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COLLAPSE CONTROL OF IRREGULAR WALL BUILDINGS USING STORY-SAFETY FACTOR

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SUMMARY

Wall buildings with vertically irregular configurations have been severely damaged or collapsed due to a story mechanism during severe earthquakes. This paper presents a criterion to prevent such failures. A story-safety factor is defined to represent the relative reserve strength against a story mechanism of the structure. The validity of this factor was examined by conducting dynamic response analyses of various analytical models of 7- and 11-story wall structures with an irregularity at the first story using two real earthquake records with long and short vibration periods and their numerous generated motions. The results show that the story-safety factor well controlled the failure mechanism of the structures. When the story-safety factor was larger than the corresponding dynamic shear magnification factor proposed by Paulay and Priestley [11] minus unity, a story mechanism of the structures did not occur in all cases. Practical procedure of using the story-safety factor for preventing a story mechanism at irregular stories is also presented.

INTRODUCTION

During the 1994 Northridge and 1995 Kobe earthquakes, many wall buildings with irregular configurations were severely damaged or collapsed. In such buildings, the irregularity is often located at the first story in the form of discontinuous wall panels due to the functional requirements. As a consequence, this may lead to a significant reduction in stiffness and strength and initiate an undesirable collapse mechanism at the first story of the buildings, while the other stories behave elastically. Figure 1 illustrates the undesirable and desirable failure mechanisms of an irregular wall building. The severity of the collapse will increase with the number of stories, because the plastic energy accumulated at the weak story of the building increases. Thus, control of the collapse mechanism in irregular wall buildings under earthquake excitation is needed especially in high-rise buildings.

There have been numerous experimental and analytical studies investigating the seismic performance of buildings with vertical irregular configurations. Moehle and Alarcon [1] have concluded that the inelastic analysis methods have advantages over the elastic analysis methods in anticipating the effects of the

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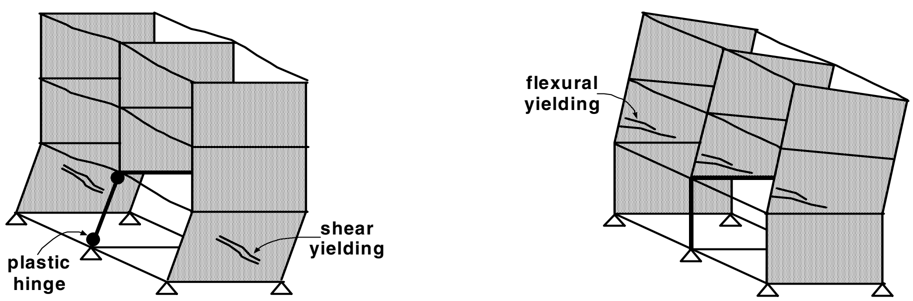
structural discontinuities, which is also discussed by Hidalgo *et al.* [2]. Kabeyasawa *et al.* [3] further note that neglecting shear transfer of slab due to the formulation of an overall collapse mechanism underestimates the base shear of wall-frame systems with a soft first story. In addition, Chopra [4] shows that the story ductility demands on multistory buildings with weak and soft stories vary depending on the relative yield strengths. Recent studies by Al-Ali and Krawinkler [5], Dooley and Bracci [6], and Lu [7] demonstrate that the effect of stiffness on the seismic response is much smaller than that of strength. Such an effect is negligible on the estimation of the seismic response when the building responds primarily in the fundamental mode as discussed by Miranda [8]. More recently, Das and Nau [9] suggest that the use of the equivalent lateral force procedure is not necessarily restricted for certain types of vertically irregular buildings, such as with a taller or heavier story.

The FEMA document [10] includes various rules related to the discontinuities of story strength, which is defined as the total strength of all seismic-resisting elements sharing the story shear. For example, the seismic design categories E and F in the document prohibit a weak story in which the story strength is less than 80 percent of that in the story above. However, there may still be lacking a criterion applicable to the evaluation of the collapse mechanism, particularly in vertically irregular wall buildings.



(a) Undesirable Mechanism **(b) Desirable Mechanism**

Fig. 1 Failure Mechanisms of Irregular Wall Building

In recent years, the capacity design philosophy proposed by Paulay and Priestley [11] has been a powerful tool for the seismic design of buildings, in which potentially plastic hinge regions are identified and other regions are strengthened by using dynamic magnification factors to remain elastic in all future seismic events. The present study is an extension of the capacity design to wall buildings with vertical irregularities.

The objective of this study is to present a criterion for preventing a story mechanism of wall buildings with vertically irregular configurations under earthquake excitation. The criterion was examined by conducting dynamic response analyses of various analytical models using various ground motions with long and short frequency contents.

STORY-SAFETY FACTOR

In a building with structural walls, the probability of a story mechanism decreases as the shear strength of the walls increases, as discussed by Park and Paulay [12]. In a frame building, the probability of a story mechanism decreases as the column-to-beam strength ratio increases, as discussed by Dooley and Bracci [6]. To integrate these tendencies, a story-safety factor, f_i, is defined by the following equation [13]:

$$f_i = \frac{\Delta V_i}{V_{ui}} \quad \text{for } \Delta V_i = V_{si} - V_{ui} \tag{1}$$

