COLUMN-TO-BEAM STRENGTH RATIO REQUIRED FOR ENSURING BEAM-COLLAPSE MECHANISMS IN EARTHQUAKE RESPONSES OF STEEL MOMENT FRAMES

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SUMMARY

This paper examines: (1) the magnitude of column overstrength (*COF*) required for ensuring column-elastic behavior in steel moment frames; (2) the uniformity of story drift and beam rotations along the height that can be achieved by such frames; and (3) the change in response for frames having smaller *COF*s. The *COF*s required for ensuring column-elastic responses increase steadily with the increase of the ground motion amplitude, reaching about 1.5 for the ground motion amplitude of 0.5 m/s in maximum ground velocity. The steady increase is attributed primarily to higher (second) mode responses that tend to increase linearly despite that many plastic-hinges are formed in the frame. For frames in which column-elastic behavior is ensured, the maximum story drift angle is 1.5 to 2.5 times as large as the maximum overall drift angle. Change in response is gradual with the decrease of the *COF*, and the maximum overall drift angle and story drift angle remain relatively unchanged for *COF*s not smaller 1.0. The maximum overall drift angle and maximum story drift angle of a multi story frame are 0.7 to 1.0 and 1.5 to 2.0 times the maximum drift angle of the equivalent SDOF system, respectively.

INTRODUCTION

Since the disclosure of serious damage to modern steel moment frames in the 1994 Northridge and 1995 Hyogoken-Nanbu Earthquakes, extensive research is underway on various issues of steel moment frames. One of the related research subjects is how to design a "strong-column weak-beam" frame in order to ensure a beam-hinging mechanism during the response [for example, Roeder et al. 1993]. A specific research target along this line is the overstrength needed for columns relative to the adjoining beams to secure the beam-hinging response. In this paper, the ratio of column plastic moment capacity (considering the presence of axial loads) to beam plastic moment capacity is designated as the column overstrength factor (*COF*), whose definition follows that stipulated in the AISC Seismic Provisions (1997). AISC (1997) requires *COF*s not smaller than 1.0 for a "strong-column weak-beam" frame. It is, however, known that *COF*=1.0 cannot restrict plastic-hinging only to beams [for example, Gupta and Krawinkler 1998]. The degree of uniformity in deformations like story drifts that can be achieved along the height of a "strong-column weak-beam" frame is also of interest because uniform distribution of story drifts and

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therefore uniform damage along the stories is what is intended in such a frame. Such information, however, remains rather limited with the present state of knowledge. The objectives of the paper are to examine: (1) the magnitude of *COF*s needed to restrict the formation of plastic-hinges only to beams in earthquake responses of steel moment frames (such responses are called the column-elastic responses in this paper); (2) the uniformity of the story drift along the height achieved with such frames; and (3) the change in response if column plasticification is permitted.

MODEL AND ANALYSIS VARIABLES

The analysis was carried out for generic frames shown in Fig.1. Both the column heights and beam lengths were assigned on the member centerline basis, and the panel zone size, strength, and stiffness were not represented. The frame was simplified into a stick model but attached with a rotational spring at each floor. The rotational spring represents resistance provided by all beams in the concerned floor level, with the assumption that the rotations of all joints lying in one floor level are identical and beams are rigid in their longitudinal direction. Multiple columns in one story are also condensed into one column, with the assumption that all joint rotations are the same in one floor level and also by neglecting the axial elongation and contraction of columns. The mass was assumed to be concentrated in each floor level. The model is similar to a simple shear-type stick model, but joint rotations included in this model make it possible to account for changes in column moment distribution caused by beam-yielding. One *COF* was assigned for each floor level in this model. Inelastic action of beams was taken into account by adjusting the spring's stiffness, and the column yielding was considered by inserting a rigid-plastic hinge at each end of the column. The validity of this model was discussed in [Ogawa et al. 1999].

