Control of Seismic Drift Demand for Reinforced Concrete Buildings with Weak First Stories

Manabu Yoshimura [1)]

1) Department of Architecture, Tokyo Metropolitan University, Minamiosawa 1-1, Hachioji, Tokyo, 192-03, Japan.

ABSTRACT

This paper studies seismic drift demand for RC buildings with weak first stories, the potential seismic vulnerability of which has been revealed in many past earthquakes including the 1995 Kobe and 1999 Chi-Chi earthquakes. In a building that collapsed during the Kobe earthquake the strength balance between the first story and the upper stories is shown to have had a significant effect on the collapse of this building. Nonlinear dynamic analyses are then conducted for a model representing weak-first-story buildings to study the first story drift demand, where the first-story strength and the strength balance along the height are taken as analysis variables. Based on the results, conditions that the two parameters should satisfy for controlling the first-story drift demand within an allowable level are discussed.

INTRODUCTION

Many RC buildings damaged in the 1995 Kobe earthquake were constructed before 1981, when Japanese building code requirements for the seismic design were extensively revised. However, even amongst RC buildings constructed after this code revision, some suffered severe damage, and most of them were weak-first-story buildings. In this type of building, few or no walls are provided at the first story, while many are placed in the upper stories. In consideration of the still remaining vulnerability of those weak-first-story buildings, complementary provisions were added to the code requirements as an appendix in 1997. The provisions require that weak-first-story buildings shall not suffer a first-story collapse. Such provisions lead to unreasonably large columns for the first story, nearly prohibiting the construction of such buildings.

As recommended by many researchers, a total collapse mechanism design is desirable to control drift demand. However, it is unrealistic to design weak-first-story buildings so that the total collapse mechanism may result. To resolve this situation, development of a more rational design method is needed. Formation of the first-story collapse mechanism may be permitted as long as the first-story drift demand is controlled within an allowable level. A primary factor governing the first-story drift demand is the first-story strength itself. However, the strength balance between the first story and upper stories is also known to affect the first-story drift demand significantly [1].

The first part of this paper introduces an example of a weak first-story building that collapsed during the Kobe earthquake, and highlights significant effects of the strength balance along the height on the first-story drift demand. In the second part, nonlinear dynamic analyses are conducted for a model representing weak-first-story buildings, where the first-story strength and strength balance along the height are taken as analysis variables. Presented also are conditions that the two parameters should satisfy for controlling the first-story drift demand within an allowable level.

COLLAPSE OF WEAK-FIRST-STORY BUILDING DURING THE KOBE EARTHQUAKE

Building

The building was a RC seven-story apartment complex without a basement. The first story was used exclusively for parking lots. Figures 1 and 2 show the plan views and framing elevation views

