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Model of restoring force characteristics of X-steel braces

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ABSTRACT: A simple and practical analytical model of the characteristics of restoring force (a q-γ model) is proposed for the dynamic analysis of steel X-braced frames. Data obtained from the authors' experiments on reduced-scale model specimens of actual X-braces are used. This q-γ model combines perfect elasto-plastic hysteresis curves with pinched hysteresis curves by using a distribution ratio. Both this ratio and the vertex points of all hysteresis curves are obtained from a generalized slenderness ratio. To make this generalization, a coefficient of the buckling length of the brace is required. The coefficients for each type of frame-to-brace connection were determined by evaluating the test results. This model is considered to be a powerful tool for the dynamic analysis of braced frames.

1 INTRODUCTION

In order to design nuclear power station buildings, which involves estimating quantitatively the seismic safety of the buildings, dynamic nonlinear seismic response analysis using a restoring force characteristics model, i.e. a q-γ (q:lateral shear force, γ:horizontal deflection angle) model is useful. Such q-γ models for reinforced concrete structures (as are nuclear reactor buildings) have already been proposed. Establishment of a model for the steel-braced frames is extremely desirable.

In this paper, a simple and practical q-γ model for the X-braces is proposed. Data obtained from the experiments performed by Nakamura (a co-researcher of the authors) et al.(1991) on reduced-scale model specimens of actual X-braced frames are used.

2 OUTLINE OF THE TEST

Experiments were conducted to investigate the characteristics of elasto-plastic hysteresis for X-braces. Test parameters were brace slenderness ratio (40, 60, 80), flange width-to-thickness ratio (6, 9, 13), and the type of connection to the frame (bracket, composite gusset plate, double gusset plate). The experiments were performed on eleven reduced-scale (1:2.5 and 1:3.5) model specimens: nine braced frame models and two rigid frame models. Dimensions and details of the specimens

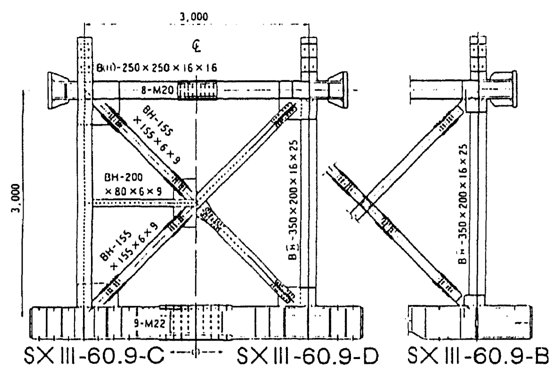


Figure 1. Typical Specimen Configuration

were designed referring to those used in nuclear power station buildings. The combinations of test parameters and an explanation of the specimen codes are shown in Table 1. A typical specimen configuration is shown in Figure 1. The material used for the braces was SS400 and its material properties are shown in Table 2. The test specimen was fixed to a test bed, and lateral loads equivalent to those produced by earthquake motion were applied simultaneously and in the same direction to both left and right ends of the top frame member.

From the experimental observations, it was seen that after brace buckling the specimens with smaller slenderness ratios showed a stable spindle-shaped hysteresis curve, while those with larger slenderness

Table 1. Specifications of Model X-Brace Test Specimens

Specimen Codes and Joint Type			Brace Member			Dimensions of Rigid Frame
Bracket Type	Composite Gusset Plate Type	Double Gusset Plate Type	λ	$\frac{b}{t_f}$	Section Size	
SXII-40・6-B	———	———	40	6.0	H-155×155×6×12 (35 *1, 6.5 *2)	*3 S=H=2.0m
SXII-40・9-B	———	———		9.0	H-155×155×6×9 (38,8.6)	
SXIII-60・6-B	———	———	60	6.0	H-155×155×6×12 (52,6.5)	S=H=3.0m
SXIII-60・9-B	SXIII-60・9-C	SXIII-60・9-D		9.0	H-155×155×6×9 (55,8.6)	
SXIII-60・13-B	———	———		13.0	H-155×155×6×6 (57,12.9)	
SXIII-80・9-B	SXIII-80・9-C	———	80	9.0	H-110×110×6×6 (80,9.4)	
SOII : S = H = 2.00m, SOIII : S = H = 3.00m } Rigid Frame Specimen						

