FUNDAMENTAL EXAMINATION ON HYSTERESIS MODEL OF STEEL MEMBERS BY EXPERIMENTAL RESULT OF SHAKING TABLE TEST

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ABSTRACT

Shaking table test is the most effective method to examine the earthquake resistant performance of structural system under severe earthquake. Former part of this paper, experimental method of full scale real time shaking table test of partial steel frame is briefly introduced. Using this system, structural performances of steel structures, i.e. plastic deformation capacity of beam-to-column connection determined by brittle fracture, was investigated. Of course, that is the main purpose of the experiment. However, experiment results can be effectively used to examine the hysteretic model used in response analysis. Especially, the set-up of this experiment is so simple as to be considered a SDOF system. In the latter part of this paper, fundamental examination of hysteresis model of steel members used in response analysis is discussed. SDOF systems with bi-linear models as well as multi-linear elasto-plastic models considering Bauschinger effect were considered in the response analysis. Models with their parameters that matched the experimental results well were examined.

INTRODUCTION

With the development of computer and numerical analysis methods, response prediction of steel structures based on time history analysis is gaining more and more popularity. Different hysteresis models on the level of story, member and material are being used together with various mechanical models. It has become an important topic that how hysteresis models influence the results of response analysis in evaluating earthquake-resistance performances of steel frames.

Effect of different hysteresis models on the response analysis (Matsushima 1980; Yamada et al. 1986) as well as suggestions on new hysteresis models based on experimental results (Kato et al. 1977; Akiyama et al. 1990; Takahashi et al. 1997) are being studied, among which, Ohi and Takanashi's research (1988) on the appropriate hysteresis models used to evaluate response performance of steel structures catches adequate attention. In this research, story drifts and story-shear force relations obtained in the experiment of scaled steel frames were approximated by a 4 components hysteresis model as a parallel connection consists of one elastic component, two elastic-perfectly plastic and one slip-type component. Stiffness and strength parameters as well as energy dissipation of specimens were predicted fairly well using this hysteresis model. However, final values of the parameters of this model were determined after several trials of calibrating some indicators to fit the experimental results, which is actually impossible before the experiments. Therefore, it's still necessary to simulate hysteresis models accurately to predict the performance of steel members before earthquake happens.

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In this research, response analysis were carried out based on the simplified system of a full-scale shaking table test of a steel beam-to-column connection, where the most basic single-degree-of-freedom-system (SDOF) was combined with a series of various bi-linear models and multi-linear elasto-plastic models considering Bauschinger effect with changing yielding points (Q_y) and second stiffnesses (K_2). Analytic responses were compared with the experimental results of the shaking table test to point out hysteresis models with their parameters that matched the experimental results well.

FULL-SCALE SHAKING TABLE TEST

Experimental data of the following full-scale shaking table test in Akiyama et al.'s research were referred to estimate the accuracy of steel members' hysteresis models in response analysis under random earthquake effect.

Set-up is shown in Figure 1 and 2. The specimen, steel beam-to-column connection which was rotated 90^o counter-clockwise with its beam standing vertically and column lying horizontally, was installed on the shaking table together with its loading system. The 2250 KN mass, which was set on the loading frame supported by rubber bearings considered as elastic springs, offered inertia force during shaking. The inertia force was applied to the free beam-end of specimen as shear force through a loading beam. It was possible to regard the steel beam as a Single-Degree-of-Freedom-System (SDOF) parallel connected with the loading system. An accelerometer was installed on the shaking table to record the real-time input accelerogram.

According to Akiyama et al.'s research, 8 specimens were tested during the experiment, where the data of Specimen No. 5 were used in this research. The full-scale H section beam RH-600x300x12x25 (SM490A) was welded onto full-scale box section column BBox-500x500x22 (SM490A) with inner-diaphragm; no weld access hole construction method was used in this specimen.

