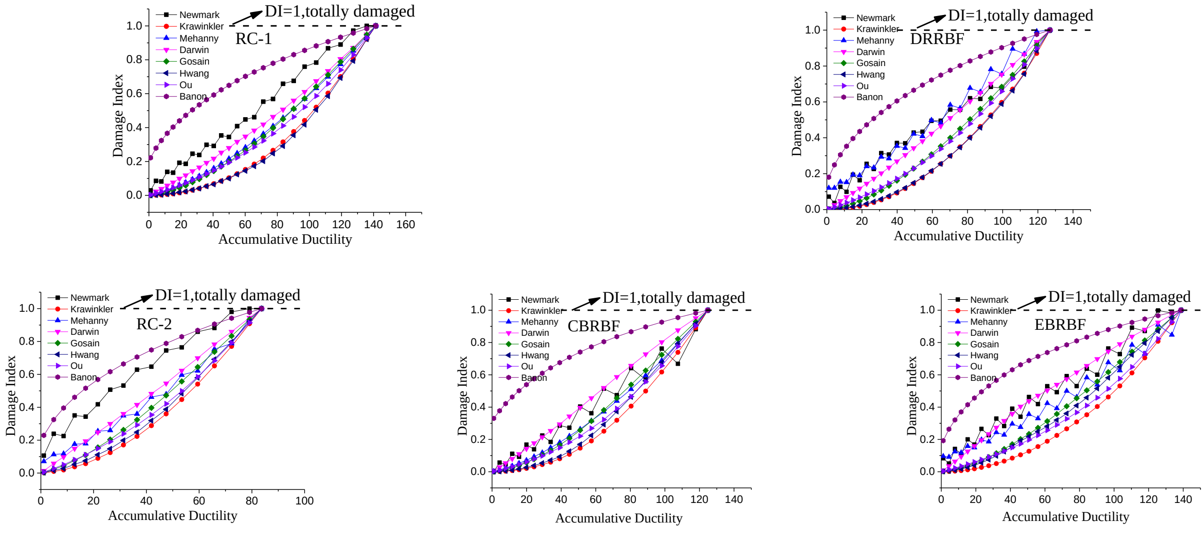
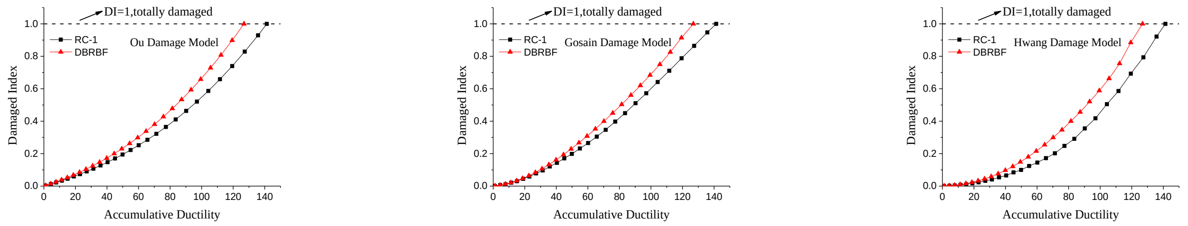


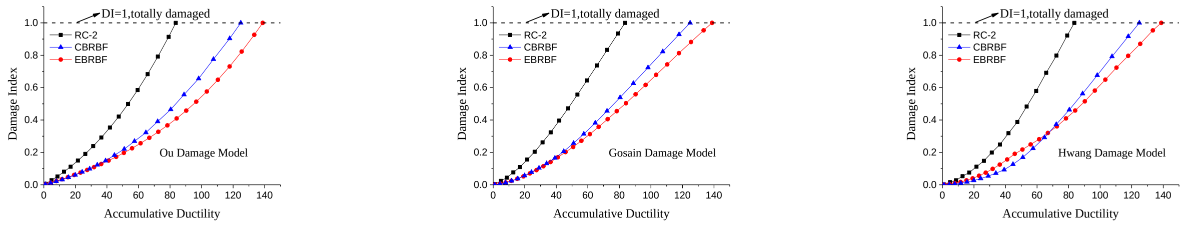
Fig. 9 Calculation of different damage model for specimens

was the smallest. For Darwin, the damage result developed almost linearly with the cumulative ductility, but for Newmark damage model and Mehanny model damage, fluctuation in the damage development was observed. The calculated damage result of Gosain damage model, Hwang damage model and Ou damage model was close.

