13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 438

EARTHQUAKE RESPONSE TESTS ON AN EXISTING STEEL MODEL STRUCTURES FOR SEISMIC MONITORING

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SUMMARY

Scaled 3-story steel structure models were constructed on the actual ground in 1982, and a project of seismic response and failure observation during earthquake has been on-going. These structural models have undergone a number of small earthquakes, and large amount of response data have been collected. Among them, four events are focused herein, and earthquake response tests are again performed pseudo-dynamically by portable loading apparatus. The response test results demonstrate that the pseudo-dynamic test technique provides satisfactory regeneration of real structural response. Furthermore, the inelastic behavior and earthquake mitigation effects of hysteretic dampers are studied through a series of pseudo-dynamic tests on one of the models with dampers installed. The results show the significant mitigation effect of hysteretic dampers.

INTRODUCTION

Pseudo-dynamic response tests and shake table tests are recognized as effective techniques to observe and study earthquake responses and inelastic behaviors of steel structures. These techniques, however, have some difficulties when certain test conditions need to be dealt with as follows:

1) Limitation of capacity of testing apparatus when a full-scale structural model needs to be tested.
2) Complicated test setup and measurement planning when multi-degree of freedom excitation and corresponding structural responses need to be considered.

To overcome these difficulties and to collect realistic response data, a project of response and failure observation on ‘weak’ structure models has been on-going in Chiba Experiment Station, Institute of Industrial Science, the University of Tokyo, since August 1983. One of the models is designed so that it may be slightly damaged by a moderate earthquake of Intensity Ⅳ through Ⅴ (Japan Meteorological Agency Scale, less than around 80 gals in the ground acceleration). That is the reason why this model is named as a ‘weak’ structure model.

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This structural model has been undergone a number of small earthquakes since 1983, and a large amount of response data have been collected. Among them, four events are dealt with herein, and the date of earthquake occurrence and focal information such as magnitude and location are summarized in **Table 1**. The location of the observation site and epicenters of the earthquake are illustrated in **Fig.1**. Pseudo-dynamic earthquake response tests are performed on the 'weak' steel structure model, and it is assumed that the model is again subjected to these past ground acceleration records.

Recently, seismic retrofitting or upgrading technique utilizing hysteretic dampers, especially made of low-yield-point steel, has been applied to existing buildings and new construction as well. In these days, many researches have conducted enormous test and analytical studies on their seismic behavior and performance. In this paper, the inelastic behaviors of such a damper during earthquakes, and its earthquake mitigation effects have been studied through a series of pseudo-dynamic tests on the 'weak' structural model with dampers installed.

Table 1 Summary of earthquake records

Earthquake	Ibaragi-Chiba-ken-zakai (Ibaragi-Chiba Prefecture Border)	Boso-hanto-oki (Off Boso Peninsula)	Chiba-ken-toho-oki (Off East Chiba Prefecture)	Choshi-oki (Off Choshi)
Date	1985. 10/4	1986. 6/24	1987. 12/17	1996. 9/11
Epicenter	140° 09'E 35° 52'N	140° 43'E 34° 49'N	140° 29'E 35° 22'N	140° 03'E 35° 07'N
Focal Depth	78km	73km	58km	55km
Magnitude	6.1	6.5	6.9	6.2
Peak acceleration	0.88m/sec^2	0.39m/sec^2	2.77m/sec^2	0.23m/sec^2
Damper	Not installed	Not installed	Not installed	Installed

