Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Nonlinear dynamic analysis of X-steel braces for design use

T. Hirotani
Shimizu Corporation, Tokyo, Japan

H. Taniguchi
Takenaka Corporation, Tokyo, Japan

M. Yamamoto
Obayashi Corporation, Tokyo, Japan

M. Izumi
Taisei Corporation, Tokyo, Japan

ABSTRACT : Simple restoring force characteristics model of X-shaped braces for design purposes have been proposed by the authors. With the objective of making an evaluation, elasto-plastic earthquake response analyses were performed using restoring force characteristics model, those proposed, and those of member level with which the test results could be precisely reproduced. The results of response analyses with the two showed good correspondence. As a result, it was ascertained that the proposed restoring force characteristics model are appropriate as restoring force characteristics for design purposes in both the aspects of convenience and accuracy. Further, with the purpose of evaluating the margin of safety in earthquake resistance of braced frames designed, the critical value of deformation capacity was set up as the function of slenderness ratio based on experiments and earthquake response analyses.

1. INTRODUCTION

Elasto-plastic earthquake response analyses are performed in Japan for verifying the seismic safeties of nuclear power station buildings in large-scale earthquakes.

With the purpose of proposing restoring force characteristics model of braced steel frames in nuclear power station buildings, a series of experiment on reduced models of X-shaped braces were conducted by the authors. Further, they proposed simple restoring force characteristics model for X-shaped braces based on the results of the experiments and past research achievements. (see Fig.1)

The appropriateness of the restoring force characteristics model proposed is studied in this paper by comparing response analysis results of the simplified technique of these restoring force characteristics model proposed for design purposes and the precise technique of closely simulating test results.

Still further, the limit of deformation capacity was set for the purpose of evaluating the margin of safety in earthquake resistance of the X-shaped braced frame designed.

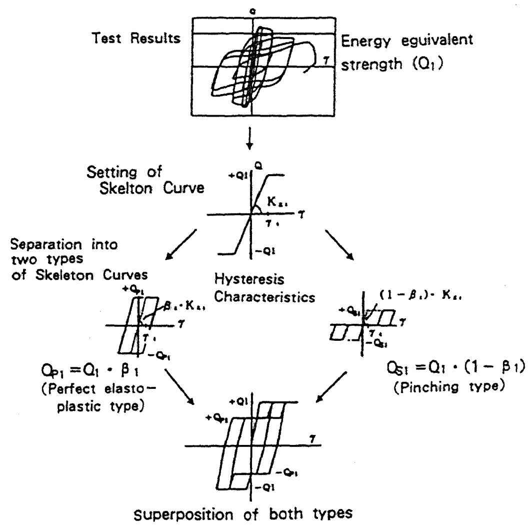


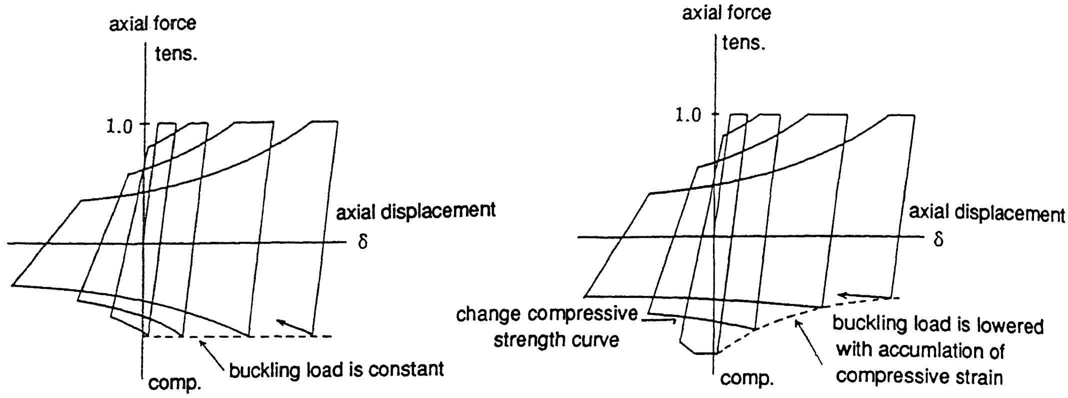
Fig.1 Proposed restoring force characteristics of X-shaped brace for design use

2. ANALYSIS CONDITIONS

2.1 Setting up of precise restoring force characteristics model

Restoring force characteristics model developed by Dr. Wakabayashi et al. was used as the basis for the precise restoring force characteristics model of the brace element. This Wakabayashi's model has been applied to restoring force characteristics of a single brace element subjected to repetitions of axial loading in static and dynamic response analysis.

