STUDY ON CONDITIONS FOR PREVENTING PROGRESSIVE COLLAPSE IN MULTISTORY STEEL FRAMES

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ABSTRACT:

There are two possible cases of behaviors of multistory frames after the vertical collapse of one story, where the collapse occurs due to an event such as a fire, an explosion or an earthquake. In one case, the collapse proceeds to a certain extent and then ceases, while in the other, the collapse occurs continuously until all stories collapsed completely. In the latter case, the collapse is called a progressive collapse, which is an unstable phenomenon of frames resulting from gravity load. This study elucidates the frame conditions that enable the stories to resist progressive collapse by comparing the gravity potential energy released by the collapsed story with the energy absorbed by columns before they completely collapse due to compressive load.

KEYWORDS: Progressive collapse, Multi-mass system, Collision, Energy absorption, Balance of energy, Time history analysis

1. INTRODUCTION

The World Trade Center disaster on September 11, 2001, is a typical case of a progressive collapse [AIJ, Bažant]. In the case of earthquakes, e.g., the 1985 Mexico City earthquake in Mexico and the 1999 Izmit earthquake in Turkey, incidents where all stories of multistory buildings collapsed have been reported, and it is considered that such incidents have been caused by progressive collapse. In the 1995 South Hyogo earthquake in Japan, the intermediate stories of some tall buildings collapsed completely although none of the buildings experienced progressive collapse. However, it is considered that only on the basis of this fact, it cannot be concluded that the earthquake-resistant designed buildings in Japan are immune to progressive collapse. At present, the possibility of the occurrence of a progressive collapse after the collapse of an intermediate story in a high-rise building is not considered sufficient.

Progressive collapse is an unstable phenomenon of frames resulting from gravity load. In this paper, an index for the stability of frames under gravity is introduced. A dynamic response analysis of multi-mass system models is carried out, and then, the frame conditions for preventing the progressive collapse of multistory buildings are investigated.

2. STUDY MODEL

The behavior of multistory steel frames after the vertical collapse of one story owing to a certain cause is studied. When a story loses its vertical load bearing capacity, parts of the building above this story fall and they collide with the floor. Following this, there are two possible cases of behaviors of multistory frames. In one case, the collapse ceases partially, while in the other case, the collapse progresses continuously until all stories collapse completely. The outlines of the model used in this study for investigating the relationship between the condition of the building and the behavior of the collapse are given below.

a) Multi-mass model

This analytical model is a multi-degree-of-freedom system that consists of one mass and one vertical spring for each story, as shown in Figure 1 (a). The story that loses its vertical load bearing capacity is the starting point of the collapse. This story number is set as "f-th" and this story is termed the "collapse start story." When a column member of the f-th story is removed from a state balanced with gravity as shown in Figure 1 (a), the system changes as shown in Figure 1 (b). It is assumed that the collapse start story does not absorb any energy such as a free fall and the collision between the masses is an elastic process.

b) Load–deflection relationship of normal stories

The load–deflection relationship of the vertical spring of each story is determined from the test results on the behavior of centrically loaded box-section steel columns [Minami]. A typical behavior of a centrically loaded steel column until complete collapse is shown in Figure 2.

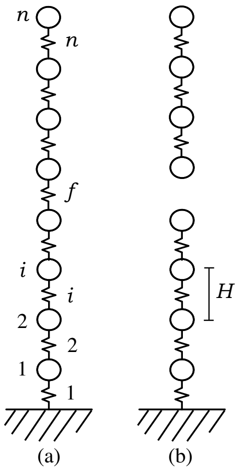


Figure 1 Multi-mass-spring system model

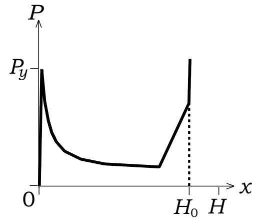


Figure 2 Load–deflection relationship for spring of each story

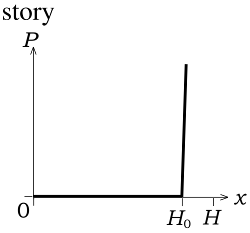


Figure 3 Load–deflection relationship for spring of collapse start story

c) Load–deflection relationship of collapse start story

The removal of the column member of the collapse start story (f-th story) implies that the spring shown in Figure 2 replaces instantaneously that shown in Figure 3 as the f-th story.

d) Damping

It is safe to assume that the collapse start story does not have any damping and energy absorption at the period of the collision. After the collision, the system does not absorb any energy except for that absorbed by the plastic deformation in the vertical spring of each normal story.