NS component of JMA Kobe Record (According to the Japan Meteorological Agency of Kobe, 1995), which was scaled to a peak velocity of 1.0 m/s, was used in the test. Steel beam of the specimen was plastified but not ruptured under the first excitation, which was also the ultimate excitation, where the column remained elastic during the test due to the relatively large thickness of its cross section. The load-displacement relation obtained during this ultimate excitation was taken as the reference to compare with analytic responses.

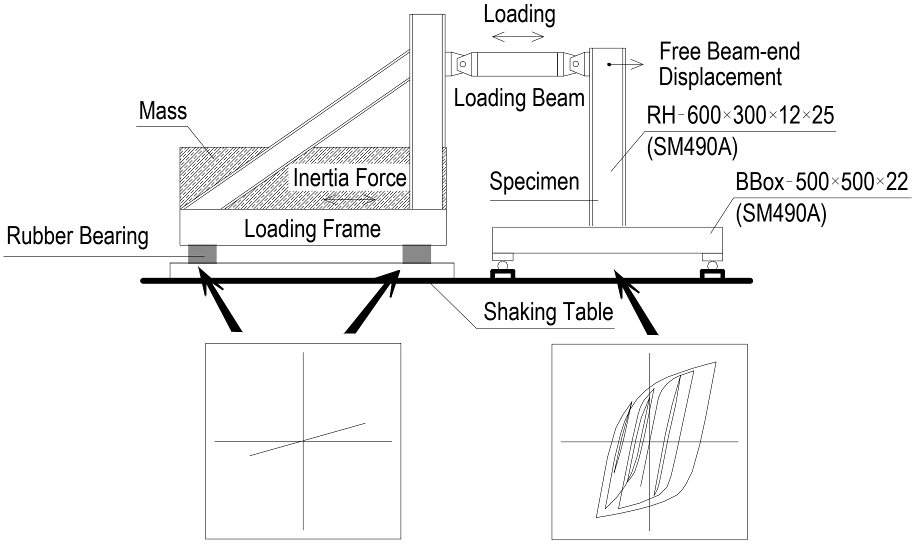


Figure 1 Specimen and test set-up

Figure 2 Overview of test set-up

RESPONSE ANALYSIS

Outline of the Analysis

It is possible to model the whole set-up including specimen by a single degree of freedom system shown in Figure 3. Hysteresis model of the beam was the main parameter of the response analysis. The characteristics of the other parts of this system are listed below. An analytic model of a fixed period of 0.629 sec was formed, while that obtained though Zero Crossing Method from the data of pulse excitation was 0.626 sec, which made it possible to deduce it a reasonable analytic model.

Total weight of Mass and Loading Frame -- 220 ton
Horizontal stiffness of 4 Rubber Bearings --- 204 N/m
Horizontal stiffness of Loading Frame and Loading Beam------------------- 10,000 N/m
Elastic stiffness of Steel Beam (Considering shearing displacement) --------- 3,520 N/m
Stiffness of Column and Panel of specimen (Elastic spring) ------------------ 8,630 N/m

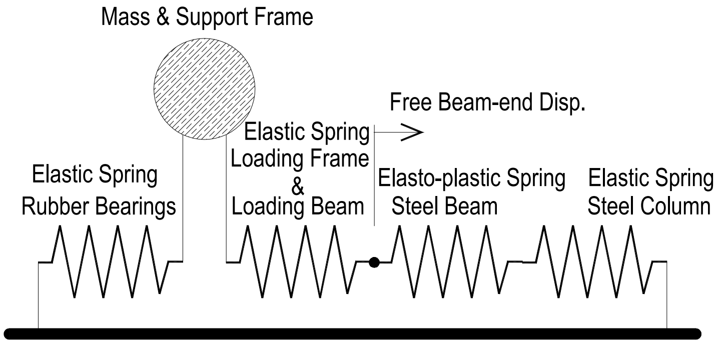


Figure 3 Spring-mass vibration model of test set-up

Main parameters of the hysteresis model were set as follows:
(1) Types of hysteresis model (2 types)
Bi-linear (including elastic-perfectly plastic) models and Multi-linear elasto-plastic models considering Bauschinger effect; (Akiyama and Takahashi 1990)
(2) Yield point (5 levels)
Nominal yielding strength of SM490A (According to the Japanese Code, F=325 N/mm^2), 1.1 F, 1.2 F, 1.3 F, and the result of tensile strength test (369 N/mm^2) (1.135 F)
(3) Second stiffness (6 levels)
Second stiffness ratio (k2/ke): 0, 1%, 2%, 3%, 4%, 5%