Upon analyses of the test results obtained by the authors, the peak loads in the compression zone (buckling loads) showed a trend of decreasing with repeated loading at the initial stage of experiments. On the other hand, these test results cannot be expressed with Wakabayashi's model since buckling load is



(a) Original model

(b) Modified Wakabayashi's model

Fig.2 Modification of Wakabayashi's model for precise restoring force characteristics

expressed as the strength of a steady loop under repetitive loading.

Therefore, with the fundamental rule of Wakabayashi's model left unchanged, the strength curve on the compression side was changed, along with which a change was made for buckling load to be lowered through the accumulation of the compressive strain. By this modification, it was made possible for the characteristics of the test results to be reflected. This modified model was used as the precise restoring force characteristics of the brace element (hereinafter referred to as "modified Wakabayashi's model"). A conceptual drawing of the model modification is shown in Fig.2.

An example of simulation analyses of the test results by the modified Wakabayashi's model is shown in Fig.3. The dashed line shows the story shear force - relative story displacement relationship obtained by the test (Nakamura,N. et al.1990) and the solid line shows the analysis result. It can be seen that the analysis results are extremely close to the test results.

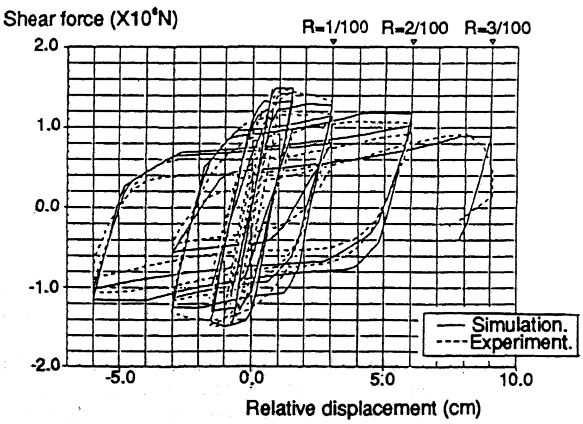


Fig.3 Example of simulation of the test result (Nakamura et.al, 1990)

2.2 Conditions for earthquake response analysis

The modified Wakabayashi's model can be directly used in dynamic analyses since it has been set up as being capable of following any repetitive deformation. Because of agreement in the static loading experiments, results according to the modified Wakabayashi's model were considered as precise solutions in earthquake response analyses.

Here, the results of earthquake response analyses performed respectively using the modified Wakabayashi's model and the previously-proposed simple restoring force characteristics model for design purposes were compared, and the appropriateness of the proposed restoring force characteristics model was evaluated by the degree of agreement between the two results.

As the object of earthquake response analysis, multi-storied plane frames consisting of beams, columns, and X-shaped braces simplifying the steel braced frame of the existing nuclear power station buildings were set up.

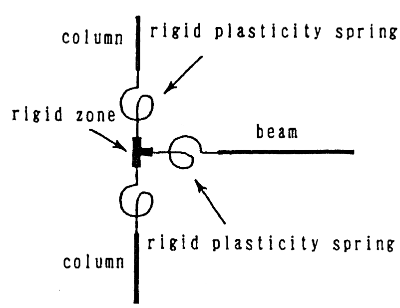
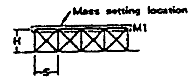
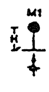
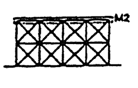
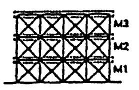
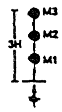


Fig.4 Beam-column joint in the presice analysis

Table 1 Specification of frame model with X-shaped brace

Analysis Model		Dimensions
Method P	Method S	
X 0 1  S×H=7.5m×7.5m		M_1=4950 ton Column : BH-800×400×25×35 Beam : H-458 ×417×30×50 Brace : H-414 ×405×18×28 Joint type: Bracket type
X 0 2 		M_2=2110ton
X 0 3, X 0 4 		X 0 3 M_1 =M_2 =M_3 =740ton X 0 4 M_1 =M_2 =M_3 =590ton Brace : H-400 ×400 ×13×21 Joint type: Double gusset type

