Journal of Mechanics Engineering and Automation 10 (2020) 110-119
doi: 10.17265/2159-5275/2020.04.002

Dynamic Reliability Analysis of Braced Frame Structures Considering Inter Story Correlation

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Abstract: Adding buckling restrained braces (BRB) of reinforced concrete frame structure can effectively improve the safety performance of the structure. The dynamic reliability analysis based on Poisson continuous process assumption and the first exceeding failure probability can be used to obtain the failure probability of the buckling restrained brace frame system under earthquake load, and the relationship between the failure probabilities of each floor of the structure is analyzed to obtain the frame system reliability interval of frame structure. The results show that the reliability of BRB frame structure is higher than that of pure frame structure, and the discrete failure probability is lower.

Key words: Reinforced concrete frame, BRB, dynamic reliability analysis, inter story failure correlation.

1. Introduction

How to improve the seismic performance of structures and ensure the safety of people's lives and property is the main research direction in the field of earthquake resistance of engineering structures, and is also the key demand of national social development. In order to improve the seismic performance of the structure and ensure that the structure has enough ductility under the earthquake, researchers at home and abroad have studied a variety of energy dissipation devices. BRB (buckling restrained brace) is a kind of displacement passive energy dissipation member, which is widely used in frame structure. BRB frame system shows good ductility performance under earthquake loads, and BRB members can be easily replaced after a large earthquake, which is very efficient and economical. BRB component originated from Japan, and has been widely used in the United States, Japan and China Taiwan. Due to its excellent seismic energy dissipation capacity, theoretical research on BRB and research and development of new BRB have begun to take shape in mainland China, but the practical application of BRB is still limited to developed cities.

The BRB consists of a core, a filler material and a steel sleeve of the restrained shell. The steel core bears all the loads. Meanwhile, to prevent the core from buckling, the core is placed in the steel tube and injected with mortar or concrete. Due to the Poisson effect, the core material expands under compression, so a layer of un-bonded material or air layer (GAP) is set in the core material and mortar. Both ends of the BRB are connected with the frame structure through the gusset plate. The BRB structure and the frame connection form have been shown in Fig. 1.

The traditional brace design concept is to increase the lateral stiffness of the structure, and to make the structure bear more seismic load with strong rigid support. The BRB is a new type of support based on the improvement of the traditional brace. It changes the disadvantage of the traditional brace which buckles under the action of reciprocating tension and compression in the case of large earthquake. It enables the brace to enter the plastic state to absorb energy, and transforms the seismic concept into a reduction. Compared with the traditional braced frame system, the restrained buckling braced frame system has higher

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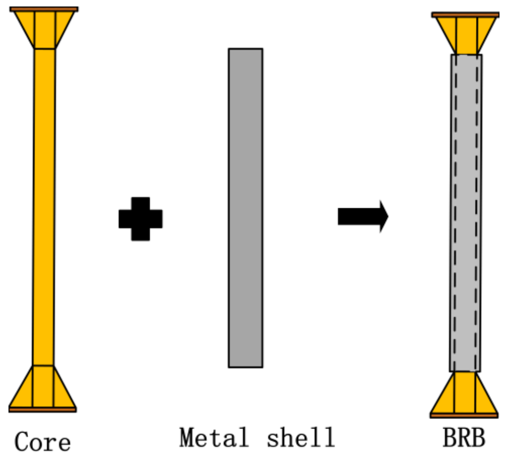


(a) BRB composition

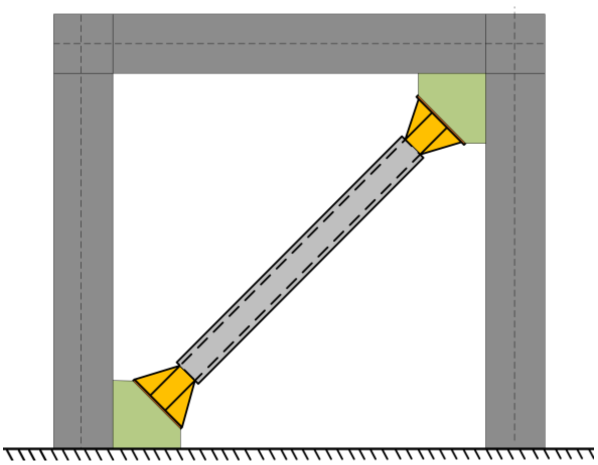

(b) BRB frame composition

Fig. 1 BRB for practical engineering applications.

