Proceedings of the 2nd International Conference on Civil, Structural and Transportation Engineering (ICCSTE'16)
Ottawa, Canada – May 5 – 6, 2016
Paper No. 110

A Framework of Seismic Design Based on Structural Resilience

Ning An, Zheng He*
Department of Civil Engineering, Dalian University of Technology
No.2 Linggong Road, High-tech District, Dalian 116024, China
21306114@mail.dlut.edu.cn; hezheng@dlut.edu.cn

***Abstract* -** On the basis of the definition and quantification of structural seismic resilience, the relationship between the structural seismic resilience and the absolute seismic resistance is discussed. According to the law of structural damage evolution, two main design methods are put forward to improve the seismic resilience of structures, and the applicability of each method is defined. Thus the seismic design process based on resilience is preliminary formed. The results of case study show that the structural seismic resilience indexes of the isolated structure and the structure with viscous dampers can be improved by 16.87% and 14.42% respectively. The improvement effect is mainly reflected in the DS_2~DS_4 regions, which indicates that the seismic capacity of reinforced structures are kept at relatively a high level at serious damage states. At the severe damage state, the seismic resilience of reinforced structures is still better than that of the original structure, but theirs seismic resistance are significantly reduced, and the isolated structure's seismic resistance is plunging faster than the structure with viscous dampers.

***Keywords*:** Resilience; damage evolution; isolation; viscous damper; performance objective.

1. Introduction

The concept of resilience is derived from the mechanical dynamics, which is the ability of the material to deform and store the potential energy in the condition of no fracture or complete deformation [1]. The concept has been extended to other areas of materials science, psychology, economics, ecological systems, engineering and so on. In the engineering field, Bruneau et al [2] suggested that resilience could be conceptualized along four dimensions: technical, organizational, societal and economic (TOSE), from the perspective of a system. It can be further defined as consisting of the 4 properties: robustness, redundancy, resourcefulness, rapidity.

In view of this conceptual framework, many scholars have given different quantitative measure of resilience. Chang and Shinozuka [3] contribute to the literature on disaster resilience discussing a quantitative measure of resilience based on the case study of the Memphis water system. They explored the extent to which earthquake loss estimation models can be used to measure resilience: 200 Monte Carlo simulations for each of the 3 retrofit cases (1, 2 and no retrofit) for two earthquake scenarios were run. The results are given in terms of percentage of simulations meeting performance criteria. Cimellaro et al [4] quantify the resilience by fragility functions whose multiple parameters are used to characterize system functionality and safety. In this definition, six sources of uncertainties are considered: earthquake intensity measures, response parameters, performance threshold, damage measures, losses and recovery time. Bocchini and Frangopol [5] firstly introduced the concept of resilience into earthquake damage assessment of the traffic transportation network. Resilience is considered as the optimal criterion of the restoration to help decision makers strengthen earthquake disaster management. Based on [5], Decò et al [6] propose a probabilistic approach for the pre-event assessment of seismic resilience of bridges, focusing on the effect of different restoration strategies and recovery parameters. Different from other scholars, He and An [7] proposed the concept that only considering the change of the seismic capacity of structures, defined and quantified it based on the rule of structural damage evolution. And according to the importance of structures, the suggested performance levels of the seismic resilience are given.

On the basis of Ref. [7], this paper intends to analysis of further relationship between the structural seismic resilience and the absolute seismic resistance, and proposes the seismic design method based on resilience with numerical validation.

2. Quantification of Structural Seismic Resilience

In paper [7], the definition of the structural seismic resilience and the formulas to quantify it are proposed (Eqs.1~3).The structural seismic resilience is defined as the capacity of the damaged-structure to recover to its initial state (design state), which characterizes the macroscopic changes of the residual seismic resistance of the structure under the condition of no damage, minor damage, moderate damage, severe damage, and even collapse.

