COLLAPSE RESISTANT RELIABILITY OF ISOLATED FRAME-SHEAR-WALL WITH STRUCTURE AND EXCITATION RANDOMNESS

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Abstract

This paper presents reliability analysis of the isolated frame-shear-wall using the reliability theory considering both randomness of structure and excitation. Through isolation application experience, the shear-wall in an isolated frame-shear-wall structure is not only decided by the vertical loading, but dominantly controlled by the horizontal earthquake action, and the placement of isolators should be decided by considering reasonable balance between isolator displacement and inter-story shear force ratio, which might be balanced by structural reliability. In this paper, The analysis of reliability is carried out for an isolated frame-shear-wall designed by the author’s research team, and the collapse probability of the isolated frame-shear-wall structure under the horizontal earthquake is obtained intuitively. The results show that under the action of earthquake, especially under strong earthquake, the rubber bearing under the shear wall is more vulnerable to tensile and compression, and its damage index is generally larger than that under the column under in the isolated frame.

Keywords: isolated structures; frame-shear-wall structure; collapse probability; reliability

1. Introduction

Frame-shear-wall structures, one of the most commonly used type of structural system for high- and medium- rise buildings, find more and more applications in the actual isolation project. With the aspect ratio increasing, the overturning effect of isolated frame-shear-wall under horizontal earthquake is more obvious compared to isolated frame structure with similar aspect ratio. The shear-wall in the isolated frame-shear-wall structure carries most of the overturning moment of building, which makes the tensile stress to appear in the rubber bearing under the shear wall. Thus, the placement of isolators under the shear-wall in an isolated frame-shear-wall structure is not only decided by the vertical loading, but dominantly controlled by the horizontal earthquake action, and should be decided considering reasonable balance between isolator displacement and inter-story shear force ratio of the super structure. An ideal balanced value might be searched using structural reliability theory. In this paper, the analysis of reliability is carried out for an example of isolated frame-shear-wall, which is a real building project designed by the author's research team, and the collapse probability of the isolated frame-shear-wall structure under the horizontal earthquake is obtained intuitively considering both randomness of structure and excitation.

2. Collapse Reliability Analysis of Lateral Increment of Isolated Frame-Shear Wall

2.1 Limit state equation of earthquake damage of the whole structure

For the isolation structure, damage index is taken as the performance index for the whole structure of isolated frame-shear-wall, which makes up the deficiency of the deformation criterion. The hysteresis energy consumption of the component can be considered for the super structure, and the deformation, energy consumption, tensile and compression characteristics might be involved for the rubber bearing. Therefore, the limit state function of the seismic damage of the overall isolated frame-shear-wall structure in terms of the damage index can be expressed as:

$$Z_{\mathrm{f}} = g_{\mathrm{f}}(x) = L_{\mathrm{f}} - D_{\mathrm{f}} \tag{1}$$

$$Z_{\mathrm{I}} = g_{\mathrm{I}}(x) = L_{\mathrm{I}} - D_{\mathrm{I}} \tag{2}$$

Where, Z_f is the limit state function of the super structure. L_f is the limit value of earthquake damage index of the super structure. D_f is the damage index of the super structure. Z_I is the limit state function of the isolation layer. L_I is the limit value of earthquake damage index the isolation layer, and D_I is the damage index of the isolation layer.

2.2 Probability of cumulative damage using SORM and probability density evolution

Using improved Rosen Bruce quadratic fourth-order moment (QFM) and probability density evolution method, the first four origin- and centre-moment can be calculated, respectively. The statistical parameter of the first four centre-moment for standardized random variable *R*(0, 1, *C*_r*Z*, *E*_k*Z*) and the probability density corresponding to maximum entropy can be derived

$$\int_{-\infty}^{+\infty} R_r^i \exp\left(-\sum_{j=0}^{4} \lambda_j R_r^j\right) dR_r = \rho_i \qquad (i = 0,1,2,3,4) \tag{3}$$

After solving for λ_i, the failure probability of the structure can be obtained:

$$P_{\mathrm{f}} = P(Z<0) = P(R < -\frac{\mu_R}{\sigma_R}) = \int_{-\infty}^{-\frac{\mu_{R_Y}}{\sigma_{R_Y}}} R_Y^i \exp\left(-\sum_{i=0}^{4} \lambda_i R^i\right) dR \tag{4}$$

3. Reliability Analysis of Vertical Progressive Collapse of Isolated Frame-Shear-Wall

This section deals with traditional progressive collapse issue of isolated frame-shear-wall structures without earthquake action involved.