Note) ・Damping factor of each menber is h=2%
・Dimensions are the same as those of X01 unless otherwise noted

Table 2 Analysis Cases for dynamic response

No.	Model	input acceleration	α_0(gal)
1	X 0 1	1.5 α	167.1
2		2.0 α	
3		3.0 α	
4		6.0 α	
5	X 0 2	1.5 α	403.4
6		2.0 α	
7		3.0 α	
8	X 0 3	2.0 α	506.8
9	X 0 4	2.0 α	550.8

The particulars of the individual members were determined based on investigations of existing nuclear power station buildings in Japan. The specifications of the subject frame are given in Table 1. The braces has H-shaped section and its slenderness ratio corresponding to the distance between end and center joint was 60, while the width-to-thickness ratio was 9. Two joint type of brace is set up, one causes in-plane buckling and another causes out-of-plane buckling.

The following two earthquake response analyses were performed on this frame:

1.Method S (Simple method)
The frame is replaced with a lumped mass and spring system, and the previously-proposed simple restoring force characteristics model (Fig.l) is used as the restoring force characteristics of the X-shaped brace.

2.Method P (Precise method)
The frame is modeled member by member with restoring force characteristics given for each. The previously-mentioned modified Wakabayashi's model (Fig.2) is used as the restoring force characteristics of the brace. Regarding the beam and column, rigid plasticity rotating springs are considered at ends of elastic members as shown in Fig.4.

The primary natural periods of the individual frames were set at 0.3 sec, the average value for steel frames in existing nuclear power station buildings. The parameters in analyses taken were the number of stories as shown in Table.1 and intensity of inputted seismic waves. The inputted seismic waves were artificial seismic waves having the phase characteristics of Taft EW waves. The input levels were taken at 1.5 times, 2.0 times, 3.0 times, and 6.0 times the inputted acceleration α at which the dynamic response shear force of the brace would become equal to the elastic limit. A list of the cases analyzed is given in Table 2.

3. DYNAMIC RESPONSE ANALYSIS RESULTS AND EVALUATION

The earthquake response analysis results are given in the form of comparisons of Method S and Method P. The maximum response displacements in the individual cases are shown in Fig.5 and the maximum response accelerations in Fig.6. Examples of story shear force-relative story displacement relationships are shown in Fig.7 and examples of floor response acceleration spectra in Fig.8.

Regarding maximum response displacements important as results of elasto-plastic response analyses, the response values of Method S in relation to response values of Method P were distributed in a range of 0.90 to 1.21, and it may be said that the correspondence of the two was good.

With respect to maximum response accelerations, the results for Method S were slightly smaller, and this was because the skeleton strength of the restoring force characteristics model was obtained as the strength on average after buckling.

According to the comparisons of story shear force - relative story displacement relationships of Fig.7, the hysteresis configurations and cyclic properties for Methods S and P were of approximately similar trends, and it may be considered that the energy absorption capacities are also equal.

The comparison of floor response spectra of Fig.8 shows that the predominant periods and frequency characteristics of the two are roughly equal.

The results of the study above showed that the simple restoring force characteristics model proposed indicate almost equal response results to the precise one according to results of experiments. Based on the foregoing, it is judged that the proposed restoring force characteristics model are appropriate as restoring force characteristics for design in the aspects of simplicity and precision.