In the design method of seismic resilience, the seismic performance at a damage state is expressed as a relative quantization value: residual seismic capacity ratio. It is defined as the ratio of the residual seismic capacity of the structure under specific damage state to its initial state. As follows:

$$C(D) = \frac{IM_{collapse,D}}{IM_{collapse}} \tag{1}$$

where, $IM_{collapse,D}$ is the collapse ground motion intensity of the structure with damage state, D; $IM_{collapse}$ is the collapse ground motion intensity of the initial structure with no damage. The modified Park-Ang damage model [8] is selected to describe the structure damage evolution, and its value is 1 when structures collapse.

The relationship between residual seismic capacity ratio and damage accumulation is nonlinear. As shown in Figure 1, the seismic capacity ratio curve describes the decline rate of structure residual seismic capacity at different damage states. The R, which is a global seismic resilience index of structure, is introduced:

$$R = \int_0^1 C(D)\, dD \tag{2}$$

The R_{DSi} is defined as local structural seismic resilience (shown in Figure 2), which can be expressed as the mean value of the ratio of the seismic capacity of the structure in a certain damage region, the equation can be written as:

$$R_{DSi} = \frac{\int_{D_{i,0}}^{D_{i,1}} \mathrm{C}(D)\, dD}{D_{i,1} - D_{i,0}} \tag{3}$$

where $D_{i,0}$ and $D_{i,1}$ is the boundary values of the damage region i. Referring the partition method of [9] and [10] about damage regions, the global structure damage can be divided into five states: no damage (DS_1)， minor damage (DS_2), moderate damage (DS_3), severe damage (DS_4) and collapse (DS_5).

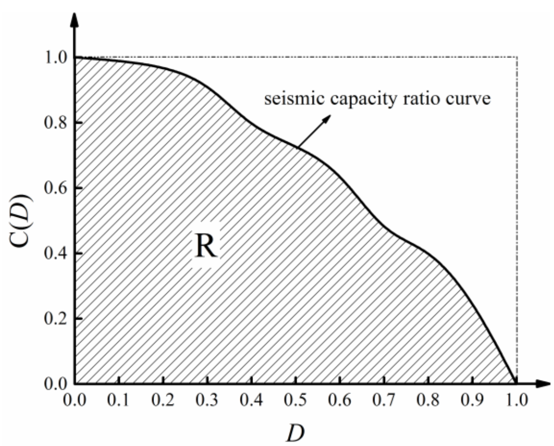

Fig. 1: Structural seismic resilience index.

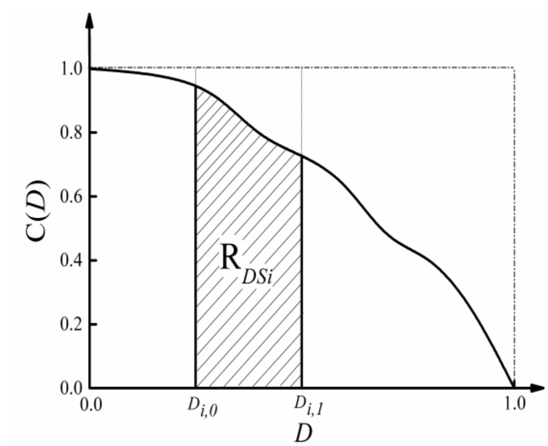

Fig. 2: Structural seismic resilience corresponding to a certain damage region.

The structure residual seismic capacity ratio curves can be divided into 5 categories [7], shown in Figure 3. The curve I can be regarded as the suggested target curve and the curve III is the minimum curve whose R is equal to 0.5.

3. Design Method of the Seismic Resilience and Its Improvement

3.1. Seismic Design Concept of Resilience

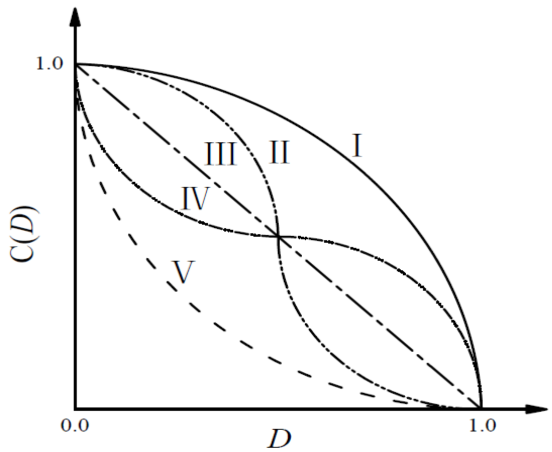

Fig. 3: Typical residual seismic capacity ratio curves.