3.1 Discrimination of the most vulnerable rubber isolator under earthquake action

As is known to all, the load bearing capacity limit state is relatively a conservative limit state of a structure, especially under the earthquake action, the failure of the component is a kind of low-cycle fatigue damage. Therefore, this paper will use the cumulative damage limit state method to identify the most vulnerable components under earthquake action. Only the case of rubber bearing failure will be considered in this paper, and the reliability of the structure is analyzed for vertical progressive collapse. The calculation method of damage index of isolation bearing is given as follows (Du, et al, 2018b)

$$D_{IS} = \max\left(\frac{r_i}{R_i}\right) + \frac{\beta^-}{Q_d \delta_d}\sum E_d + \beta^+ \frac{\sigma_i}{\sigma_u} \quad (i = 0,1,2,3,4) \tag{5}$$

Where r_i, R_i are the shear deformation and ultimate shear deformation, respectively, of the rubber isolator. Q_d, δ_d are the yielding load and ultimate displacement, respectively, of the rubber isolator. $\sum E_d$ is the cumulative hysteresis energy damage of the rubber isolator (Du, *et al*, 2018a). σ_i, σ_u are the stress and ultimate stress, respectively. β^- is the energy dissipation factor, and β^+ is the damage factor (tensile or compression). The limit state equation of the rubber isolator in terms of cumulative damage is

$$Z_{IS} = g[L_{IS}, D_{IS}(x)] = L_{IS} - D_{IS}(x) \tag{6}$$

In Eq (6), D_{IS} is the damage index under earthquake action, and L_{IS} is the limit value of damage index of the rubber isolator.

3.2 Limit state equation of vertical progressive collapse of isolated frame-shear-wall structure

Where r_i, R_i are the shear deformation and ultimate shear deformation, respectively, of the rubber isolator. Q_d, δ_d are the yielding load and ultimate displacement, respectively, of the rubber isolator. $\sum E_d$ is the cumulative hysteresis energy damage of the rubber isolator (Du, *et al*, 2018a). σ_i, σ_u are the stress and ultimate stress, respectively. β^- is the energy dissipation factor, and β^+ is the damage factor (tensile or compression). The limit state equation of the rubber isolator in terms of cumulative damage is

$$\alpha = \frac{D + 0.25L}{Q} \tag{7}$$

Where Q is the maximum vertical dynamic load which the remaining structure can carry.

The index α has been applied in the analysis of structural reliability, which was used to evaluate the vertical progressive collapse resistant ability of the structure (SONG and LYU, 2013). This paper adopts α as the performance index for measuring the damage of structure. With this, the limit state equation for the vertical progressive collapse of the remaining structure after the failure of isolation bearing is:

$$Z = g(\alpha) = \alpha(D + 0.25L) - D - L \tag{8}$$

It can be seen from equation (8) that the structure is safe when the maximum vertical dynamic load $\alpha(D + 0.25L)$ is less than $(D + L)$. The structure will be at the limit state of vertical progressive collapse when the maximum vertical dynamic load $\alpha(D + 0.25L)$ is equal to $(D + L)$, and the vertical progressive collapse will occur in the remaining structure when the maximum vertical dynamic load $\alpha(D + 0.25L)$ is greater than $(D + L)$ (Huang, *et al*, 2017):

4. Limit State of damaged Isolated Frame-Shear-Wall for Lateral Collapse

This section deals with lateral incremental collapse issue of isolated frame-shear-wall structures considering aftershock of earthquake.

4.1 Discrimination of the most vulnerable beam in isolation layer under earthquake action

Under the action of the main- and after- shock sequence type of earthquake, the process of damage to collapse of the structure is the process of damage accumulated from initial state to failure under the action of earthquake. Because the column of the super-structure is supported on the beam in isolation layer after the isolator is removed, and the collapse of the column is decided by the damage of the supporting beam. The damage index of the most severely damaged beam in the damaged span will be chosen as the index of vertical progressive collapse caused by the failure of beam with the isolator removed. The most vulnerable beam in isolation layer can be identified according to this idea using the reliability index from the following limit state equation (Huang, et al, 2018a)

$$Z_{bi} = L_{bi} - D_{bi} \tag{9}$$

Where D_{bi} , L_{bi} are the damage index and ultimate value of the damage index, respectively, of the supporting beam in the isolation layer. The beam span with least value of reliability index and $Z_{bi} < 0$ might be identified as the most vulnerable beam in isolation layer under earthquake action after the isolator is removed.