3. INDEX FOR FRAME STABILITY

The stability of a system is considered to be attributed the balance of energy. Strain energy $E(x)$ that the column absorbs by the vertical displacement of a story in the model, shown in Figure 2, is obtained by the following equation.

$$E(x) = \int_0^x P(x)dx \tag{3.1}$$

When the total mass of the part above the story is given by M, potential energy Mgx (g: gravity acceleration) is released by the displacement x of the story, and the energy released is input into the structure. Therefore, $E_r(x)$, which is obtained by the following equation, is regarded as the effective absorbed energy due to the displacement of the story.

$$E_r(x) = E(x) - Mgx \tag{3.2}$$

When the values of Mg are those represented by broken lines #1 $\sim$ #3 shown in Figure 4 (a) and the load–deformation relationship of the story represented by the solid line in Figure 4 (a), the absorbed energy $E(x)$ and Mgx are represented by the solid line and broken lines, respectively, in Figure 4 (b). Then, the values of the effective absorbed energy E_r can be represented by the solid line in Figure 4 (c).

The value of E_r when $x = H_0$ is denoted by E_{r0}; it is termed the "effective energy absorption ratio" α, which is defined as follows.

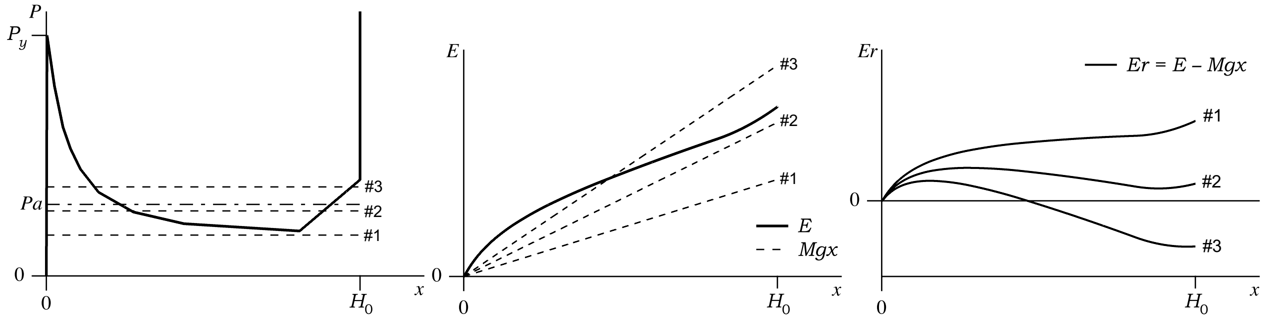
$$\alpha = \frac{E_{r0}}{MgH_0} \tag{3.3}$$

Here, the average value of the force of the column for $0 \leq x \leq H_0$ is determined from the mean strength P_a.

$$P_a = \frac{\int_0^{H_0} P(x)dx}{H_0} \tag{3.4}$$

When $x = H_0$ in Eqn. 3.2,

$$E_{r0} = P_a H_0 - MgH_0 \tag{3.5}$$



(a) Load–deflection relationship and value of Mg

(b) Absorbed energy E and potential energy Mgx

(c) Effective absorbed energy E_r

Figure 4 Effective absorbed energy of story

Therefore, α can be expressed as follows.

$$\alpha = \frac{P_a}{Mg} - 1 \tag{3.6}$$

The value of P_a for the load–deformation relationship shown in Figure 4 (a) is indicated by the dash-dotted line shown in this figure. It can be assumed that α is the basic index of the stability of the system. For example, it is considered that the potential energy released due to the fall of the collapse start story can be absorbed by the adjacent story and the collapse does not progress continuously in the case of a frame with $\alpha > 1$. The probability that a progressive collapse occurs is high because energy is released by the deformation due to the collapse in the case with $\alpha < 0$.

4. NUMERICAL DYNAMIC ANALYSIS

4.1. Analytical Method

4.1.1 Vibration system

First, for the vibration system shown in Figure 1 (a), the characteristics of all the springs are set as shown in Figure 2, and the calculation is performed using gravity as an external force. Then, the system reaches a static balance state since viscous damping is added. In the next instant, only for the collapse start story (f-th story), the load–deflection relationship of the spring becomes that shown in Figure 3, and the damping is simultaneously removed. The calculation after the collapse proceeds.