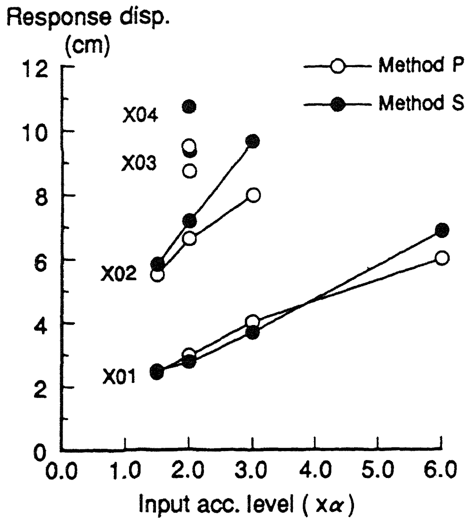


Fig.5 Maximum response displacement

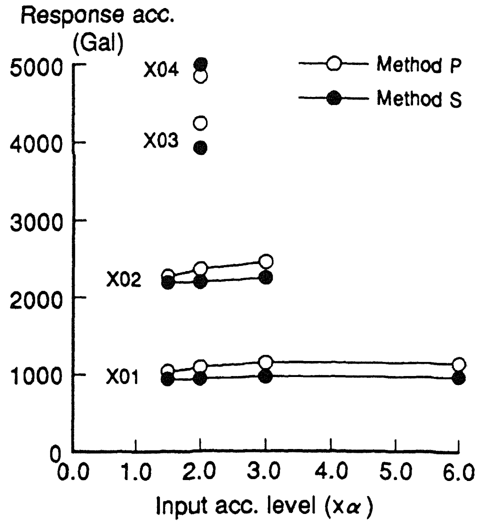


Fig.6 Maximum response acceleration

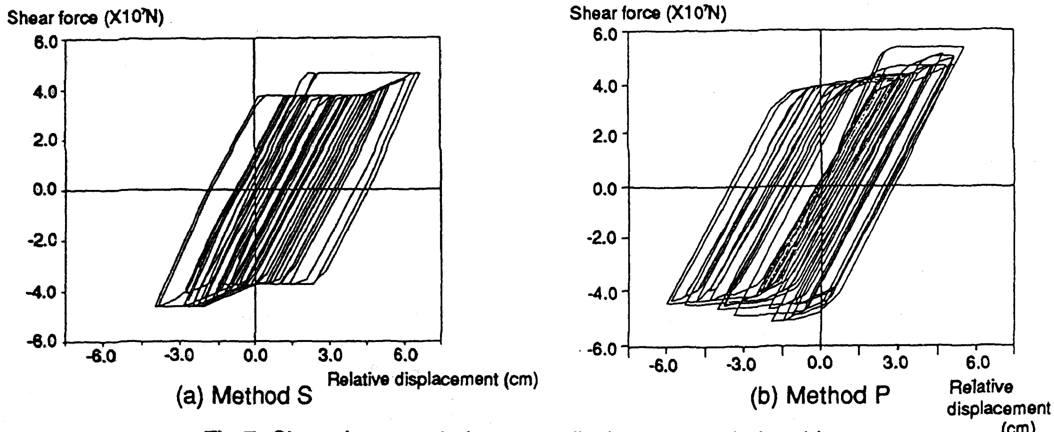


Fig.7 Shear force - relative story displacement relationship
(Frame model X01: inputted 6* α)

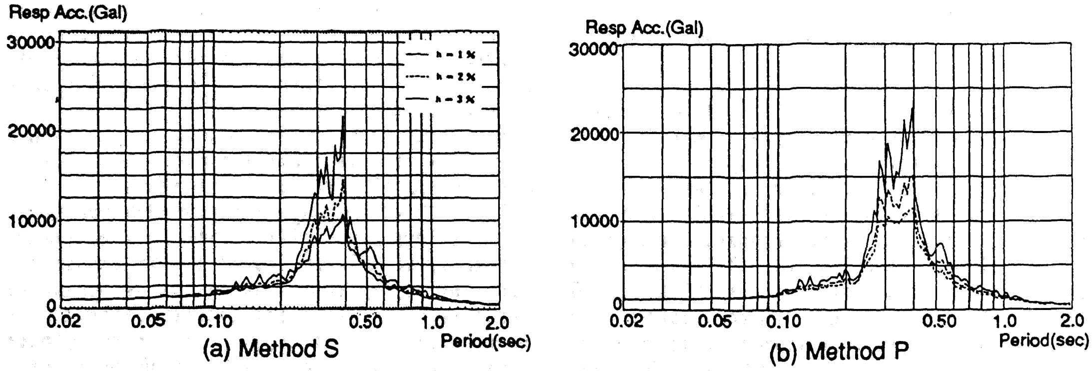


Fig.8 Floor response spectra (Frame model X01: inputted 6* α)

4. ESTABLISHMENT OF CRITICAL VALUE OF DEFORMATION CAPACITY

To Evaluate the allowance in earthquake resistance of a braced frame which has been designed, the input level of the seismic wave used in design is gradually raised, and the coefficient of the input level is regarded as an index of the margin of safety when the response has reached a certain limit to deformation. Hence, to establish the critical value of deformation capacity has great significance in earthquake resistant design.