linear elastic stiffness under small earthquake, and it is easier to meet the deformation requirements of the code; at the same time, it eliminates the buckling problem of brace in the process of yielding under tension and compression, and has stronger and more stable energy dissipation capacity when encountering large earthquake.

BRB has the characteristics of clear energy dissipation mechanism, significant energy dissipation and damping effect, stable performance, convenient construction and installation, and is easy to standardize production, so it has become a more widely studied and applied energy dissipation member. In 1973, Wakabayashi [1], a Japanese researcher, initially proposed that the steel plate brace should be clamped between precast reinforced concrete slabs. Compression tests and subsystem tests were carried out to verify the stiffness and strength of members and the reliability of end connections, which is the rudiment of buckling restrained brace. On this basis, Fujimoto [2] studied the BRB filled with mortar and obtained the stiffness and strength design criteria of steel casing. In 1999, Clark [3] conducted three large-scale BRB tests, and the test data provided support for the design and construction of the first building with BRB in the United States [4]. On this basis, Black and Aiken [5] also carried out the stability analysis of the overall buckling, the high-order modal buckling behavior of the inner core and the plastic torsion problem.

Numerical simulation is an important tool to study the seismic performance of BRB due to the complexity of component manufacturing and seismic simulation. Field [6] for the first time used the finite element software LS-DYNA to simulate a buckling restrained brace, and the simulation result was in good agreement with the test data, which verified the feasibility of simulation replacing the experiment; Liu [7] established the plane frame support model through the finite element software ANSYS and carried out the seismic time history analysis, and summarized the modal of the frame structure under different supporting conditions. Jia et al. [8] established an analysis model for BRB-frame with nine floors and four types of sites, carried out time history analysis and pushover analysis of BRBF system under large and small earthquakes, and found that the displacement of BRBF system was reduced by 25%-75% compared with the original frame structure.

2. Principle of Dynamic Reliability

When the structural system is subjected to stationary random excitation, the dynamic response is a stochastic process. In general, it can be considered that the cross between the dynamic response and the allowable limit of the structural system obeys Poisson distribution. Taking the deformation capacity as the main failure mode of the BRB frame system, and taking the maximum inters story displacement of the weak story of the main frame structure exceeding the ultimate displacement of the story for the first time as the failure limit of the structure system, the dynamic reliability probability of the structure can be obtained. The reliability probability of the structure is as follows:

$$P_s(T) = \exp[-\frac{T}{\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\exp(-\frac{[\theta]^2 L^2}{2\sigma_x^2})] \quad (1)$$

Here $\sigma_{\dot{x}}$ and $\sigma_{\dot{x}}$ are the displacement standard deviation and the velocity standard deviation extracted from the structural response point, θ is the given safety limit; the solution of the sand $\sigma_{\dot{x}}$ needs to take the complete non-stationary earthquake action as the excitation input and extract the time history analysis results to obtain; and θ represents the maximum elastic-plastic interlayer displacement angle of the structure.