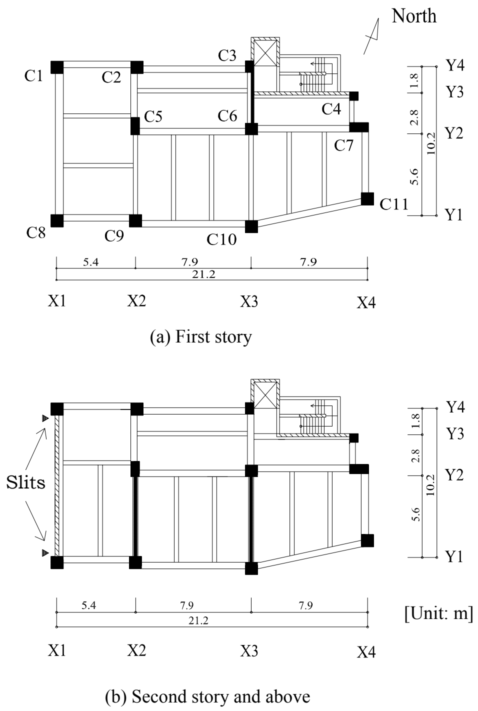


Fig. 1 Plan views

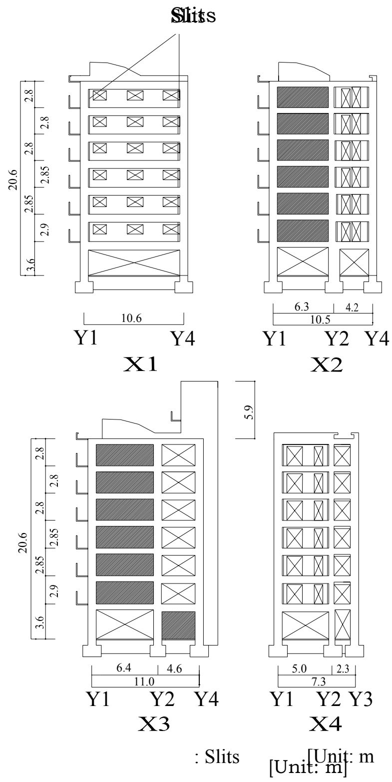


Fig. 2 Framing elevation views (X direction)

of the north-south (X) direction, for which major damage occurred. The first story was nearly a pure moment-resisting frame, including only a short wall in the X3 plane. In contrast, the second story and above included two long walls in the X2 and X3 planes. In addition, they had a wall in the X1 plane that was designed as a nonstructural wall by being separated from the edge columns using slits. Details of the slit are shown in Fig. 3. The slit, although called so, did not perfectly separate the nonstructural wall from the edge column: the slit thickness, 50mm, was merely one third of the wall thickness, 150mm. It is widely acknowledged that slits whose thickness is less than half the wall thickness are ineffective, which implies that this nonstructural wall behaved as a structural wall. As will be discussed later, the existence of the nonstructural wall had a crucial effect on the seismic drift demand, and hence on the collapse of this building.

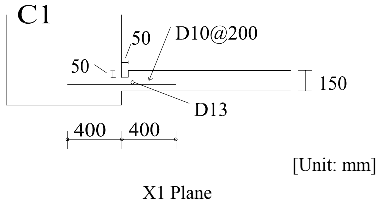


Fig. 3 Details of slit

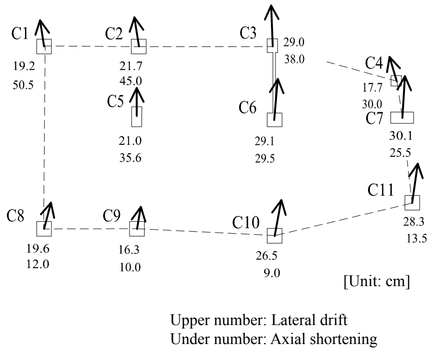


Fig. 4 Observed Residual displacement of first story columns

Observed Damage

Figure 4 shows residual lateral drifts and axial shortening observed at the first-story columns. The arrow in the figure indicates the amplitude and direction of the lateral drift. All columns were observed to move nearly to the north with extremely large lateral drifts ranging from 160 to 300mm (230mm on the average). The axial shortening was much larger for the north columns than for the south columns, apparently corresponding with the residual lateral drifts to the north.

Photo 1 shows observed damage to some of the first story members, where C1 and C8 represent the north and south columns. C1 crashed at the top while C8, although seriously damaged, avoided failure. The difference in the degree of damage between the two columns is related to the larger axial shortening sustained by the north columns relative to the south ones. The first-story wall in the X3 plane completely crashed at mid-height along with the edge column. On the other hand, practically no damage existed in members above the second-floor level, including the slits in the X1 plane. Thus, a first-story mechanism was formed for the X direction.

Computed Drift Demand

Nonlinear dynamic drift demand of this building was evaluated using the ground motions recorded near the building site. In the analysis, the X1 plane above the second floor level was modeled in two ways: first as the structural wall (Case 1), where the slits were assumed ineffective, and then as the moment-resisting frame (Case 2), where the slits were assumed effective. Analysis methods similar to those stated in later parts were

(a) C1 (East face) (b) C8 (East face) (c) First story wall and C3 (West face)

Photo 1 Observed damage

used [2].