4.1.2 Treatment of collision

The collision at the collapse start story is considered to be between perfectly inelastic and perfectly elastic. For an inelastic collision, it is considered that the ratio of energy spent due to inelastic collision to kinetic energy immediately before the collision is comparatively small. Thus, in this analysis, a perfectly elastic collision is assumed as a safety aspect.

For the characteristics of the restoring force shown in Figure 5, it is desirable that the stiffness K_1 in $x \geq H_0$ is large enough. The value of K_1 and the time interval Δt are decided in such a manner that the numerical calculations are accurate and stable.

The force and displacement of the spring of the collapse start story always progress as represented by the thick solid line shown in Figure 5, and there is no distorted energy absorption by this spring.

4.1.3 Characteristics of restoring force for normal story

Figure 6 shows the hysteresis characteristics of the restoring force for a normal story. In the section between points A and B, the force unloads elastically in the case of a negative displacement. After having reached point B, the

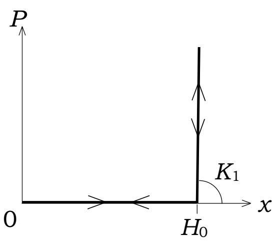


Figure 5 Hysteresis characteristics of collapse start story

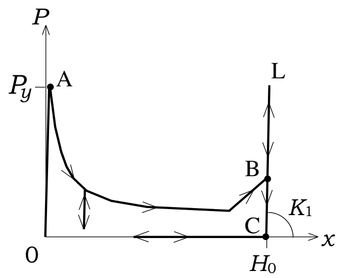
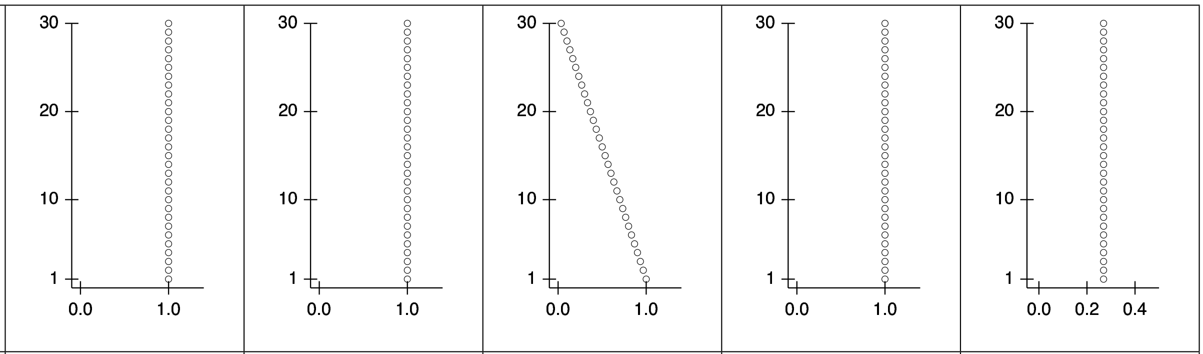
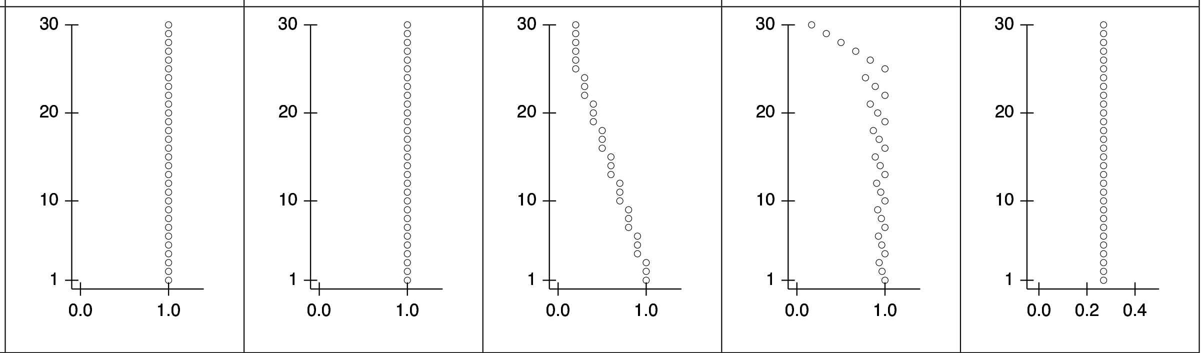
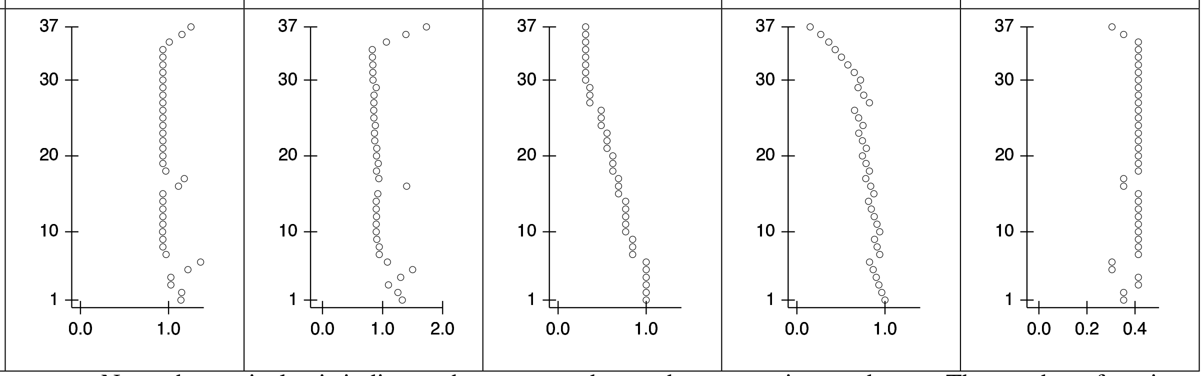