In order to furthermore describe the damage development of tested specimens, the damage of different components was analyzed. At the beginning, the specimens were in good condition with no crack or few slight cracks, the damage was insignificant and the development was sluggish. However, with load increasing, more new cracks occurred and previous cracks extended and widened, damage continuously accumulated, leading to more serious damage of components. Under larger deformation, notable residual deformation of braces, yielding of components and the crush of concrete resulted in the quick development of damage. Based on the analysis of results of different damage models, it was found that Gosain damage model, Hwang damage model and Ou damage model could



(a) Series 1



(b) Series 2

Fig. 10 Damage comparison results

pertinently reflect the actual damage development of tested specimens.

4.3.2 Influence of brace on damage development

Based on the analysis of all damage models, it was determined to adopt Gosain damage model, Hwang damage model and Ou damage model to further discuss the influence of different layout of brace on the damage development.

Considering that the span length of specimen was not the same, all tested specimens was classified into 2 categories. Series 1 includes specimen RC-1 and specimen DBRBF while series 2 comprises the other 3 specimens. Fig. 10 exhibited the calculation results for different specimen based on the 3 selected damage models.

According to the observation during test, it was clear that before brace yielded, the specimen developed good cooperation between members and it could be presumed that no damage occur for the elastic stage. However, with the brace and reinforcement yielding, occurrence of cracking and development of damage, different members damaged gradually. It could be seen from the damage curve that the damage index was small and increased slowly initially. Nevertheless, the damage increased more quickly especially under larger deformation and it also coincided with the observation in the test. Buckling-restrained braces dissipated energy with plastic deformation and the mechanism was changed after brace yielded, the main RC frame suffered from larger load effect, besides, the transferred force due to brace deformation added more demand on the framing members. Much cracks were found at beam ends, column ends as well as the beam-to-column joints. Moreover, due to the vertical component of brace axial force, serious damage was found at the mid-span of beam.

However, due to the different layout of buckling-restrained braces, the development of damage was sort of different after brace yielding. For DBRBF, the damage development was more severe than RC-1, which was different from the other two braced frames. It was possibly caused by the direct support to brace from RC joints, which imposed more demand on the joints and columns. In addition, the difference in compression and tension for buckling-restrained brace due to frictional effect led to different response of the columns. More damage on column for DBRBF was observed compared with other specimens. For CBRBF and EBRBF, the damage development was improved, but it was clear that the damage development of CBRBF was more serious than that of EBRBF after on the order of 75mm. Based on the experimental observation, the serious damage at the middle of beam occurred with severe concrete cracking and the bond-slip of reinforcement, resulting in extensive concrete collapse. And with deformation increasing, the serious damage would worsen development of damage in return. But for EBRBF, the development of damage was comparatively stable due to the contribution of link beam. After brace yield, the plastic deformation of link beam could help absorb additional energy and protect the other ordinary framing members from serious damage.

5. Conclusions

On the basis of the analysis and discussion of the experimental results for 5 tested specimens, the calculated damage result corresponding to different damage model could be obtained and some major conclusions could be drawn as followings:

(1) In terms of different damage models, it was found that using hybrid damage index could better describe the feature of damage development of structure and reflect the dynamic characteristics on the damage development.

(2) According to the observation during test, the damage was minor before yielding with almost no crack developing, but the damage gradually accumulated and developed quickly afterwards, resulting in serious damage or even

failure of structure. By comparison, it was validated that for different specimens, Gosain damage model, Hwang damage model as well as Ou damage model could pertinently reflect the actual damage development. Damage curve for these 3 damage models was similar, and the damage increased slowly when the deformation was small before yielding, then it increased gradually quickly under large deformation.

(3) From the damage result for different buckling-restrained braced frame, it was verified that the layout of brace had influence on the damage evolution of braced frame. The damage development for CBRBF was most serious compared with other type of braced frames, due to the severe damage of mid-span of beam at the interaction with braces caused by the differences in mechanical behavior of buckling-restrained braces in compression and in tension. The link beam could improve the damage development especially under large deformation, the plastic deformation of link beam could help dissipate energy and protect the other ordinary framing members from serious damage after brace yielding.