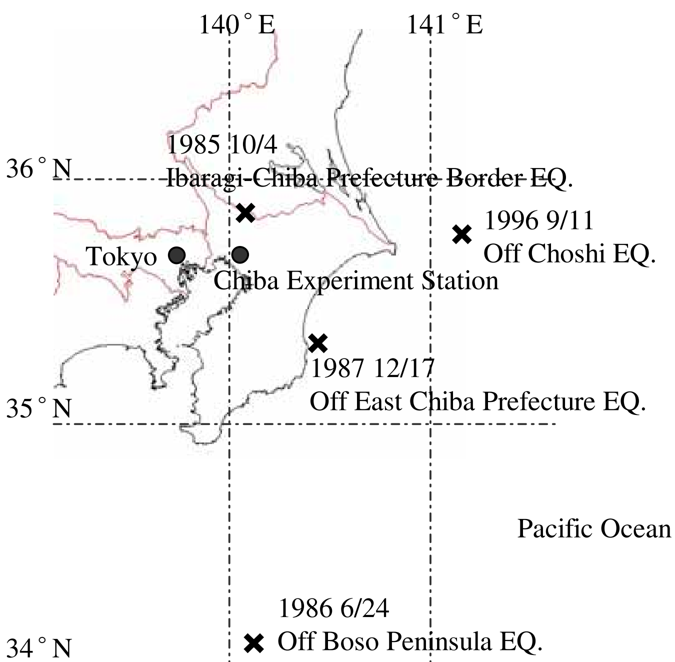


Fig.1 Dates and epicenters of earthquake

OUTLINES OF OBSERVATION PROJECT AND PSEUDO-DYNAMIC RESPONSE TESTS

'Weak' structural model (TAKANASHI [1]; OHI [2], [3])

A structural steel model (called as 'weak' structural model in this paper) was constructed on the ground at the Chiba Experiment Station of Institute of Industrial Science, University of Tokyo in 1982.

This 'weak' structural model is a three-story one-span frame composed of H-shaped columns (H-$125\times125\times6.5\times9$) and H-shaped girders shown in **Photo 1**. The yield strengths of web and flange of the columns are 325MPa and 365MPa, respectively. The column failure mechanism is expected because the strength and the stiffness of beams are stronger than those of columns. The parameters of this 'weak' structural model are summarized in **Table 2**.

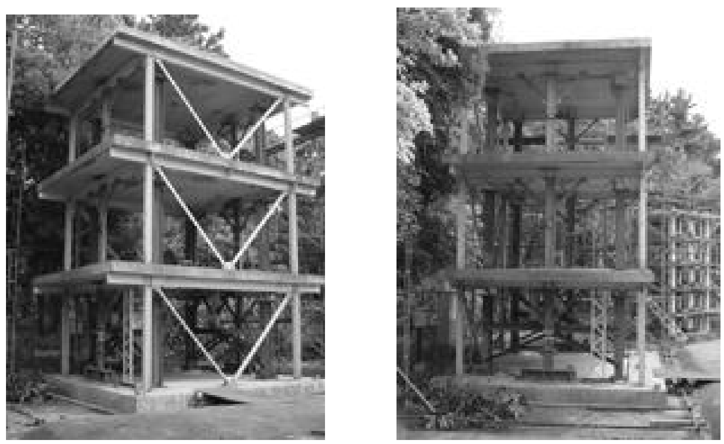


Photo 1 'Weak' structural model constructed on the actual ground at Chiba Experiment Station

Table 2 Summary of 'weak' structural model

Weight of each floor	12,700kg	
Steel grade	JIS SS400	
Steel member	H-$125\times125\times6.5\times9$	
Base shear coefficient when columns yield	Weak direction	0.20
	Strong direction	0.43

Pseudo-dynamic response tests are performed on the structural steel model in the direction where the H-shaped columns bent about weak-axis ('in the weak direction'). The states of the 'weak' structural model when pseudo-dynamic response tests performed, and also when monitored during the original natural event, are classified into two states: 1) with hysteretic dampers installed and 2) without hysteretic dampers.

Harmonic-forced vibration tests were performed on the 'weak' structural model without hysteretic dampers in the past study (NISHIDA [4]; OHI [5]). From the results of harmonic-forced vibration tests, the natural circular frequency and the damping ratio of 'weak' structural model without hysteretic dampers are obtained as shown in **Table 3**. If we ignore the viscosity of the hysteretic dampers, the damping coefficient matrix $[C]$ for viscosity is not changed before and after the installation of hysteretic dampers. According to this assumption, the damping ratio of the 'weak' structural model with hysteretic dampers installed is given as shown in **Table 3**.