In the traditional seismic design, the absolute seismic resistance (ASR) of structures can be expressed by the intensity of earthquakes that structure can withstand or the deformation of the structure under the earthquake with certain intensity. In essence, all these methods depict ASR by the performance of structures under some damage state that coursed by an earthquake. By controlling the ASR, the safety of structures can be assured with no collapse or large deformation. With the improvement of the seismic demand of the structure, it is not the only aim to ensure the safety of structures. In resilient seismic design, the seismic performance is assessed by regions or even overall process of damage evolution, which is more precisely helpful in controlling the attenuation process of ASR according to the functional requirements of different buildings and ensure structures to resist aftershocks or be repaired with lower cost after an earthquake.

The seismic design based on structural resilience is a supplement to the existing design method based performance, which puts forward a higher requirement for the seismic performance of structures. So meeting the current code of ASR is the premise. The relationship between the seismic resilience and the ASR is shown in Figure 4. Theoretically, there is no upper limit to the absolute seismic resistance of structures, but the theoretical upper limit of the structural seismic resilience is 1, which is impossible to reach this limit in practical application. Therefore, the relationship between R and ASR is not a simple incremental relationship. When the ASR reaches a certain degree, R tends to reach the theoretical optimal objective. Considering practical applications with various factors such as structure importance, construction cost and so on, the design optimal target of resilience is that the ASR meets the seismic code, the R satisfies design level objective of seismic resilience and the construction cost is lowest.

3.2. Design Method for Improving the Seismic Resistance

The first thing to note is that the structural damage evolution described in this paper refers to the damage of the reinforced concrete members (beams, columns, plates, walls, etc.), which does not include the failure of the structural damping members or replacement members. This is because the damage of reinforced concrete members is irreversible and cannot be repaired in a short time (or too costly), and structural vibration damping members or replaceable components are often used as a structural reinforcement plans, whose failure does not directly lead to the collapse of the structure. The earthquake resistant capacity of the structure can be recovered immediately after the replacement of the members.

Since the structural seismic resilience index reflects the characteristics of the structure itself, the R and ASR is determined after the completion of the initial design. From Figure 4 shows that in a certain range, R is monotonically increasing with ASR, and finally close to the maximum value. Obviously, it is not desirable to improve ASR by enhancing the components, which will directly affect the function of the structure and increase the cost. So the structural seismic resilience can be improved mainly by the two methods:

(1) Optimizing structure system, component design and layout. When the structure has a significant weak layer or damage concentration, it will lead a sharp drop of seismic capacity curve at a certain damage state, which also make seismic resilience index of some damage region don't meet the requirements or the global seismic resilience index too low. Hence, it is an effective method to improve structural seismic resilience, which is to optimize structure system, component design and layout to avoid the obvious weak layer and damage concentration. Compared with the method of enhancing the component, the optimization of the structure systems can improve the structure of the absolute seismic capacity with no impact on structure function and cost control. However, when the structure system is simple and the number of components is not much, which means the scope of optimization is limited, the improved rang of its seismic resilience is limited too.

(2) Setting isolation and energy dissipation devices. The isolation and energy dissipation devices are used as additional components of the main structures, which consume seismic energy and reduce vibration and deformation of the main structures. These devices can not only improve the absolute seismic capacity of the structure, but also can be replaced in a short time after failure, so that the function of the devices has been restored and the seismic resistance of the structure remains at a high level after earthquakes. In view of the built structures, theirs systems and components have been unable to optimize, this method is the only way to improve structural seismic resilience. In the seismic design method based on resilience, this kind of components that can significantly improve structural seismic resilience is called resilient component.