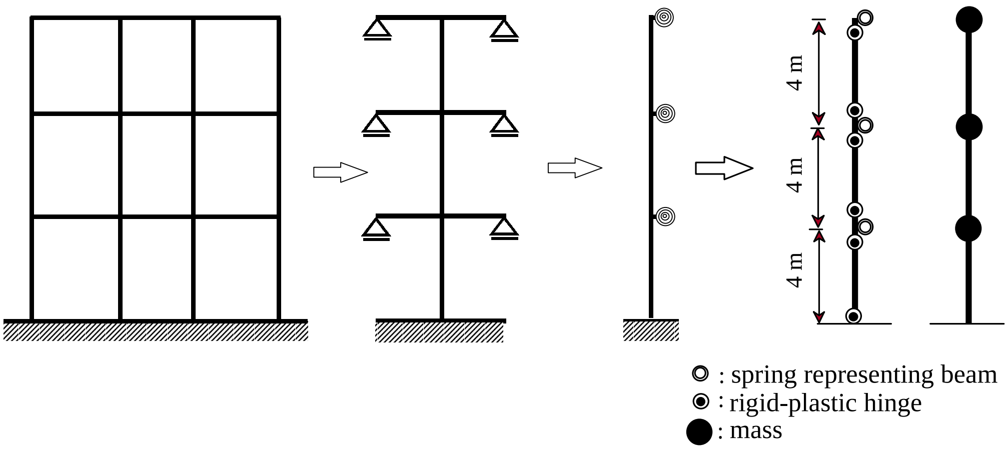


Figure 1: Generic steel moment frame adopted in analysis

The major variables in this study were: (1) the number of stories (three to twelve); (2) the type of ground motion; (3) the amplitude of ground motion; and (4) the *COF*. The structural properties were determined using the standard design procedures stipulated in the Japan's seismic code [BCJ 1997]. That is, the story drift angle was to reach 1/200 against the design earthquake force profile with the standard base shear coefficient of 0.2; and all beams and the first story column base were assigned to reach respective full-plastic moments for the standard base shear coefficient of 0.3. The moment-plastic rotation relationship of rigid-plastic hinges (assigned at column ends) was taken to be rigid and perfectly plastic, whereas the moment-rotation relationship of the beam (spring) was taken to be trilinear, with the yield and maximum moments corresponding to the standard base shear coefficients of 0.2 and 0.3, respectively. Three ground motions were adopted in the analysis, that is: El Centro-NS (1940), NTT-NS (1995) ("Strong" 1995), and Yokohama ("Manual" 1992). The NTT-NS record is one of the records obtained during the Kobe Earthquake, and the Yokohama motion is a synthesized ground motion that fits to the standard earthquake response spectrum stipulated in the Japanese seismic code. The amplitude of the three ground motions was adjusted to 0.25 m/s, 0.5 m/s, 0.75 m/s, 1.0 m/s, and 1.25 m/s in terms of the maximum ground velocity. The amplitude of 0.5 m/s is that considered as the large earthquake level in the Japan's seismic design code. The magnitudes of 0.75 m/s to 1.25 m/s are larger than those considered in the current design practice but adopted intentionally to provide data on the behavior of frames subjected to ground motions beyond the code specified. The analysis was carried out with initial stiffness proportional damping having 2% of critical for the elastic first mode, and the unconditionally stable Newmark method was employed to obtain necessary data.

The P-Δ effect was not included in the analysis. According to a separate study [Nakashima and Sawaizumi 1999], this effect on the overall response would remain minimal for the frames analyzed in this study if realistic material strain hardening is taken into account. The type of frame (to allow for discrete choice of member sizes) and type of beam's moment-rotation relationship (to consider various hysteresis) were also adopted as analysis variables. Because of space limitation, the results are not presented in this paper but referred to when their effects were significant. In the discussion to follow, the results with the El Centro ground motion are presented primarily, because effects of ground motion on the response were found secondary. Full details of the analysis variables and results are presented in [Nakashima and Sawaizumi 1999].

ANALYSIS TO EXAMINE REQUIRED *COF*S

First, columns were assumed to remain elastic except for the first story column base. The ratio of the maximum moment (M_{Cmax}) exerted to the elastic column to the full-plastic moment (M_{pB}) of the adjoining beam becomes the *COF* required for ensuring the column-elastic response. Figures 2 shows examples of the results; Figs.2(a) and (b) show the story distribution of the maximum story drift angles (*SDA*), normalized by the maximum overall drift angle (*ODA*); and Fig.2(c) and (d) show the story distribution of (M_{Cmax}/M_{pB}), meaning required *COF*s. The *ODA* was defined as the maximum roof displacement divided by the total height. Figure 3 shows a summary of the results. The abscissa and ordinate of these figures are the ground motion amplitude and the responses (*SDA/ODA* and required *COF*), respectively. In the ordinate, the maximum (*max*), the average (*av*), and the coefficient of variation (*cov*) with respect to the story are plotted.

