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System Reliability Analysis of Existing Frame Structure Based on Failure Correlation

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Abstract: Using Monte-Carlo simulation method, through failure correlation analysis of sectional constraints under medium and small earthquakes respectively, the failure correlation rules of sectional constraints of frame structure are obtained, and they are simplified into hypothesis which can be used in reliability evaluation of existing frame structure. Moreover, the use of correlation rule in system reliability analysis is illustrated by two examples.

Key words: existing structure; frame structure; system reliability

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Introduction

System reliability of structure is an important index indicting the integral safety, so it is very appropriate that system reliability is used to represent the integral bearing capacity of frame structure. However, due to the limit of research level, in current reliability appraisal practice, the bearing capacity of a member or the whole structure is determined by the bearing capacity of the most vulnerable section in a worst member. As a result, the appraisal result obtained in this way is usually far away from the factual bearing capacity of a frame structure.

The failure of a frame structure can be expressed as the failure of a series system consisting of all failure modes of the structure, and that is

$$P_f = P\{\overline{\Omega_s}\} = P\{\bigcup_{j=1}^{k} \overline{\Omega_j}\} . \qquad (1)$$

Herein, $\overline{\Omega_s}$ denoting the failure domain, $\overline{\Omega_j}$, $j = 1, \cdots, k$ denoting k failure modes.

While, the failure of a certain mode of frame structure system can be expressed as the failure of a parallel system composed of all failure elements of this mode, and it is as follows:

$$P\{\overline{\Omega_j}\} = P\{\bigcap_{i \in N_j} F_i\} \quad (j = 1 \sim k) . \qquad (2)$$

Herein, N_j denoting that there are totally N_j failure elements in the j_{th} failure mode, and F_i denoting the i_{th} failure element in the j_{th} failure mode.

However, there may be hundreds of thousands failure modes occurred in one factual high-rise frame structure, and there also exists complicated statistical correlation among all failure modes. So it is very onerous and difficult to calculate the system reliability of frame structure when directly using Eq.(1) and Eq.(2), and it may be impossible at sometimes. The common practice is to introduce some hypothesis to simplify the computation of system reliability.

As to the existing frame structures, based on structural diagnose, survey and sectional check, the number of key failure constraints may be limited, with the correlation between sectional constraints being taken into consideration, it is feasible to calculate the system reliability of frame structure under a certain failure criterion[1].

1 Failure Correlation between Sectional Constraints

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1.1 Analysis method

The methods adopted by this paper include Monte - Carlo random simulation method and correlation checking of series. The fundamental theories of random analysis see reference[2].

1.2 Analysis parameters

In this paper, random simulation tests are mainly done on the RC frame structures less than 5 spans and 12 stories. In detail, the test modes can be classified into three categories, i.e. design symmetric regular frame structure, approximate symmetric regular frame structure, and non - symmetric irregular frame structure. While each kind of frame structure is also classified into two groups of structure of 6 and 12 stories respectively, and their detailed parameters can be seen in Table 1 and Table 2.

Table 1 The parameters of RC frame of 12 stories

No. of types		span/m	story height/m
	(1)	6.0,3.6,6.0	6.0,4.5,3.6×10
	(2)	6.0,3.6,6.0	6.0,3.6×11
	(3)	6.0,3.6,6.0	6.0,3.6×10,4.5
A	(4)	6.0,3.6,6.0	4.5,3.6×11
	(5)	6.0,3.6,6.0	4.5,3.6×10,4.5
	(6)	6.0,3.6,6.0	4.5,4.5,3.6×10
	(7)	3.6×5	4.5,3.6×11
	(8)	3.6×4	4.5,3.6×11
B	(9)	6.9,3.3,7.2	6.0,3.6×11
	(10)	6.9,3.3,7.2	6.0,4.5,3.6×10
C	(11)	6.0,4.8,7.2	6.0,3.6×11
	(12)	6.0,4.8,7.2	6.0,4.5,3.6×10

Table 2 The parameters of RC frame of 6 stories

No. of types		span/m	story height/m
	(13)	6.0,3.3,6.0	6.0,3.6×5
A	(14)	6.0,3.6,6.0	6.0,3.6×5
	(15)	6.0,3.6,6.0	4.5,3.6×5
	(16)	6.0,3.6,6.0	6.0,3.6×5
B	(17)	6.9,3.3,7.2	6.0,3.6×5
C	(18)	6.9,4.5,7.2	6.0,3.6×5
	(19)	6.0,4.8,7.2	6.0,3.6×5

Note: A is for design symmetric structure; B is for approximate symmetric structure; C is for non - symmetric structure.