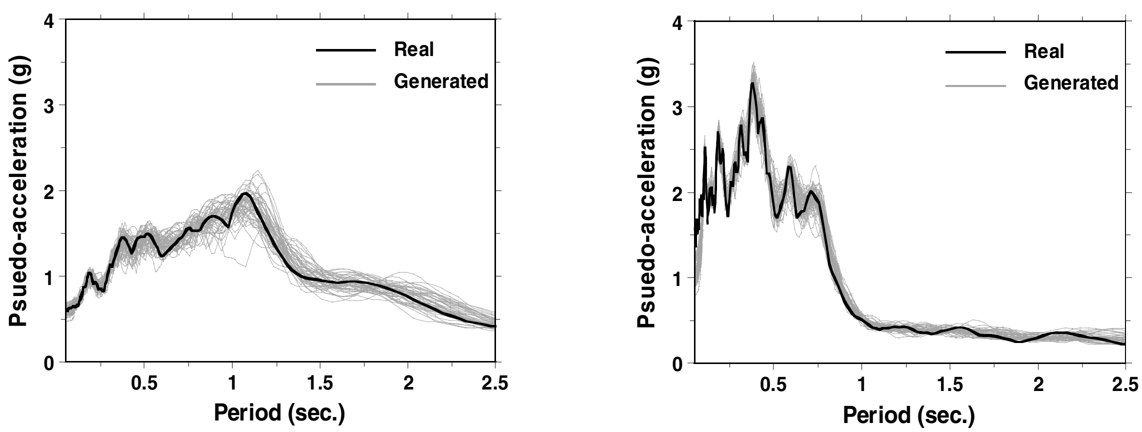
where V_{si} is the strength under the forces causing a story mechanism of the *i*th story as shown in Fig. 2(a) (the sum of the shear strength of the wall and the flexural/shear strength of the columns), and V_{ui} is the shear force of the *i*th story when a failure mechanism occurs under the seismic lateral forces specified in the international building code [14] as shown in Fig. 2(b). The difference between V_{si} and V_{ui} in Eq. (1) represents the strength margin against a story mechanism. If a building fails due to a total mechanism under static loading (Fig. 2(b)) but the value of f_i of some of the stories is approximately zero, then it is probable that mechanisms will occur at these stories under seismic excitation.

(a) Story Mechanism **(b) Total Mechanism**

Fig. 2 Failure Mechanisms and Story Shears

The story-safety factor is used in the Japanese Standard for the seismic evaluation of existing reinforced concrete buildings [15; 16] to predict failure mechanisms. This factor can also be used to evaluate the mean and standard deviation of seismic story drifts [17]. In the Eurocode 8 [18], 'the story shear overstrength factor' is defined as the ratio of story shear strength (V_{si} in this paper) to the design story shear force, which is also useful in quantifying the frame irregularity [7]. The story-safety factor defined in this paper is similar to that in Eurocode 8 but is more powerful in predicting the failure mechanisms, since the story-safety factor directly represents the reserve strength against a story mechanism that potentially may develop.

INPUT GROUND MOTIONS



(a) Long-Period JEN292 Motions **(b) Short-Period TAR360 Motions**

Fig. 3 5% Damping Elastic Psuedo-acceleration Response Spectra

We considered two long- and short-period records of Jensen Filter Plant JEN292 and Tarzana Cedar Hill TAR360, respectively, from the Northridge earthquake occurred on January 17, 1994. These records, hereafter called JEN292 and TAR360 records, were downloaded from the web site of the Pacific

Earthquake Engineering Research Center [19] and had, respectively, peak ground accelerations of 0.593 g and 0.99 g and peak ground velocities of 99.3 cm/s and 77.6 cm/s. Based on the generation technique of varying phase angles but keeping the acceleration spectrum within a dispersion range of 10% to that of the real record [20], 50 other artificial motions for each record were created. In addition, these real and generated motions were scaled with multiplying by various magnification factors, k. The thin and thick lines in Fig. 3 show the 5% damping elastic pseudo-acceleration spectra of the ground motions with $k = 1$, respectively. We assume that such a number of ground motions sufficiently represent the variety of seismic characteristics and intensities that affect the inelastic responses of buildings.

ANALYTICAL MODELS

In vertically irregular wall structures as illustrated in Fig.1, the effect of the geometrical irregularity on the use of the story-safety factor for preventing a story mechanism was negligible as discussed later. For that reason, we considered two 7- and 11-story wall structures with their elevations and dimensions shown in Figs. 4(a) and (b), respectively. The equal story weights of 1000 kN were assumed for both the structures. The dimensions of the square boundary columns at the first story of the 7-story structure were 70 cm×70 cm and at the first and second stories of the 11-story structure were 75 cm×75 cm. These dimensions were reduced by 5 cm every three stories. The thickness of the wall panels were 20 cm across all stories of the structures.

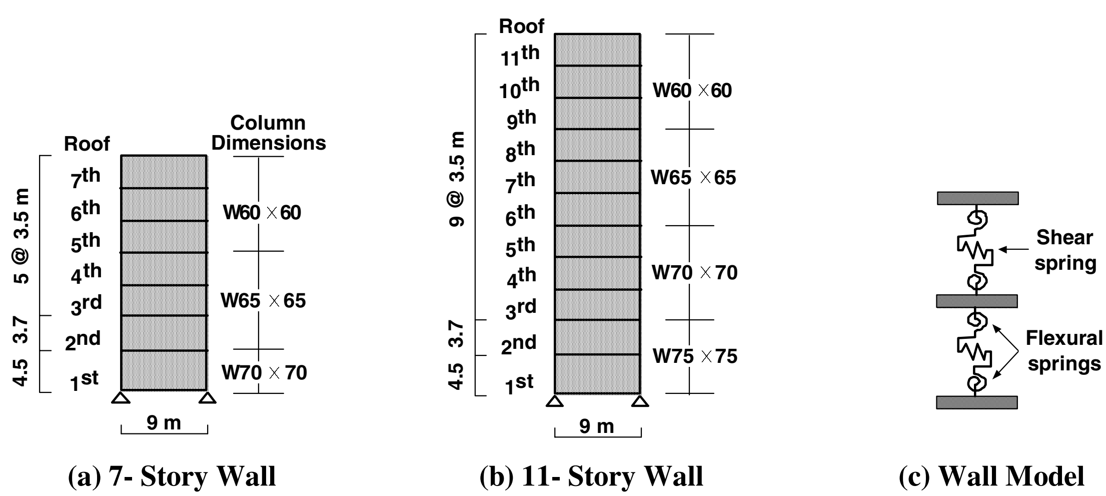
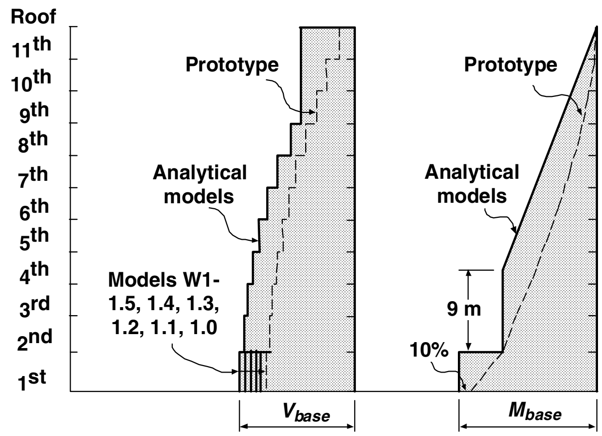