4.2 Limit state equation of damaged structure for main- and after-shock type of earthquake

Under the action of the main- and after- shock sequence type of earthquake, the overall damage index of the isolation layer is taken as the index of the lateral progressive collapse caused by the earthquake action after the isolator is removed. Because the structure is usually assumed to have been damaged in the main shock of earthquake, the lateral progressive collapse of such type of structure in the after-shock then became an issue of progressive collapse of a damaged structure, and the limit state equation of the lateral progressive collapse of the damaged structure in the after-shock can be expressed as:

$$Z_{bi} = L_{bi} - D_{bi} \tag{10}$$

Where D_{di} , L_{di} are the damage index and ultimate value of the damage index in after-shock, respectively, of the super-structure in the isolated frame-shear-wall structure, which has been damaged in the main shock of earthquake. The failure probability can be obtained using general reliability analysis method corresponding to $Z_{di} < 0$.

5. Numerical Examples

In this paper, an RC frame-shear-wall structure in high intensity area, which is revised from a real project designed by the author's team, is taken as a numerical example. The building is a production dispatch complex with typical irregular plan. The height of the first, second and eighth storey is 5.4m, and the rest is 4.8m. One may notice that this building is of relatively larger storey height because of functional requirements. The seismic fortification intensity of the building site is 8 degrees (0.2g), and fortification category of the structure is the class B, according to Chinese seismic design code. The design earthquake group type is the group three, and the site ground category is class II. In order to meet the functional requirements of user, six columns in the eighth floor marked with red box need to be removed as shown in the plan Figure 1. (Huang, 2017).

RC frame-shear-wall structure is adopted for this building, taking into account that the total structural height exceeds 40m, the storey height is relatively large and plan layout and column arrangement of the building is a little bit more complicated.

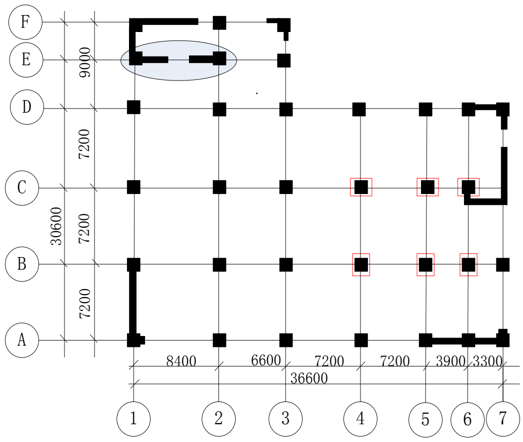
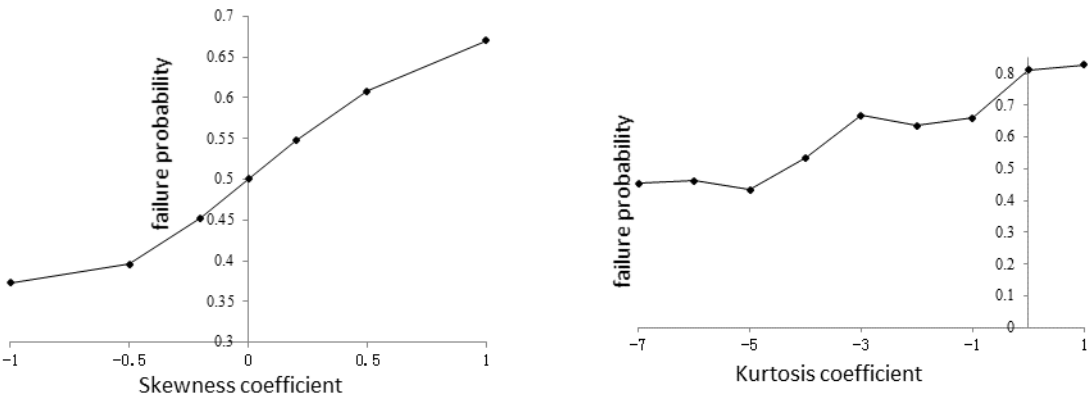


Fig. 1 –plan of production dispatch of RC frame-shear-wall structure

The steel HRB335 is used as the main reinforcement of beams, plates, columns, shear walls and other structural components, except for the constructional reinforcement, which uses steel HPB235. The thickness of shear wall in the A-B axis is 400mm and the rest is 300mm. The size of the beam's section is 300×700 mm2. The thickness of floor is 100mm. The cross-sections are 800×800, 700×700 and 600×600 mm^2 , respectively, for the side columns, middle columns in floor1-5 and in floor 6-8. The remaining parameters of the structure and detailed calculation using ABAQUS and PERFROM-3D can be found in the PhD thesis by the second author (Huang, 2017).