Maximum interstory drifts along the building height are compared in Fig. 5. The two results are quite different. For Case 1, almost all the drift concentrated in the first story, with a maximum story drift of 250mm (drift angle of 7.9%), while for Case 2 such extreme concentration in the first story did not occur, with a maximum story drift of 100mm (drift angle of 3.2%). The first story strength was the same for both cases, while the strengths in upper stories were larger for Case 1 than for Case 2. These observations clearly indicate that the strengths of the second-story and above, or the strength balance between the first-story and upper stories, had a crucial effect on the seismic drift demand of this building. This issue is a major focus in a later section.

It is also apparent from the above results that Case 1 reproduced the damage observations reasonably, while Case 2 underestimated the first-story drift demand significantly. This suggests that the building collapsed (at least partly) because the slits were ineffective. Problems in nonstructural walls are often addressed in view of their failure or their effect on the behavior of adjoining structural members. However, the existence of nonstructural walls can even affect the overall behavior of the building.

CONTROL OF FIRST-STORY DRIFT DEMAND [3]

Model Building and Analysis Methods

The effect of the first-story strength and the strength balance on the first-story drift demand was examined for a model building, and conditions that these two parameters should satisfy for controlling the first-story drift demand within an allowable level are discussed. The model building was a 14-story RC wall-frame. Figures 6 and 7 show the plan views and framing elevation views of the X direction. This direction consisted of three cantilever walls (X1, X4 and X8) continuous from the base to the top of the building and five weak-first-story frames (X2, X3 and X5 to X7) with no wall at the first story but with walls in all upper stories. The model building, deemed a typical weak-first-story building in Japan, was designed according to pre-Kobe (before 1997) code requirements. The analysis methods were as follows.

(1) The building was represented by a two-dimensional plane frame comprising three cantilever walls and five weak-first-story frames. Each column was idealized as a line member, and each wall was modeled as a deep column located at the wall centerline.

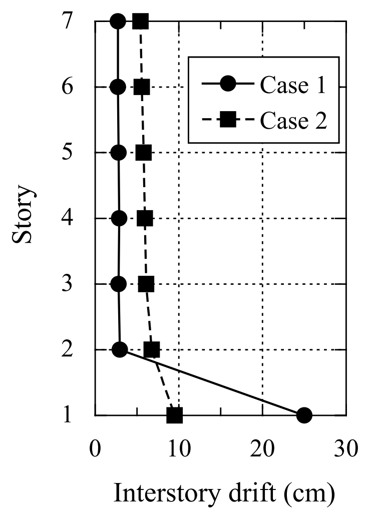


Fig. 5 Maximum interstory drift

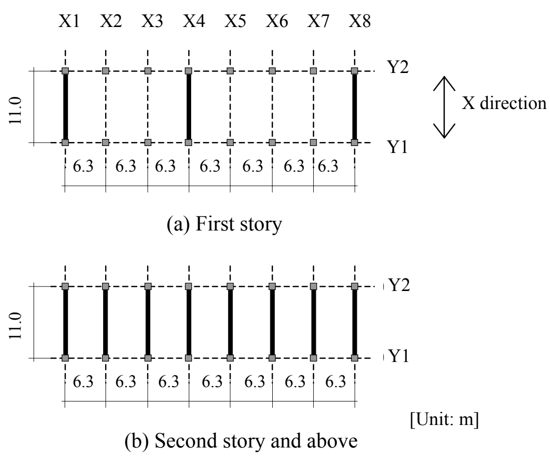


Fig. 6 Plan views

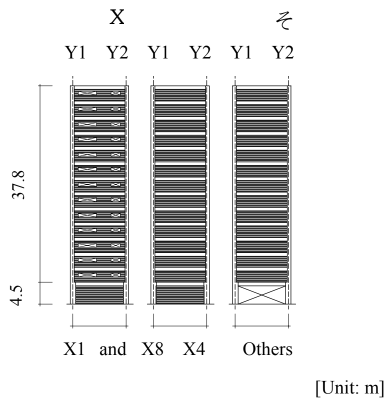


Fig. 7 Framing elevation views (X direction)

(2) For columns, flexural nonlinearity was considered using two springs placed at both ends, the hysteresis of which was represented by the Takeda model [4]. For walls, flexural and shear nonlinearities were considered; flexural nonlinearity was represented by the Takeda model, and the shear nonlinearity by a origin-oriented model [5].