1.3 Correlation rules

1.3.1 Under minor earthquakes

As to the RC frame structure designed according to aseismatic specification, the correlation rules among sectional constrains are very weak. The more the vertical loads taken into consideration, the weaker the failure correlation is. According to a large amount of stochastic simulation test, we reach a conclusion that under minor earthquakes the failures of sectional constraints of RC frame structure can be taken as independent.

1.3.2 Under medium earthquakes

(1) As to the design symmetrical or approximately symmetrical frame structure, the failure of sectional constraints of frame beams and columns of the same type and at the symmetrical positions are fully correlated.

(2) For non - design symmetrical frame structures, the failures of sectional constraints of frame beams of the same type and of the symmetrical positions are fully correlated, while the failures of sectional constraints of frame columns of the same type and of the symmetrical positions are approximately independent.

2 Basic Hypothesis and Calculation Method

2.1 Basic hypothesis

In order to simplify the calculation of system reliability, based on the obtained failure correlation rules of sectional constraints and available earthquake hazard references[4], the following hypothesis are presented.

(1) There are only two states of sectional constraints taken into consideration, and they are "reliable" denoted by "1" and "failed" denoted by "0";

(2) When a minor earthquake lower than reference level occur, all the sectional constraints of frame structure are assumed as failure independent.

(3) When hit by a medium earthquake, the failure of all sectional constraints of frame columns is assumed as fully correlated, while the failure of sectional constraints of frame beams is reckoned as independent.

2.2 Simplified method of system reliability

2.2.1 Under minor earthquake

According to the stipulation of "No Damage under Minor Earthquake" in "Aseismic Design Code of Building Structure" (GBJ 11 - 89), the failure of any sectional constraint of frame structure under minor earthquake can be thought as the failure of frame structure itself. That is to say, any failed sectional constraint can be regarded as a failure mode. So, the failure probability of a frame structure under minor earthquake can be written as:

$$P_f = 1 - \prod_{i=1}^{n} (1 - P_{fi}) . \qquad (3)$$

Herein, P_{fi} representing the failure probability of each sectional constraint.

Once the failed sectional constraints of frame structure and their failure probability are obtained through structural diagnose and analysis, the failure probability of the whole system can be got according to Eq.(3).

2.2.2 Under medium earthquake

Through the analysis of reference [3], under medium earthquakes, all the sectional constraints of structure are not fully correlated, so some states in the expression of structural failure domain may not occur. In this case, fully correlated constraints in structural failure domain should be dealt with according to the hypothesis of "Weakest Constraint", and then the integral failure probability can be obtained, see reference[3].

3 Examples[3]

3.1 Under minor earthquakes

Example 1: A six - story RC frame designed according to the aseismatic code is shown in Fig.1. After serving several years under ordinary atmospheric environment, through structural inspection and sectional check, the probable failure constraints is found and numbered, and their places are shown in Fig. 1. Their failure probabilities are listed in Table 3. Please determine the system reliability of the structure under minor earthquakes.

Table 3 Failure probability of constraints of the structure shown in Fig.1

failed constraint	1	2	3	4	5	6	7	8	9	10
failure probability	0.001	0.001	0.002	0.002	0.001	0.003	0.001	00.001	0.003	0.003

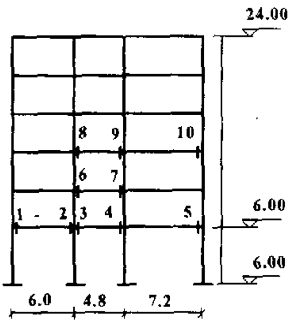

Fig.1 Sectional constraints of example 1

When the hypothesis of "failure independence" is adopted under small earthquakes, the number of failed sectional constraints of the structure is equal to the number of the minimum failure set. So the structure in Fig. 1 has 10 minimum failure sets, and they are $\{0_1\}, \{0_2\}, \{0_3\}, \{0_4\}, \{0_5\}, \{0_6\}, \{0_7\}, \{0_8\}, \{0_9\}, \{0_{10}\}$ The failure probability of structural system with parameters shown in Table 3 will be

$$P_f = 1 - \prod_{i=1}^{10} (1 - P_{fi}) = 0.01786 .$$

To check the accuracy of above result, Monte - Carlo simulation method (2000 times) was used to obtain the failure probability of the same frame structure, and the failure probability is 0.018. The error of the two methods is less than 5%.