Fig.4 Structural Configuration and Wall Model

Wall panels with two boundary columns at each story were modeled as an equivalent column member with two flexural springs at the top and bottom and a shear spring in the middle as shown in Fig. 4(c). At these springs, the Takeda model [21] was used to represent flexural deformation and the origin-oriented degrading stiffness model to represent shear deformation. The elastic stiffness of walls was calculated from their overall dimensions assuming a Young's modulus of concrete of 26 kN/mm^2 and a Poisson's ratio of 1/6. The yield curvature was calculated according to Priestley and Kowalsky [22] assuming the reinforcement yield strain $\varepsilon_y = 0.002$. The shear deformation angle at the strength was assumed as 0.0025. The post-yield stiffness was assumed as 0.001 times the elastic stiffness. Wall base rotation due to deformations of the ground was ignored in the study. The damping factor was 0.05 in proportion to the tangential stiffness. The resulting fundamental periods were 0.30 sec and 0.62 sec for the 7- and 11-story wall structures, respectively.

As a basis of analytical models, the prototype structures were designed as follows. Base shear coefficients were assumed to be 0.65 and 0.5 for the 7- and 11-story structures, respectively. The shear strengths of the structures were assigned in accordance with the static lateral forces [14]. Based on the assigned shear strengths, the flexural strengths of the walls were determined so that flexural yielding occurred simultaneously with shear failure in each story. The broken lines in Figs. 5(a) and 5(b) show, respectively, the shear and flexural strengths of the 11-story prototype structure. The cracking strengths of the walls were assumed as one-second of the corresponding yield strengths.



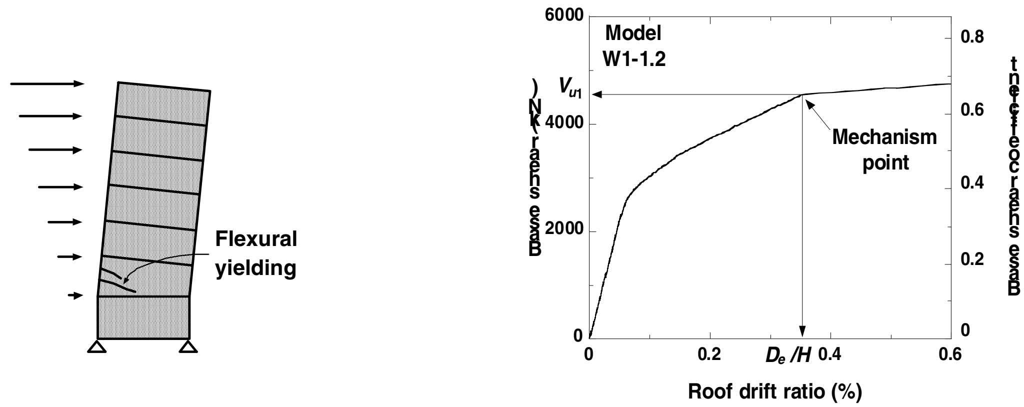
(a) Shear Strength **(b) Flexural Strength**

Fig. 5 Strengths of 11-Story Wall Structure. l_w = wall span (9 m)

Analytical models were obtained based on the prototype structure by multiplying the shear strengths of the walls in the first stories by a factor ψ = 1.0, 1.1, … or 1.5 and in the upper stories by a factor of 1.5. The flexural strengths at the base were increased by 10 percent, since desirable flexural yielding was expected at the bottom of the second story walls (Fig. 1(b)). To prevent flexural yielding at mid-stories, which would be rare in actual wall structures, the flexural strengths were increased according to Paulay and Priestley [11] as shown in Fig. 5(b) by the solid lines for the 11-story structure. The shear strengths were also increased according to Paulay and Priestley [11], so that those of the eighth to eleventh stories as shown in Fig. 5(a) by the solid lines were half of that of the second story. Thus, the story-safety factors at the irregular first stories, f_1, were in the order 0, 0.1, … or 0.5 (corresponding to ψ = 1.0, 1.1, … or 1.5), and those at the other stories were 0.5. Similar values of f_1 were also obtained using the static lateral forces corresponding to the Ai distribution factor specified in the Japanese building standard law [23].

The name W1-1.0 model implies that the story-safety factor was zero at the irregular first story (f_1 = 0) and equal to or larger than 0.5 at the upper stories. Under the static lateral forces [14; 23], model W1-1.0 failed due to simultaneous total and story mechanisms with flexural yielding at the bottom of the second story walls and shear yielding at the first story, respectively, while model W1-1.1, 1.2, … or 1.5 failed due to a pure total mechanism.

Figure 6 shows the failure mechanisms and the relationships between the base shears or base shear coefficients and the roof drift ratios (defined as the roof displacement, D_{roof}, divided by the overall height, H, of the structure) obtained from pushover analyses under the static lateral forces [14] for model W1-1.2 of the 7-story structure. The mechanism induces flexural hinges at the bottom of the second story walls. In Fig. 6(b) the open circles indicate the corresponding mechanism points, representing V_{u1} and D_e/H.