5.1 Reliability analysis of lateral incremental collapse of isolated frame–shear-wall structure

According to the quadratic fourth order moment method, the failure probability of the structure can be calculated by adjusting the skewness and the kurtosis coefficient, as shown in Figure 2a and Figur 3b.



(a) Effect of skewness coefficient (b) Effect of kurtosis coefficien

Fig. 2 –Effect of parameters on failure probability

From Figure 2a, one can see that the smaller the skewness coefficient is, the greater the degree of the bias of the damage index to the left side of the mean, and the smaller the value of failure probability is; the larger the skewness coefficient, the greater the damage index bias is to the right side of the mean value, and the greater the degree of failure probability is. The largest failure probability is 0.671, and the minimum failure probability is 0.373, which brings a difference of 44.356%. Similarly, the effect of the kurtosis coefficient on the failure probability can be seen from Figure 2b. The maximum failure probability is 0.827, and the minimum failure probability is 0.455, with the difference being 45.09%.

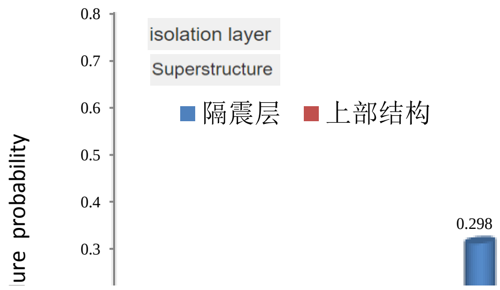


Fig. 3 – Failure probability of the structure

From Figure 3, when the peak ground acceleration is less than 0.6g, the probability of lateral incremental collapse are 0 for both the super structure and isolation layer, which means that when the PGA value is less than 0.6g, almost not need to consider the risk for lateral incremental collapse of the structure. When the peak value of ground acceleration is 0.8g, the probability of failure of the isolation layer is 0.021, and the probability of failure of the super structure is still 0, which means that when the value of PGA reaches 0.8g, lateral incremental collapse of the structure might occur due to the failure of the isolation layer, but the probability of collapse is fairly small. In contrast to the above situation, when the value of PGA reaches 1.0g, the lateral incremental collapse is likely to occur either in the superstructure or in the isolation layer. With the increase of the PGA, the failure probability increases correspondingly, which indicates an increased possibility of lateral incremental collapse with higher PGA value, and show that the model and method proposed in this paper is basically reasonable.

For the isolation structure, because the isolation layer and the superstructure forms a serially connected system, any of the two parts fails, the structure is regarded as being failed. Usually, the failure probability of the isolation layer is regarded as the failure probability of the isolated structure, because the isolation layer has a relatively larger failure probability in a properly designed isolated structure.

5.2 Reliability analysis of vertical progressive collapse of isolated frame-shear-wall

The alternate load path (ALP) method is used to simulate progressive collapse of the remaining structure after the rubber isolators at both ends of the shear wall and the rubber isolators under the frame column removed without the action of the earthquake considered. When the action of earthquake is considered, the ALP method is used combined with the pushover analysis to simulate the failure of the remaining structure with the rubber isolators at both ends of the shear wall and the rubber bearing under the frame column removed. The first four statistical moments of the limit state function are calculated using the improved Rosen Bruce method combined with the vertical stochastic IDA analysis, as shown in Table 1. The failure probability of vertical progressive collapse of isolated frame-shear-wall structure is calculated using QFM, by substituting the values of the four statistical moments into the limit state equation for the vertical progressive collapse, as shown in Figure 4.

Table 1 –First four statistical moments of limit state function

Earthq Action	Failed bearing	Mean	Variation	Skewness	Kurtosis
Yes	A2	-0.453	-0.391	0.809	-0.314
		-0.204	-1.161	0.788	-0.319
No	A1B1	0.322	1.225	0.795	-0.317
		0.958	0.604	0.823	-0.268