(3) Two ground-motion records were used for the dynamic analyses: the 1995 Kobe (NS) record and 1940 El Centro (NS) record. For both records, the ground-motion level was adjusted so that the maximum ground velocity would be 0.5m/s. This level is often used to represent severe earthquakes in Japanese seismic design. Damping was assumed to be of viscous type and proportional to the instantaneous stiffness with a damping ratio of 3% with respect to the fundamental natural frequency. The fundamental natural period of the building was 0.52sec.

Analysis Variables

The first-story strength and the strength balance between the first story and upper stories were taken as analysis variables.

The first-story strength of the model was computed by adding up the smaller of the flexural or shear strength of each column or wall. Wall flexural strength was estimated by assuming a point of contra-flexure lying at the mid-height of the building. The same point of contra-flexure was used to estimate wall shear strength. The obtained story strength was expressed as the first-story shear coefficient (C_1). Note that this procedure is adopted in the second level procedure for the seismic evaluation of existing buildings in Japan [6].

The strength balance of the model was expressed as the Strength Balance (SB) index, as defined below. First, the strength of each story was computed using the procedure stated above, and the respective story shear coefficients (C_i, i = 1 to n, n: number of stories; fourteen in this study) were obtained. Here the coefficient is defined as the strength divided by the weight that the concerned story carries. Second, C_i is divided by the design shear coefficient distribution factor (A_i, $A_1 = 1.0$) of the corresponding story. The factor, called the A_i distribution and prescribed in the Japan's seismic code, specifies the design story strength distribution, given as the coefficient relative to the weight that the concerned story shall sustain. Third, SB is determined, given as a ratio of C_1 / A_1 at the first story to the minimum of all C_i / A_i at the second story and above. Note that SB is smaller than unity for ordinary weak-first-story buildings and that C_i / A_i is generally minimal at the second story among the upper stories. With these in mind, SB is commonly expressed as:

$$\mathrm{SB} = \frac{C_1 / A_1}{\min(C_i / A_i)_{i=2 \to n}} = \frac{C_1 / A_1}{C_2 / A_2} \tag{1}$$

The mode of wall yielding, either shear or flexure, values of C_i, A_i, C_i / A_i for all stories, and the resultant SB are shown in Table 1. Here, C_1 and SB were 0.57 and 0.89, respectively.

Table 1 Structural properties of model building

Story	Wall yielding mode	C_i	A_i	C_i / A_i	SB
14	Shear	10.36	2.76	3.75	0.89
13	Shear	4.51	2.12	2.13	
12	Shear	3.02	1.86	1.62	
11	Shear	2.27	1.69	1.34	
10	Shear	1.80	1.57	1.15	
9	Shear	1.61	1.48	1.09	
8	Shear	1.36	1.40	0.97	
7	Shear	1.08	1.33	0.81	
6	Shear	0.91	1.27	0.72	
5	Shear	0.78	1.21	0.65	
4	Shear	0.74	1.15	0.64	
3	Shear	0.71	1.10	0.64	
2	Shear	0.67	1.05	0.64	
1	Flexure	0.57	1.00	0.57	

Parametric studies were carried out for different C_1 and SB values. For each case, the member strength was determined to be equal to that of the original model multiplied by a factor of (C_1 / 0.57) for members associated with the first story, and a factor of (C_1 / 0.57) × (0.89 / SB) for the members for the upper stories. All other structural properties, such as the member stiffness and story mass, were assumed to be the same as those of the original model. Hence, the fundamental period was the same for all cases. Note also that the A_i distribution was assumed to be the same for all cases.