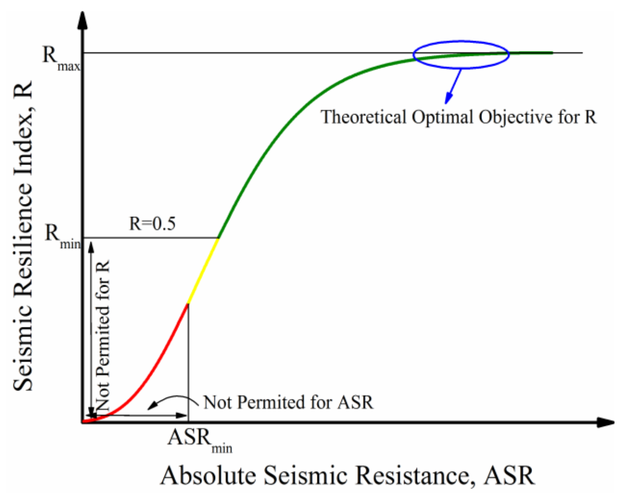

Fig. 4: The relationship between R and ASR

According to the seismic design requirements and cost control and other aspects of consideration, the optimization of structure system, component design and layout is the first priority to meet the requirements of the resilience. If it still does not meet the requirements, setting isolation and energy dissipation devices can be the second plan. The design process is shown as Figure 5.

4. Case study

4.1. Basic Information

The 8-story frame is designed in accordance with [11], shown as Figure 6 (a). Seismic fortification intensity of the building is 8 degree. The site class is II and the seismic design classification is the first group. Concrete grade C30 is used for beams, slabs and columns. Rebar takes HRB335. The first three order vibration periods of the structure are 1.61sec, 0.55sec and 0.32sec. Since the structure system is simple, these two kinds of methods are used to improve the seismic resilience by setting lead-rubber isolation bearings (LRB) and viscous dampers (VD). The initial stiffness of LRB is 7800 kN/m and the yield strength is 130kN. The initial stiffness of VD is 300 kN/m and the viscous parameter of damper is 300 kN(s/m). The layout is shown in Figure 6 (b) and (c).

OpenSEES [12] is used as the finite element platform in this paper. In the incremental dynamic analysis, 22 strong motions with the standard spectrum fitting are selected. Referencing [7], this case used Housner's spectral intensity (SI) and modified Park-Ang damage model [8].

4.2. Seismic Resilience Index of Original Structure

There is large difference of structure residual seismic capacity curves and the R, under different ground motions. Figure 7 shows the maximum and the minimum of R under the selected 22 ground motions. All the residual seismic capacity ratio curves are convex curve, which mean the attenuation rate of seismic capacity is less than the rate of damage accumulation. The average value of all samples is illustrated in Figure 8, including the global R and the R_{DSi}. It can be seen that the decline of seismic capacity is slow at the DS_1~DS_3 states, but the attenuation is significantly accelerated at the DS_4 states