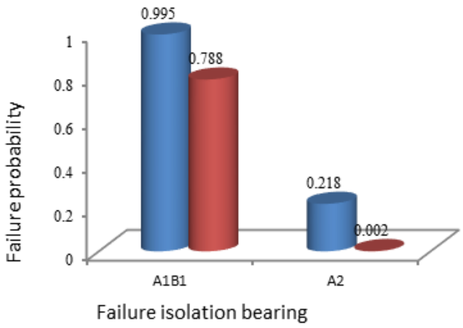
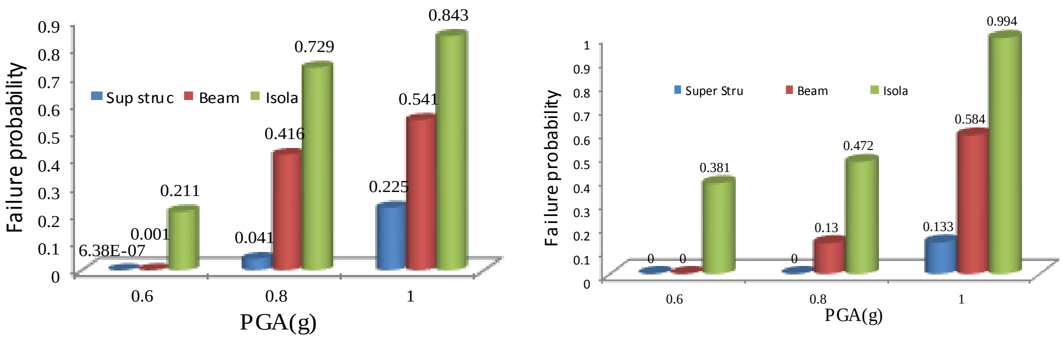


Fig. 4 –Failure probability of vertical progress collapse

5.3 Reliability analysis of progressive collapse of damaged isolated frame-shear-wall

In this section, the main shock is set to be 1.2g, and a higher aftershock of 0.6g, 0.8g and 1.0g, are used to investigate the damaged structure, using the main- and after- shock sequence type of earthquake as input. With the rubber isolator under side column of the frame structure, and under the shear wall removed, the failure probability of the remaining structure for lateral incremental collapse, are shown in figures 5a, and 5b, respectively.



(a) isolator under side column removed (b) isolator under shear-wall removed

Fig. 5 – Failure probability with isolator at different positions removed

Comparing figure 5a, and 5b, one can see that when the main shock of the earthquake is 1.2g and the aftershocks is 1.0g, the failure probability of the vertical progressive collapse due to the failure of the isolation layer is 0.843 with the isolator under side column removed, and the failure probability of the lateral progressive collapse with the isolator under middle column removed is 0.208 (figure not listed). The failure probability of the vertical progressive collapse is 0.541 due to the failure of the beam, and the failure probability of the lateral progressive collapse is 0.587. For the case with the isolator under the shear wall removed, the failure probability of the vertical collapse of the super structure due to the failure of the beam is 0.133, and the failure probability of the isolation layer for the lateral progressive collapse to occur is 0.994, indicating that the failure probability of lateral progressive collapse of the structure is the highest due to the isolation layer failure for the case with the isolator under the shear wall removed. The failure probability of the structure with the isolator under the side column removed is the second highest, and the most likely failure mode may be the vertical progressive collapse due to the failure of the beam in the isolation layer. The failure probability of the remaining structure with the isolator under the middle column removed is the smallest, with the most possible failure mode being lateral progressive collapse due to the failure of the super structure.

6. Conclusion

1) The damage to collapse of a structure is a complicate process of structural performance state transition, and is usually difficult to identify due to the complexity of the structural damage system and failure mode. Using damage index together with structural reliability seems to be a fairly useful method for measuring the structural performance to resist the vertical and lateral progressive collapse, as well as to identify the most likely failure mode.

2) The results show that the method proposed in this study is reasonable, and can be used for reliability analysis of the isolated frame-shear-wall structure. The failure probability can not only provide better understanding for the damage and collapse mechanism of the isolated frame-shear-wall structure with and without earthquake action, but also provide useful information for structural design and post-quake retrofit for isolated frame-shear-wall structure.

3) Using the seismic damage based reliability analysis method, the failure probability of the overall structure can be obtained, which enables the reliability analysis be realized from the component level to the structural level for the isolated frame-shear-wall structure, and clearly provided the failure probability of different parts of structure, i.e., the super structure and the isolation layer.

4) For the case considering earthquake action, especially under strong earthquake, the rubber bearing under shear wall is more prone to tensile and compression damage, and its damage index is generally larger than the damage index of isolation bearing under the column in a frame. The parameter of isolators under the shear-wall in an isolated frame-shear-wall structure is not only decided by the vertical loading, but dominantly controlled by the horizontal earthquake action Therefore, in the isolation design, the rubber bearing under shear wall need more attention and further special treatment.

7. Acknowledgements

This research is financially supported in part by the Natural Science Foundation of China under Project No. 51778276 and 51578274, and in part by the Key R&D Plan of Gansu province under Project No. 18YF-1FA067. This support is gratefully acknowledged.

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