Effect of Strength Balance on First-Story Drift Demand

To study the effects of the strength balance on the first-story drift demand, nonlinear dynamic analysis was conducted for cases with C_1 being a constant value of 0.3 and SB ranging from 0.5 to 1.0. The maximum first-story drift, the sum of the maximum interstory drifts at the second story and above, and the maximum roof floor drift are shown in Fig. 8 for the El Centro record. As SB increases, the drift demand tends to decrease at the first story but increase at the upper stories. This trend is most pronounced for 0.70 ≤ SB ≤ 0.80. The maximum roof floor drift demand is nearly unchanged with about 200mm or a slightly larger for 0.5 ≤ SB ≤ 0.9.

Pushover analysis was also conducted for comparison between the dynamic and static analyses. Lateral load distribution was taken to correspond to the A_i distribution. The results attained up to a roof floor drift of 200mm are shown in Fig. 9 in the same form as for the dynamic results (Fig. 8). The static results were similar in trend to the dynamic ones; with the increase in SB, the drift demand tends to decrease at the first story but increase at the second story and above. Further, the trend is most pronounced for 0.75 ≤ SB ≤ 0.90. The discussion to follow refers to the static results.

Interstory drift versus story shear relations and associated yield conditions obtained from the pushover analysis are shown in Fig. 10 for SB = 0.75 and 0.85. For SB = 0.75 (Point A in Fig. 9), the first-story drift demand is not reduced, while

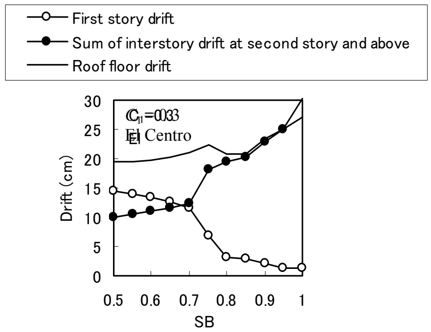


Fig. 8 Dynamic analysis (Maximum drift)

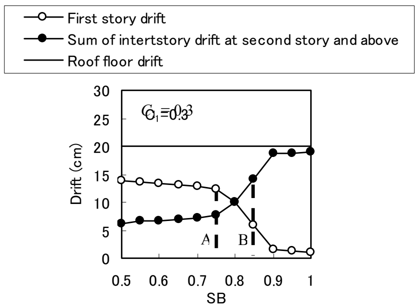
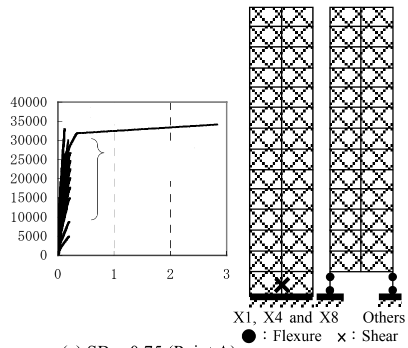
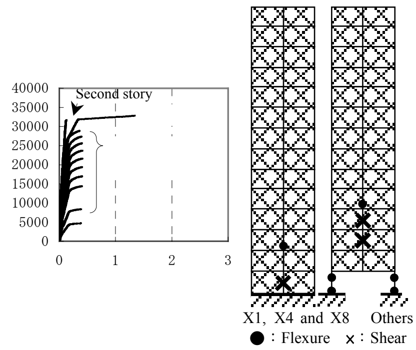


Fig. 9 Pushover analysis (Roof floor drift = 20cm)



(a) SB = 0.75 (Point A)



(b) SB = 0.85 (Point B)

Fig. 10 Pushover analysis (SB = 0.75 and 0.85) for SB = 0.85 (Point B in Fig. 9) reduction is significant. For SB = 0.75, a complete first story mechanism was formed, with neither shear nor flexural yielding occurring at the upper stories, resulting in an extreme drift concentration on the first story. For SB = 0.85, a collapse mechanism was also formed above the third-floor level after the formation of the first-story collapse mechanism. This resulted in a drift on the first story remaining significantly smaller than that corresponding to SB = 0.75. Be reminded that the first-story strength was the same for both cases (C_1 = 0.3). This reduction in drift indicates that the strength balance can have a significant effect on the first-story drift demand.

