13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3448

AN INVESTIGATION ON COLUMN OVER-DESIGN FACTORS AVOIDING WEAK STORY MECHANISMS OF STEEL STRUCTURES

Yan-Gang ZHAO[1], Tetsuro ONO[2] and Kazuhiro YOSHIHARA[3]

SUMMARY

In the earthquake resistance design of a frame structure, the yielding of all the beams in flexure prior to possible yielding of columns, is generally considered to be a preferable failure mode. The reason is that the failure mode has a large ability to absorb earthquake energy before the structure actually collapses. Structures are therefore generally weak-beam-strong-column designed with a column over-design factor (COF). In reality, however, the designed weak-beam-strong-column structure may not collapse according to the preferable failure mode because of the considerable uncertainties in the external loads and the member strengths. These uncertainties may change the column over-design factor and the structure may collapse according to some unpreferable failure modes such as the weak story mechanisms. It is a general requirement to provide a suitable target value of the COF for which the occurrence probability of unpreferable failure modes can be limited to a specified tolerance. In the present paper, the likely failure modes of a weak-beam-strong-column designed structure with uncertain loads and with uncertain member strengths are investigated. The target value of column over-design factor avoiding weak story mechanisms is discussed in probabilistic terms. From the investigation, it can be found that the larger the number of stories, the larger the target value of the COF is required so that the probability ratio is limited to a given tolerance level.

INTRODUCTION

When carrying out the deterministic design of steel frame structures, some preferable failure modes are often selected and the strengths of the structural members are designed according to these selected failure modes. The weak-beam-strong-column designed structure is commonly used in earthquake resistance design to make the frame structure collapse according to the entire failure pattern, which allows the yielding of all the beams in flexure prior to possible yielding of columns (here after, it is referred as the beam-hinging pattern). This is considered to be a suitable failure pattern because of its large ability to absorb earthquake energy before the structure actually collapses [1, 2].

[1] Assoc. Professor, Nagoya Institute of Technology, Nagoya, Japan. E-mail: zhao@nitech.ac.jp
[2] Professor, Nagoya Institute of Technology, Nagoya, Japan. E-mail: ono@nitech.ac.jp
[3] Graduate student, Nagoya Institute of Tech., Nagoya, Japan. (Engineer, Kumagaigumi Co., Ltd., Nagoya, Japan) E-mail: kyoshiha@ku.kumagaigumi.co.jp

In order to ensure that a frame structure collapses according to the beam-hinging pattern, the columns of the structure are generally over-designed with a column over-design factor (COF). However, when a frame structure is designed as a weak-beam-strong-column structure, an important problem is that whether or not the designed structure collapses according to the designed failure mode. This problem is caused by the large uncertainties in the external loads and the member strengths. These uncertainties may change the designed COF, and the structure may collapse according to some unpreferable failure modes such as the partially column-failure pattern.

To introduce the uncertainties of the external loads and the member strengths into structural design, it is necessary to investigate all or at least some of the more important failure modes that result from these uncertainties. However, the number of potential failure modes is generally too large and the searching important failure modes may be complicated. It is almost impossible for a design engineer to consider such a large number of failure modes and their occurrence probabilities. It is a general requirement for researchers to give a suitable target value of the COF for which the occurrence probability of unpreferable failure modes can be limited to a specified tolerance.

Some case studies have been conducted and basic knowledge has been obtained on the value of COF that results in the beam-hinging pattern mode [3]. Weak story mechanisms are investigated in the paper, and the target value of the COF required to ensure that frame structures collapse according to the beam-hinging pattern is discussed. The target value of column over-design factor avoiding weak story mechanisms is discussed in probabilistic terms. From the investigation of this paper, it is found that the larger the number of stories, the larger the target value of the COF. The higher the reliability level is set when the structure is designed, the smaller the target value of the COF is required to limit the probability ratio to a given tolerance level.

DEFINITION AND ASSUMPTIONS

Basic Assumptions

For the ductile frame structures considered in this study, several commonly used assumptions are applied:

(1) Elastic-plastic frame structures are considered. The failure of a section means the imposition of a hinge and an artificial moment at this section.