The multi-linear elasto-plastic model considering Bauschinger effect consists of skeleton curve, Bauschinger part and elastic unloading part, among which the skeleton curve corresponding to monotonic load-displacement relation, was modeled though the same method as the modeling of bi-linear hysteresis model mentioned previously.

The average acceleration method was used to do numerical integration in the response analysis, with damping factor set to 1.86% according to the data of pulse excitation. Furthermore, the accelerogram recorded by the accelerometer installed on the shaking table mentioned before (lasted for 30 sec, with the time increment of 1/200 sec) was taken as the input record of the response analysis.

Estimation of the analytic response compared with the experimental data was based on the summed squared errors of load (e_Q) and displacement (e_δ) at free beam-end according to the time history response (refer to Eqn. 1, 2). More over, normalization method was introduced into the analysis, which divided each of the summed squared errors by those of the elastic-perfectly plastic model with nominal yielding strength (e_{Q0}, $e_{\delta0}$). The indicators of e_Q/e_{Q0} and $e_\delta/e_{\delta0}$ named 'Load Error Indicator' and 'Displacement Error Indicator' were able to be obtained.

$$e_Q=\Sigma(Q_{a,i}-Q_{ei})^2 \tag{1}$$

$$e_{\delta}=\Sigma(\delta_{a,i}-\delta_{ei})^2 \qquad (2)$$

Where, Q_{ei} is the experimental load, $Q_{a,i}$ is the analytic load, δ_{ei} is the experimental free beam-end displacement, $\delta_{a,i}$ is the analytic free beam-end displacement
All data lasted for 30 sec, with the time increment of 1/200 sec.

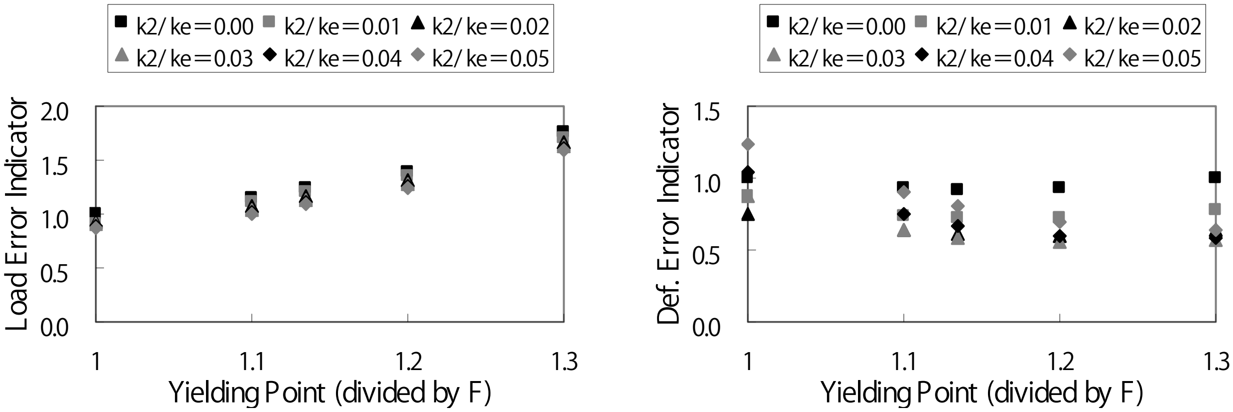
Evaluation of Analytic Response

Bi-linear (including elastic-perfectly plastic) models. Figure 4 (1), (2) show the load and displacement error indicators in the case of bi-linear hysteresis models. It is clear that the effect of yielding point to the load was larger than that of the second stiffness; where the errors of models with lower yielding points were smaller. The reason was that under cyclic loading, stiffness of steel member tends to decrease earlier around its yielding point due to Bauschinger effect. On the other hand, both yielding point and second stiffness affected the displacement to some extent, the errors were relatively smaller while yielding point is a little larger than F and the second stiffness ratio is around 2~4%.