Conditions Required to Control First-Story Drift Demand Within an Allowable Level

To further study the effects of the two parameters, nonlinear dynamic analysis was carried out for various C_1 and SB values. Relations between C_1, SB and the maximum first story drift are shown in Fig. 11 for the El Centro record. As expected, the first-story drift demand decreases as C_1 and/or SB is increased.

The allowable first-story drift is commonly assumed to be 1% or 2%. Those values can be achieved if sufficient lateral reinforcement is placed at the first-story columns and walls. A set of C_1 and SB values corresponding to the allowable drift can be obtained from Fig. 11. Resulting C_1-SB relations are shown in Fig. 12. Using these relations, we can determine C_1 if SB is given, or vice versa, and the obtained set ensures that the first-story drift demand is within the allowable limit. However, the C_1-SB relations are not necessarily explicit in that SB itself includes C_1. For design purposes, relationships between C_1 and C_2 (required C_1-C_2 relations) are much more practical.

The relations between C_1 and SB defined by Eq. (1) are shown in Fig. 12 as a set of straight lines for various C_2 values. The required C_1-C_2 relations are obtained as the intersection of the required C_1-SB relations and these straight lines. For example, for the 2% drift, if C_2 is 1.0, C_1 is given as 0.51 (C_1 should be more than 0.51 to meet the allowable drift requirements). Similarly if C_1 is 0.5, C_2 is given as 0.9 (C_2 should be less than 0.9).

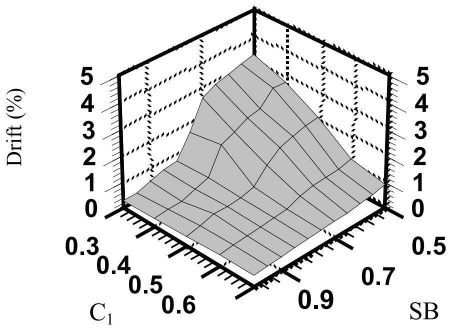


Fig. 11 C_1-SB-first story drift relations (El Centro)

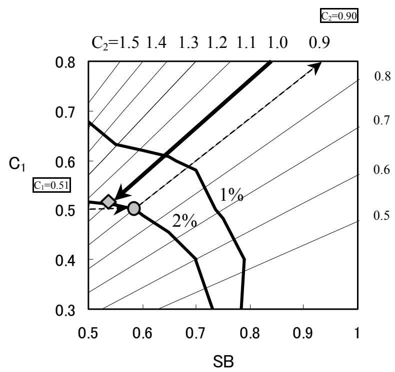


Fig. 12 Required C_1-SB relations (El Centro)

Results of the required C_1-C_2 relations are shown in Fig. 13 for the two ground-motion records and two allowable drifts. It turns out that C_1 tends to decrease as C_2 decreases, or C_2 tends to increase as C_1 increases, except for the case with the Kobe record and 2% drift, where C_1 is nearly constant regardless of C_2.

C_1 determined from a given C_2 value and C_2 determined from a given C_1 value are shown in Figs. 14 and 15 for the 1% drift. It proves from Fig. 14 that C_1 is as large as 0.67 for C_2 = 1.5 (high), a slight reduction to 0.63 for C_2 = 1.0 (medium), but becomes as small as 0.44 for C_2 = 0.5 (low). If only the first-story drift demand is of concern, apparently stories above the first should not be excessively strong. Figure 15 also proves that C_2 is as low as 0.70 for C_1 = 0.5 (low), increasing to 0.90 for C_1 = 0.6 (medium), and becoming as high as 1.50 for C_1 = 0.7 (high). In this way, we can determine the required first-story strength from the given second-story strength and vice versa if the allowable drift is specified. C_1 determined from a given C_2 value is shown in Fig. 16 for 2% drift. C_1 values are 0.52, 0.51 and 0.39 for C_2 = 1.5, 1.0 and 0.5, respectively which are considerably smaller than those determined for the 1% drift. Naturally, the required first-story strength decreases for a large story drift.