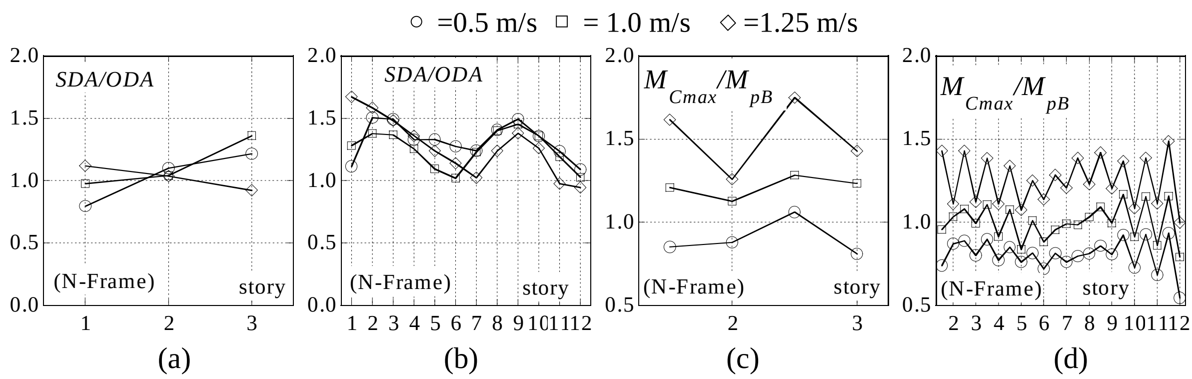


Figure 2: Story distribution of responses: *SDA/ODA* for three (a) and twelve (b) story frame; Required *COF* for three (c) and twelve (d) story frame

The story drift distribution is relatively uniform for the three story frame regardless of the ground motion amplitude, whereas it fluctuates more significantly for the twelve story frame [Figs.2(a) and (b), and Figs.3(a) and (b)]. The fluctuation is primarily because of larger participation of the higher (second) mode vibration, and more conspicuous for larger ground motions. Reminded that plastic hinges were permitted only in beams and first story column base in the analyzed frames, the degree of story drift fluctuation shown in Figs.2 and 3 is what is to be tolerated even for frames in which the column-elastic response is ensured. The results shown here as well as those obtained for other parameters [Nakashima and Sawaizumi 1999] indicate that the ratio of the maximum story drift to the maximum overall drift (*SDA/ODA*) reaches about 1.7 for the ground motion amplitude of 0.5 m/s and about 2.0 (up to nine story frames) and 2.5 (twelve story frames) for the amplitude of 1.0 m/s.

The *COF*s required for ensuring column-elastic responses are distributed rather uniformly along the height [Figs.2(c) and (d)], indicating that an extremely large *COF* is not required for a particular story. It is notable that the *COF*s for ensuring column-elastic responses increase steadily with the increase of the earthquake amplitude [Figs.(c) to (h)]. For the ground motion amplitude of 0.5 m/s, the maximum of required *COF*s reaches about 1.5, and for the amplitude of 1.0 m/s, it reaches about 2.0. Figures 4 shows the column moment diagrams for the three story frame. The diagram (C) is for the time (4.37 to 4.38 s) when the first story column top sustained the largest bending moment, the diagram (A) is for a time (4.24 to 4.26 s) slightly before (C), and the diagram (B) is the increment from (A) to (C). In the moment distribution (A), the point of contraflexure of the columns remain nearly in the mid-height for all stories, and the equivalent earthquake forces of all floor levels (F_1, F_2, and F_3) act in the same direction. For ground motion amplitudes of 1.0 m/s and 1.25 m/s, the first story column base and the beams in all floor levels sustain the full-plastic moments, the frame forms the beam-hinging mechanism, and therefore the magnitudes of the column moments are about the same for both ground motions [Fig.4(b) and (c)]. In the incremental moment diagram (B), the equivalent earthquake force in the roof level (F_3) is reversed, and the beam in the roof level is unloaded (regaining the elastic stiffness), while already plastified first story column base and the beams in the second and third floor levels sustain further rotations. This incremental behavior is analogous to the behavior of an elastic long column in which the column base is pin-supported, and an elastic spring is arranged at the top. The moment distribution of such a column is of a bowing mode, and the moment magnitude can be larger for a larger ground motion, because the long column is elastic. The moment diagram (B) of Fig.4(a) to (c) clearly shows such a bowing mode, which is larger for a larger ground motion. The moment magnitude of (A) is not so different from each other (because of the formation of the beam-hinging mechanism), but the moment magnitude of (B) is larger for larger ground motions. It is for this reason that the magnitude of (C), given as the sum of (A) and (B), is made larger for larger ground motions.