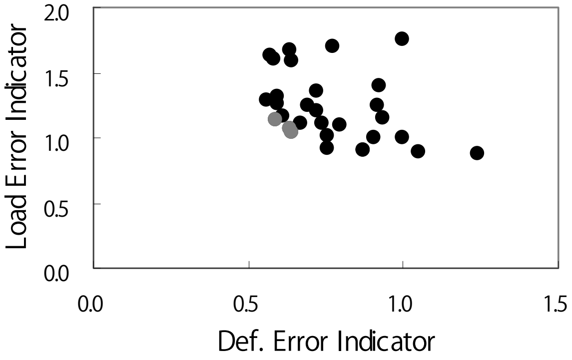
In Figure 4 (3), displacement error indicator is plotted on the X-axis while Y-axis is defined as load error indicator, to show the effect of those two parameters to the load-displacement relation. It's obvious that plots in gray near to the origin are those with smaller composite errors. 3 plots were picked up, two with yielding point of 1.1 F and second stiffness ratio of 2% and 3%, one with its yielding point same as the tensile test strength and a 3% second stiffness ratio. The comparison of the experimental load-displacement relation and the analytic response of the hysteresis model with a yielding point of 1.1 F and a second stiffness ratio of 2% are shown in Figure 5 as an example.

Multi-linear elasto-plastic models considering Bauschinger effect. Figure 6 (1), (2) show the load error indicators and displacement error indicators of Multi-linear elasto-plastic models considering Bauschinger effect. The combinations of lower yielding points and higher second stiffness or higher yielding points and lower second stiffness tend to have smaller load errors, while the displacement errors seem to be independent of the yielding point and are smaller when second stiffness ratio is higher than 3%.

Compare Figure 6 (3) of Multi-linear elasto-plastic models considering Bauschinger effect with Figure 4 (3), which shares the same X-axis and Y-axis, the former shows a significant decrease of load-displacement error. Therefore, with models considering Bauschinger Effect, it is possible to obtain analytic responses that are close to the experimental result. The four models with smaller load-displacement error indicators were plotted gray in Figure 6 (3), two models with yielding points of 1.2 F (1.05 times the tensile test strength) and 1.3 F while second stiffness ratio is 2%, as well as two models with yielding points of 1.2 F and the tensile test strength while second stiffness ratio is 3%. The comparison of the experimental and analytic response of the model with yielding point of 1.2 F and second stiffness ratio of 3% is shown in Figure 7.



