Collapse modes of steel frames under earthquake excitations

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ABSTRACT: In order to define quantitatively the ultimate limit state of steel structures, it is necessary to examine which collapse mode most significantly dissipates the energy input exerted by an earthquake. This paper describes a scheme how to specify a dynamic collapse mode under earthquake loading by means of a static analysis with a certain horizontal force distribution for the steel frames. A proportional static loading test and an on-line earthquake response test were carried out for 3-story frame models. After the validity of analytical model was checked by the comparison with the test results, static and dynamic numerical analyses were carried out also for other various types of frame models. It was found that the most likely collapse mode and the associated strain energy absorbed under earthquake loading can be predicted reasonably from those obtained under static loading.

1 INTRODUCTION

It seems a general approach to estimate the ultimate resistance of steel structures against earthquake excitations in the term of the energy absorbing capacity. There, the safety of the structures at the seismic design can be estimated by comparing the energy absorbing capacity of the structure with the energy input due to earthquakes (Housner 1956,1959, Akiyama 1985). In order to define quantitatively the ultimate limit state of steel frames, it is very important to know which collapse mode most significantly dissipates the energy input exerted by earthquakes, because the energy absorbing capacity of frame very much depends on the type of the collapse mode (Ohi 1989).

The study procedures in this paper are as follows : A proportional static loading test and an on-line earthquake response test (pseudo-dynamic test) were performed on 3-story moment resistant frames. The static and dynamic numerical analyses were carried out for different types of frame models, weak-beam type and weak-column type. Based on the results of the tests and the numerical analyses, it is examined whether the likely collapse mode in dynamic response can be predicted by that under proportional static loading or not.

2 EXPERIMENTS

2.1 An outline of the tests

A test frame and test setup are shown in Fig.1, and a typical stress vs. strain curve of the steel material derived from coupon tests is shown in Fig.2. Two identical frame models with one bay and three stories,
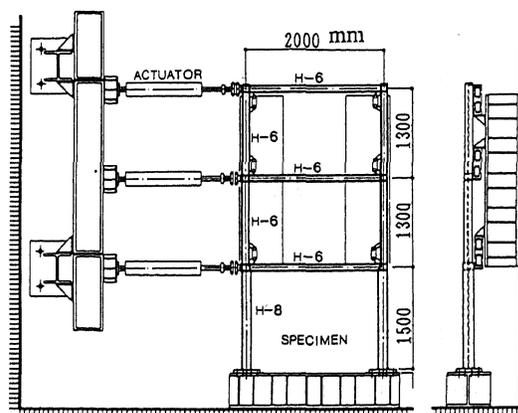

Fig.1 Test setup and test frame

which were designed as the weak-beam type, were tested under horizontal loads applied at each floor levels. A test frame is composed of a set of combination of the member sections denoted as H-6 and H-8. The section properties of the members are summarized in Table 1. For the static loading test, the test frame was loaded horizontally in the vertical distribution with the ratios, 3 to 2 to 1.

For the on-line earthquake response test, the NS component of El Centro 1940 was used as the input acceleration, the peak value of which was magnified to 606 cm/sec^2. As for the fundamental period of the frame model, 0.80 sec is assigned. Accordingly, the value of mass was assumed as the same at all floor levels and determined from the specified natural period and the frame stiffness, which was evaluated by preliminary static tests prior to the on-line response test.
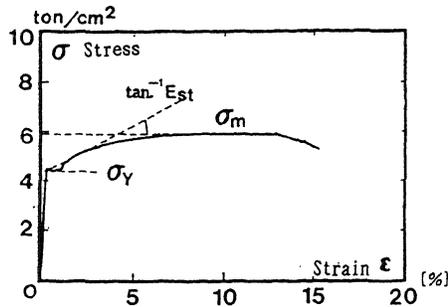
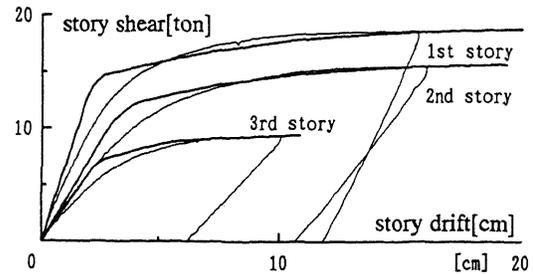Fig.2 Typical stress–strain curve of steel material