Figure 4(d) shows the modal equivalent force responses (from 4.0 s to 5.0 s) obtained for the three story frame. Those responses were obtained by decomposing the equivalent force responses with respect to the elastic eigen modes [Nakashima and Sawaizumi 1999]. In Fig.4(d) the first two modes are plotted for the amplitudes of 0.5 m/s, 1.0 m/s, and 1.25 m/s. At 4.24 to 4.26s, when the point of contraflexure was approximately located in the mid-height and the beam-hinging mechanism was formed for 1.0 m/s and 1.25 m/s of the ground motion

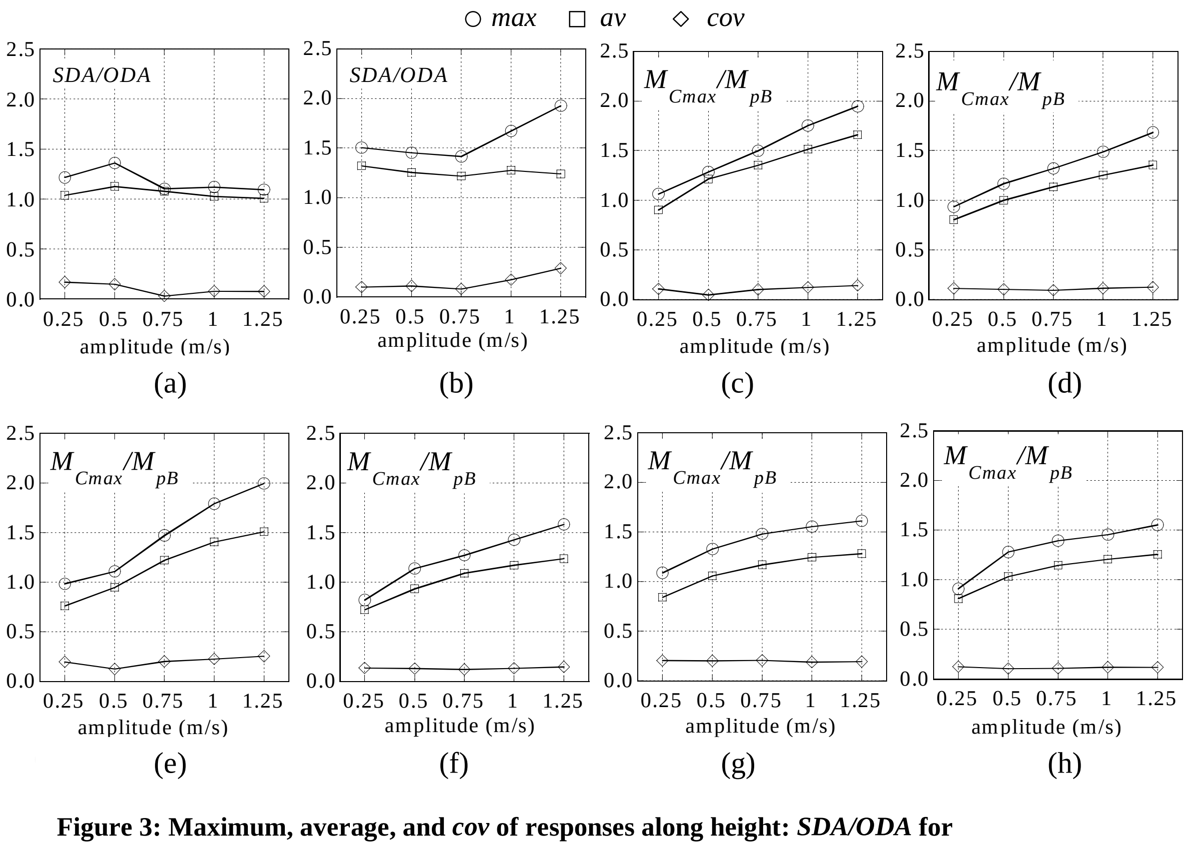


Figure 3: Maximum, average, and *cov* of responses along height: *SDA/ODA* for three (a) and twelve (b) story frame; Required *COF* for three (c) and twelve (d) story frame (El Centro motion); Required *COF* for three (e) and twelve (f) story frame (NTT motion); Required *COF* for three (g) and twelve (h) story frame (Yokohama motion);