Figure 6 Hysteresis characteristics of normal story

Table 1 Specifications of frame models

Items	Height of story	Mass	Yield strength	Axial ratio	Mean strength
Horizontal axis	$H_i/\overline{H}_i$	$m_i/\overline{m}_i$	P_{yi}/P_{y1}	p_i/p_1	P_{ai}/P_{yi}
Frame A $n = 30$					
Frame B $n = 30$					
Frame C $n = 37$					

Note: the vertical axis indicates the story number or the mass point number. n: The number of stories.

force and displacement progress along the semi-infinite line CBL and the line OC. Thereafter, this spring does not absorb any strain energy.

4.1.4 Frame models

The following three types of frame models are assumed for use in the analysis.

Frame A: 30-storied frame where all the stories have equal characteristics.

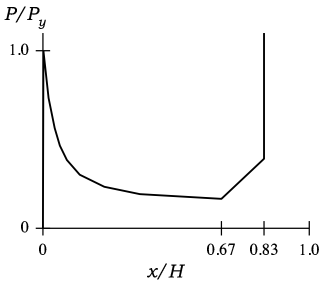
Frame B: 30-storied frame where the stories have unequal characteristics, and the cross-section of three consecutive stories (six consecutive stories from the top) is the same.

Frame C: 37-storied frame where the stories have more unequal characteristics as compared to those of Frame B. The modeling is based on an existing high-rise building.

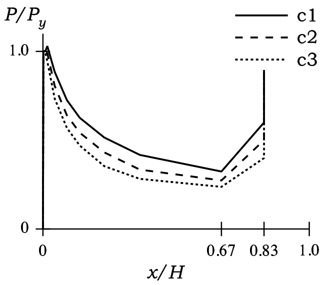
The basic characteristics of each frame are listed in Table 1. The following notations are used in the table.

H_i: Height of the i-th story, $\overline{H}_i$: Average of H_i
m_i: Mass of the i-th mass point, $\overline{m}_i$: Average of m_i
P_{yi}: Axial yield strength of the spring of the i-th story
$M_i = \sum_{j=i}^{n} m_j$: Total mass above the i-th story
$p_i = M_i\, g/P_{yi}$: Axial ratio of the spring of the i-th story
P_{ai}: Mean strength of the spring of the i-th story (See Eqn. 3.4.)

The properties of the spring used for each frame are shown in Figure 7. The properties of the springs of Frames A and B are set as shown in Figure 7 (a). The properties of the spring of Frame C are represented by c1 $\sim$ c3 shown in Figure 7 (b). The properties of the spring of each story of Frame C are shown in Table 2.