(a) Failure Mechanism **(b) Base Shear - Roof Drift Ratio Relationship**

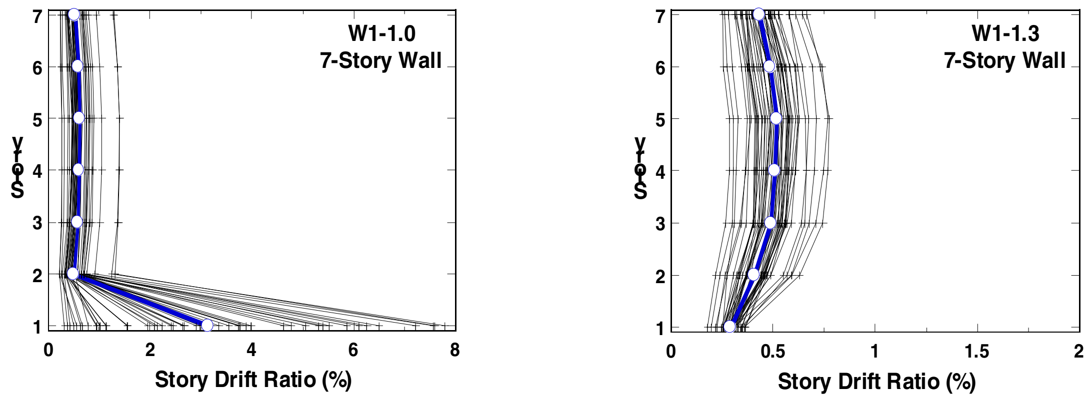
Fig. 6 Pushover Analysis Results of Model W1-1.2 of 7-Story Structure

STORY-SAFETY FACTOR VERSUS STORY MECHANISM

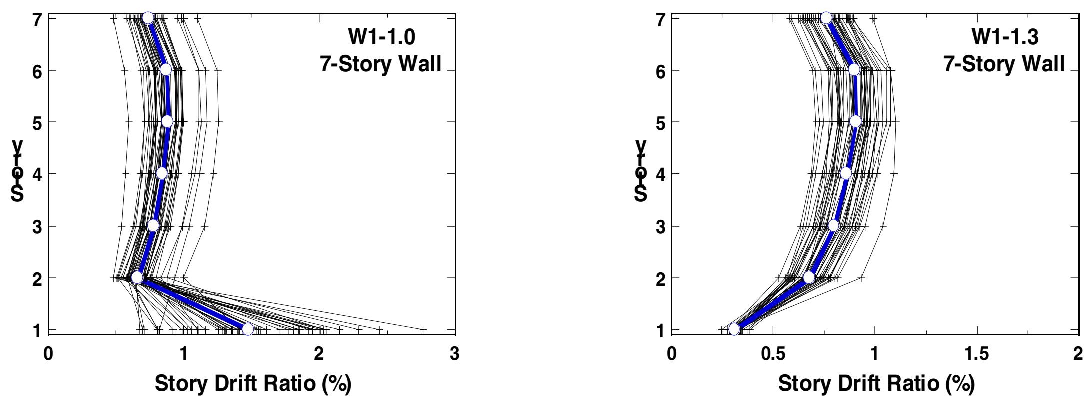
In this section, dynamic response analyses of various analytical models were performed to examine the use of the story-safety factor in preventing a story mechanism at the irregular first story. Figure 7 shows the story drift ratios of 7-story wall models W1-1.0 and 1.3 for the long-period JEN292 and short-period TAR360 records and their generated motions with k = 1 (50 generations for each record). In the figure, each continuous thin line with crosses indicates the results of the dynamic analyses for each motion while the thick lines with open circles indicate the corresponding mean values. It is observed that plastic deformation due to a story mechanism with shear yielding was resulted in the first stories of models W1-1.0 for both the cases of JEN292 and TAR360 motions, although plastic deformation due to a total mechanism with flexural yielding at the second story wall was larger in the case of TAR360 than JEN292 motions as indicated by uniform plastic deformation in the upper stories. However, almost no plastic deformation due to a story mechanism was observed at the first stories of models W1-1.3, and the structure failed due to a total mechanism with flexural yielding at the bottom of the second story walls as shown in Fig. 6(a) for most of the ground motions.

In addition, Fig. 8 shows the relationships between the maximum shear ductility factors and the story-safety factors, f_1, for the first stories of the 7-story wall structure under the given ground motions. The results show that the maximum ductility factors varied with the input ground motions, and the ranges of variation for the long-period JEN292 and short-period TAR360 motions as shown in Figs. 8(a) and (b), respectively, were more different when the factor f_1 was smaller. For example, the ductility factor ranged from unity to 30 for the former and 2 to 10 for the latter when the value of f_1 was 0.1. This is attributable to the difference in the response spectra of the motions as discussed in the next section. However, in both the cases of long- and short-period motions the ductility factors tended to decrease with increased story-safety factors. In other words, the higher the story-safety factor, the lower the probability of a story mechanism.

Further dynamic analyses of the analytical models against motions scaled with various intensity levels also indicate that the probability of a story mechanism was lower as the story-safety factor was higher, and the decreasing trend of the maximum ductility factor varied with intensities of the ground motions. Thus, it can be concluded that although the seismic response of the structure varied with characteristics and intensities of the ground motions, the use of the story-safety factor well prevented a story mechanism of the structures against earthquakes.