Studies in recent years have shown that the deformation capacity of a steel structure subjected to the large scale earthquakes can be evaluated by the average cumulative inelastic deformation ratio ($\bar{\eta}$) which is an index based on energy absorption. $\bar{\eta}$ is expressed by the equation

$$\bar{\eta} = \Sigma W/(2*2*W_E), \qquad (1)$$

where ΣW is the accumulative inelastic strain energy and W_E is the elastic limit strain energy.

The relationship of ultimate average cumulative inelastic deformation ratio ($\bar{\eta}_{\alpha}$) of X-braced frame determined from the results of experiments conducted by the authors and results of past experiments under similar conditions (Wakabayashi,M.,et al.) to the generalized slenderness ratio (λe) is shown in Fig.9. λe is expressed by the equation

$$\lambda e = \psi * \lambda \sqrt{\sigma y/(\pi^2 * E)}, \qquad (2)$$

where ψ is the coefficient of buckling length considering end conditions and λ is the slenderness ratio corresponding to the distance between end and center joint of X-shaped brace; σy is the yield stress and E is the modulus of elasticity.

The open circles in the figure are results of experiments conducted by the authors and the closed circles are results of experiments conducted in the past. A trend can be seen for $\bar{\eta}_{\alpha}$ to decrease as λe increases. Further, since adopting the lower-limit value will be on the conservative side in design, the critical value of deformation capacity of X-braced frame was set as a function of λe by the following equations. These are shown by the solid lines in Fig.9.

When $\lambda e < 0.4$

$$\bar{\eta}_{\alpha} = 25 \qquad (3)$$

When $0.4 < \lambda e < 0.8$

$$\bar{\eta}_{\alpha} = -30 * \lambda e + 37 \qquad (4)$$

Further, an attempt was made to express this critical value of deformation capacity by maximum value of deformation in consideration of convenience in design. The relationship between average cumulative inelastic deformation ratio and maximum deformation value was investigated based on the results of response analyses by the precise restoring force characteristics model (Method P) on the single-story frame model given previously in Table 1 (X01 model). The previously mentioned artificial seismic wave and El Centro NS wave were used as inputted seismic waves. The maximum deformation value is represented by the average inelastic deformation ratio ($\bar{\mu}$) expressed as

$$\bar{\mu} = \delta max/\delta y - 1, \qquad (5)$$

where δmax is the average value of maximum story displacement in the positive and negative direction, and δy is the limit deformation of elasticity.

The relationship between $\bar{\eta}$ and $\bar{\mu}$ obtained as a result of response analyses is shown in Fig.10.