(a) Frames A and B



(b) Frame C

Figure 7 Properties of springs

Table 2 Properties of spring of each story of Frame C

Story	Spring	Story	Spring
37	c3	14	c1
36	c2	⋮	⋮
35	c1	8	c1
34	c1	7	c1
⋮	⋮	6	c3
19	c1	5	c3
18	c1	4	c1
17	c2	3	c1
16	c2	2	c2
15	c1	1	c2

Table 3 Analytical conditions

Frame	f	α_f
A	15	0.0 $\cdots$ 1.0
	1	0.0 $\cdots$ 0.5
B	15	0.03, 0.24, 0.55
	14	0.06, 0.27, 0.59
	13	0.08, 0.30, 0.62
C	20	0.26, 0.58, 1.2
	10	0.11, 0.39, 1.0

For each frame, the position of the collapse start story f and the size of the mass are changed, however, the distribution form of the mass is not changed. The effective energy absorption ratio α of each story is determined depending on the size of the mass and the frame. In the case of Frames B and C when the value of α is not equal with each story, α_f is estimated as the average value of α for stories immediately above and below the collapse start story.

The frame conditions are listed in Table 3. The analytical case is indicated as follows.

Frame - "collapse start story" (α_f)

For example,

B-15 (0.5)

expresses the case in which the frame is Frame B, the collapse start story is the 15th story and α_f is approximately 0.5.

4.2. *Analytical Results*

4.2.1 Results of Frame A

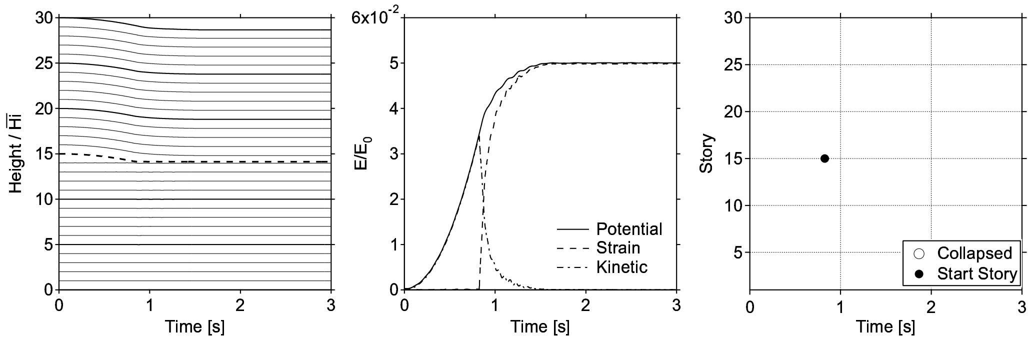
The results of A-15 (1.0) are shown in Figure 8. Graphs (a) and (b) show the time histories of the displacement and energy, respectively. Graph (c) shows the time when the maximum displacement H_0 of each story is achieved. The solid circle indicates the collapse start story. In this figure, the open circle denotes the story that collapses completely. The potential energy released when all the stories collapse E_0 in graph (b) is given by

$$E_0 = \sum_{i=1}^{n} \left\{ m_i \, g \left(\sum_{j=1}^{i} H_{0j} \right) \right\} \tag{4.1}$$

In the case of A-15 (1.0), the energy is absorbed by the entire frame, and a progressive collapse does not occur. Figures 9 and 10 show the results of A-15 (0.2) and A-15 (0.0), respectively. In the former case, only some stories collapsed, while in the latter, the large-scale collapse of all the stories occurred. In Figure 10, graph (b) shows the behavior of an unstable progressive collapse, in which the kinetic energy increases without being absorbed. On the other hand, graph (c) shows that first, the collapse proceeds sequentially from the collapse start story and then, the collapse begins near the topmost story.