Table 3 Natural circular frequency and damping ratio

	Without hysteretic dampers (test result)		With hysteretic dampers (calculation)	
Mode	Natural circular frequency	Damping ratio	Natural circular frequency	Damping ratio
1^{st}	0.94Hz	0.87%	2.72Hz	0.30%
2^{nd}	2.76Hz	0.40%	7.43Hz	0.17%
3^{rd}	4.10Hz	1.07%	10.20Hz	0.42%

Hysteretic damper of low-yield-point steel (NISHIDA[4]; OHI [5]; SHIMAWAKI [6])

The shear panel damper made of low-yield-point steel (LYP100) is shown in **Fig.2**. The properties of low-yield-point steel are summarized in **Table 4**. **Fig.3** shows the setup, where the hysteretic dampers are attached to 'weak' structural model (a stud with hysteretic damper installed is called as an 'earthquake resistant stud' in this paper).

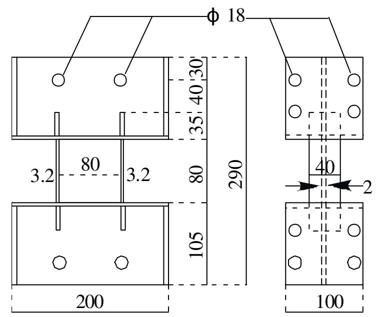
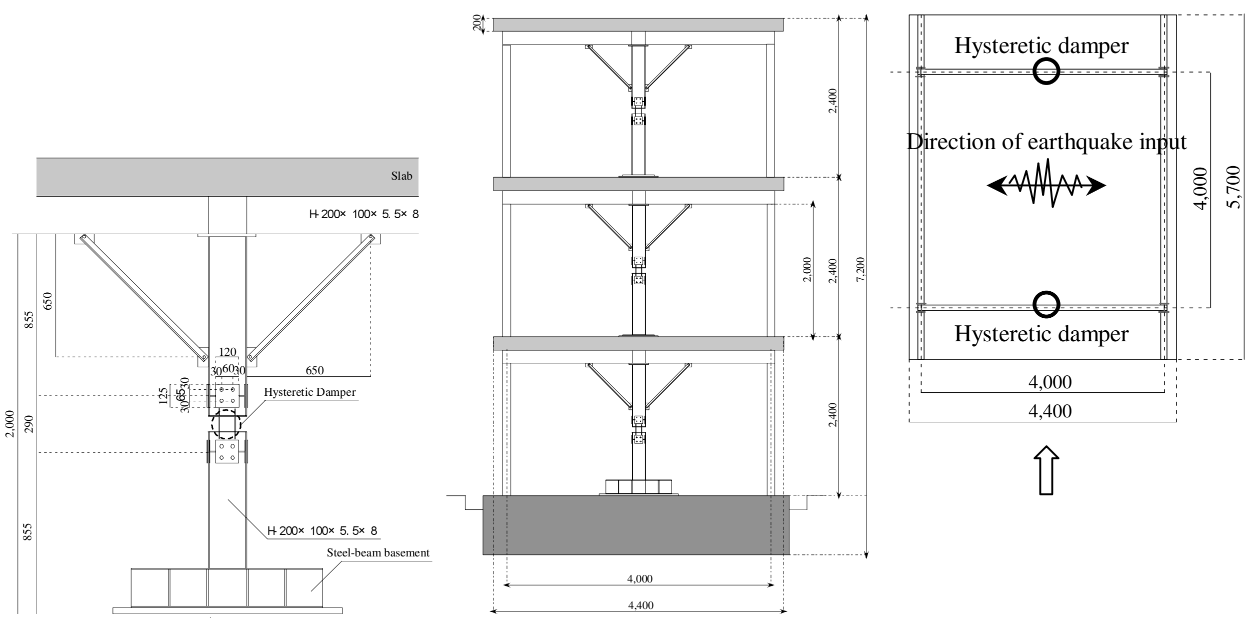