amplitude [(A) in Figs.4(b) and (c)], the first mode response dominates. At 4.38 s, when the maximum moment was exerted to the first story column top [(C) in Fig.4(a) to (c)], the first mode response is nearly identical for the amplitudes of 1.0 m/s and 1.25 m/s, because the beam-hinging mechanism was formed in both responses. The second mode response at that period, however, is larger for a larger ground motion. This observation also demonstrates the promotion of second mode response at the instant when the column moment was most enhanced.

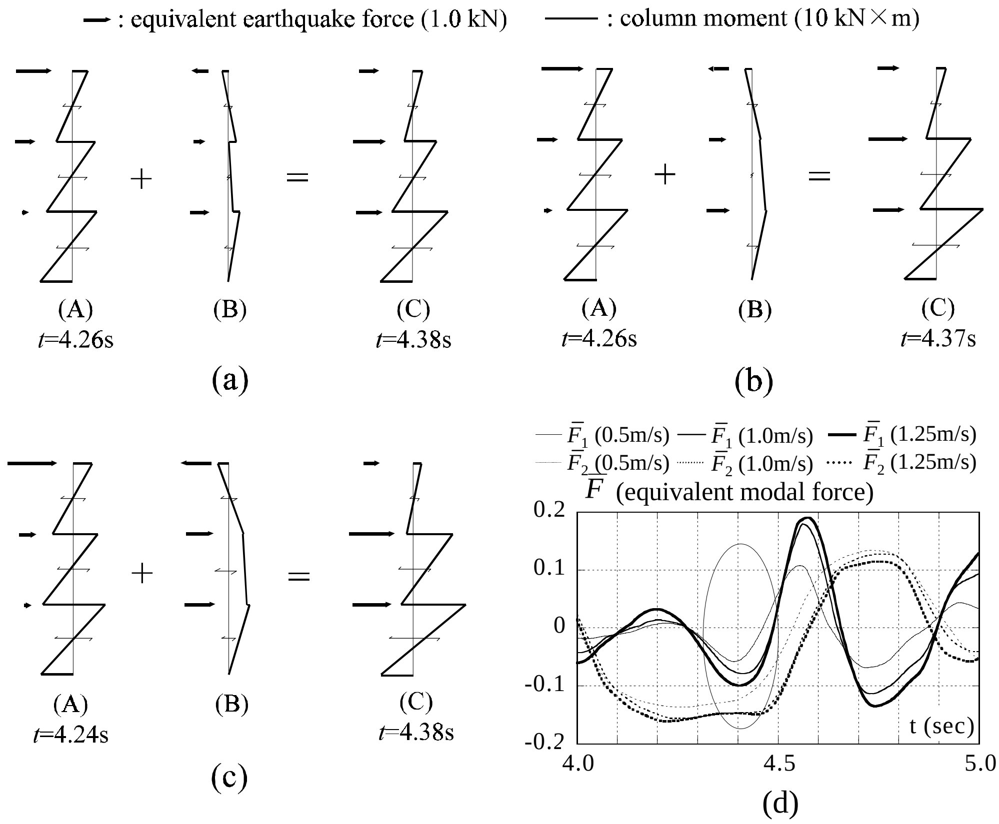


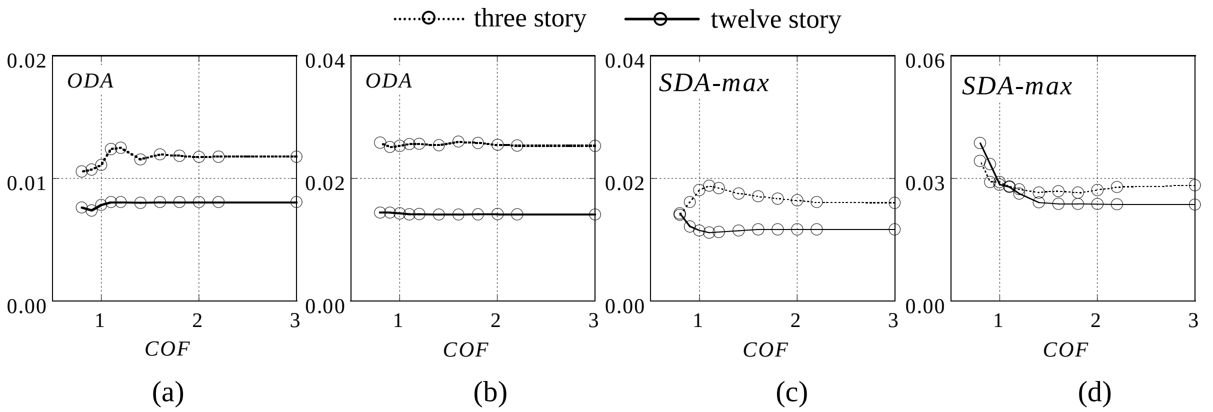
Figure 4: Column moment diagrams when first story column top is reaching maximum: (a) amplitude = 0.5 m/s; (b) amplitude of 1.0 m/s; (c) amplitude of 1.25 m/s; (d) first and second mode equivalent force responses

ANALYSIS OF FRAMES INVOLVING COLUMN YIELDING

The frames examined above were reanalyzed, but this time with finite column strength. The adopted *COF*s were from 2.2 to 0.8, with the successive decrement of either 0.2 or 0.1. The same *COF* was used for all floor levels except for the first story column base whose strength was unchanged. The full-plastic moments of the column top and bottom were assigned to be the chosen *COF* times the full-plastic moment of the joining beam.

Figure 5(a) and (b) show how the maximum overall drift angle (*ODA*) changes with respect to the *COF*. The ordinate denotes the *ODA* in rad, and the abscissa denotes the *COF*, with *COF*=3.0 corresponding to the case in which the column-elastic response is ensured. This quantity remains almost unchanged for *COF*s not