3.2 Under medium earthquakes

Example 2: A one - bay two - story RC frame designed according to the aseismatic code is shown in Fig.2.

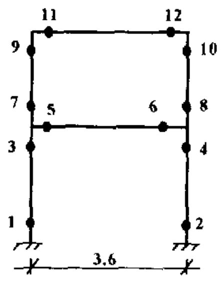

Fig.2 Sectional constraints of example 2

After serving several years, through structural inspection and sectional check under medium earthquake, the reliability parameters of sectional constraints of the structure are obtained and listed in Table 4. Please determine the system reliability of the structure under medium earthquake.

Table 4 Failure probability of constraints of the structure shown in Fig.2

failed constraint	1	2	3	4	5	6	7	8	9	10	11	12
failure probability	0.015	0.014	0.012	0.01	0.020	0.020	0.011	0.10	0.010	0.010	0.018	0.016
representing constraint	1	1	3	3	5	5	7	7	9	9	11	11

(1) On the basis of hypothesis above, there are six pairs of constraints correlated, and they are 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, 11 and 12. Making use of the "Weakest Constraint" hypothesis, we can get the representing constraint of each controlling constraint, they are shown in Fig.2, too.

(2) Under the medium earthquake, "Mechanical Failure" criterion is often used to judge whether a RC frame structure is failed or not. So the fame shown in Fig. 2 has 6 failure modes as below:

$\{0_1 \cap 0_3\}, \{0_7 \cap 0_9\}, \{0_7 \cap 0_{11}\}, \{0_1 \cap 0_5 \cap 0_7\}, \{0_1 \cap 0_5 \cap 0_9\}, \{0_3 \cap 0_5 \cap 0_9\}$.

The failure domain of the structure is written as

$$\overline{\Omega_S} = \{0_1 \cap 0_3\} \cup \{0_7 \cap 0_9\} \cup \{0_7 \cap 0_{11}\} \cup \{0_1 \cap 0_5 \cap 0_7\} \cup \{0_1 \cap 0_5 \cap 0_9\} \cup \{0_3 \cap 0_5 \cap 0_9\}.$$

(3) According to the "non – crossing" method[1], the complete expression of the failure domain of the structure can be changed into

$$\bar{\Omega}_S = 0_1 0_3 + 1_1 1_3 0_7 0_9 + 1_1 1_3 1_9 0_7 0_{11} + 1_3 1_9 1_{11} 0_1 0_5 0_7 + 1_3 1_7 1_{11} 0_1 0_5 0_9 + 1_1 1_7 1_{11} 0_3 0_5 0_9.$$

Because the representing constraints are independent each other, we can replace the failure states (0) of the representing constraints by their failure probabilities, and the reliable state (1) by their reliable probability. The failure probability of structural system with parameters shown in Table 2 can be obtained as below

$$P_f = 4.862 \times 10^{-4}.$$

The failure probability by Monte – Carlo simulation method (10000 times) of the same frame structure system is found to be 0.0005239, and the error of the two methods is 7.75%. So, the above calculation result can basically meet the demands of application in practical engineering.

4 Conclusions

Through the analysis above, some significant conclusions and suggestions can be obtained.

(1) Referring to the seismic hazard data[4] and the analysis of this paper, we suggest that different failure correlation hypothesis should be adopted respectively considering the failure correlation of the sectional constraints under the medium and minor earthquakes;

(2) Making use of the failure correlation of the sectional constraints will decrease the number of structural failure constraint and failure mode taken into consideration, and transform two kinds of correlation, namely the correlation of failure mode and the correlation of failure constraints, into one kind of correlation by "non – crossing" technique;

(3) For existing frame structures, the failure probability of the structural system can be obtained by the method proposed above, because the number of controlling failed sectional constraints is limited on the basis of actual diagnose and sectional check.

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基于相关性的在役框架结构体系可靠性分析

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摘　要：利用Monte – Carlo随机模拟方法，分别通过小震和中震下的失效相关性分析，得出了框架结构截面效应约束的失效相关性规律，并将其简化为便于可靠性分析的假设.通过算例给出了相关性规律在框架结构体系可靠性分析的应用.

关键词：在役结构；框架结构；体系可靠性