Fig.2 Dimensions of shear panel made of low-yield-point steel (unit: mm)

Table 4 Properties of low-yield-point steel (LYP100)

Yield stress σ_y	Tensile strength σ_u	Elongation ε	Shear yield stress $\sigma_y / \sqrt{3}$
80.4MPa	246MPa	40.7%	47.0MPa



(a) 1^{st} story (b) Elevation (c) Plan

Fig.3 Setup of 'weak' structural model with hysteretic damper installed

Summary of pseudo-dynamic response tests

Pseudo-dynamic response tests were performed on the 'weak' structural model subjected to the observed ground acceleration records listed in **Table 1**. Duration is commonly 30sec and time increment for numerical integration Δt is taken 0.005sec. Two actuators were attached parallel to the weak direction at the 1^{st} story of 'weak' structural model.

A hybrid structural model is used in the pseudo-dynamic response tests as illustrated in **Fig.4**. The restoring force of 1^{st} story of the hybrid structural model is obtained from the actuator load cell during loading tests, and the restoring forces of 2^{nd} story and 3^{rd} story are obtained from the numerical simulations that are performed simultaneously in on-line computer. Hysteresis model of columns in hybrid simulation of 2^{nd} story and 3^{rd} story is assumed to follow a linear-elastic model, and if a hysteretic damper at 2^{nd} story or 3^{rd} story yields, it is assumed to follow a bi-linear model. The stiffness of each member arranged for the hybrid structural model is summarized in **Table 5**.

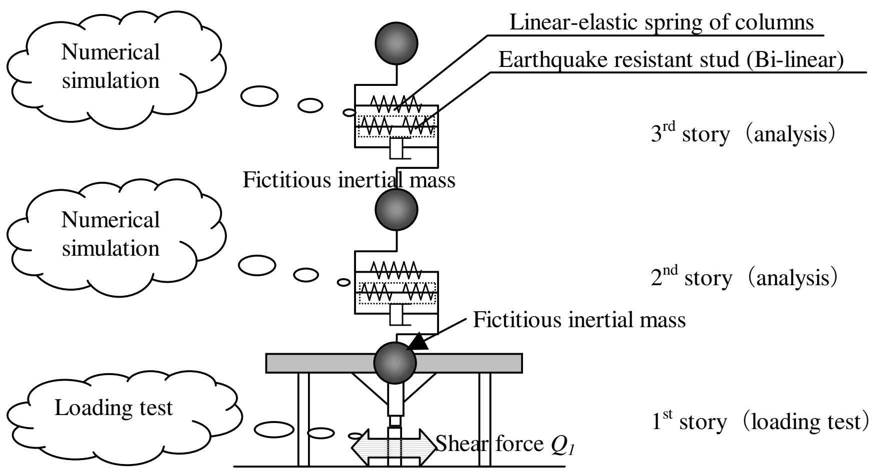


Fig.4 Hybrid structural model for the pseudo-dynamic response test

Table 5 Stiffness of each member (unit: kN/m)

	Columns	Hysteretic damper	Stud	Earthquake resistant stud	Total
1^{st} story*	1,290*	45,700*	14,700*	11,100*	12,400*
2^{nd} & 3^{rd} story	1,290	45,700	7,000	6,060	7,350

* Not referred in the hybrid simulation

Equation of motion and transformation of coordinates

The equation of motion for a multi-degree- of-freedom system with viscous damping and hysteretic inelastic restoring force under seismic excitation is represented as:

$$[M]\cdot\{\ddot{x}\}+[C]\cdot\{\dot{x}\}+\{f\}=-[M]\cdot\{1\}\,\ddot{g}_0 \qquad (1)$$

where $[M]$ is mass matrix, $\{\ddot{x}\}$ and $\{\dot{x}\}$ are acceleration vector and velocity vector relative to the ground, respectively, $\{f\}$ is restoring force vector including plastic resistance of a frame, and $\ddot{g}_0$ is the ground acceleration.