Acknowledgements

It is gratefully acknowledged for the financial support from National Natural Science Foundation of China (Grant No. 51578443) and Science and Technology Foundation of FuZhou Council (Grant No.2018-G-31), as well as the support from Fujian University of Technology (Grant No. GY-Z18165). However, all the opinions and conclusions presented in this paper are only those of the authors and do not necessarily represent the perspectives of the funding institute mentioned herein.

References

Ahmad, N., Shahzad, A., Ali, Q., Rizwan, M. and Khan, A.N. (2018), "Seismic fragility functions for code compliant and non-compliant RC SMRF structures in Pakistan", *Bulletin Earthq. Eng.*, **16**(10), 4675-4703. https://doi.org/10.1007/s10518-018-0377-x.

Ahmad, N., Shahzad, A., Rizwan, M., Khan, A. N., Ali, S. M., Ashraf, M., Naseer, A., Ali, Q. and Alam, B. (2019), "Seismic performance assessment of non-compliant SMRF reinforced concrete frame: Shake Table Test Study", *J. Earthq. Eng.*, **23** (3), 444-462. https://doi.org/10.1080/13632469.2017.1326426.

Akbar, J., Ahmad, N. and Alam, B. (2018), "Seismic performance of RC frames retrofitted with haunch technique", *Struct. Eng. Mech.*, **67**(1), 1-8. https://doi.org/10.12989/sem.2018.67.1.001.

Andre, J., Beale, R. and Baptista, M. (2015), "New indices of structural robustness and structural fragility", *Struct. Eng. Mech.*, **56**(6), 1063-1093. https://doi.org/10.12989/sem.2015.56.6.1063.

Banon, H., Irvine, H.M. and Biggs, J.M. (1981). "Seismic damage in reinforced concrete frames", *J. Struct. Eng.*, ASCE, **107**(9), 1713-1729.

Borg, R.C. and Rossetto, T. (2010). "Comparison of seismic damage indices for reinforced concrete structures", *Proceedings of the 14th European Conference on Earthquake Engineering*, Macedonia, September.

Cao, V.V., Ronagh, H.R., Ashraf, M. and Baji, H. (2014), "A new damage index for reinforced concrete structures", *Earthq. Struct.*, **26**(6), 581-609.

Chen, Z.P., Xu, J.J., Chen, Y.L., Xue, J.Y. and Liang, Y. (2015), "Seismic damage of SRC special shaped column frame joints based on modified Park-Ang model", *J. Building Struct.*, **36**(8), 90-98.

Darwin, D. and Nmai, C.K. (1986), "Energy dissipation in RC beams under cyclic load", *J. Struct. Eng.*, ASCE, **112**(8), 1826-1846. https://doi.org/10.1061/(ASCE)0733-9445(1986)112:8(1829).

Duran, B., Tunaboyu, O., Kaplan, O. and Avsar, O. (2018), "Effectiveness of seismic repairing stages with CFRPs on the seismic performance of damaged RC frames", *Struct. Eng. Mech.*, **67**(3), 233-244. http://doi.org/10.12989/sem.2018.67.3.233.

Fu, G., Liu, B.Q. and Xing, G.H. (2013), "The research and calculation on modified Park-Ang double-parameter seismic damage model based on energy dissipation", *Eng. Mech.*, **30**(7), 84-90.

Ghosh, S., Datta, D. and Katakdhond, A.A. (2011), "Estimation of the Park–Ang damage index for planar multi-storey frames using equivalent single-degree systems", *Eng. Struct.*, **33**, 2509-2524. https://doi.org/10.1016/j.engstruct.2011.04.023.

Gosain, N.K., Brown, R.H., Jirsa, J.O. (1977), "Shear requirements for load reversals on RC members", *J. Struct. Eng.*, ASCE, **103**(7), 1461-1476.

Hwang, T.H. and Scribner, C.F. (1984), "RC member cyclic response during various loading", *J. Struct. Eng.*, ASCE, **110**(3), 477-489. https://doi.org/10.1061/(ASCE)0733-9445(1984)110:3(477).

Kamaris, G.S., Hatzigeorgiou, G.D. and Beskos, D.E. (2013), "A new damage index for plane steel frames exhibiting strength and stiffness degradation under seismic motion", *Eng. Struct.*, **46**(1), 727-736. https://doi.org/10.1016/j.engstruct.2012.07.037.