(2) The structural uncertainties are represented by considering only moment capacities as random variables.

(3) Geometrical second-order and shear effects are neglected. The effect of axial forces on the reduction of moment capacities is also neglected.

Definition of Column Over-Design Factor

The likely failure modes of a specific structure under specific load are mainly dependent on the mean value and coefficient of variation of the member strength. Because a specific structure is generally constructed using the same kind of material (generally steel or concrete) through the whole structure and the coefficient of variation is mainly dependent to the material, the coefficient of variation of each member strength is assumed to be the same for all the members in the structure. The mean values of the member strengths can be therefore used as the main factor in the investigation.

For a one-storey one-bay structure, the COF is defined simply as the ratio between the mean value of the column strength and the mean value of the beam strength. This is because there is only one beam and one column at each node for such structure.

$$\mathrm{COF} = \frac{M_{pc}}{M_{pb}} \tag{1}$$

where M_{pc}, M_{pb} are the mean values of the ultimate moment of the columns and beams respectively.

For a multi-storey multi-bay structure, because the number of beams or columns is different for each node, the COF used in the investigation is defined for each node as the ratio between the sum of the mean values of the column strengths and the sum of mean values of the beam strengths, at that node, as follows

$$\mathrm{COF}(k) = \frac{\sum_i M_{pci}}{\sum_i M_{pbi}} \tag{2}$$

where k refers to the *kth* node and M_{pci}, M_{pbi} are the mean value of the ultimate moment of the columns and beams, connecting to the *kth* node, respectively.

Computational Assumptions

For convenience of investigation, the following assumptions are applied.

(1) All of the beams and columns are designed to make the structure have the same value of the COF at every node, i. e. there is only one value of the COF for a specific structure.

(2) The external load is considered to consist of only the static lateral earthquake loads which is often used for simple seismic design. This is assumed to be concentrated forces triangularly distributed along the height of the structures in consideration.

(2) Plastic moment capacities of sections are statistically independent of the applied loads and independent of each other.

All the variables are assumed to have a lognormal distribution. Because the frames in consideration are steel, the coefficient of variation of the member strengths is taken to be 0.1 [4]. Because the coefficient of variation for ground motion is generally taken to be 0.6-0.7 [5] and considering the other uncertainties included in load modeling, the coefficient of variation for the lateral forces is assumed to be 0.8.

INVESTIGATION ON WEAK-STORY MECHANISMS

Since there are so many weak-story mechanisms for a frame structure, it is necessary to investigate the likely mechanisms that dominantly influence the target COF. In the paper, these mechanisms are investigated using a 7-story and 2-bay frame.

Investigation on the Upper Collapse Type

The upper collapse type mechanisms are shown in Fig. 1 and the corresponding appearance probabilities are shown in Fig. 3. As shown in the figures, the order of appearance of the modes is not affected by the value of COF, and the more stores collapse, the higher the appearance probabilities. Since mode 5 is the most likely mechanisms among such collapse types, we only need to consider mode 5 when we investigate the target COF.