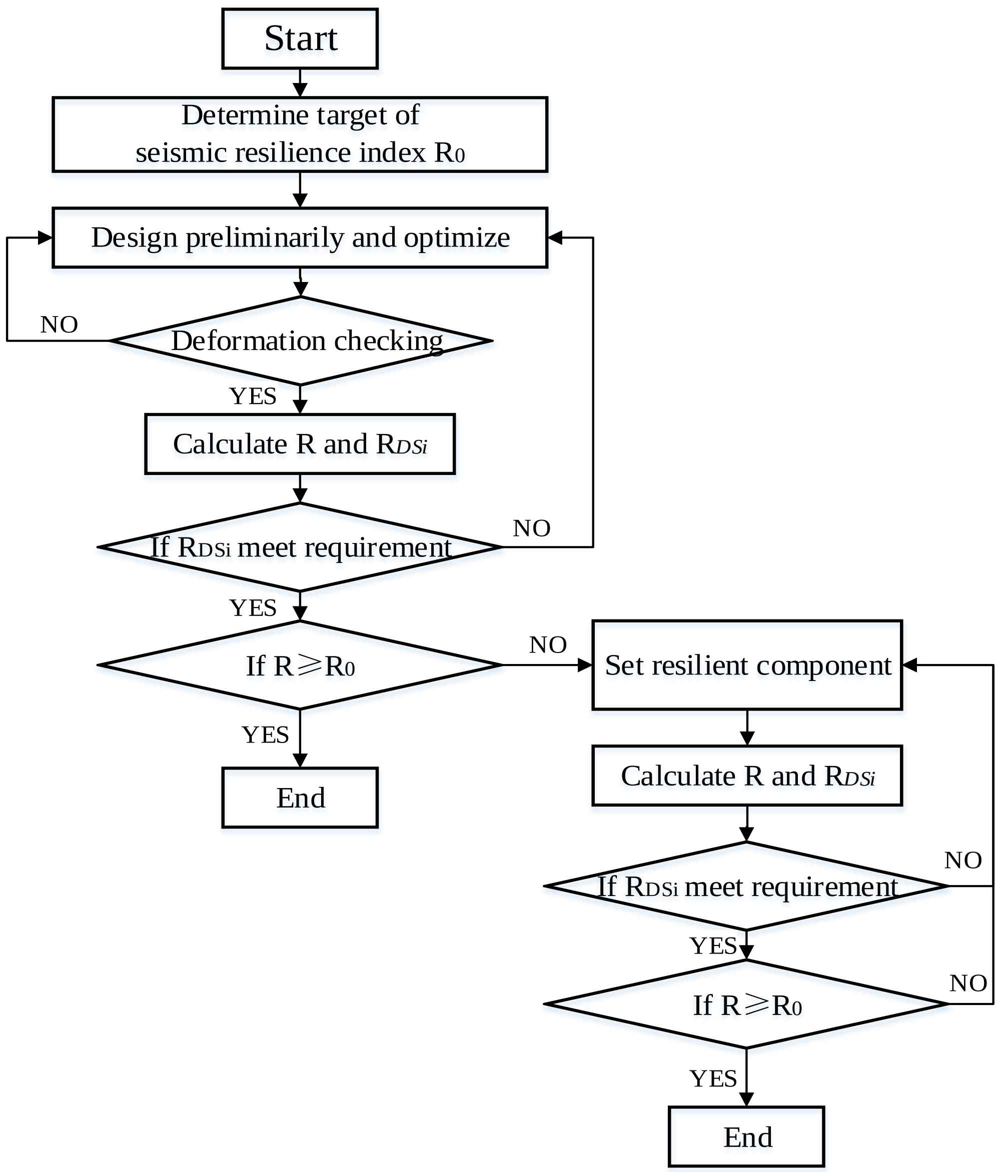

Fig. 5: Flow chart of seismic design method based on resilience.

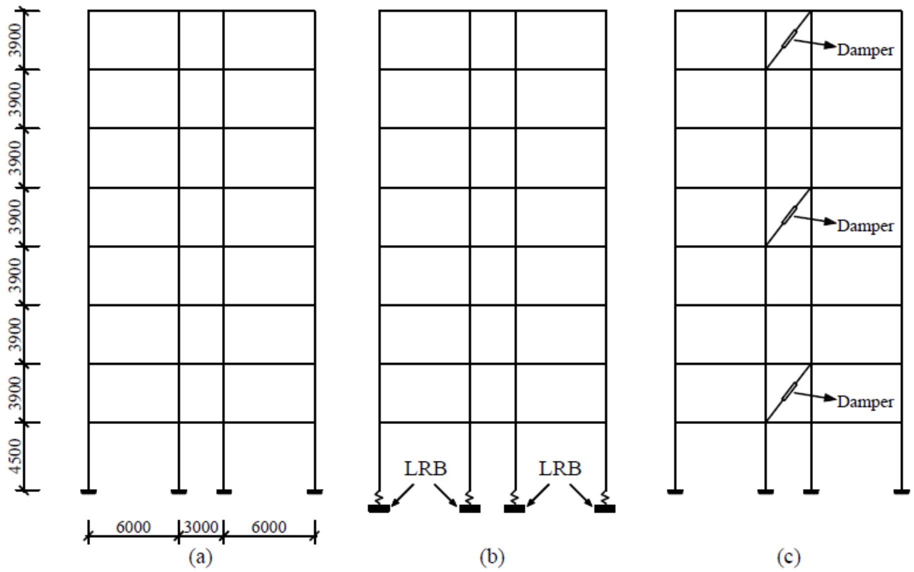

Fig. 6: Elevation of the three frames.