The existing research shows that the failure mode of reinforced concrete frame structure system under rare earthquake action is that each layer is interrelated. Therefore, it is not enough to analyze the reliability of the weak story only, and the overall reliability of the structure should be considered. In this case, the overall dynamic reliability of the structure can be expressed by the following formula:

$$P_s(\mathrm{t}) = 1 - P(b,\mathrm{t}) \quad (2)$$

$$P_{fn}(\mathrm{t}) = 1 - \prod_{i=1}^{n} P_s(\mathrm{t}) \quad (3)$$

According to the suggestion of Academician Guang-Yuan Wang [9], the following calculation formula is adopted for the parallel system of reinforced concrete frame:

$$P_f = 1 - (1 - P_{fn}^{\max})\prod_{n=2}^{N}[(1-\mu_n)(1-P_{fn}) + \mu_n] \quad (4)$$

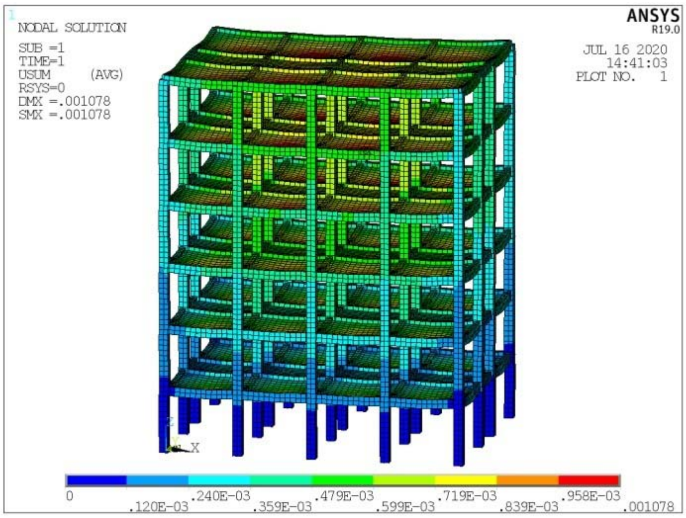
In the formula, the distribution parameters μ_n are obtained according to the following Eq. (5):

$$\mu_n = 0.06 I_0 + 0.30 \quad (I_0 = 7 \sim 10) \quad (5)$$

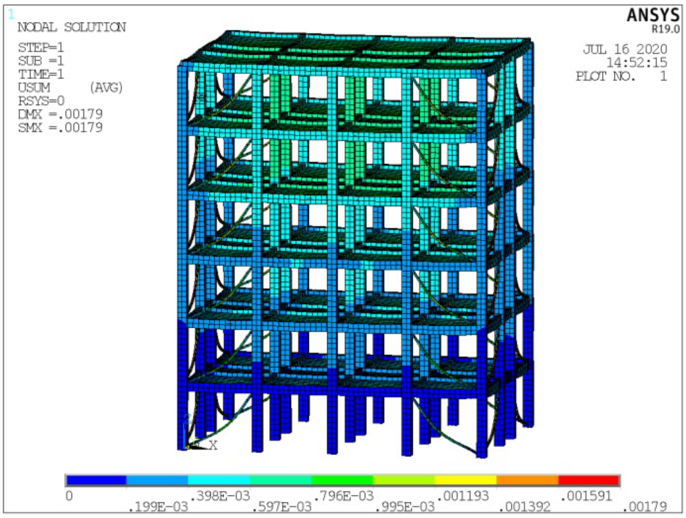
3. Engineering Example

Six stories reinforced concrete frame structure with BRB, RC frame structure with traditional brace and pure frame structure are established. The height of the floor is 3.6 m, with 6 floors in total, with a total height of 21.6 m. The seismic fortification intensity is 8, and the design basic seismic acceleration is 0.2 g. The design earthquake is divided into the first group and the seismic fortification category of the building is class C. The floor dead load is 6 kN/m^2, whose live load is 2.5 kN/m^2; the roof dead load is 3 kN/m^2, the roof live load is 0.5 kN/m^2, and the line load of beam is 8 kN/m. The reinforcement ratio of beam and column is 1.5%, and the reinforcement grade is HRB335. The limit of elasto-plastic inters story displacement angle θ given in the code for seismic design of buildings is 1/50, and it can be seen that the safety limit of the analysis structure is b = 72 mm, the finite element model of the structure is shown in Fig. 2.