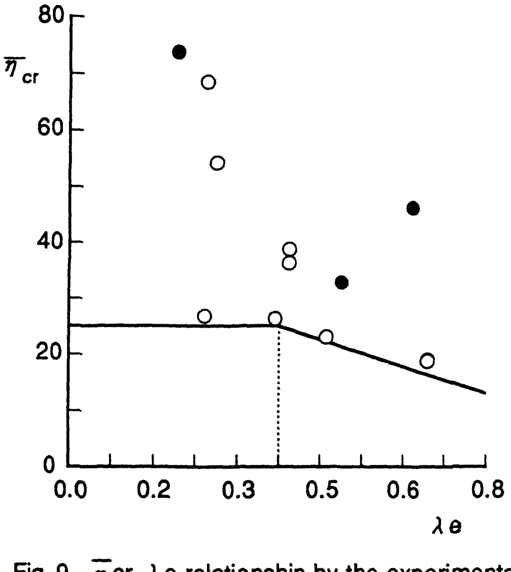


Fig. 9 $\bar{\eta}_{cr}$- λe relationship by the experiments

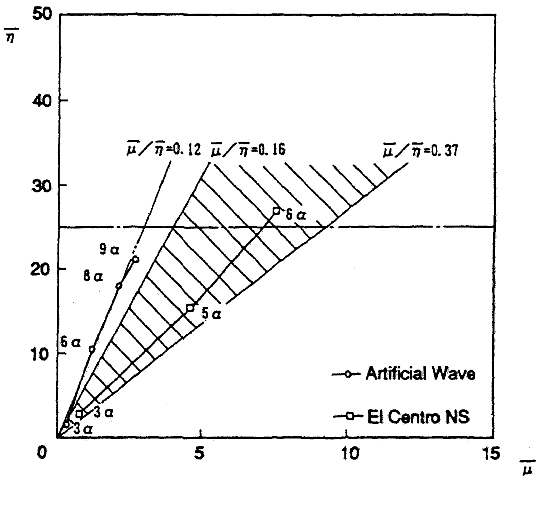


Fig.10 $\bar{\eta}$ - $\bar{\mu}$ relationship by response analysis

The circles in the figure are the results by the artificial seismic wave and squares are by El Centro NS wave. The dash-dotted line shows the $\overline{\eta}\alpha$ (=25) of this frame model X01. The two were in a roughly linear relationship, and the ratios of $\overline{\mu}$ to $\overline{\eta}$ were 0.12 for the artificial seismic wave and 0.25 for the El Centro NS wave. In past studies, the values used were 0.16 to 0.37 from analyses using actual seismic waves (diagonally hatched part in figure :Akiyama, H.1985). Here, 0.12 was adopted as a value on the conservative side.

Using this relationship and expressing the previously-indicated critical value of deformation capacity (Eq.3,4) by the average inelastic deformation ratio($\overline{\mu}$), the following equations are obtained:

When $\lambda e < 0.4$

$$\overline{\mu}\alpha = 3 \qquad (6)$$

When $0.4 < \lambda e < 0.8$

$$\overline{\mu}\alpha = -3.6 * \lambda e + 4.44 \qquad (7)$$

5. CONCLUSIONS

With the objective of evaluating the simple restoring force characteristics model for X-shaped braces proposed by the authors for design purpose, elasto-plastic earthquake response analyses using the proposed restoring force characteristics and restoring force characteristics of member level with which experimental results can be precisely reproduced were conducted.

The results of response analyses by the two indicated good correspondence. As a result, it was ascertained that the proposed restoring force characteristics model, considered together with their convenient nature, were appropriate as restoring force characteristics for design purposes.

Further, the limit of deformation capacity was set for the purpose of evaluating the margin of safety in earthquake resistance of the braced frame designed. This limit is expressed by the index based on the energy absorption and the maximum deformation.

ACKNOWLEDGEMENTS

This study was carried out as a part of joint research "Research on restoring force characteristics of steel frames in buildings of nuclear power stations" by ten Japanese electric power companies (Tokyo, Hokkaido, Tohoku, Chubu, Hokuriku, Kansai, Chugoku,Shikoku, Kyushu and Japan Atomic) being cooperated by five construction companies (Obayashi,Kajima,Shimizu, Taisei and Takenaka). The work was performed under the guidance of a research committee chaired by Professor Emeritus Ben Kato (The University of Tokyo). The authors wish to acknowledge to the valuable cooperation and suggestions given by the members of the committee.

REFERENCES

Akiyama, H. 1985. *Earthquake-resistant limit-state design for buildings*. University of Tokyo press.

Kato, B. and Akiyama, H. 1977. Restoring force characteristics of the steel frames equipped with diagonal bracings. *Trans. A.I.J. No.260*: 99-107.

Nakamura, N. 1991. Restoring force characteristics of the steel frames of nuclear power station buildings. *Proc. 11th SMiRT Vol. K13*: 351-356. Tokyo.

Wakabayashi, M. et al. 1977. Hysteretic behavior of steel braces subjected to horizontal load due to earthquake. *Proc.6th WCEE*: 3188-3193. New Delhi.

Wakabayashi, M. et al. 1977. Experimental studies on the elasto-plastic behavior of braced frames under repeated horizontal loading. *Bulletin of the disaster prevention research institute Vol.27*: 121-154. Kyoto Univ.,Japan.