FUNDAMENTAL EXAMINATIONS ON HYSTERESIS MODELS OF STEEL MEMBERS USED IN RESPONSE ANALYSIS

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ABSTRACT :

With the development of computer and numerical method, different mechanical as well as hysteresis models are applied in time history analysis, which is gaining popularity in recent response prediction of steel structures. Nevertheless, accurate simulations for steel members' hysteresis characteristics used in response analysis are still under discussion.
In order to figure out hysteresis models with sufficient accuracy which can be used to achieve hysteresis loops of steel members in earthquake resistance design, analytic response were compared to the results of a full-scale shaking table test of a steel beam-to-column connection. Basic single degree of freedom (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 pointed out.

KEYWORDS: Steel Structure, Single degree of freedom system, Restoring Force Characteristic, Bilinear Elastic-perfectly Plastic, Bauschinger Effect

1. BACKGROUND

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.

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.

2. GENERAL INTRODUCTION OF THE FULL-SCALE SHAKING TABLE TEST

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

Figure 1 shows the detail of test set-up. The specimen, steel beam-to-column connection which was rotated 90° 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.

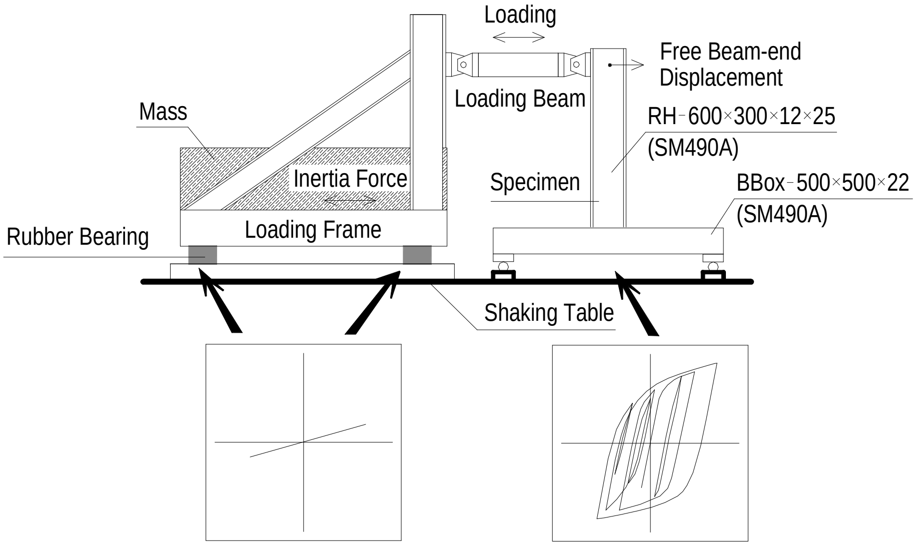


Figure 1 Specimen and Test set-up

3. DETAIL OF THE RESPONSE ANALYSIS

3.1. Outline of Response Analysis

It is possible to model the whole set-up including specimen by a spring-mass vibration system shown in Figure 2. 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.