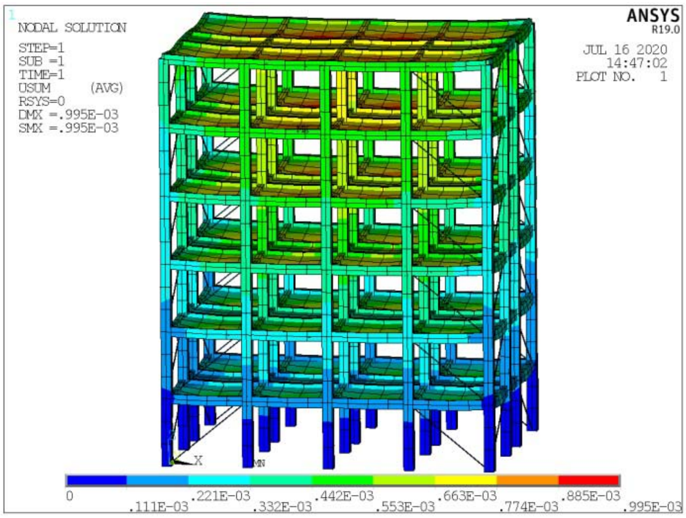
Fig. 2 shows the displacement of RC common frame, traditional braced frame and buckling restrained braced frame structure after applying dead weight and live load. It can be seen that the deformation degree of the three kinds of structures is close, and the maximum deformation occurs in the center of the top plate, which indicates that the installation of support has no obvious effect on the deformation of the structure itself; the traditional support has slight bending under the action of constant live load, which may develop into the overall buckling of the member under the larger earthquake load, leading to the decline of bearing capacity or even withdrawal from work; the BRB mining technology is characterized by the following aspects: 1 with link 8 element modeling, because only one element is divided, it can be seen that the rod element has no bending obviously, and the effect of “buckling prevention” is realized reasonably.



(a) Common frame



(b) Traditional support frame



(c) BRB frame

Fig. 2 Finite element model.

The above-mentioned structure can be regarded as a linear structure with multiple degrees of freedom, and its dynamic response equation can be obtained under the action of earthquake acceleration:

$$[M]\ddot{X}(t) + c\dot{X} + k\dot{X} = F(t) \tag{6}$$

In order to reasonably reflect the spectrum characteristics of bedrock ground motion, the modified filtered white noise model proposed by clough-penzien is adopted [10], and the power spectral density function of seismic acceleration is given as follows:

$$S_{\ddot{x}}(\omega) = \frac{\omega_g^4 + 4\xi_g^2\omega_g^2\omega^2}{(\omega_g^2-\omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2}\frac{\omega^4}{(\omega_f^2-\omega^2)^2 + 4\xi_f^2\omega_f^2\omega^2}S_0 \tag{7}$$

For the nonstationary random ground motion model, the concrete formula of dynamic reliability can be obtained:

If $0 \le t < t_1$:

$$P(b,t) = \exp[-\frac{1}{\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\int_0^t \exp(-\frac{b^2}{2\sigma_x^2\cdot(s/t_1)^4}ds)] \tag{8}$$

Else $t_1 \le t \le t_2$:

$$P(b,t) = \exp\{-\frac{1}{\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}[\int_0^{t_1}\exp(-\frac{b^2}{2\sigma_x^2\cdot(s/t_1)^4}ds) + \int_{t_1}^{t}\exp(-\frac{b^2}{2\sigma_x^2})ds]\} \tag{9}$$

Else $t_2 < t \le T$:

$$P(b,t) = \exp\{-\frac{1}{\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}[\int_0^{t_1}\exp(-\frac{b^2}{2\sigma_x^2\cdot(s/t_1)^4}ds) + \int_{t_1}^{t_2}\exp(-\frac{b^2}{2\sigma_x^2})ds + \int_{t_2}^{t}\exp(-\frac{b^2}{2\sigma_x^2\exp(-2c(s-t_2))})ds]\} \tag{10}$$

4. Determination of Parameters of Nonstationary Random Ground Motion Model

According to the above site conditions, the parameters of the unsteady ground motion model can be obtained [11]: ω_g =17.95 Hz, ξ_g = 0.72, ω_f = 0.0856 Hz, ξ_f = 0.72, t_1 = 0.8 s, t_2 = 7.0 s, a = 0.35. The values of coefficient S_0 of Clough-Penzien model are shown in Table 1.