Fig.3 Story shear vs. story drift––tested(thin curves) and computed(bold curves)
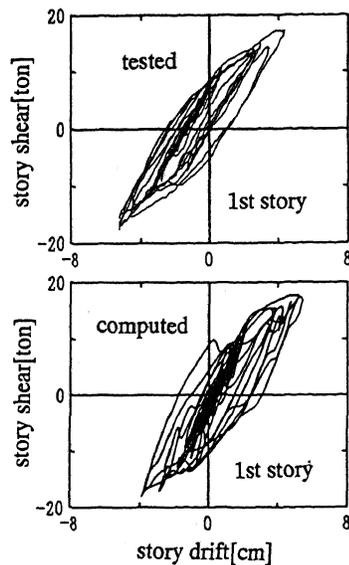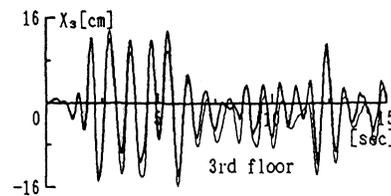

Fig.4 Hysteresis loops––tested and computed

Fig.5 Time histories of response displacements ––tested(thin curve) and computed(bold curve)

Table 1 Section properties of members

	t_f mm	t_w mm	2b mm	b/t_f	I_x cm^4	
H–6	9	6	108	6	514	
H–8	9	6	144	8	1280	
H–12	9	6	216	10	4560	

2.2 Test results and considerations

Story shear vs. story displacement diagrams obtained from the static loading test is shown in Fig.3 by thin curves. Fig.4 illustrates the hysteresis loop of the 1st story obtained from the on–line response test, and the time history of response displacement at 3rd floor is shown in Fig.5 by thin curve. Since the distribution of inertial forces acting on each floors during vibration are important to identify the likely collapse mode of the frame, we present trajectories of the inertial forces, denoted by F_1, F_2 and F_3 in Fig.6, observed during the on–line test. The solid line in each figure indicates the trajectory of the load profile adopted in the static loading test. The broken line indicates the trajectory of the load profile corresponding to the 1st mode vibration. Figs.7(a) and 7(b) show the distribution of the energy dissipated by each story shear for the cases of the static loading and the on–line earthquake response tests, and the ratios of the energy dissipated at each story to the total energy are enumerated in Table 2. From these test results, the following observations are derived :

1) The trajectory of the inertial forces collect along both the solid line and the broken line. It suggests the possibility of representing the dynamic load effects by an equivalent static profile, say, the adopted as in the static loading, since the effects of higher–mode vibration are generally small in such a low–rise building frame.
2) There is no difference between the ratios of the story energy absorption to total energy absorption under the static loading and during earthquake response.

3 NUMERICAL SIMULATIONS

3.1 Member model used in frame analysis

It is assumed herein that a steel member can be divided into two kinds of elements : one is an elastic beam element and the other is the inelastic elements composed of four inelastic bar–springs and an elastic shear
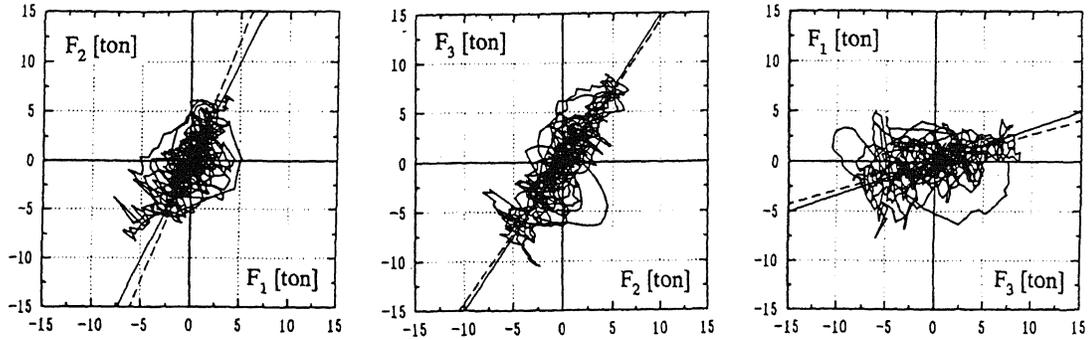
Fig.6 Trajectories of inertial forces—tested
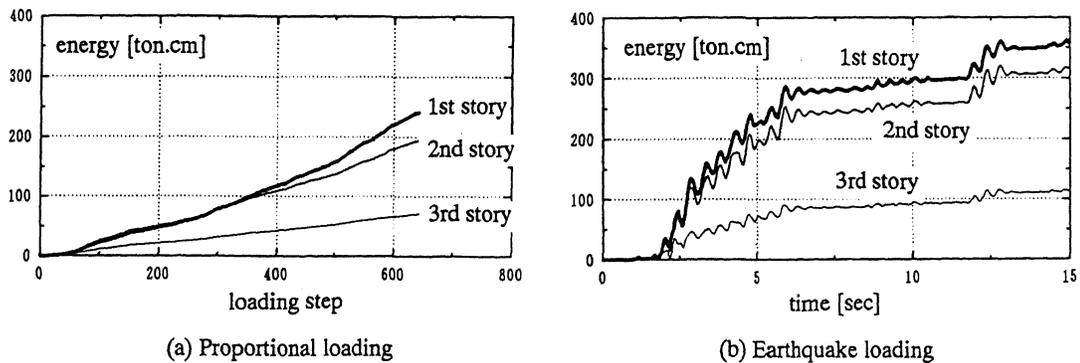