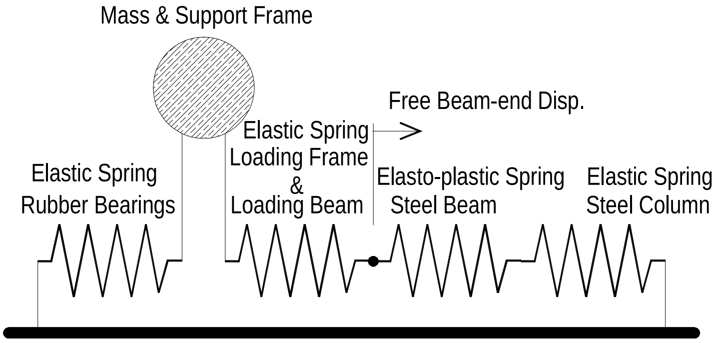


Figure 2 Spring-mass Vibration Model of Test Set-up

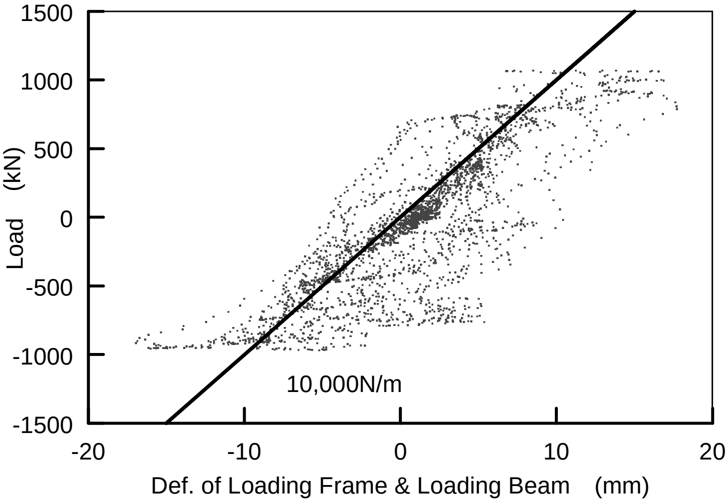


Figure 3 Horizontal Stiffness of Loading frame and Loading Beam

Total weight of Mass and Loading Frame -- 220 ton
Horizontal stiffness of 4 Rubber Bearings -- 204 N/m
(According to the experimental reports of the products)
Horizontal stiffness of Loading Frame and Loading Beam-- 10,000 N/m
(Obtained from the load-deformation relation of the free beam-end input load and the deformation difference between free beam-end and the basement of loading frame recorded during the ultimate excitation (Figure 3))
Elastic stiffness of Steel Beam (Considering shearing deformation) --------------------------------------- 3,520 N/m
Stiffness of Column and Panel of specimen (Elastic spring) --- 8,630 N/m
(Transformed from the stiffness corresponding to the fixed beam-end moment neglecting off-center between pin and the column axis, to the horizontal stiffness corresponding to the free beam-end shear force)

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) Yielding point (5 levels)

Nominal yielding strength of SM490A (According to the Japanese Code, F=325 N/mm2), 1.1 F, 1.2 F, 1.3 F, and the result of tensile strength test (369 N/mm2) (1.135 F)
3) Second stiffness (6 levels)
Second stiffness ratio (k_2/k_e): 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-deformation 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 deformation (e_δ) at free beam-end according to the time history response (refer to Eqn. 3.1, 3.2). 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}, $e_{\delta 0}$). The indicators of e_Q/e_{Q0} and $e_\delta/e_{\delta 0}$ named ‘Load Error Indicator’ and ‘Deformation Error Indicator’ were able to be obtained.

$$e_Q=\Sigma(Q_{a,i}-Q_{ei})^2 \tag{3.1}$$

$$e_\delta=\Sigma(\delta_{a,i}-\delta_{ei})^2 \tag{3.2}$$

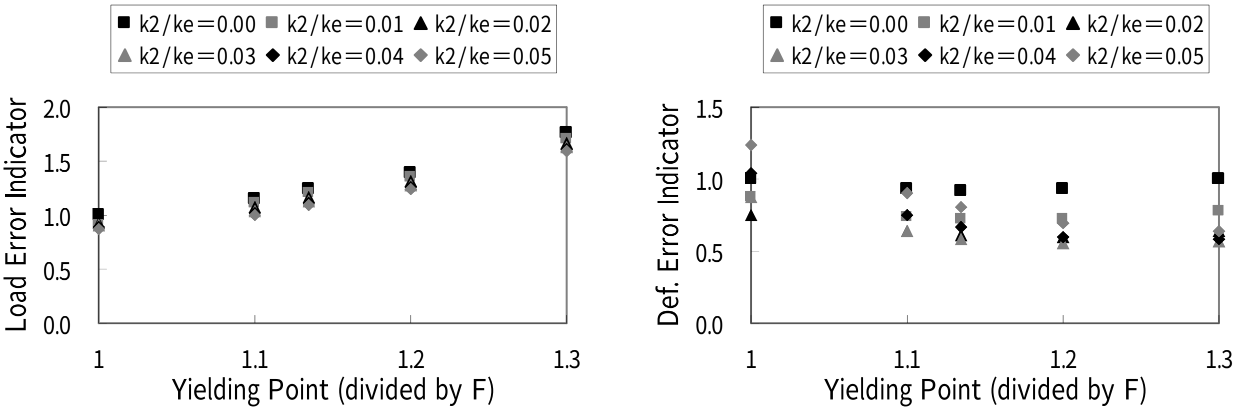
Where,
$\{Q_{ei}\}$ is the experimental load
$\{Q_{a,i}\}$ is the analytic load
$\{\delta_{ei}\}$ is the experimental free beam-end deformation
$\{\delta_{a,i}\}$ is the analytic free beam-end deformation
All data lasted for 30 sec, with the time increment of 1/200 sec.