The earthquake duration t is defined as the vibration time when the intensity exceeds 50% of the peak value [12]. According to the model studied in this chapter, t = 8.73 s can be calculated, the input power spectral density is shown in Fig. 3.

5. Dynamic Reliability Calculation

According to the time history analysis results of pure frame structure, traditional braced frame structure and buckling restrained braced frame structure, the inter story displacement angles displacement and velocity time history curve of each floor can be extracted to obtain the story displacement variance and velocity variance of the three structures. The dynamic reliability of the structure under rare earthquake and extremely rare earthquake is analyzed.

It can be seen from Fig. 4 that the frame structure with BRB is in a relatively safe category under rare earthquake action, and the structural reliability probability is about 96%, which is higher than that of traditional frame structure and pure frame structure, so it is a safe and reliable structural system. Under extremely rare earthquake, the reliability probability of pure frame structure is only 38%, while the reliability probability of traditional braced frame structure in buckling restrained braced frame structure is 60% and 69% respectively, which greatly improves the anti collapse ability of the structure under seismic load.

Table 1 The values of coefficient S_0 of Clough-Penzien model.

Earthquake intensity	Frequent earthquake	Medium earthquake	Rare earthquake	Extremely rare earthquake
$S_0/(\times 10^{-4}\ m^2 \cdot S^{-3})$	6.327	50.045	200.177	484.416

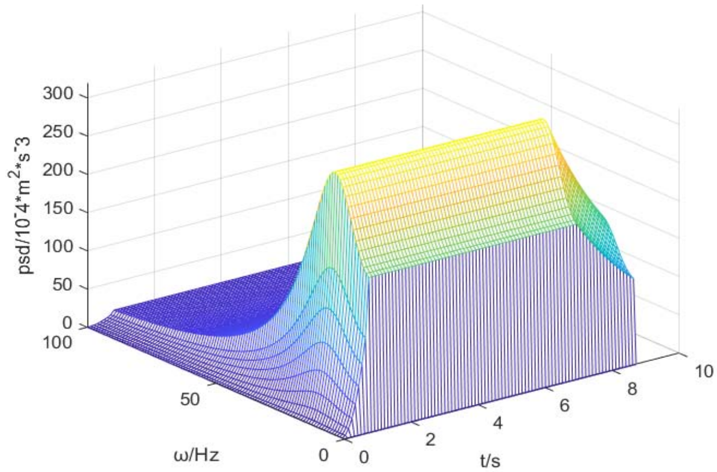
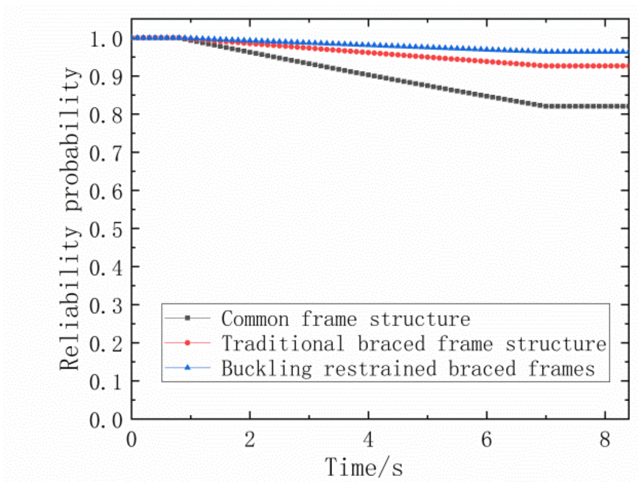
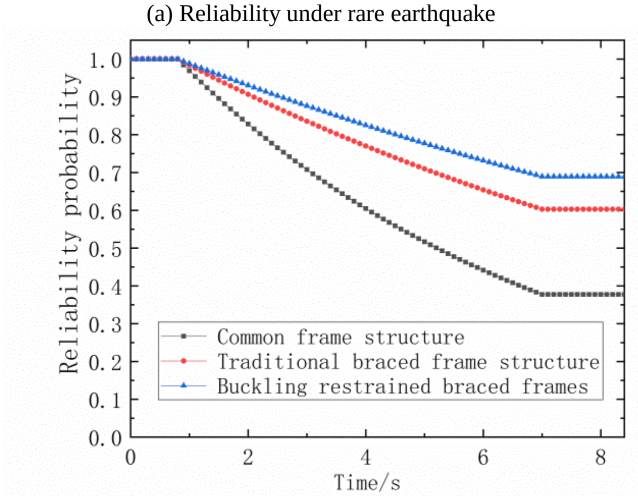