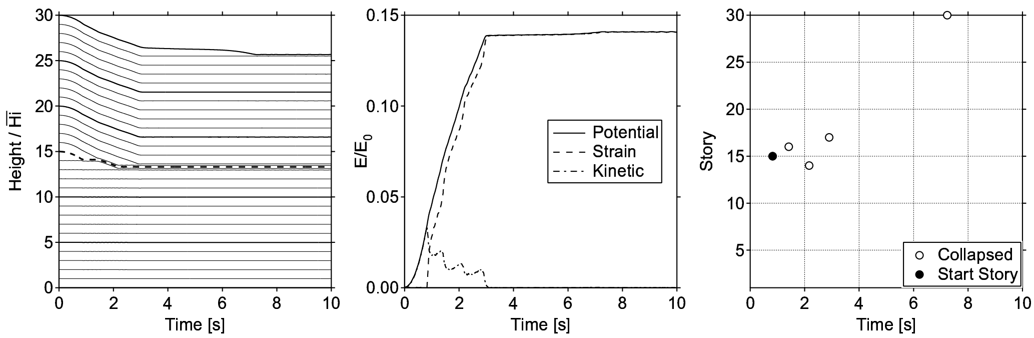
4.2.2 Results of Frame B

B-15 (0.24), B-14 (0.27), and B-13 (0.30) have the same frame specifications; however, the collapse start stories are the 15th, 14th and 13th stories, respectively. The results are shown in Figures 11 to 13. In the case of B-15 (0.24) and B-13 (0.30), the story that collapses following the collapse start story is that immediately above the collapse start story; however, in the case of B-14 (0.27), the story is that below the collapse start story. The 25th story, which is above the collapse start story, also collapses, where the column section changes significantly (See Table 1); therefore, the concentration of strain energy is observed.



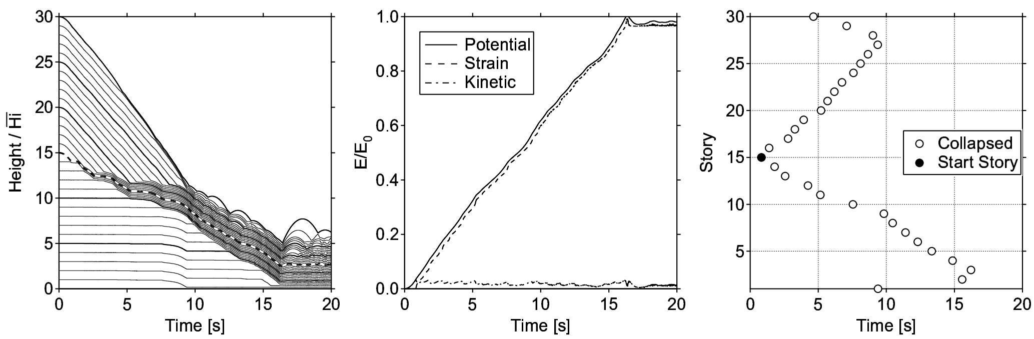
(a) Displacement (b) Energy (c) Collapsed stories

Figure 8 Time histories of A-15 (1.0)



(a) Displacement (b) Energy (c) Collapsed stories

Figure 9 Time histories of A-15 (0.2)



(a) Displacement (b) Energy (c) Collapsed stories

Figure 10 Time histories of A-15 (0.0)

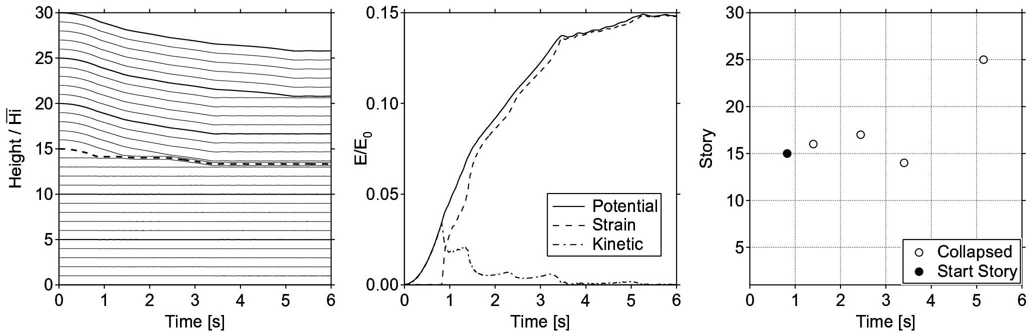
4.2.3 Results of Frame C

The results of Frame C are shown in Figures 14 to 16. In the case of C-10 (0.39), the collapsed stories are the 1st story and that immediately above the collapse start story. In the case of C-10 (0.11), many stories collapse because the effective energy absorption ratio α_f is small. The collapse begins near the collapse start story, while the 1st and 27th stories collapse where the capacity of strain energy absorption is less than that in the vicinity of the stories. Figure 16 shows the result of C-20 (0.26). Although this frame is the same as that of C-10 (0.11), few stories collapse because the value of α is comparatively large around the 20th story.