(a) Proportional loading

(b) Earthquake loading

Fig.7 Histories of energy absorbed at each story
—tested

panel. The hysteresis rule proposed by the authors (Ohi 1992), in which strain–hardening, the stiffness–softening due to Bauschinger's effect, as well as the resistance deterioration due to local buckling failure are considered, is assigned for each bar–springs.

Numerical analyses were carried out for the test cases described before. The results are shown in Fig.3 and Fig.5 (by bold curves). Comparing the numerical results with the test results, it can be confirmed that their global responses are well predicted by the present analyses. In the following sections, analyses based on the same model are made for other various types of frames and excitations.

3.2 An outline of the numerical analyses

The frame models for numerical analyses, as shown in Fig.8, are a weak–beam type same as the tested frame models, and a weak–column type. The static analyses were carried out to examine the collapse behaviors under horizontal proportional loading with the vertical distribution, 3 to 2 to 1. For the dynamic analyses, three ground accelerations were employed : the NS component recorded at El Centro in 1940 and the NS and EW components recorded at Hachinohe Harbor in

Table 2 Ratios of energy absorbed at each story to total energy absorption—tested

| Code	$\Psi_1(\%)$	$\Psi_2(\%)$	$\Psi_3(\%)$
Static test	47. 7	38. 3	14. 0
On-line test	45. 5	40. 0	14. 5

1968. Their peak acceleration values were so adjusted that the complete collapse occurs in each the frame models. The input acceleration records are shown in Fig.9. Also 0.80 sec is commonly assigned for the fundamental period of the frame models. Accordingly, the value of mass, which is assumed as same at all the nodes in the frame models , is determined from the natural period and the frame stiffness. No damping is assumed for the dynamic analyses. Constant vertical loads were applied to all the nodes in the frame models, as much as 20 percent of the yield loads of the 1st story column. Table 3 summarizes the outline of the numerical analyses.

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Table 3 List of numerical analyses

Code	Frame mode type	Load	Max. input
			[cm/sec^2]
WBSC-S	Weak-beam	Static	
WBSC-ENS	Weak-beam	EL centro(NS)	1418
WBSC-HNS	Weak-beam	Hachinohe(NS)	1296
WBSC-HEW	Weak-beam	Hachinohe(EW)	538
SBWC-S	Weak-column	Static	
SBWC-ENS	Weak-column	EL centro(NS)	774
SBWC-HNS	Weak-column	Hachinohe(NS)	968
SBWC-HEW	Weak-column	Hachinohe(EW)	729

(a) Weak-beam type   (b) Weak-column type

Fig.8 Frame models analyzed
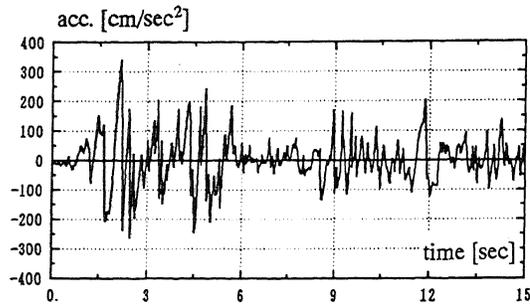
(a) El centro (NS)
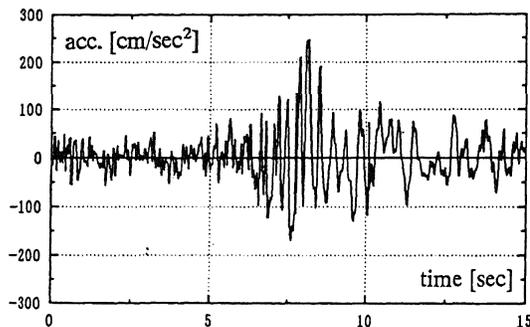
(b) Hachinohe (NS)
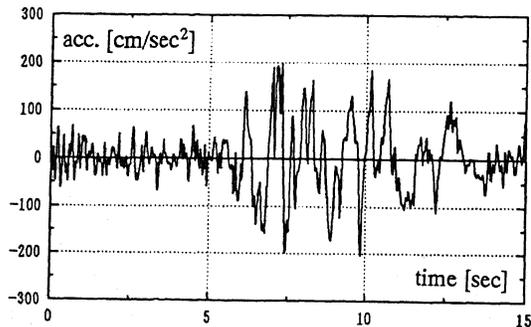
(c) Hachinohe (EW)