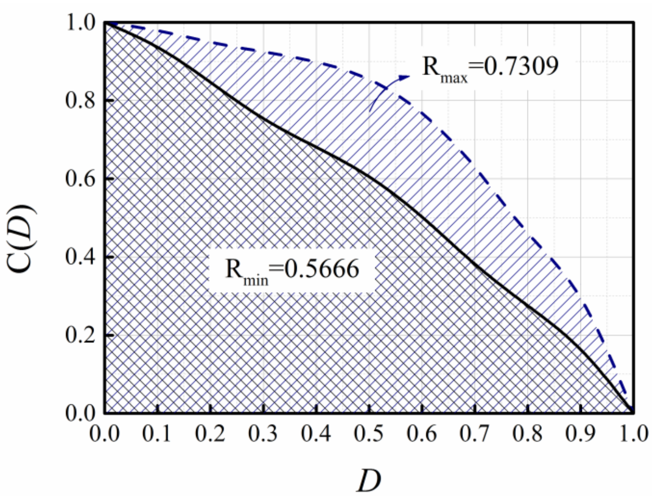

Fig. 6: The maximum and minimum of the R

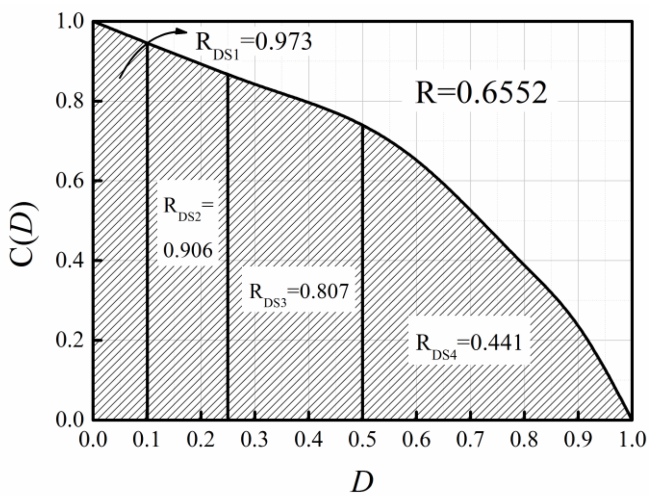

Fig. 7: Average value of the R

4.3. Seismic Resilience Index of Reinforced Structure

In this paper, two kinds of common reinforcement methods are selected: lead-rubber isolation bearings (LRB) and viscous dampers (VB). In the OpenSEES [12], the element ElastomericBearingBoucWen is used to simulate the LRBs and the VBs is simulated by uniaxial material ViscousDamper and twoNodeLink element. The collapse vulnerability analysis of the three frames is shown in Figure 8, and Table 1 exhibits the collapse probability and the collapse margin ratio (CMR) [13]. The results show that the ASR of reinforced frames is significantly improved, and the two frames won't collapse almost under design major earthquake. The reinforcement effect of the isolated structure is better than that of the structure with viscous dampers, and the CMR is improved by 63.82% and 32.91% respectively compared with the original structure.

Table 1: Collapse probability under major earthquake and CMR of the three frames.

Indexes	Original Frame	Frame with LRBs	Frame with VBs
Collapse Probability (major earthquake)	8.98%	0.01%	0.73%
CMR	1.255	2.056	1.688