5. DISCUSSION

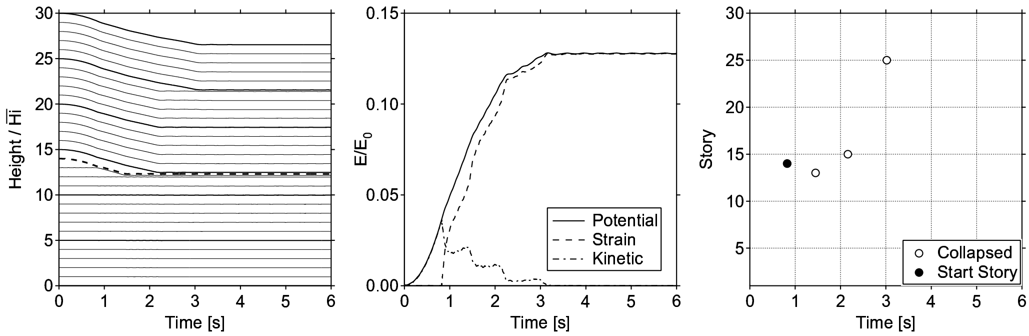
The relationship between the effective energy absorption ratio and the number of collapsed stories except the collapse start story is shown in Figure 17. When $\alpha_f = 0$, all the stories collapse. The number of collapsed stories decreases as α_f increases. If α_f is greater than 1, the potential energy released can be absorbed by either the story that is immediately below or immediately above the collapse start story, in the worst case.

If the number of stories that collapse is assumed to be $n_f = 1/\alpha_f$, it is considered that only these stories can absorb the potential energy released by the collapse. The curves of $n_f = 1/\alpha_f$ are shown by the broken lines in Figure 17. The curves appear to almost be consistent.



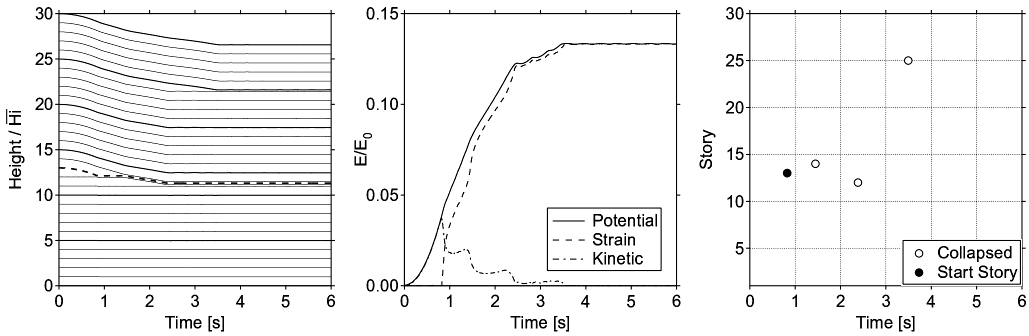
(a) Displacement (b) Energy (c) Collapsed stories

Figure 11 Time histories of B-15 (0.24)



(a) Displacement (b) Energy (c) Collapsed stories

Figure 12 Time histories of B-14 (0.27)



(a) Displacement (b) Energy (c) Collapsed stories

Figure 13 Time histories of B-13 (0.30)

6. CONCLUSIONS

The frame conditions for resisting the progressive collapse of multistory buildings have been investigated by comparing the gravity potential energy released by the collapsed story with the strain energy absorbed by the column members. The effective energy absorption ratio α_f is introduced as an index for frame stability. The behavior of progressive collapse has been investigated by performing a numerical analysis of multistory frame models. The results are summarized as follows.

1) The collapse begins near the collapse start story, although the stories away from the collapse start story that are relatively weak collapse, as well.
2) The collapse ceases only close to the collapse start story when α_f is greater than approximately 0.5.
3) Progressive collapse occurs regardless of the location of the collapse start story for $\alpha_f \leq 0$.
4) It is considered that the collapse scale (number of collapsed stories) can be roughly estimated by $1/\alpha_f$.