Here we define the transformation of displacement relative to the ground $\{x\}$ and restoring force into modal coordinates as:

Transformation of displacement: $\{x\}=[\Phi]\cdot\{q\}$ (2)

Transformation of restoring force: $\{f\} = \left[\Phi^T\right]^{-1} \cdot \{r\} = [\Psi] \cdot \{r\}$ (3)

where $\{q\}$ is modal displacement vector, $\{r\}$ is modal restoring force vector, $[\Phi]$ is modal participation matrix based on classical normal modes for a linear-elastic frame system $= \left[{}_1\beta\{{}_1u\},\ {}_2\beta\{{}_2u\}, \cdots,\ {}_n\beta\{{}_nu\}\right]$, n is the number of vibration modes, and $\{{}_j\psi\}$ is the j-th base vector for force given as a column vector of $[\Psi] = \left[\Phi^T\right]^{-1}$.

By this transformation, the equation of motion on the modal space is given by:

$$ {}_j\ddot{q} + 2\ {}_jh\ {}_j\omega\ {}_j\dot{q} + {}_jr / {}_jM^* = -\ddot{g}_0 \quad (4)$$

where ${}_jh$ is the j-th modal damping constant, ${}_j\omega$ is the j-th natural circular frequency, and ${}_jM^*$ is the j-th effective mass.

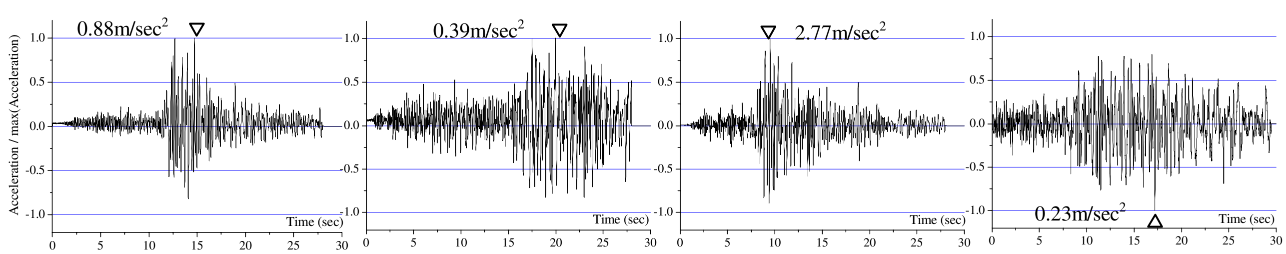
The modal displacement increment can be calculated based on an explicit numerical integration (central finite difference) from the j-th modal component of restoring force:

$$\Delta q_j^{\,k\to k+1} = \frac{\left(1 - {}_jh\ {}_j\omega\,\Delta t\right)\Delta q_j^{\,k-1\to k} - \Delta t^2\left({}_jr / {}_jM^* + \ddot{g}_0\right)}{\left(1 + {}_jh\ {}_j\omega\,\Delta t\right)}\ ,\quad j = 1, 2, \cdots, n \quad (5)$$

where $\Delta q_j^{\,k\to k+1} = {}_jq^{(k+1)} - {}_jq^{(k)}$

RESULTS OF PSEUDO-DYNAMIC RESPONSE TESTS

The time histories of input excitations in the pseudo-dynamic response tests are shown in **Fig.5**. The acceleration response spectra are shown in **Fig.6**. Pseudo-dynamic response tests are performed on the hybrid structural model (**Fig.4**) without hysteretic dampers and also the hybrid structural model with hysteretic dampers installed as shown in **Table 6**. **Fig.7** compares the time histories of story drift at 1st story in case of regenerated tests (solid curve: pseudo-dynamic test, broken curve: monitored at natural event), and **Fig.8** compares the time histories of story drift at 1st story in case of contrastive tests (solid curve: pseudo-dynamic test, broken curve: monitored at natural event). **Fig.9** shows the hysteresis loops of shear force vs. drift of hysteretic dampers at 1st story.