Fig. 3 Power spectral density of unsteady ground motion model under rare earthquake.



(a) Reliability under rare earthquake



(b) Reliability under extremely rare earthquake

Fig. 4 Dynamic reliability based on maximum story drift angle.

Due to the uncertainty of seismic load and structural parameters, each floor of the building structure may be damaged. The overall failure probability of the structure can be obtained by considering the connection between floors. The failure probability and overall failure probability of each floor are shown in Tables 2 and 3.

It can be seen that the overall reliability performance of BRB frame system is significantly higher than that of pure frame structure. In practical engineering, the reliability of frame system should be integrated according to Eq. (1), and the reliability interval of structural system can be obtained as shown in Figs. 5 and 6.

It can be seen from Fig. 5 that under rare earthquake, the reliability performance of the structure decreases after entering the stable section of seismic peak value. The reliability probability of frame system with BRB is significantly higher than that of traditional brace and pure frame system, and the upper and lower limits of structural reliability interval are closer.

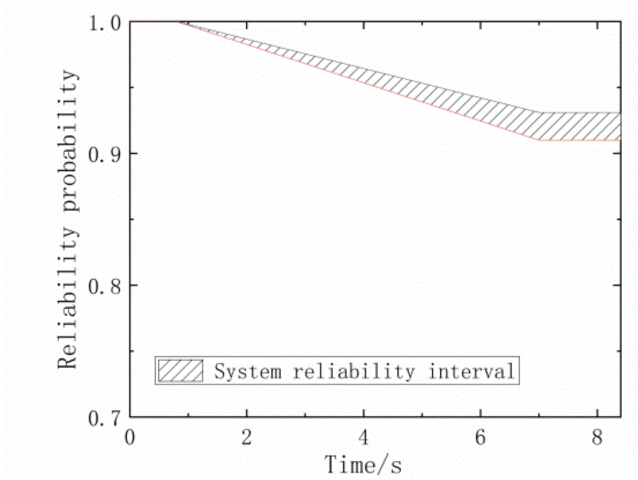
It can be seen from Fig. 6 that in the case of extremely rare earthquake, the reliability performance of the frame system strengthened with traditional braces is weak, and the reliability probability of the structure can still be effectively improved by using buckling restrained brace, but there is no obvious difference between the upper and lower limits of the reliability interval.

Table 2 Failure probability of each floor of structure under rare earthquake.