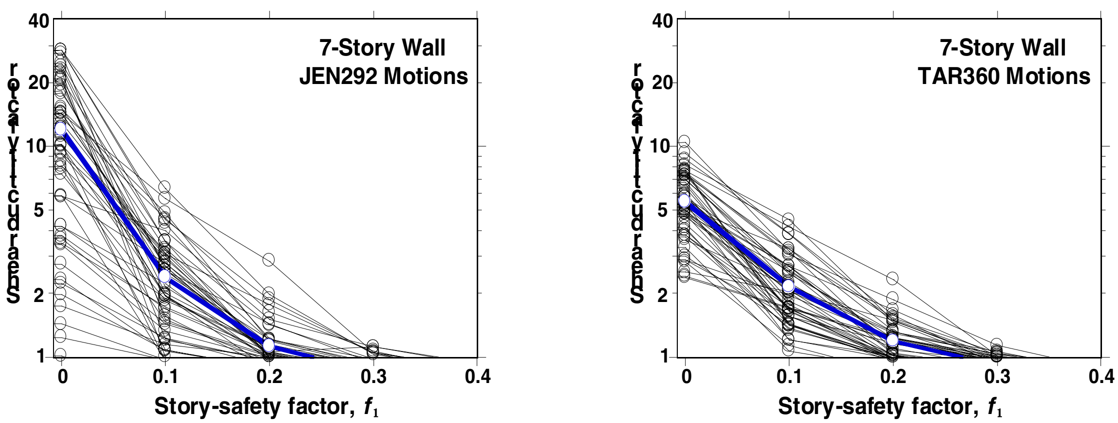


(a) Long-Period JEN292 Record and 50 Generated Motions



(b) Short-Period TAR360 Record and 50 Generated Motions

Fig. 7 Story Drift Ratios Obtained from Dynamic Analyses of 7-Story Wall Models W1-1.0 and 1.3. The thick lines with open circles show the mean values.



(a) Long-Period JEN292 Motions (b) Short-Period TAR360 Motions

Fig. 8 Relationships between Maximum Shear Ductility Factors Obtained from Dynamic Analyses and Story-Safety Factors for the First Story. The thick lines with open circles show the mean values.

REQUIRED STORY-SAFETY FACTOR

Shear failure of structural walls due to reversed cyclic loading usually results in a significant reduction of strength as discussed by Paulay and Priestley [11]. For that reason, we defined the story-safety factor required for preventing a story mechanism at an irregular story as that corresponding to the initiation of shear yielding, or associated with the shear ductility factor of unity. Such a defined safety factor, hereafter, is referred to as a 'required story-safety factor.' Figure 9 illustrates the calculation of the required safety factor, in which the ductility factor corresponding to each certain value of f_1 can be obtained from dynamic analysis and a linear line of the ductility factors between two successive values of f_1 is assumed.

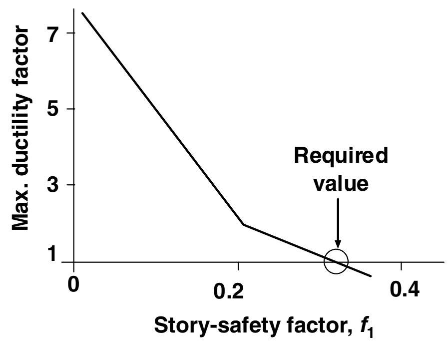
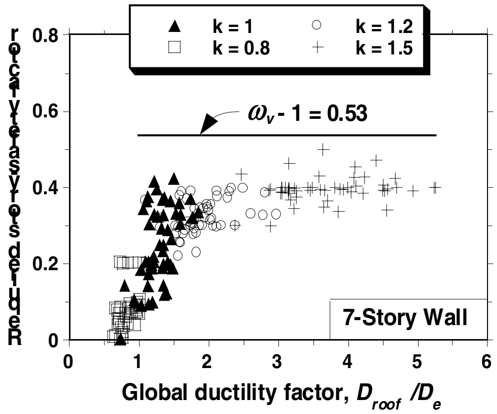


Fig. 9 Calculation of the Required Story-Safety Factor

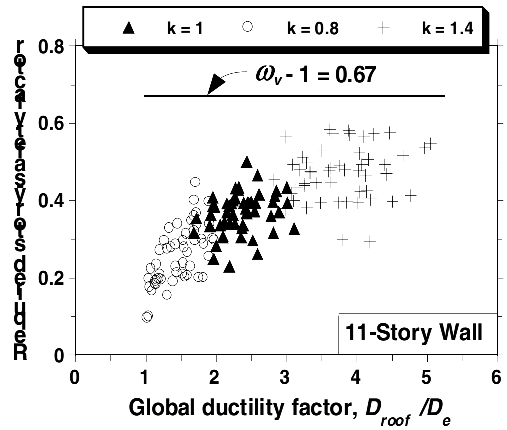
Figure 10 shows the resultant relationships between the required story-safety factors and the global ductility factors, D_{roof}/D_e, for the 7- and 11-story structures under the given real and generated motions with various values of the magnification factor, k. In this figure, D_{roof} is the maximum roof displacement obtained from dynamic analysis and D_e is the elastic displacement determined based on pushover analysis when failure mechanism occurs under static loading. Results corresponding with D_{roof}/D_e greater than 6 were neglected because most walls in actual buildings would not have such a large ductility. It is observed that the required story-safety factor varied with characteristics and intensities of the input ground motions. This implies that the likelihood of a story mechanism to future seismic events cannot be evaluated based only on the results of a static analysis.

Furthermore, the required story-safety factor tended to increase with the global ductility factor, D_{roof}/D_e, or the seismic intensity. In the case of long-period JEN292 motions, the required safety factor tended to increase within a range of D_{roof}/D_e from about unity to 6. However in the case of short-period TAR360 motions, the required safety factor tended to increase within a smaller range of D_{roof}/D_e from unity to 4 and unity to 3 for the 7- and 11-story structures, respectively. Such a difference in the range of D_{roof}/D_e is attributable to the fact that roof displacements caused by long-period motions are much longer than those by short-period motions as seismic intensity is larger, as illustrated in Figs. 11(a) and (b) in terms of the capacity diagram corresponding to the first vibration mode of the 7-story wall model W1-1.2 and the demand diagrams for the given real records with various values of k.