3.2. Evaluation of Analytic Response

3.2.1 Bi-linear (including elastic-perfectly plastic) models

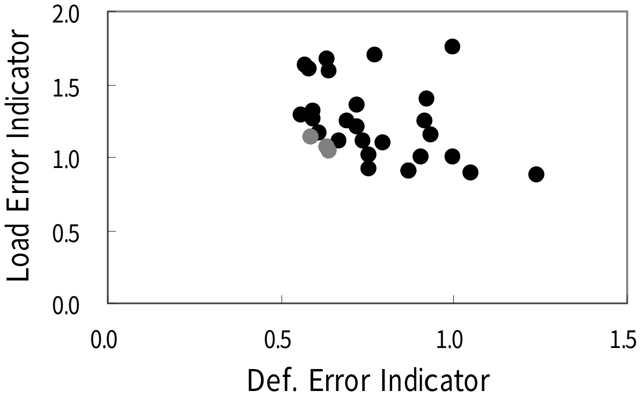
Figure 4 (1), (2) show the load and deformation error indicators in the case of bi-linear hysteresis models. It is clear that the effect of yielding point to the load was larger than that of the second stiffness; where the errors of models with lower yielding points were smaller. The reason was that 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 deformation 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), deformation 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-deformation 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-deformation 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.



(1) Load Error Indicator

(2) Deformation Error Indicator



(3) Load-Deformation Error Indicator

Figure 4 Error Indicator of Bi-linear hysteresis models

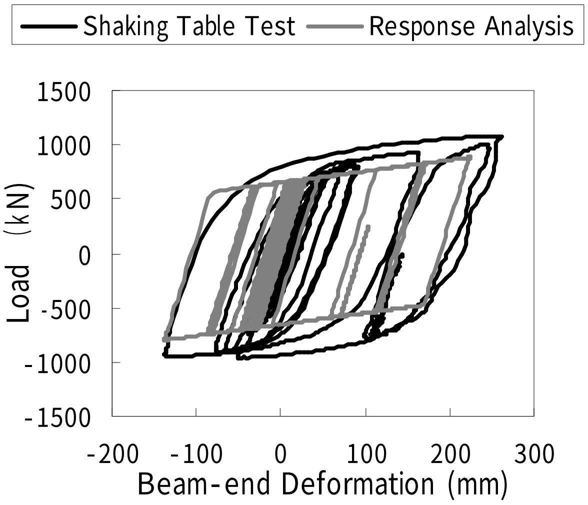
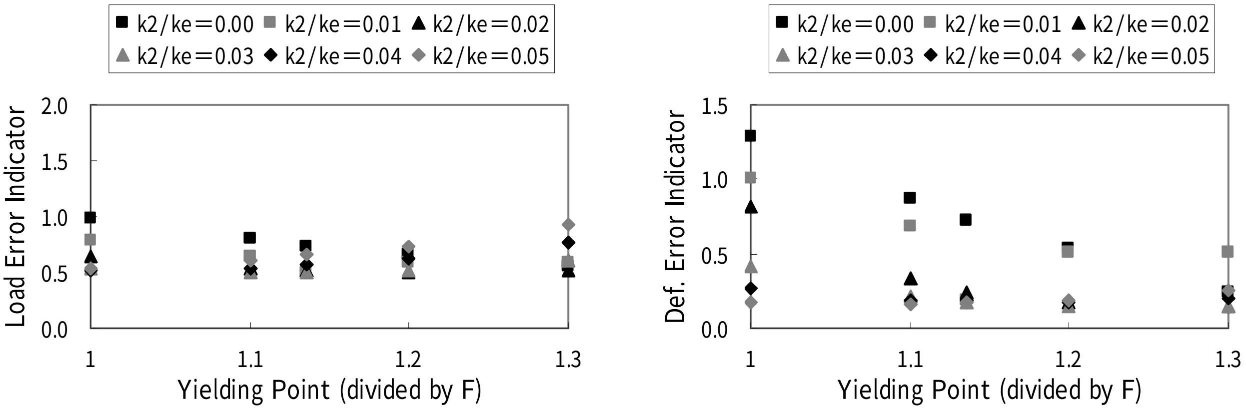
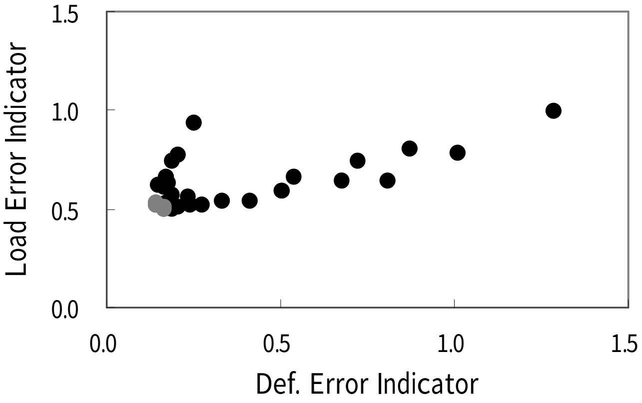