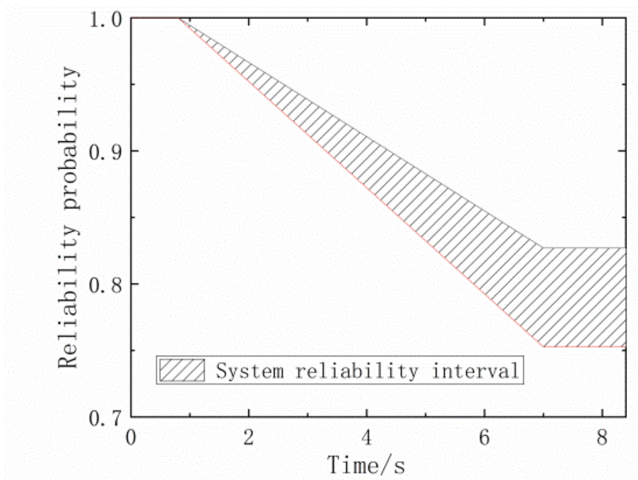
Floor	Common frame structure	Traditional braced frame structure	Buckling restrained braced frames
1	7.377×10^{-2}	2.481×10^{-2}	2.471×10^{-2}
2	1.730×10^{-1}	6.900×10^{-2}	4.100×10^{-2}
3	1.316×10^{-1}	2.857×10^{-2}	2.591×10^{-2}
4	4.315×10^{-2}	1.177×10^{-3}	9.875×10^{-4}
5	1.057×10^{-3}	7.323×10^{-5}	2.970×10^{-5}
6	3.323×10^{-8}	0	0
Whole failure probability	0.2474	0.0941	0.0604

Table 3 Failure probability of each floor of structure under extremely rare earthquake.

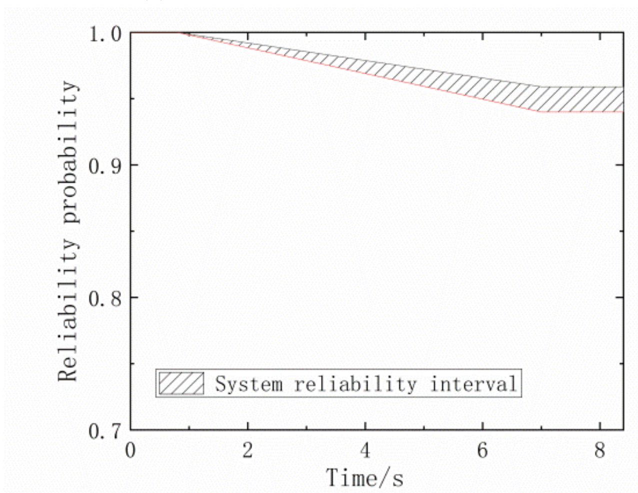
Floor	Common frame structure	Traditional braced frame structure	Buckling restrained braced frames
1	2.748×10^{-1}	1.431×10^{-1}	1.856×10^{-1}
2	6.210×10^{-1}	4.780×10^{-1}	3.080×10^{-1}
3	4.795×10^{-1}	1.648×10^{-1}	1.946×10^{-1}
4	1.559×10^{-1}	6.788×10^{-3}	7.418×10^{-3}
5	3.794×10^{-3}	4.224×10^{-4}	2.231×10^{-4}
6	1.193×10^{-7}	5.735×10^{-9}	0
Whole failure probability	0.7347	0.5640	0.4087