*1 : Actual slenderness ratio
*2 : Actual width-to-thickness ratio
*3 : S ; Span, H ; Height

Table 2. Properties of Specimen Material

Test piece	Yield strength σ_y (N/mm²)	Tensile strength σ_u (N/mm²)	$\frac{\sigma_y}{\sigma_u}$	Rupture strain (%)
PL-6	370	488	0.757	22.4
PL-9	282	432	0.654	29.0
PL-12	265	424	0.626	31.2

ratios exhibited a tendency toward a pinched hysteresis curve. These restoring force curves are shown in Figure 8. These are hysteresis curves for the X-braces only, obtained by removing those of the frames. They are plotted together with curves calculated using the proposed q-γ model for comparison. The curves obtained from the test may be too complex to be applied to dynamic response analysis, and consequently a simplified q-γ relationship such as a model combining perfect elasto-plastic curves with pinched curves is desirable for design purposes.

3 CONSIDERATION OF THE TEST RESULTS

3.1 Coefficient of buckling length

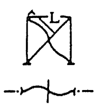
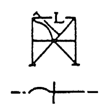
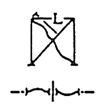
The deflection modes of the braces after buckling are shown in Table 3. It is clear that deflection was constrained at both the ends and the centers of the brace members. The constraining effect of the joints can be evaluated based on these deflection modes in terms of an effective buckling length αL. The coefficient of buckling length α was determined to be 0.65 for the bracket and the composite gusset plate joints and 0.40 for the double gusset plate joints. The constraining effect of each type of joint is so high that brace members can be considered to be fixed at each end. Therefore, to estimate the buckling strength of the brace we should use a generalized slenderness ratio (λe) in place of the ordinary slenderness ratio. Although the ordinary slenderness ratio is based only on the brace length, the generalized slenderness ratio is based on the constraining effect of the brace as described in Equation 1. This equation employs the coefficient of the buckling length and the normalized slenderness ratio.

$$\lambda e = \alpha (L/iy)\sqrt{(\sigma_y / (\pi^2 E))} \qquad (1)$$

where L is the length between brace nodes, iy is the radius of gyration, E is the modulus of elasticity, and σ_y is the brace yield strength.

Maximum strength of the specimens was governed by their brace buckling. Brace buckling strength is in turn governed by generalized slenderness ratio. Maximum strength, normalized by the brace yield strength, and the generalized slenderness ratio are plotted in Figure 2. This curve plots values caluculated by substituting the generalized slenderness ratio into

Table 3. Buckling Modes and Effective Slenderness Ratios Corresponding to Three Types of Brace-to-Frame Joints

Joint Type	Bracket	Composit Gusset	Double Gusset
Buckling Direction	Out of plane	In plane	In plane
Buckling Mode			
α L	0.65L	0.65L	0.40L

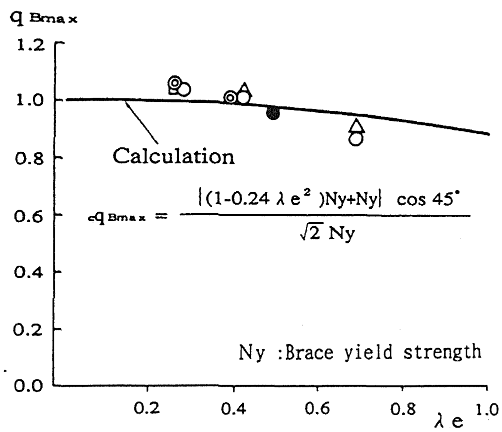


Figure 2. Relationship between Normalized Maximum Strength and Generalized Slenderness Ratio