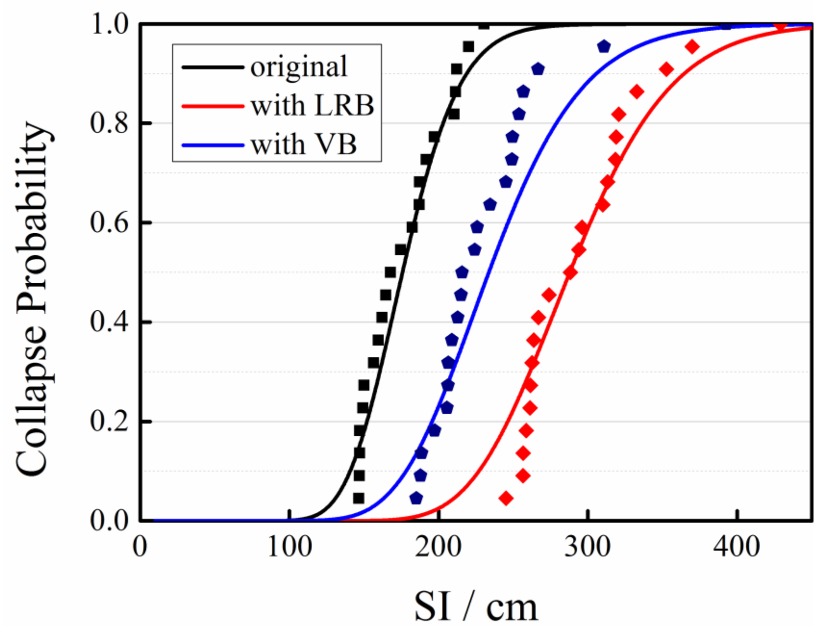

Fig. 8: Collapse vulnerability analysis of the three structures.

The comparison results of the three fames' R are shown in Figure 9. The R of the frames with LRBs and VDs are close, which are improved by 16.87% and 14.42% respectively. The lifting effect of the isolated frame is slightly larger than that of the frame with VDs. According to the classification of the resilience levels in the literature [7], the reinforced frames upgraded the resilience level from the initial C level to the B level. The R_{DSi}s of the three structures are exhibited in Table 2. It can be seen that the improvement of seismic resilience of the reinforced structures is mainly at the DS_2~DS_4 states, which means the structural seismic resistance maintains at a relatively high level when their damage are serious. This characteristic is beneficial for resisting sequence-type earthquakes and restoration after earthquakes.

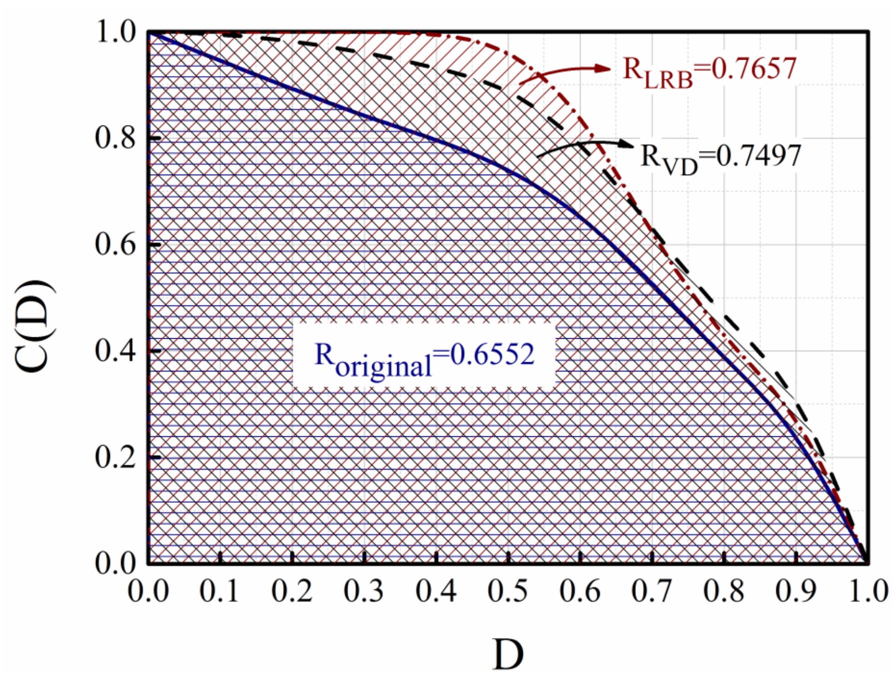

Fig. 9: Seismic resilience indexes of three frames.

Table 2: Seismic resilience indexes corresponding to damage regions of three structures.