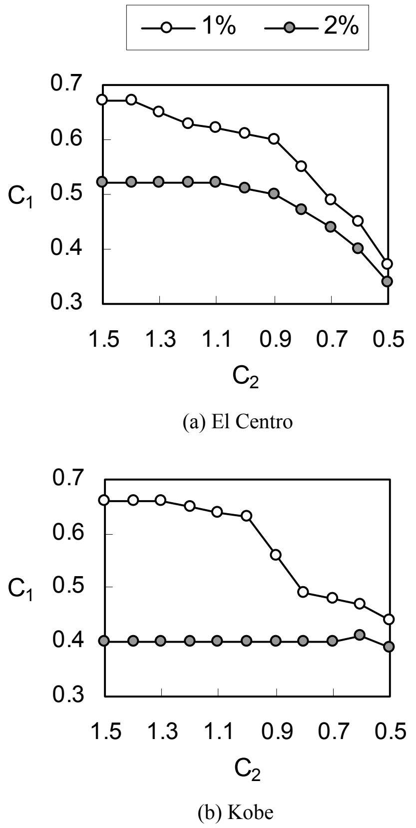


Fig. 13 Required C_1-C_2 relations

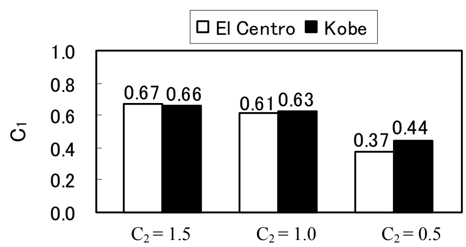


Fig. 14 C_1 determined from C_2
(Allowable drift = 1%)

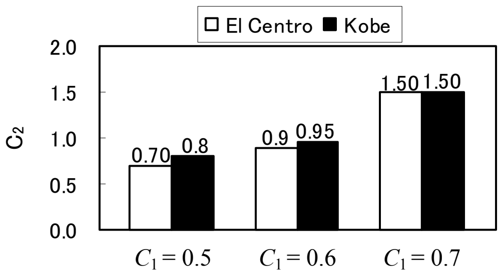


Fig. 15 C_2 determined from C_1
(Allowable drift = 1%)

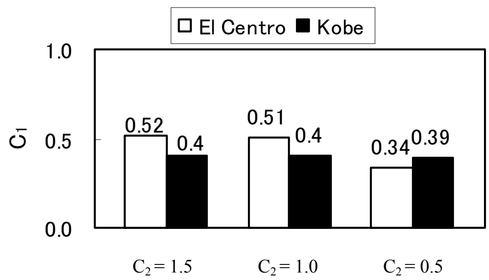


Fig. 16 C_1 determined from C_2
(Allowable drift = 2%)

CONCLUSION

This paper examined the first story drift demand for weak-first-story buildings, the vulnerability of which was revealed during many past earthquakes, including the 1995 Kobe and 1999 Chi-Chi earthquakes.

The major findings obtained from the studies are as follows.

(1) The first story drift demand is governed not only by the first story strength but also by the strength of the upper stories and the strength balance between the first story and upper stories.

(2) The first-story strength (in terms of the shear coefficient) required to limit the maximum first-story drift demand within 1% is 0.67, 0.63 and 0.44 for second-story strengths (also in terms of the shear coefficient) of 1.5, 1.0 and 0.5, respectively. The required first-story strength decreases as the second-story

strength decreases. If only the first story drift demand is of concern, excessive strength of the second story and above is not desirable for effective design.

(3) When an allowable first-story drift of 2% is adopted, the required first-story strength is reduced to 0.52, 0.51 and 0.39 for second-story strengths of 1.5, 1.0 and 0.5, respectively.

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