(1) Load error indicator (2) Displacement error indicator



(3) Load-displacement error indicator

Figure 4 Error indicator of bi-linear hysteresis models

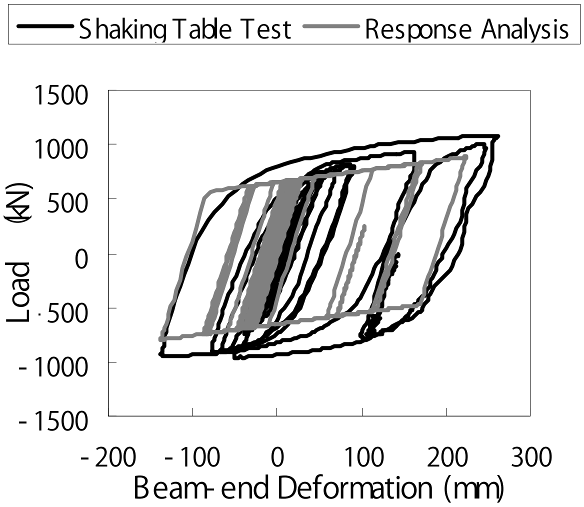
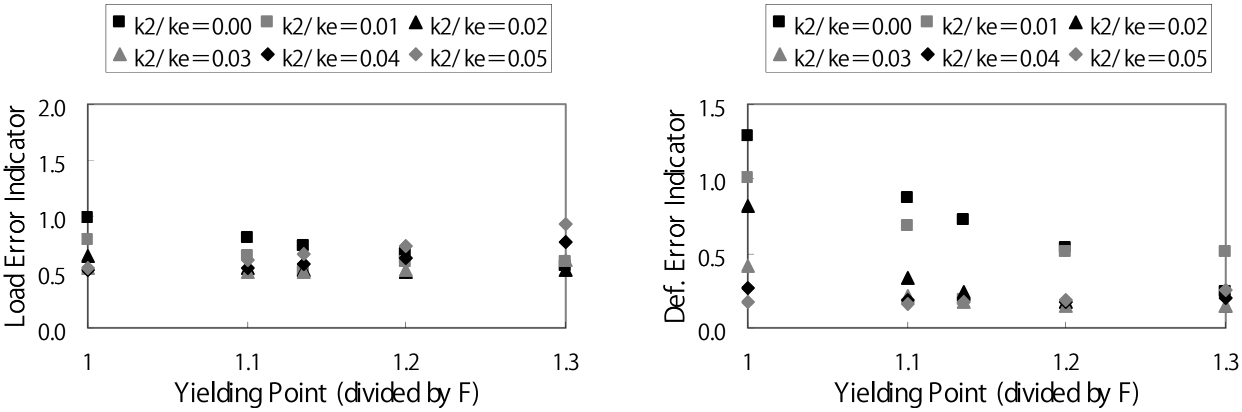
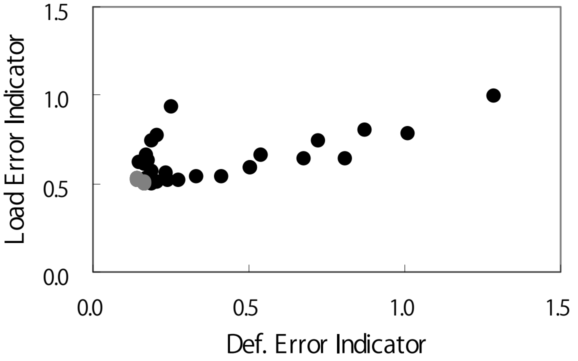


Figure 5 Comparison of experimental and analytic result
(Example No. 1: load-displacement relation, bi-linear, σy=1.1F, k2/k1=0.03)



(1) Load error indicator (2) Displacement error indicator



(3) Load-displacement error indicator

Figure 6 Error indicator of bi-linear hysteresis models

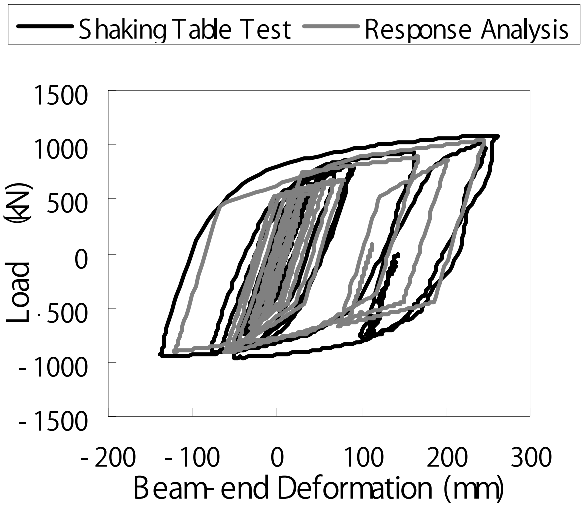


Figure 7 Comparison of experimental and analytic result
(Example No. 2: Load-displacement relation, multi-linear, σ_y=1.2F, k_2/k_1=0.02)

Moreover, the analytic load-time history of both bi-linear as well as multi-linear hysteresis model considering Bauschinger effect with their yielding points of 1.1 F and second stiffness ratios of 3%, together with the experimental data, are shown in Figure 8, while their displacement-time histories are shown in Figure 9. It is also possible to conclude that the analytic responses of the models considering Bauschinger effect are closer to the shaking table test result.