(a) 1985. 10/4 (b) 1986. 6/24 (c) 1987. 12/17 (d) 1996. 9/11

Fig.5 Earthquake inputs applied to pseudo-dynamic response tests

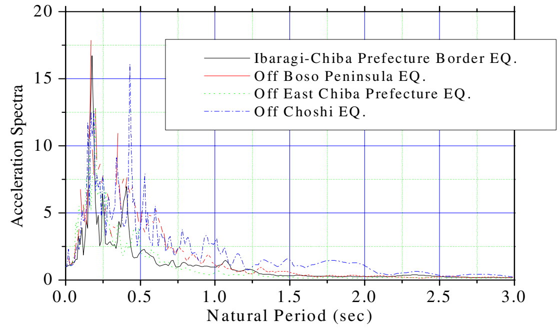
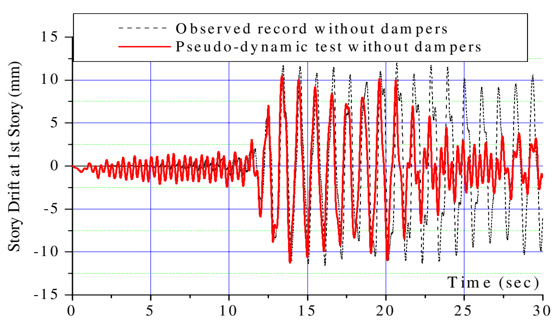


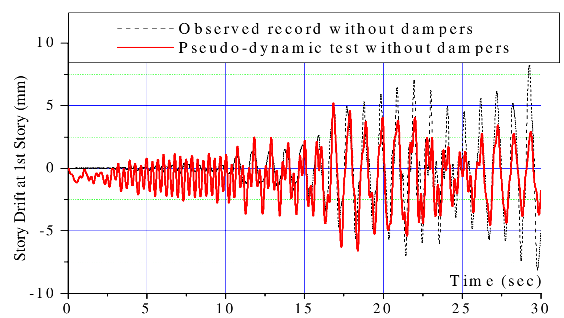
Fig.6 Normalized acceleration response spectra (in peak acceleration value)

Table 6 Summary of test cases of pseudo-dynamic response tests

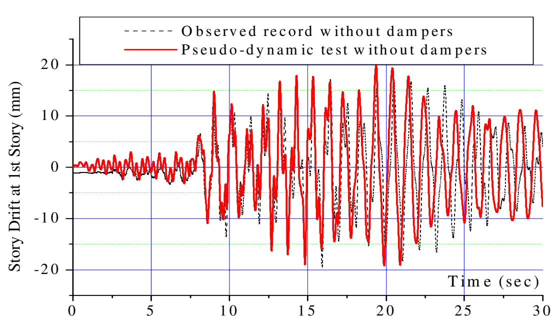
State of model / Name of earthquakes	Without hysteretic dampers		With hysteretic dampers installed	
	Monitoring at natural event	Pseudo-dynamic test	Monitoring at natural event	Pseudo-dynamic test
1985 Ibaragi-Chiba Prefecture Border EQ.	○	○(regenerated)		○(contrastive)
1986 Off Boso Peninsula EQ.	○	○(regenerated)		○(contrastive)
1987 Off East Chiba Prefecture EQ.	○	○(regenerated)		○(contrastive)
1996 Off Choshi EQ.		○(contrastive)	○	○(regenerated)



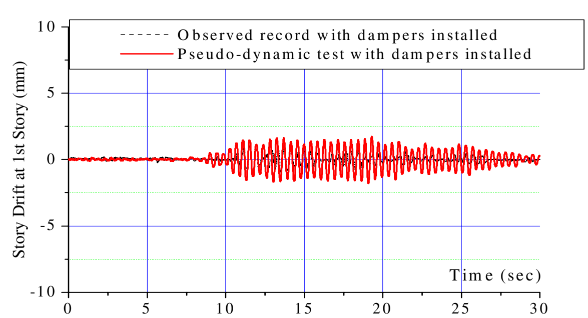
(a) 1985 Ibaragi-Chiba Prefecture Border EQ.