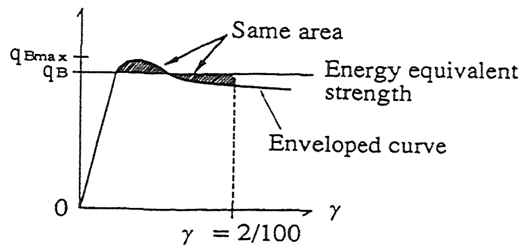


Figure 3. Simplification of the Skeleton Curve by Energy Equivalent Strength

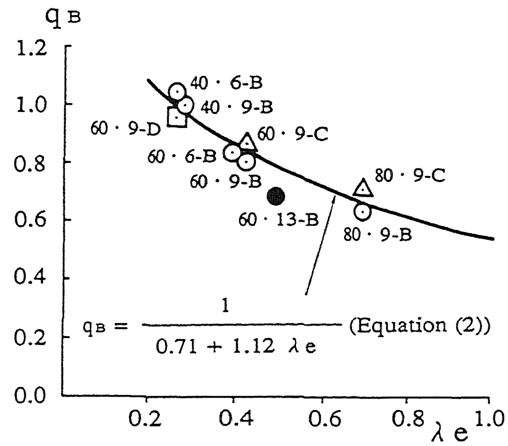


Figure 4. Relationship between Energy Equivalent Strength and Generalized Slenderness Ratio

Johnson's formula, which is used for estimating the inelastic buckling strength of struts in Japanese Design Standard for Steel Structures. Maximum strength can be estimated using this calculation. Therefore, it can be said that the coefficients of buckling length obtained from the test results are reasonable.

3.2 Energy equivalent strength

We introduce energy equivalent strength (q_B), which is normalized by the horizontal component of the brace yield strength (2Qy), in order to simplify the load and deflection curves of the X-braces, for example into bi-linear curves. In all specimens, fatal failure did not take place until the horizontal deflection angle (γ) was above 2/100. Although the energy absorbed by elasto-plastic strain can be considered up to the time when the strength of a member reaches zero, we considered only the energy absorbed before the deflection angle reaches 2/100 in order to ensure a margin of safety for seismic design. Therefore as shown in Figure 3, the energy equivalent strength (q_B) was defined so as to bi-linearlize the initial enveloped load and deflection curve and equalize its energy absorption to that derived from the initial curve.

The relationship between energy equivalent strength and generalized slenderness ratio is shown in Figure 4. The data obtained from specimen SXIII−60・13−B, which had a flange width-to-thickness ratio of 13, was disregarded because the specimen's loss of strength after brace buckling was very large. It is clear that energy equivalent strength is nearly equivalent to yield strength when λe is about 0.2, and that this value decreases as λe becomes larger. This relationship can be approximated by Equation 2:

$$q_B = \frac{Q_B}{2Qy} = \frac{1}{0.71 + 1.12\lambda e} \qquad (2)$$

Using Equation 2, we can express complicated restoring force characteristics with a bi-linear curve.