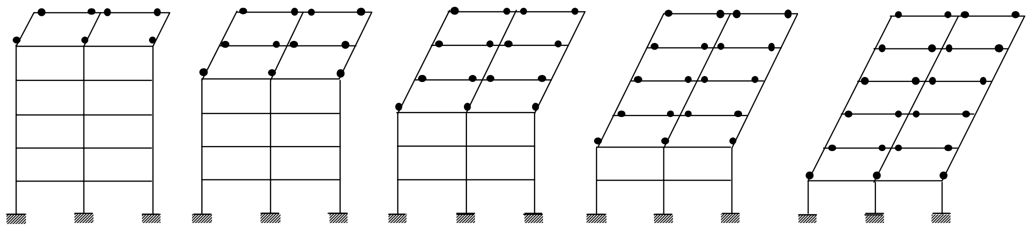


Fig. 1 Upper Collapse Type

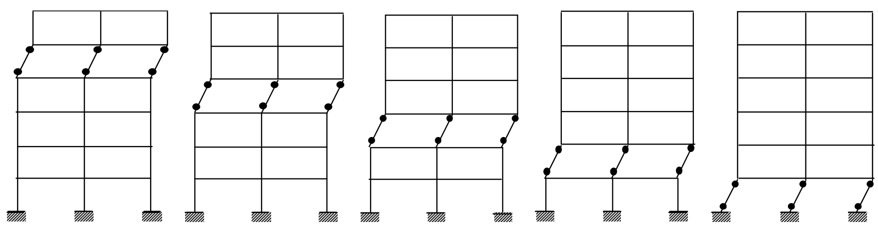
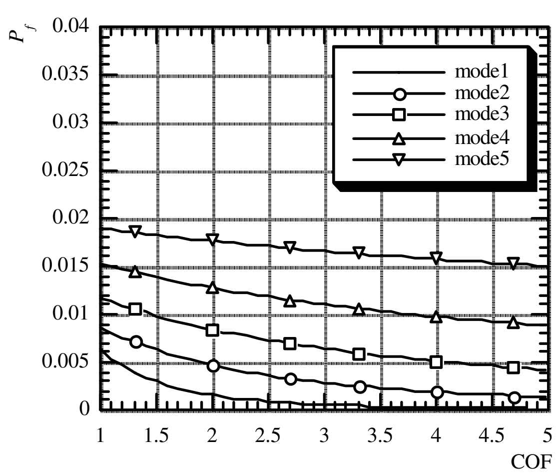


Fig. 2 Middle Collapse Type



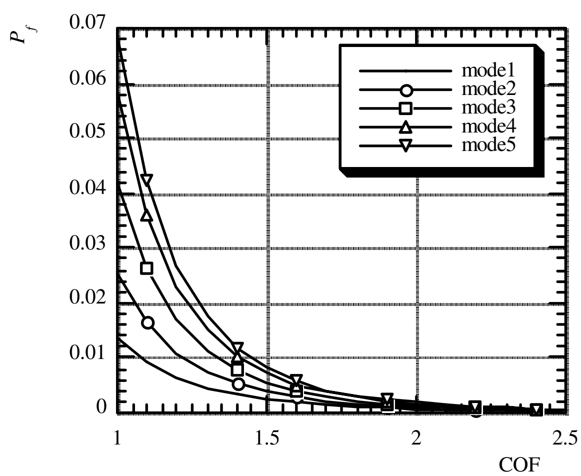


Fig. 3 Appearance prob. of upper collapse type

Fig. 4 Appearance prob. of middle collapse type

Investigation on the Middle Collapse Type

The middle collapse type mechanisms are shown in Fig. 2 and the corresponding appearance probabilities are shown in Fig. 4. As shown in the figures, the lower the stores collapse occurs, the higher the appearance probabilities, and the order of appearance of the modes is not affected by the value of COF. Since mode 5 is the most likely mechanisms among such collapse types, we only need to consider mode 5 in this type when we investigate the target COF.