(b) 1986 Off Boso Peninsula EQ.

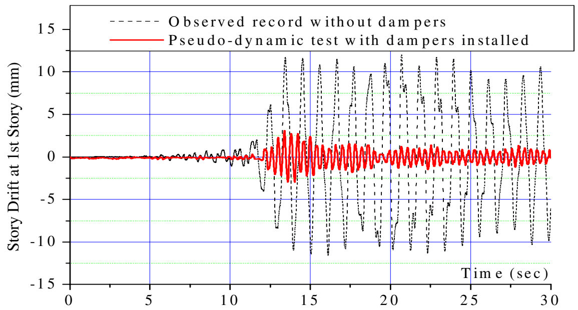


(c) 1987 Off East Chiba Prefecture EQ.

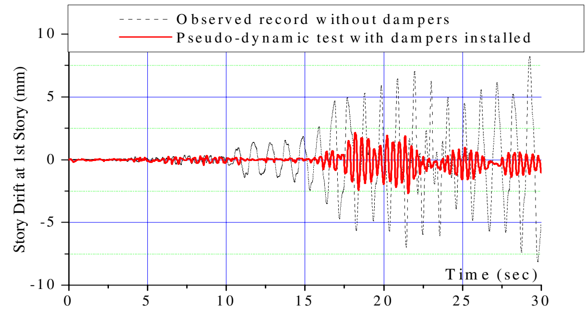


(d) 1996 Off Choshi EQ.

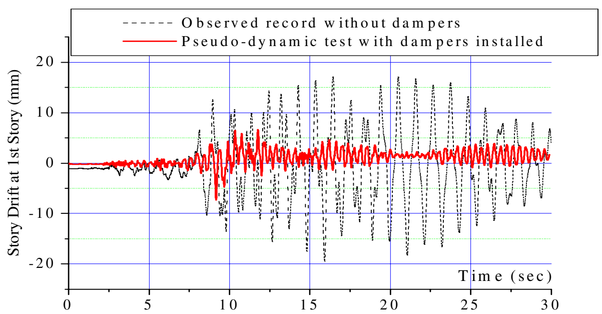
Fig.7 Comparison of response story drifts at 1st story in case of regenerated tests



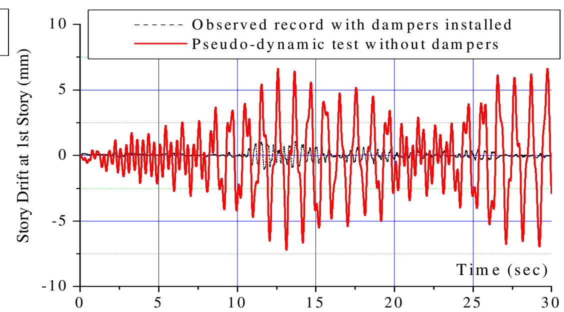
(a) 1985 Ibaragi-Chiba Prefecture Border EQ.



(b) 1986 Off Boso Peninsula EQ.

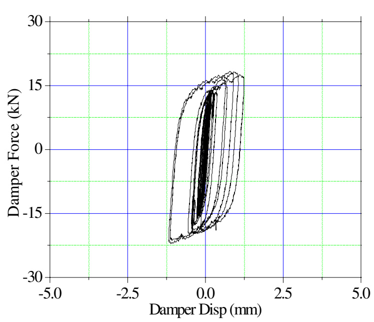


(c) 1987 Off East Chiba Prefecture EQ.

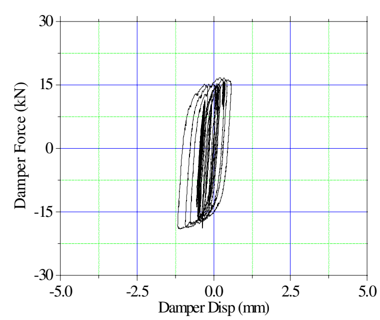


(d) 1996 Off Choshi EQ.