smaller than 1.0, and its change is still minimal even if the *COF* is smaller than 1.0. Figure 5(c) and (d) show how the maximum story drift angle (*SDA*) changes with respect to the *COF*, plotting the maximums (*max*) among the stories (*SDA-max*). They remain unchanged for larger *COF*s but tend to increase for smaller *COF*s, particularly for the amplitude of 1.0 m/s. The degree of increase, however, is not significant for *COF*s not smaller than unity. When *COF*=1.0, the most significant increase obtained among all analysis cases was 40% relative to the column-elastic case [Nakashima and Sawaizumi 1999]. These observations indicate that global deformations (*ODA* and *SDA*) are relatively unaffected by the *COF*.

Figures 6(a) and (b) show the maximums (θ_{pC}-*max*) in rad of maximum column plastic rotations among all column tops and bottoms (except for the column base) for various *COF*s. The magnitude of plastic rotations is larger naturally for the large ground motion amplitude. For the amplitudes of 0.5 m/s and 1.0 m/s, the plastic rotations remain nearly zero when *COF*s are not smaller than 1.5 and 2.0, respectively. It is also notable that the increase of θ_{pC} is not abrupt but gradual with the decrease of the *COF*. Figures 6(c) and (d) show the relationship between the *COF* and the maximum plastic rotation normalized by the maximum story drift angle of the concerned story. In this figure, the largest among all normalized maximum plastic rotations (θ_{pC}/*SDA*-max*)



is plotted. The figure indicates that the ratio reaches about 0.5 for *COF*=1.0. The maximum ratio obtained among all analysis cases was 0.7.