Damage Regions	R_{DSi} of Original Frame	Frame with LRBs		Frame with VBs	
		R_{DSi}	Improvement	R_{DSi}	Improvement
DS_1	0.9727	1	2.81%	0.9980	2.60%
DS_2	0.9058	1	10.40%	0.9853	8.78%
DS_3	0.8070	0.9939	23.16%	0.9381	16.25%
DS_4	0.4406	0.5345	21.31%	0.5352	21.47%

5. Conclusion

Based on the discussion of the relationship between the structural seismic resilience and the absolute seismic resistance, the seismic design method based resilience is established, and the following conclusions and cognition are obtained:

(1) The relationship between the R and ASR is not monotonically increasing. After reaching a certain degree of ASR, the R tends to a constant value, that is, the theoretical optimal objective. In practical applications, it is difficult to reach the theoretical target, the design optimal target of resilience is that the ASR meets the seismic code, the R satisfies design level objective of seismic resilience and the construction cost is lowest.

(2) There are two main methods to improve the seismic resilience of structures: optimization of structure seismic design and installation of isolations or damper devices. The former is preferred method, but when the structure system is simple and the number of components is small, the optimization becomes meaningless. The latter method should be chosen, especially for existing buildings.

(3) Providing with isolations and damper devices, the frames' ASR and R are improved respectively, and the improvement is significant at the serious damage states. The overall lifting effect of the two reinforcement plans is almost equal. The residual seismic resistance ratio of the isolated frame is better than that of the structure with LRBs at the law damage states; however, the attenuation rate of residual seismic capacity is higher than that of the damper structure at the stage of severe damage.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (Grant No. 91315301 and 51261120376).

References

[1] J. E. Gordon, *Structures, or, Why things don't fall down*. Da Capo Press, 2003.

[2] M. Bruneau, S. E. Chang, R. T. Eguchi, et al, "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthquake spectra.*, vol. 19, no. 4, pp.733-752, 2003.

[3] S. E. Chang and M. Shinozuka, "Measuring improvements in the disaster resilience of communities," *Earthquake spectra*, vol. 20, no. 3, pp.739-755, 2004.

[4] G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau, "Quantification of seismic resilience," in *Proceedings of the 8th US National Conference on Earthquake Engineering*, USA, San Francisco, 2006, pp. 10.

[5] P. Bocchini, D. M. Frangopol, "Optimal resilience-and cost-based post disaster intervention prioritization for bridges along a highway segment," *J. Bridge Eng.*, vol. 17, no. 1, pp. 117-129, 2010.

[6] A. Decò, P. Bocchini, and D. M. Frangopol, "A probabilistic approach for the prediction of seismic resilience of bridges, " *Earthquake Engineering & Structural Dynamics*, vol. 42, no. 10, pp. 1469-1487, 2013.

[7] Z. He and N. An, "Structural seismic resilience considering damage (in Chinese)," *Engineering Mechanics*, under review, 2015.

[8] S. K. Kunnath, A. M. Reinhorn, and J. F. Abel, "A Computational tool for seismic performance of reinforced concrete buildings," *Computers and Structures*, vol. 41, no. 1, pp. 157-173, 1992.

[9] Y. J. Park, A. H. S. Ang, and Y. K. Wen, "Damage-limiting aseismic design of buildings," *Earthquake spectra*, vol. 3, no. 1, pp. 1-26, 1987.

[10] GB/T 24335-2009. *Classification of earthquake damage to buildings and special structures*. (in Chinese). Beijing, Standards Press of China, 2009.
[11] GB50010−2010. *Code for Seismic Design of Buildings*. (in Chinese). Beijing, China Architecture & Building Press, 2011.
[12] S. Mazzoni, F. McKenna, M. H. Scott, and G. L. Fenves, Open system for earthquake engineering simulation (OpenSEES) command language manual [Online]. Available: http://opensees.berkeley.edu/wiki/index.php/Command_Manual. Version 2.4.5. 2015.
[13] ATC-63, *Quantification of Building Seismic Performance Factors*, USA, CA, Redwood City, Applied Technology Council, 2010.