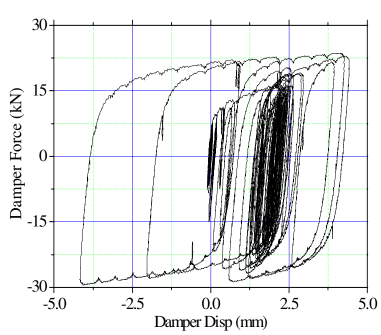
Fig.8 Comparison of response story drifts at 1st story in case of contrastive tests



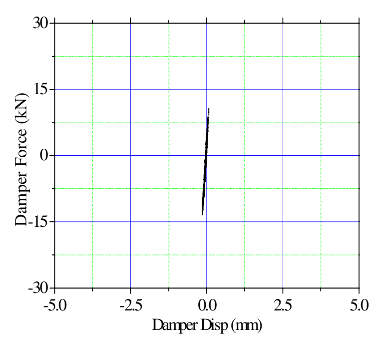
(a) 1985 Ibaragi-Chiba Prefecture Border EQ.



(b) 1986 Off Boso Peninsula EQ.



(c) 1987 Off East Chiba Prefecture EQ.



(d) 1996 Off Choshi EQ.

Fig.9 Hysteresis loops of hysteretic damper during pseudo-dynamic response tests (one damper)

Photo 2 Hysteretic dampers after pseudo-dynamic response test

Photo 3 A scene as pseudo-dynamic response test

It is seen from the regenerated test results (**Fig.7**) that the response story drifts show good agreements with the records monitored at the natural events in the early stages of simulation, during around first half of durations, while some of the responses simulated in the latter half are smaller than those monitored at natural events. These are observed in the cases of Ibaragi-Chiba-ken-zakai earthquake input (**Fig.7 (1)**) and Boso-hanto-oki earthquake input (**Fig.7 (2)**). This reason is supposed that the displacement control error did exist and was accumulated as much as 400 μ m during the first half durations of pseudo-dynamic response tests. Also these two responses were close to linear-elastic ones, and the accuracy of simulation may be sensitive to even such a small displacement control error. On the other hands, in case of Chiba-ken-toho-oki earthquake input, the whole response of story drift simulated shows good agreement with the record monitored at the natural event. In this case, the response went far beyond elastic range, and may be insensitive to the displacement control error within 400 μ m.

As for the contrastive test results (**Fig.8**), the earthquake mitigation effect of hysteretic damper is demonstrated so significant. In case of Chiba-ken-toho-oki earthquake input (**Fig.8 (3)**), the peak drift of structural model without hysteretic dampers is almost 20mm, while the peak drift with hysteretic dampers installed is mitigated to 6 mm even followed by remarkable yielding and buckling of hysteretic dampers.

CONCLUSIONS

The project of response and failure observation using 'weak' steel structure models has been carried out for more than 20 years in Chiba experiment station, Institute of Industrial Science, University of Tokyo, since August in 1983. This structural model has been undergone a number of small earthquake since 1983, and a large amount of response data have been collected. Among them, four events are dealt with herein, and the earthquake response tests are again performed pseudo-dynamically on the 'weak' steel structure model by portable loading apparatus.

The test results demonstrate that the pseudo-dynamic response test technique provides satisfactory regeneration of real structural responses to earthquake ground motions. Furthermore, contrastive pseudo-dynamic tests were also performed on the different state of model structure, with or without hysteretic dampers made of low-yield-point steel, from the original state when monitored. The results of contrastive pseudo-dynamic tests show that significant effects are expected to mitigate drift responses by hysteretic dampers of this kind.

ACKNOWLEDGMENT

The authors gratefully acknowledge a financial support from Japan Iron and Steel Federation, Grant in Aid for Researches on Steel Building Structure (2001), which made this work possible. Fujita Co. Ltd. offered low-yield-point damper specimen.

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