Figures 7(a) and (b) show the column end moment responses for the three story frame having the amplitude of 1.0 m/s, presenting a short range of responses during which the column top of the first story sustained the maximum moment. Figure 7(a) is for the frame in which the column-elastic response was ensured (*COF*=infinity), and (b) is for *COF*=1.1. As shown in Fig.4(d) (for *COF*=infinity), at 4.37 s, the elastic second mode response (responding in a bowing mode) was most promoted, but the duration of this promotion was limited (for about 0.2 s). Figure 7(a) (the column-elastic response) conforms to that response, indicating that promotion of the moment exerted to the first story column top (designated by the thick solid line) is limited in time (for 0.2 s from 4.3 to 4.5 s). Corresponding to this short moment promotion for the column elastic response, the duration of yielding of the first story column top is also limited for about 0.2 s to 0.3 s when the *COF* is 1.1 [Fig.7(b)]. The maximum column moment was obtained when the promoted second mode response (responding in a bowing mode) was superposed to the first mode response (in which a beam-hinging mechanism was formed), but the duration of such an instance was small. It is for this reason that change in global response remained rather small even for *COF*s in which column yielding was permitted.

Figure 5: Effect of *COF* on response: *ODA* (rad) for amplitude of 0.5 m/s (a) and 1.0 m/s (b); *SDA-max* (rad) for amplitude of 0.5 m/s (c) and 1.0 m/s (d)

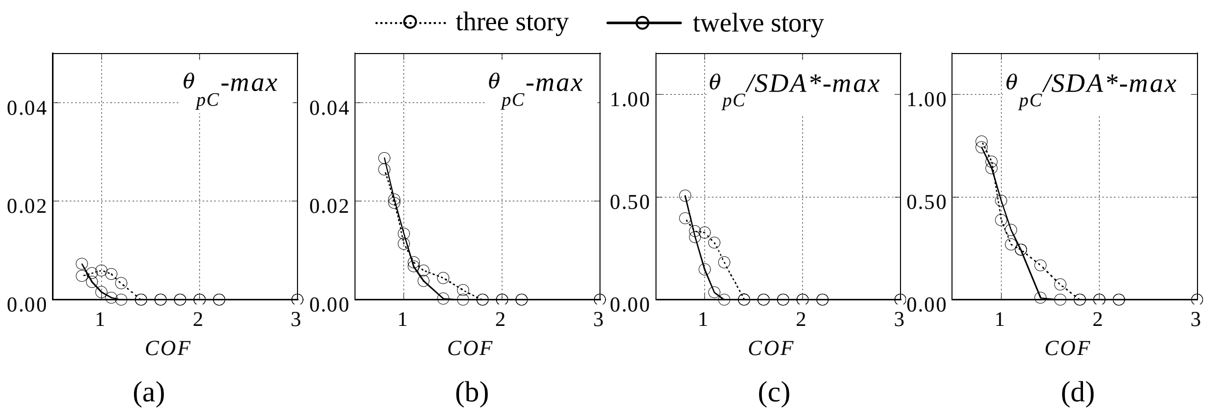


Figure 6: Effect of *COF* on column rotation: θ_{pC} *-max* (rad) for amplitude of 0.5 m/s (a) and 1.0 m/s (b); θ_{pC} */SDA*-max* for amplitude of 0.5 m/s (a) and 1.0 m/s (b)

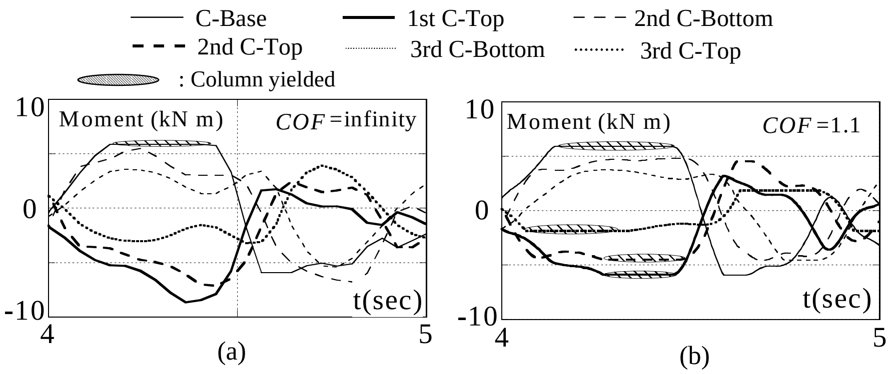


Figure 7: Column moment response: (a) *COF*=infinity; (b) *COF*=1.1

CORRELATION WITH EQUIVALENT SDOF SYSTEMS

The maximum overall drift angle (*ODA*) is considered as the quantity to be correlated with the maximum drift angle obtained for the equivalent SDOF systems. In this study, the equivalent SDOF system was defined as follows. (1) The weight of the SDOF system is the same as the total weight of the frame. (2) The elastic natural period of the SDOF system is the same as the elastic fundamental natural period of the frame. (3) The strength of the SDOF system is defined for the standard base shear coefficient corresponding to the strength of the frame (0.3 in this study), with adjustment of the effective modal mass for the first mode. (4) The force-displacement relationship of the SDOF system is taken to be trilinear, with the yield strength set to correspond to the standard base shear coefficient of 0.2. (5) The equivalent height of the SDOF system is estimated from the equivalence of the first mode overturning moment at the base of the frame and the overturning moment of the SDOF system.