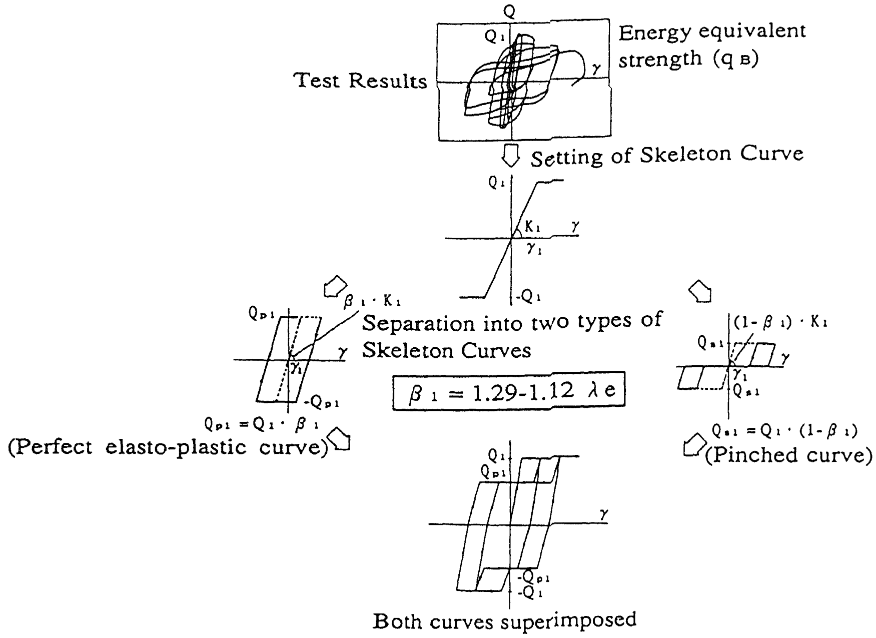


Figure 5. Flow Chart for Setting Up Model of Restoring Force Characteristics for X-Braces

4 PROPOSED q-γ MODEL

After considering the test results and practicality, a q-γ model for X-braces was set up as illustrated by the flow chart in Figure 5. First, a simple skeleton curve is established. Second, the initial skeleton curve is separated into two types of skeleton curves. Third, each skeleton curve is provided a hysteresis rule, one being perfect elasto-plastic curve, the other a pinched hysteresis curve. Using these two discrete hysteresis curves, . dynamic analysis may be completed more quickly than if a complex hysteresis curve is used.

Finally, in order to confirm that these two q-γ models are reasonable, we need to compare the results produced by the two q-γ models with the test results.

4.1 Initial skeleton curve

A bi-linear curve was adopted for the skeleton curve of the proposed q-γ model. Its vertex strength (Q_1) can be obtained from the energy equivalent strength (q_B)as shown in Equation 3, which was derived from Equation 2. The vertex deflection angle (γ_1)can be obtained from Equation 4.

$$Q_1 = 2Qy/(0.71+1.12\lambda e) \tag{3}$$

$$\gamma_1 = Q_1 / K_1 \tag{4}$$

where 2Qy is the horizontal component of a brace yield strength and K_1 is the initial shear stiffness of the X-brace.

4.2 Hysteresis characteristics

The initial skeleton curve described above is separated into perfect elsto-plastic and pinched skeleton curves using the distribution ratio β_1, the ratio of the vertex strength of the perfect elsto-plastic curve to that of the initial skeleton curve. The vertex strength of the initial skelton curve (Q_1) can be expressed as the sum of the yield strength (Qy) of the brace member in tension and the buckling strength (Qc) of the brace member in compression, as in Equation 5:

$$Q_1 = Qy + Qc \tag{5}$$

Referring to Kato and Akiyama (1977), vertex strength Q_1 is divided between the vertex strength of a perfect elsto-plastic skeleton curve (two times Qc) and the vertex strength of a pinched skeleton curve (the balance of Q_1). Therefore β_1 can be expressed as in Equation 6. This is illustrated in Figure 6. A pair of braces is shown and each hysteresis curve is abbreviated by bi-linearlizing and neglecting an elastic region. First, each hysteresis curve is further simplified such as into rectangular curves. Next, these curves are summed by folding their axis of co-ordinates. Finally, a perfect elsto-plastic curve could be obtained from the overlapping portions of the summed curve and a pinched curve could be obtained from the balance of the summed curve.