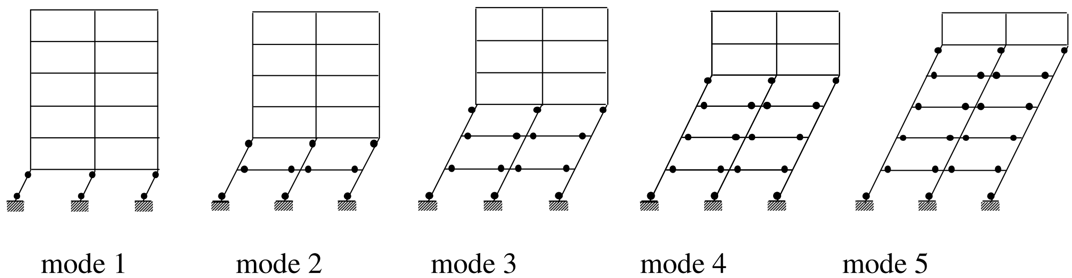


Fig. 5 Middle Collapse Type

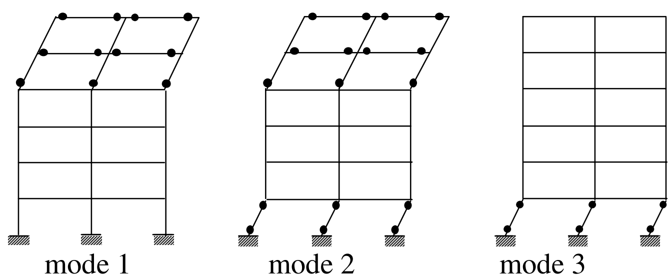
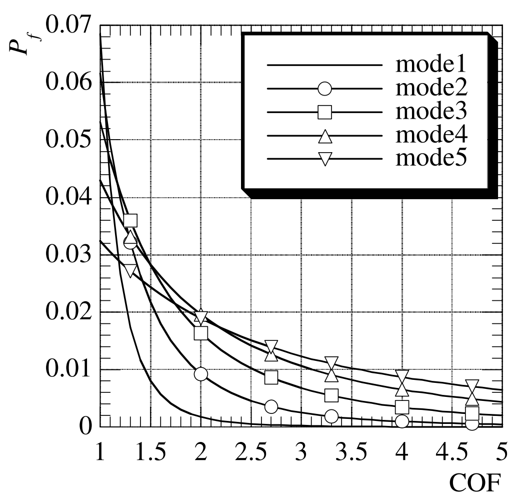


Fig. 6 Mixed Collapse Type



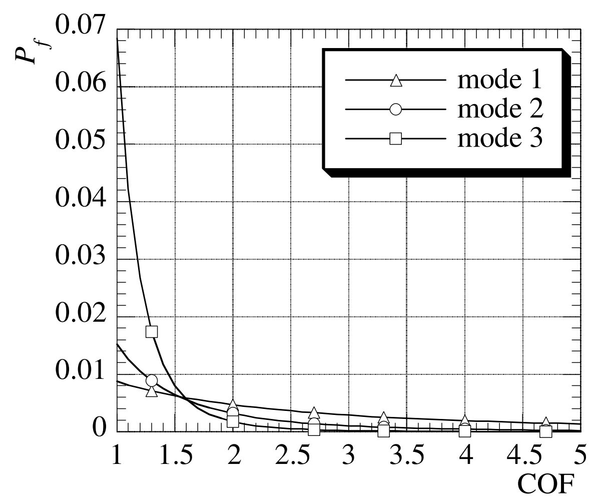


Fig. 7 Appearance prob. of lower collapse type   Fig. 8 Appearance prob. of mixed collapse type

Investigation on the Lower Collapse Type

In order to investigate occurrence probability of mixed mechanisms with comparison of upper and lower collapse type, three types of mechanism shown in Fig. 6 are considered. The occurrence probabilities corresponding to the three modes shown in Fig. 6 are shown in Fig. 8, from which one can see that in the whole investigated range of COF, mode 2 is not the most likely one among the three modes. This is to say, if the upper and lower collapse types are considered, it is not necessary to consider the mixed mode.

From the discussion above, one can conclude that in order to investigate the target COF, we need to consider all the lower collapse types and the mode 5 in the upper collapse type.

PROBABILISTIC EVALUATION OF COF

Evaluation Method

Because the structure is deterministically designed to collapse according to the entire beam-failure mode, the most likely failure mode is generally the preferable beam-hinging pattern mode, and all the other likely failure modes are unpreferable failure modes. Because the second most likely failure mode has the largest occurrence probability among all these unpreferable failure modes, the following evaluation index is used in the present paper to evaluate the relative occurrence rate of the unpreferable failure modes:

$$\gamma = \frac{P_{f2}}{P_{f1}} \tag{3}$$

Here p_{f1} is the occurrence probability of the most likely failure mode, i. e. the beam-hinging pattern mode. P_{f2} is the occurrence probability of the most likely failure mode among all the unpreferable failure modes.

In order to ensure that the designed structure collapses according to the designed preferable failure mode, the relative occurrence rate of the unpreferable failure modes γ should be limited to a specified allowable level γ_0 as follows,

$$\gamma = \frac{P_{f2}}{P_{f1}} \le \gamma_0 \tag{4}$$

The larger the value of the COF, the smaller the value of the relative occurrence rate of the unpreferable failure modes. By conducting stochastic limit analysis using different COFs for a frame structure, a γ-COF curve can be obtained, and the target value of the COF for which Eq. 4 is satisfied can be determined. In the present paper, levels of γ_0=0.7, 0.8, 0.9, 1.0 are investigated provisionally.