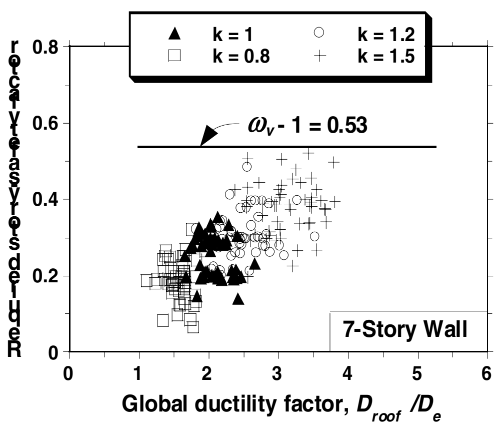
It is noted that the contribution of the second vibration mode in the case of TAR360 record as shown in Fig. 11(b) was large enough to induce shear failure at the first story. However, similar ranges of variation of the required story-safety factor for both the cases of JEN292 and TAR360 motions were observed as indicated, respectively, in Figs. 10(a) and (c) for the 7-story structure and Figs. 10(b) and (d) for the 11-story structure. In addition, Fig. 12 shows the time histories of the first story shear, V_1, for 7-story wall model W1-1.1 with various values of the first story maximum shear ductility factor, DF_1. The vibration periods were resulted from 0.3 sec. to 0.9 sec., which were much larger than the second vibration period of the structure T_2 = 0.07 sec. and closed to the corresponding equivalent periods of the structure, T_{eq}. Thus, it suggests that the effect of the higher vibration modes on the required story-safety factor in these cases was not significant.



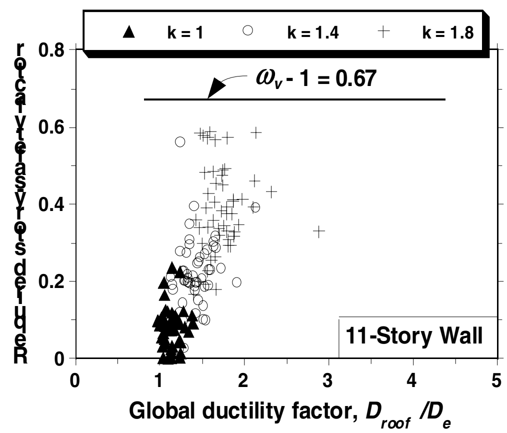
(a) 7-Story Wall, JEN292 Motions



(b) 11-Story Wall, JEN292 Motions



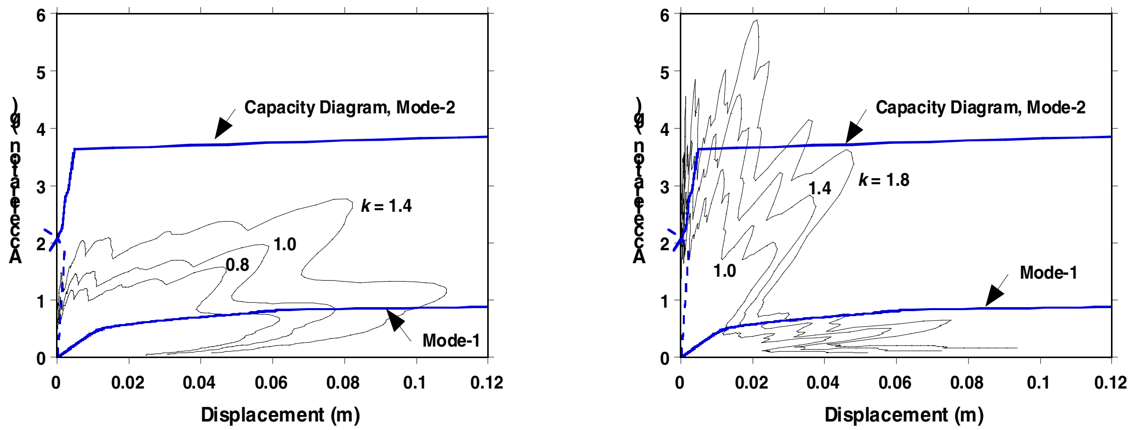
(c) 7-Story Wall, TAR360 Motions



(d) 11-Story Wall, TAR360 Motions

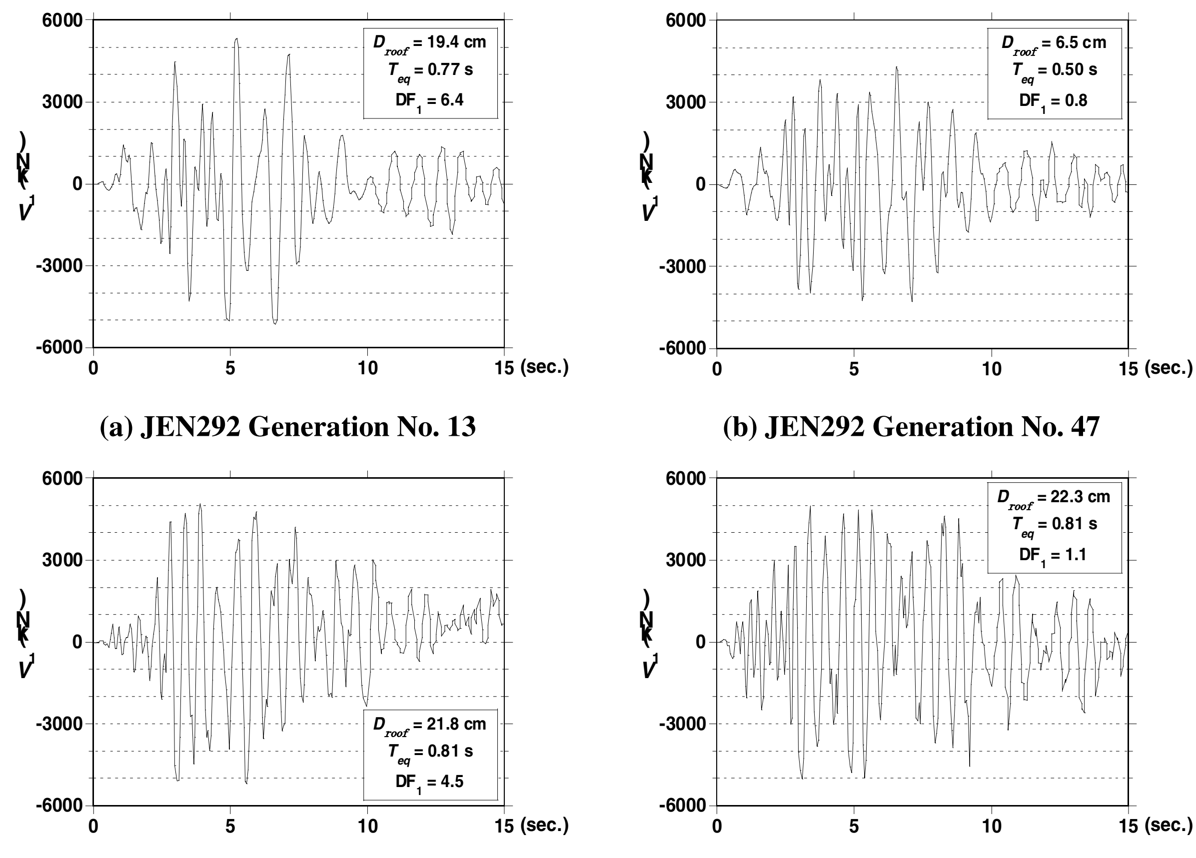
Fig. 10 Required Story-Safety Factors versus Global Ductility Factors, D_{roof}/D_e, Obtained from Dynamic Analyses under Real and Generated Motions with Various Magnification Factors for 7- and 11-Story Structures. ω_v = dynamic shear magnification factor by Paulay and Priestley [11].