Figure 8 shows correlation of the maximum overall drift angle (*ODA*) and the largest of maximum story drift angles (*SDA-max*), with respect to the maximum drift angle (designated as *EDA*) of the equivalent SDOF system. The data plotted in this figure are for multi-story frames in which column-elastic responses were ensured. Figure 8(a) shows that the correlation between the *ODA* and *ED*A is reasonable, with the *EDA* generally larger than the *ODA*, the reason of which needs further examination. The ratio of the *ODA* to *EDA* ranges approximately between 0.7 and 1.0. As noted earlier, the upper bound of the ratio of the maximum *SDA* to the *ODA* was about 1.5 for the ground motion amplitude of 0.5 m/s, and 2.0 (up to nine stories) and 2.5 (twelve stories) for the amplitude of 1.0 m/s. Because of the difference between the maximum *SDA* and *ODA*, Fig.8(b) shows that the maximum *SDA* is often larger than the *EDA*. The upper bound of the ratio of the maximum *SDA* to the *EDA* reaches about 1.5 and 2.0 for the amplitudes of 0.5 m/s (smaller drift angles) and 1.0 m/s (larger drift angles), respectively.

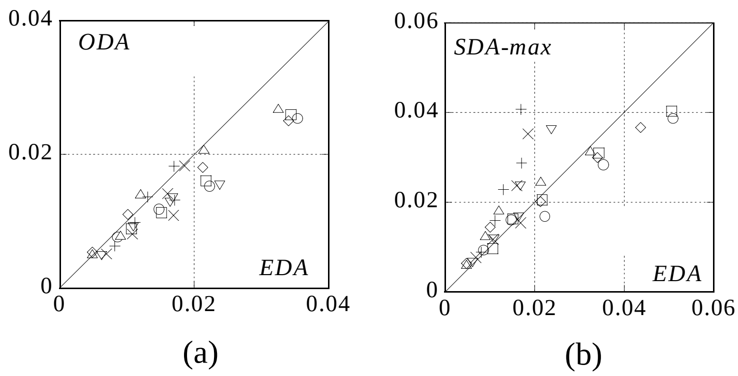


Figure 8: Correlation with equivalent SDOF system: (a) *ODA* and *EDA*; (b) *SDA-max* and *EDA*

CONCLUSIONS

The major findings obtained from the study are summarized as follows:

(1) The *COF* required for ensuring column-elastic responses increase steadily with the increase of the ground motion amplitude. The *COF* required for ensuring such responses is about 1.5 and 2.0 for the ground motion amplitudes of 0.5 m/s (equivalent to the Japan's large design earthquake level) and 1.0 m/s in the maximum ground velocity, respectively. The reason for such steady increase of required *COF*s was identified as the promotion of second mode response with the increase of ground motion amplitude, even if many plastic hinges are formed in the frame.

(2) The maximum story drift relative to the maximum overall drift was about 1.7 for the ground motion amplitude of 0.5 m/s, and 2.0 (up to nine stories) and 2.5 (twelve stories) for the ground motion amplitude of 1.0 m/s.

(3) Change in response is not abrupt but gradual with the decrease of the *COF*. The maximum overall drift angle and story drift angle remain relatively unchanged for *COF*s not smaller 1.0. The column plastic rotation remains nearly zero for *COF*s not smaller than 1.5 (for the amplitude of 0.5 m/s) and 2.0 (for the amplitude of 1.0 m/s) but increases gradually for smaller *COF*s and reaches about 0.7 times the maximum story drift angle for *COF*=1.0.

(4) The maximum overall drift angle and maximum story drift angle of a multi story frame were 0.7 to 1.0 and 1.5 to 2.0 times the maximum drift angle of the equivalent SDOF system, respectively.

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