Fig.9 Groud acceleration records used in the analyses
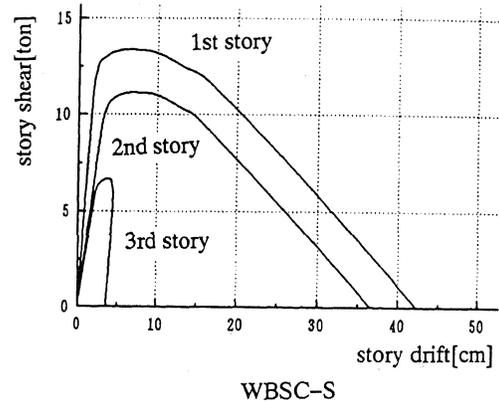
WBSC-S

SBWC-S
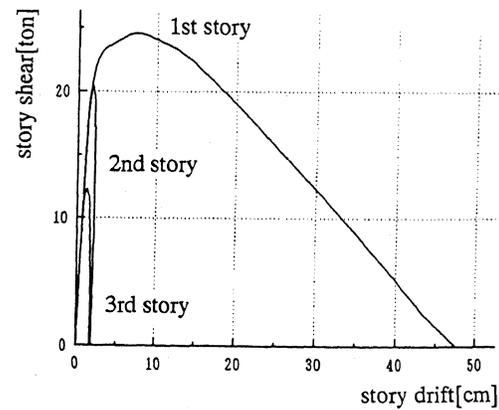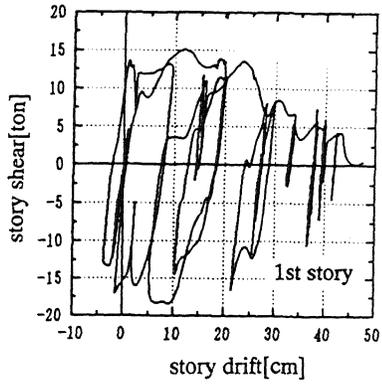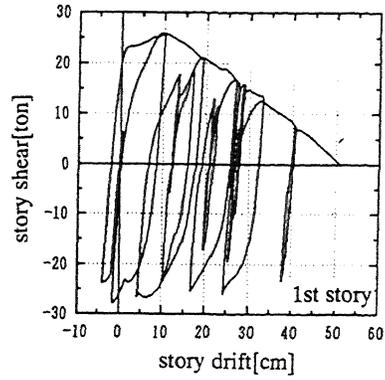
Fig.10 Story shear vs. story drift--simulated

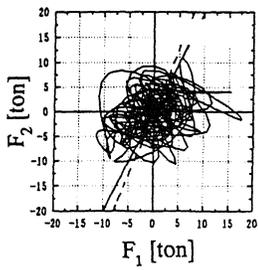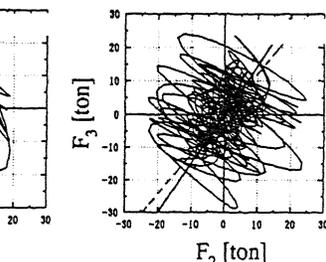WBSC-ENS   SBWC-ENS
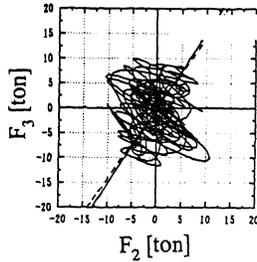
Fig.11 Hysteresis loops—simulated