Kang, J.W. and Lee, J.A. (2016), "A new damage index for seismic fragility analysis of reinforced concrete columns", *Struct. Eng. Mech.*, **60**(5), 875-890. http://doi.org/10.12989/sem.2016.60.5.875.

Kratzig, W.B., Meyer, I.F. and Meskouris, K. (1989), "Damage evolution in reinforced concrete members under cyclic loading", *Proceedings of 5th International Conference on Structural Safety and Reliability*, California, August.

Krawinkler, H. and Zohrei, M. (1983), "Cumulative damage in steel structures subjected to earthquake ground motion", *Comput. Struct.*, **16**(14), 531-541. https://doi.org/10.1016/0045-7949(83)90193-1.

Liu, L.L., Wang, Q.L. and Shen, Z.C. (2008), "Study on accumulated dissipated hysteretic energy and ductility index based on damage", *Earthquake*, **4**, 13-19

Massumi, A. and Moshtagh, E. (2013), "A new damage index for RC buildings based on variations of nonlinear fundamental period", *Struct. Design TAll Special Building.*, **22**(1), 50-61. https://doi.org/10.1002/tal.656.

Newmark, N.M. and Rosenblueth, E. (1971), *Fundamentals of Earthquake Engineering*, Prentice-Hall Inc., USA.

Ou, J.P., Niu, D.T. and Wang, G.Y. (1999), "Loss assessment and optimum design of multi-story nonlinear aseismic structures", *Comput. Struct. Mech. Appl.*, **9**(2), 171-179.

Park, Y.J. and Ang, H.S. (1985), "Mechanistic seismic damage model for reinforced concrete", *J. Struct. Eng.*, ASCE, **111**(4), 722-739. https://doi.org/10.1061/(ASCE)0733-9445(1985)111:4(722).

Rashid, M. and Ahmad, N. (2017), "Economic losses due to earthquake-induced structural damages in RC SMRF structures", *Cogent Eng.*, **4**(1), 1-15.

Rizwan, M., Ahmad, N. and Khan, A.N. (2018), "Seismic performance of compliant and noncompliant special moment-resisting reinforced concrete frames", *ACI Struct. J.*, **115** (4), 1063-1073.

Rodriguez, M.E. and Padilla, D. (2009), "A damage index for the seismic analysis of reinforced concrete members", *J. Earthq. Eng.*, **13**(3), 364-383. https://doi.org/10.1080/13632460802597893.

Sinha, R. and Shiradhonkar, S.R. (2012), "Seismic damage index for classification of structural damage–closing the loop", *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, September.

Teran-Gilmore, A., Sanchez-Badillo, A. and Espinosa-Johnson M. (2010), "Performance-based seismic design of reinforced concrete ductile buildings subjected to large energy demands", *Earthq. Struct.*, **1**(1), 69-91. http://doi.org/10.12989/eas.2010.1.1.069.

Wang, B. (2010), "Research on seismic damage of steel reinforced high strength and high performance concrete members and frame structures", M.Sc. Dissertation, Xi'an University of Architecture and Technology, China.

Wang, D.S., Si, B.J., Ai, Q.H. and Sun, Z.G. (2005), "A comparative study of modified Park-Ang model and Park-Ang model for structural seismic damage evaluation", *Earthq. Resistant Eng. Retrofitting*, **27**(S1), 138-144.

Yang, Y., Liu R.Y., Xue, Y.C. and Li, H. (2017), "Experimental study on seismic performance of reinforced concrete frames retrofitted with eccentric buckling-restrained braces (BRBs)", *Earthq. Struct.*, **12**(1), 79-89.

Ye, C.Y., Zhao, P. and Xiang, M. (2018), "Seismic vulnerability analysis of RC frame structures through different structural damage models", *China Earthq. Eng.*, **40**(4), 707-712.

Yu, Q., Meng, S.P. and Wu, J. (2011), "Deformation and energy-based seismic damage evaluation of reinforced concrete structures", *China Civil Eng. J.*, **44**(5), 16-23.

Zhang, B., Yang, Y., Wei, Y.F., Liu, R.Y., Ding, C. and Zhang, K.Q. (2015), "Experimental study on seismic behavior of reinforced concrete column retrofitted with prestressed steel strips", *Struct. Eng. Mech.*, **55**(6), 1139-1155. http://doi.org/10.12989/sem.2015.55.6.1139.

PL