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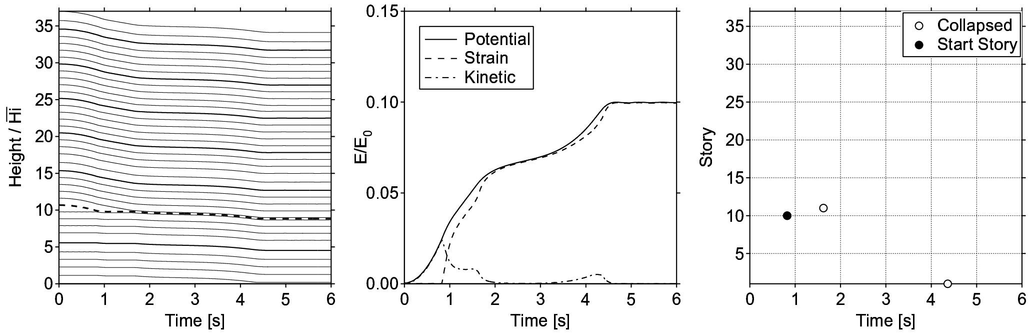
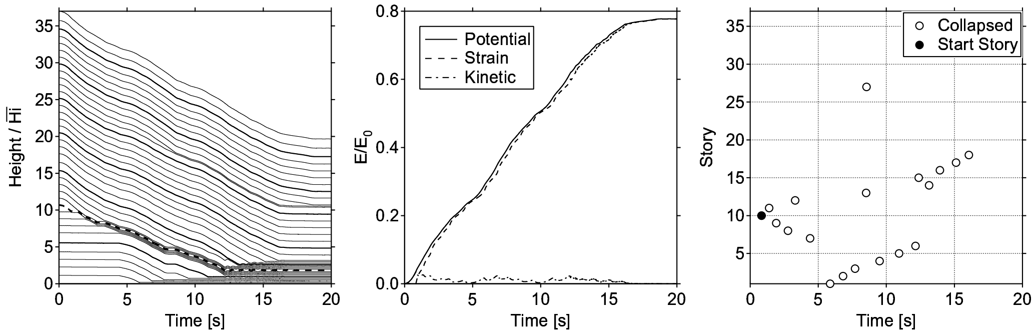


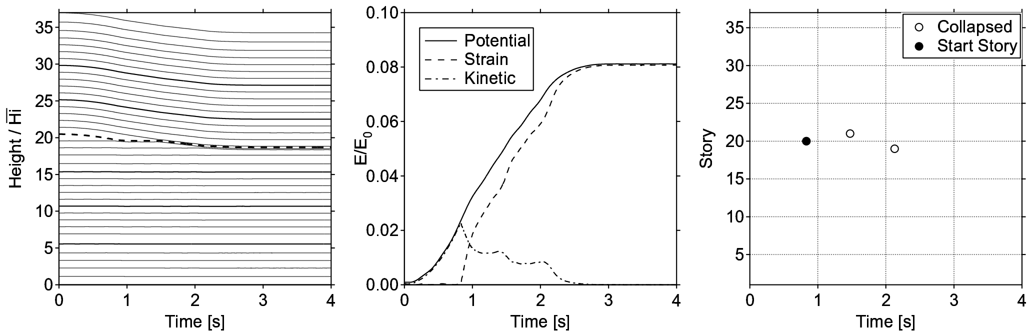
(a) Displacement (b) Energy (c) Collapsed stories

Figure 14 Time histories of C-10 (0.39)



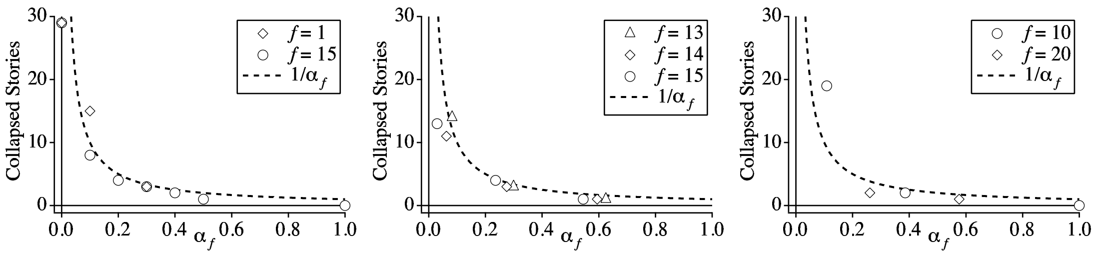
(a) Displacement (b) Energy (c) Collapsed stories

Figure 15 Time histories of C-10 (0.11)



(a) Displacement (b) Energy (c) Collapsed stories

Figure 16 Time histories of C-20 (0.26)



(a) Frame A (b) Frame B (c) Frame C

Figure 17 Number of collapsed stories

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