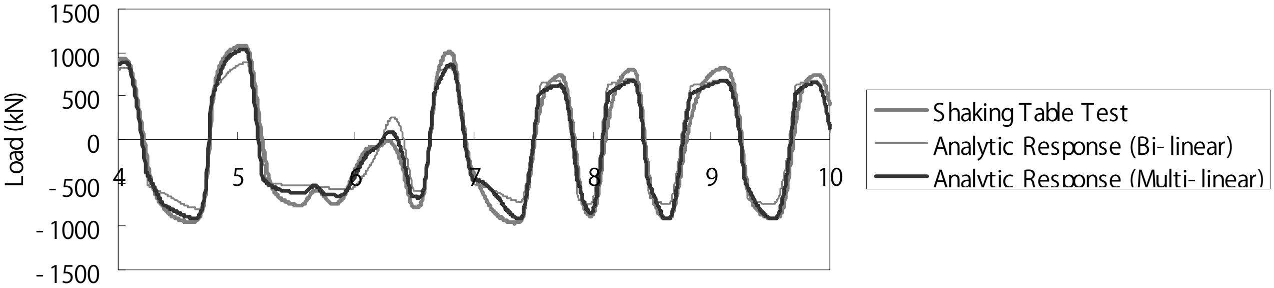


Figure 8 Comparison of experimental and analytic result (Example No. 3: load time history)

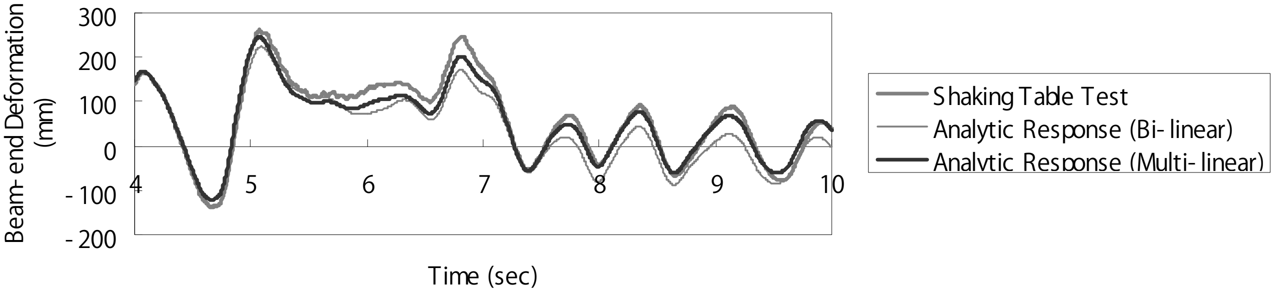


Figure 9 Comparison of experimental and analytic result (Example No. 4: displacement time history)

CONCLUSION

Analytic responses of a series of Bi-linear and Multi-linear hysteresis models were compared to the result of a full-scale shaking table test, and models with their analytic responses close to the experimental result were pointed out.

Analytic responses of Bi-linear models with yielding point slightly lower than their tensile test strength and the second stiffness ratio set to 2%~3% had better correspondence with the experimental result. In case of multi-linear models considering Bauschinger effect, when using Bi-linear skeleton curve, analytic responses of models with yielding point slightly higher than their tensile test strength and the second stiffness ratio set to 2%~3% were close to the experimental result. Furthermore, the difference between analytic responses and experimental result were smaller when Bauschinger effect was taken into account in hysteresis models.

The influence of considering Bauschinger effect in response analysis using complex hysteresis models including Rambarg-Osgood type model will be the future discussion.

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