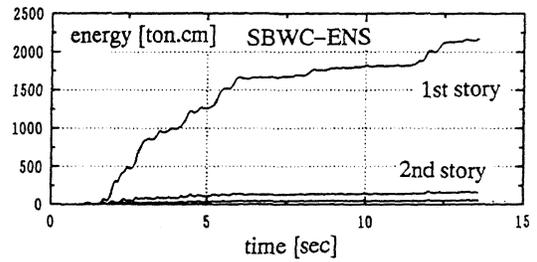WBSC-ENS   SBWC-ENS

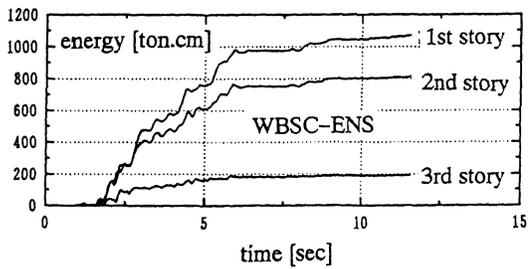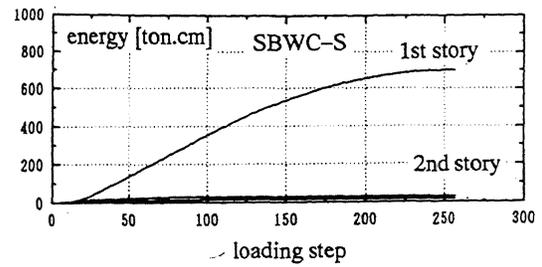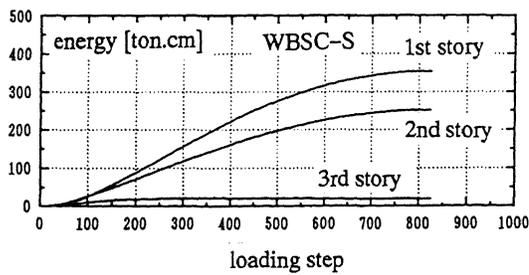Fig.12 Trajectories of inertial forces—simulated

Fig.13 Histories of energy absorbed at each story
—simulated

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Table 4 Ratios of energy absorbed at each story to total energy absorption—simulated

Code	Ψ1(%)	Ψ2(%)	Ψ3(%)	Total(ton·cm)
WBSC-S	56.4	39.1	4.5	1567.6
WBSC-ENS	51.6	39.3	9.1	2073.8
WBSC-HNS	54.5	36.5	9.0	1880.0
WBSC-HEW	56.5	36.5	7.0	1970.6
SBWC-S	92.2	5.0	2.8	1683.9
SBWC-ENS	90.9	6.8	2.3	2385.5
SBWC-HNS	90.4	7.0	2.6	2514.4
SBWC-HEW	92.6	5.1	2.3	2609.5

3.3 Numerical results and considerations

Story shear vs. story displacement diagrams obtained from the static analyses are shown in Fig.10. The results are shown in Figs.11 to 13 only for the cases under El Centro(NS) earthquake input. The collapse is defined here as the state that the frame loses completely its resistance against the horizontal loads, as shown in Figs.10 and 11. Compared with the test results shown in Fig.6, it can be seen that the trajectories of inertial forces in Fig.12 obtained from the numerical simulations considerably expand from the solid line and broken line. The reason is that no viscous damping was assumed in the simulations. However, some damping always exist during the vibration, so we can also derive the same consideration, as in the cases of the tests in the previous section, that the likely collapse mode under earthquake excitations loading can be predicted by that obtained under the horizontal proportional loading. As shown in Fig.13, the ratios of the story energy absorption to the total energy absorption are almost the same both in the cases of the static and dynamic analyses until the frame reaches to the complete collapse. The ratios of a story energy to the total energy are summarized in Table 4 for all numerical analyses.

4 CONCLUDING REMARKS

(1) A static loading test and an on-line earthquake response test were carried out for identical 3-story weak-beam type steel frame models.
(2) The collapse behaviors were numerically simulated for the various types of frame models including both weak-beam and weak-column types under the horizontal proportional loading with a certain load profile as well as earthquake loading.
(3) It is found that the likely collapse mode of the frame due to earthquake loading can be estimated reasonably by proportional static loading, as far as a certain load profile is very dominant in the trajectory of inertial forces as observed in the cases studied here.
(4) It is also found that the ratios of the story energy absorption to the total energy absorption under earthquake loading are almost same as those obtained under the static loading even until the frame reaches to the complete collapse.
These observations support the equivalent-static design procedure for low-rise steel buildings, even in consideration of the ultimate limit state, such as the complete collapse.

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