Figure 5 Comparison of Experimental and Analytic result
(Example No. 1: Load-Deformation Relation, Bi-linear, σ_y=1.1F, k_2/k_1=0.03)



(1) Load Error Indicator (2) Deformation Error Indicator



(3) Load-Deformation Error Indicator

Figure 6 Error Indicator of Bi-linear hysteresis models

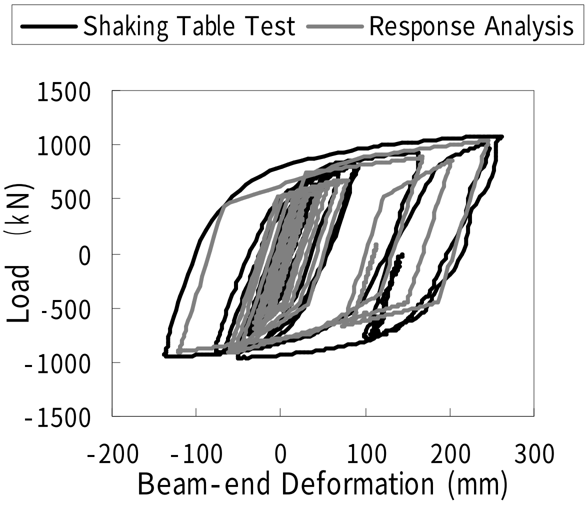


Figure 7 Comparison of Experimental and Analytic result
(Example No. 2: Load-Deformation Relation, Multi-linear, σ_y=1.2F, k_2/k_1=0.02)

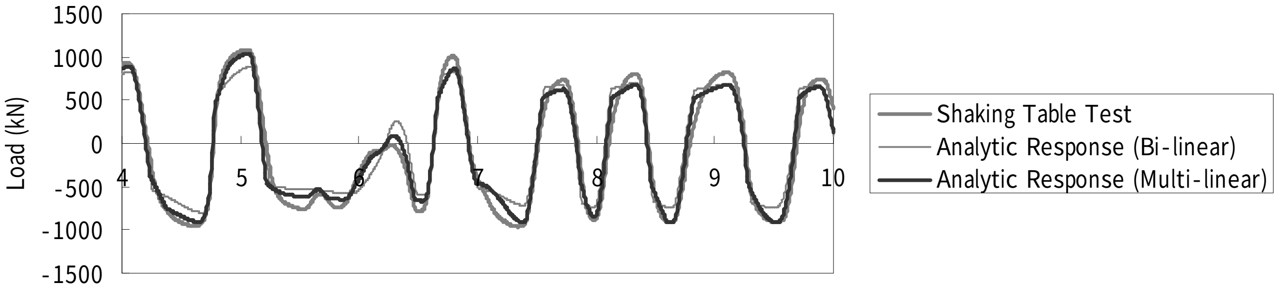


Figure 8 Comparison of Experimental and Analytic result
(Example No. 3: Load Time History)

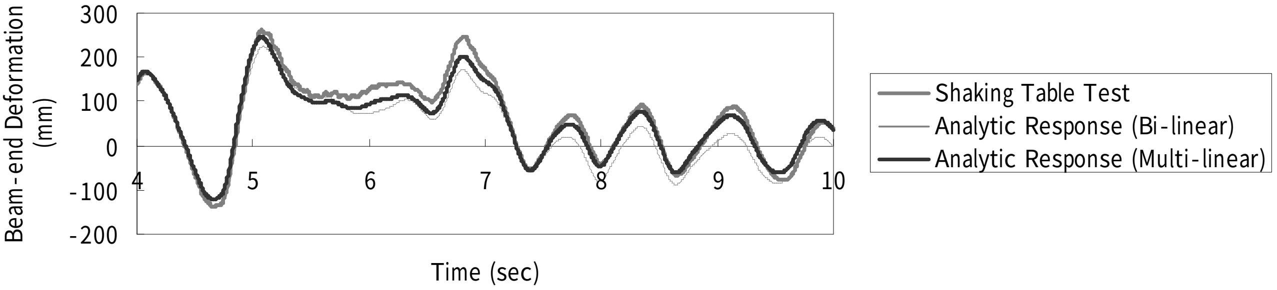


Figure 9 Comparison of Experimental and Analytic result
(Example No. 4: Deformation Time History)

3.2.2 Multi-linear elasto-plastic models considering Bauschinger effect

Figure 6 (1), (2) show the load error indicators and deformation 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 deformation 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-deformation 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-deformation 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.

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 deformation-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.

4. CONSLUSION

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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