A comparison of the plotted results in Figs. 10(a) and (b) further exhibits an increasing tendency of the required story-safety factor with the number of stories of the structure. A similar tendency is also observed for the results shown in Figs. 10(c) and (d). These results were in accordance with the recommendation of the dynamic shear magnification factor, ω_v, by Paulay and Priestley [11]. The magnification factor ω_v is expressed as a function of the number of stories for wall structures: $\omega_v = 1.3 + n/30$ for buildings over 6 and up to 15 stories, where n is the number of stories. In these cases, the corresponding story-safety factors are equal to the values of ω_v minus unity ($\omega_v - 1$), thus leading to the values of 0.53 and 0.67 for the 7- and 11-story structures, respectively. These values were larger than the computed values of the required story-safety factors in all cases, as indicated by the solid lines in Fig. 10.



(a) JEN292 Record **(b) TAR360 Record**

Fig. 11 Demand Diagrams of JEN292 and TAR360 Records with Various Magnification Factors and Capacity Diagrams of 7-Story Wall Model W1-1.2

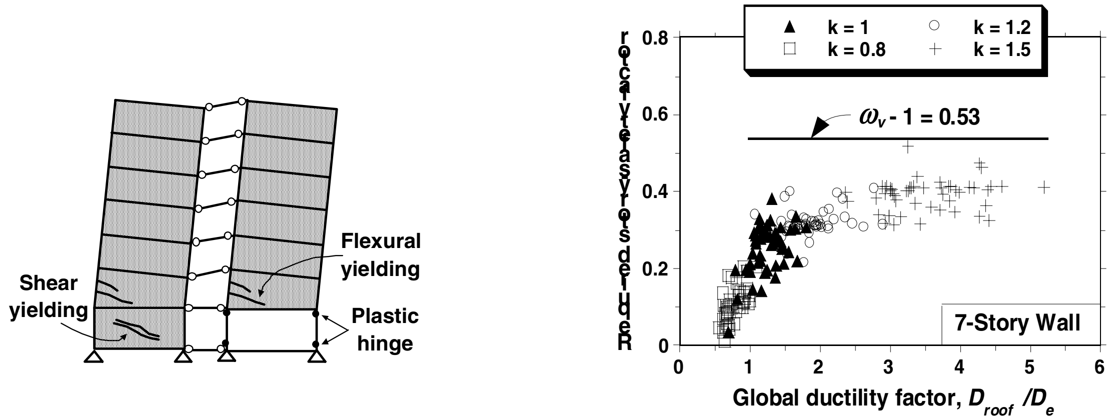


(a) JEN292 Generation No. 13 **(b) JEN292 Generation No. 47**

(c) TAR360 Generation No. 32 **(d) TAR360 Generation No. 28**

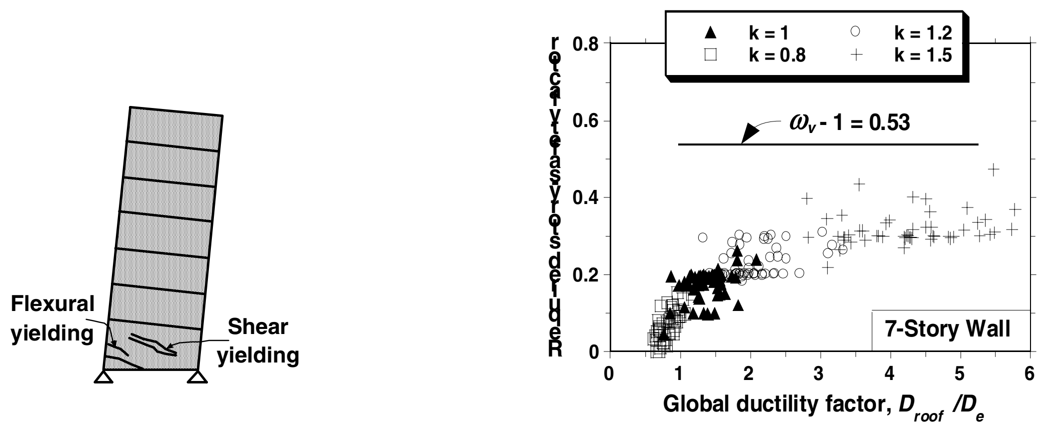
Fig. 12 Time Histories of The First Story Shear for 7-Story Wall Model W1-1.1, Yielding Strength V_{y1} = 5005 kN