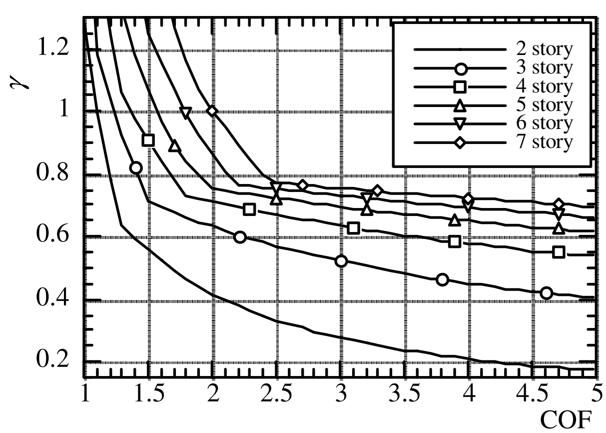


Fig. 9 γ-COF Curve (β=2.0, V_M=0.1, V_p=0.8)

Evaluation results for Target COF

Using the evaluation method above, the γ-COF curves for multi-story frames are shown in Fig. 9, where the reliability level is taken to be β=2, and the coefficients of the member strength and the earthquake load are taken to be V_M=0.1 and V_p=0.8, respectively. The target COFs for γ_0=0.7, 0.8, 0.9, 1.0 are listed in Table 1. One can see that, to avoid weak story mechanisms, a considerable larger value of the COF is required in the case that both the loads and the member strengths are uncertain than in the case of a deterministic member strength. One can also see that the target value of the COF is very sensitive to the tolerance level γ_0. For suitable stochastic evaluation of the target values of the COF, it is therefore very important to set an appropriate tolerance level. the values of the target COF increase with respect to the increase of the number of stories.

Table 1 Target COF (β=2.0, V_M=0.1, V_p=0.8)

	γ_0=1.0	γ_0=0.9	γ_0=0.8	γ_0=0.7
2-story	1.097	1.142	1.189	1.256
3-story	1.231	1.325	1.420	1.575
4-story	1.375	1.513	1.669	2.168
5-story	1.565	1.692	1.892	2.912
6-story	1.788	1.945	2.125	3.850
7-story	2.016	2.201	2.420	5.000

CONCLUSIONS

The target value of the column over-design factor avoiding weak story mechanisms was investigated in probabilistic terms. It is found that:

(1) To ensure that a frame structure collapse according to the strictly beam-failure pattern, a considerable larger value of the COF is required in the case of both the loads and the member strengths are uncertain than that in the case of a deterministic member strength.

(2) In order to investigate the target COF, it is necessary to consider all the lower collapse type mechanisms.

(3) The larger the number of stories, the larger the target value of the COF.

(4) The target value of the COF is very sensitive to the tolerance level γ_0. For suitable stochastic evaluation of the target values of the COF, it is therefore very important to set an appropriate tolerance level.

REFERENCES

1. Anderson, J.C. and Gupta, R.P. (1972), Earthquake Resistant Design of Unbraced Frames, J. Struct. Div., ASCE, 98 (ST 11), 2523-2539.
2. Lee, H.S. (1996), Revised Rule for Concept of strong column weak girder design, J. Structural Engineering, ASCE, 122(4), 359-364.
3. Kawano, A., Matsui, C. and Shimizu, R. (1998). Basic Properties of Column Over-design Factors for Steel Reinforced Concrete Frames, *J. Struct. Constr. Eng.*, No.505, 1998.3, 153-159.
4. Ultimate strength and deformation capacity of building in seismic design,(1990), *Architecture Institute of Japan*.
5. Recommendations for loads on buildings, (1993), *Architecture Institute of Japan*.
6. Ono, T. and Zhao, Y.G., (2000). Probabilistic evaluation of column over-design factors for frames, *J. Structural Engineering, ACSE, Vol.* 126*, No. 5, 605-611*