(a) Common frame structure

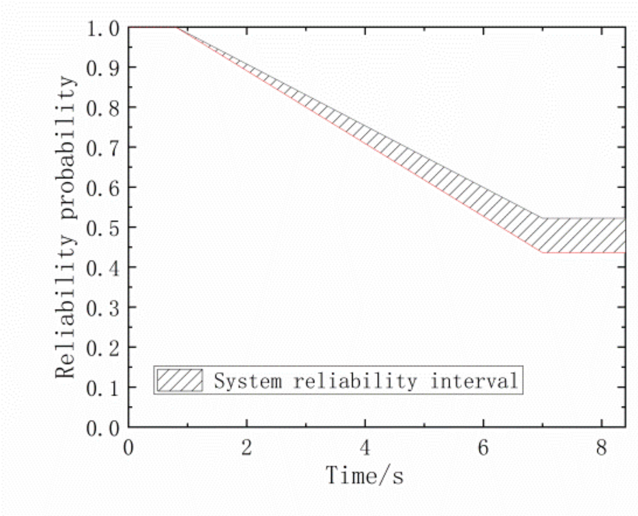


(b) Traditional braced frame structure

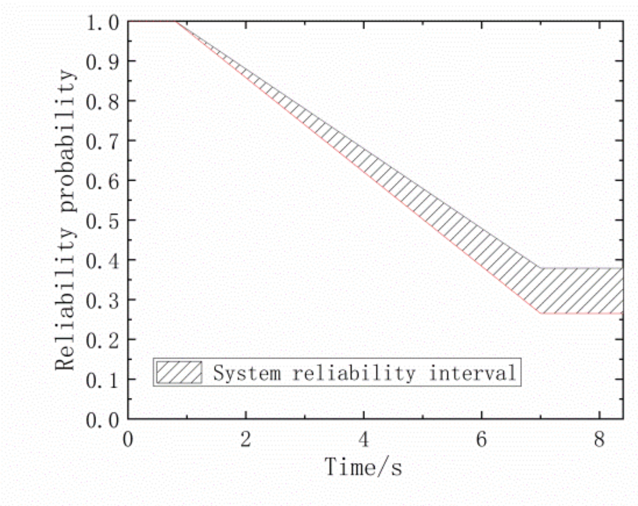


(c) Buckling restrained braced frames

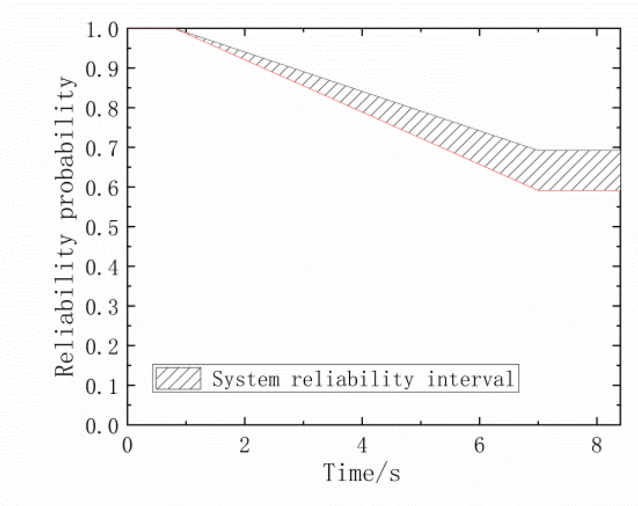
Fig. 5 Reliability interval of different structures under rare earthquake.



(a) Common frame structure



(b) Traditional braced frame structure



(c) Buckling restrained braced frames

Fig. 6 Reliability interval of different structures under extremely rare earthquake.

6. Conclusion

Based on the assumption of Poisson continuous cross process, the dynamic time history analysis of buckling restrained braced frame, traditional braced frame and pure frame under clough-penzien seismic model is carried out in this paper. The dynamic reliability of the three structures is obtained by taking the maximum elastic-plastic interlayer displacement angle as the safety limit. By considering the failure correlation between each floor of the frame structure, the structural dynamic reliability is obtained. The conclusions are as follows:

(1) Under rare earthquake, the reliability probability of BRB frame, traditional braced frame and pure frame structure are 96%, 93% and 82%, respectively. It can be seen that the BRB frame system can effectively improve the reliability probability of the structure and is a safe and reliable structural system. Under the extremely rare earthquake, the reliability probability of pure frame structure is only 38%, while the reliability probability of traditional braced frame structure is 60% and 69% respectively, which greatly improves the anti collapse ability of the structure under seismic load. The results show that the BRB is better than the traditional brace in the case of large earthquake loads that play the role of energy consumption.

(2) Under rare earthquake, the frame structure with buckling restrained brace can not only improve the reliability probability of the structure, but also the upper and lower limits of the reliability interval considering the failure correlation of each floor are closer, which shows that adding buckling restrained brace can reduce the discrete type of failure probability based on the variable capacity of the structure; under the extremely rare earthquake, the frame system with buckling restrained brace has high reliability. In the other two, the upper and lower limits of structural reliability have not changed significantly.

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