To examine the effect of geometrical irregularity, we considered an irregular 7-story structure with two structural walls connected by a rigid link at each floor level and a discontinuity of wall panel in the first story of the right wall as shown in Fig. 13(a). The properties of these walls were identical to those of the 7-story structure shown in Fig. 4(a) with the exception that the thickness of wall panel in the first story was 30 cm (rather being 20 cm identical to those of the upper stories) and the shear strength of the first story wall was assigned to be 90% of the base shear. The symbols in Fig. 13(b) show the computed results of the required story-safety factors versus D_{roof}/D_e for the JEN292 record and its generated motions with the magnification factor k = 0.8, 1.0, 1.2, and 1.5. A comparison of the results in Fig. 13(b) and Fig. 10(a) indicates that the effect of the geometrical irregularity on the required story-safety factor was negligible.



(a) (b)

Fig. 13 Required Story-Safety Factors versus D_{roof}/D_e for Irregular 7-Story Wall Structures under JEN292 Motions



(a) (b)

Fig. 14 Required Story-Safety Factors versus D_{roof}/D_e for Irregular 7-Story Wall Structures with Flexural Hinge Developing at the Wall Base under JEN292 Motions

Additionally, we examined the effects of flexural hinge location by designing the 7-story structure shown in Fig. 4(a) with allowance of flexural hinge developing at the second story wall as shown in Fig. 14(a). The symbols in Fig. 14(b) show the computed results of the required story-safety factors versus the factor D_{roof}/D_e for the JEN292 record and its generated motions with the magnification factor k = 0.8, 1.0, 1.2, and 1.5. It is observed that the results in Fig. 14(a) were somewhat smaller than those in Fig. 10(a) for the 7-story structure with flexural hinge developing at the second story wall. This is attributable to the difference of the deflected shape after flexural yielding of the walls, which can be expressed using the adaptive pushover analysis by Bracci *et al.* [24].

Thus conservatively we can conclude that if the story-safety factor is larger than the corresponding dynamic shear magnification factor [11] minus unity ($\omega_v - 1$), a story mechanism of vertically irregular wall buildings will be prevented.

PRACTICAL PROCEDURE FOR PREVENTING A STORY MECHANISM

In this section, the practical procedure for preventing a story mechanism at irregular stories of wall structures is discussed, as shown in Fig. 15. First, perform a pushover analysis of the originally designed structure under lateral static forces specified in the international building code [14] or Japanese building standard law [23]. Next, calculate the story shear, V_{ui}, when a failure mechanism of the structure occurs. Then, estimate the story strength, V_{si}, by summing the story strength of each vertical member. It is noted that the member strength should be evaluated considering dispersions of material strength and the effects of two-directional response and axial loads. Finally, calculate the story-safety factor, f_i, by Eq. (1). If the value of f_i is larger than the corresponding dynamic shear magnification factor proposed by Paulay and Priestley [11] minus unity ($\omega_v - 1$), a story mechanism would not occur at the irregular story, where failure mechanism is prohibited. If it is not, strengthen the vertical members and then repeat the procedure.

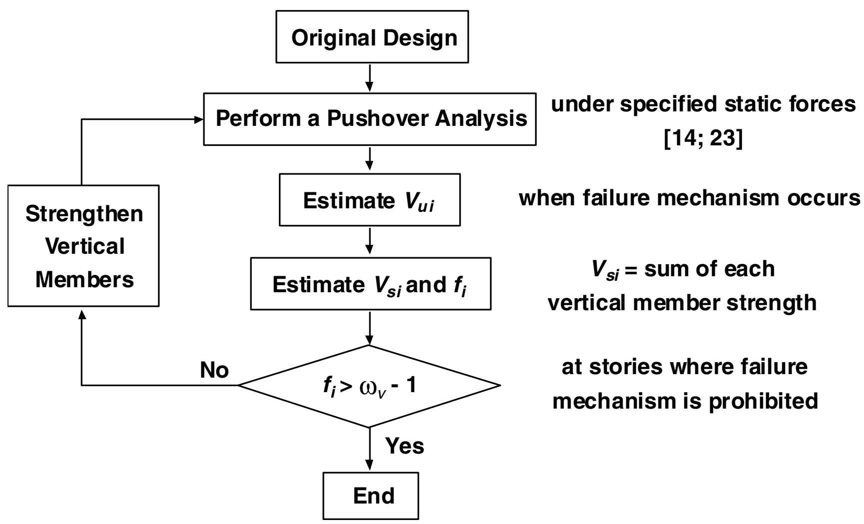


Fig. 15 Procedure for Preventing a Story Mechanism at the Irregular Stories. ω_v = dynamic shear magnification factor by Paulay and Priestley [11].

CONCLUSIONS

This paper has verified the validity of the story-safety factor used for preventing a story mechanism of vertically irregular wall buildings by conducting dynamic response analyses of various analytical models with an irregularity at the first stories for two real earthquake records with long and short vibration periods and their numerous generated motions with various intensity levels. From this study, the following can be concluded:

1. The story-safety factor defined in Eq. (1) represents the relative reserve strength for each story of a building against a story mechanism. As the story-safety factor of a story increased, the probability of a story mechanism at that story decreased.

2. The required story-safety factor for preventing a story mechanism at an irregular story varied even if the response spectra were similar. This implies that the likelihood of a story mechanism to future seismic events cannot be evaluated based only on the results of a static analysis.
3. The required story-safety factor tended to increase with the seismic intensity and number of stories of the structure. When the story-safety factor was larger than the corresponding dynamic shear magnification factor proposed by Paulay and Priestley [11] minus unity, a story mechanism did not occur in all cases. The effects of the flexural hinge location and geometrical irregularity on the required story-safety factor were minor.
4. The practical procedure of using the story-safety factor for preventing a story mechanism at irregular stories is shown in Fig. 15.

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