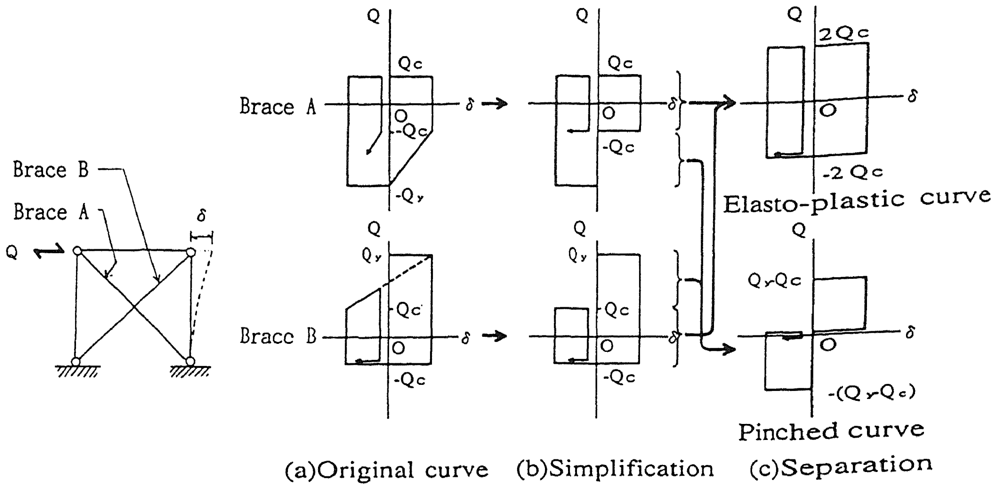


Figure 6. Simplification of Restoring Force Characteristics of X-Braces (by Kato and Akiyama)

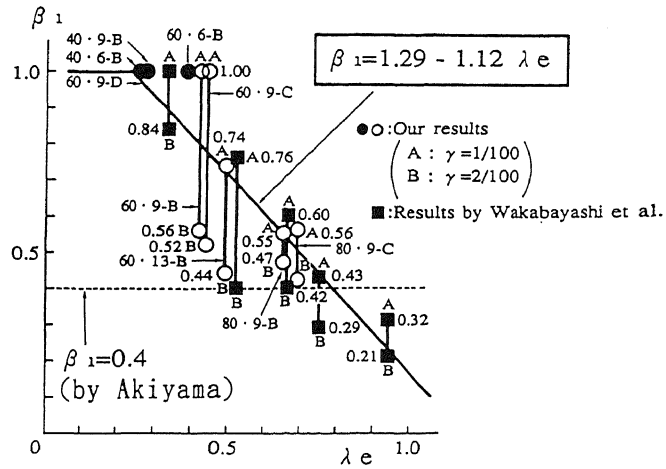


Figure 7. Relationship between Distribution Ratio and Generalized Slenderness Ratio

$$\beta_1 = \frac{2Qc}{Q_1} = \frac{2(Q_1 - Qy)}{Q_1} \qquad (6)$$

The relationship between the distribution ratios obtained from the q-γ curve and the generalized slenderness ratios of each specimen is shown in Figure 7. In this figure, circles indicate the test results, "A" refers to β_1 for hysteresis curves with a maximum deflection angle of 1/100, and "B" refers to β_1 for hysteresis curves with a maximum deflection angle of 2/100. Squares indicate the test results obtained by Wakabayashi et al.(1977). The dashed line represents data from Akiyama(1985), and the solid line shows the results produced by Equation 7 (derived from substituting Equation 3 into Equation 6).

In Figure 7, the distribution ratio varies with change in the generalized slenderness ratio, and the relationship between the distribution ratio and the generalized slenderness ratio is described well by the solid line. Therefore, it is reasonable to assume that the distribution ratio β_1 varies with change in the generalized slenderness ratio as shown in Equation 7.

$$\beta_1 = 1.29 - 1.12\lambda e \qquad (7)$$

4.3 Calculation of restoring force characteristics

The proposed q-γ model of X-braces can be obtained by superimposing the perfect elasto-plastic and the pinched skeleton curves. Figure 8 shows a comparison of the curves obtained using the proposed q-γ model and test results. The test results shown are those for the specimens whose slenderness ratios are 40, 60, and 80. The results obtained using the proposed model show good agreement with the test results.

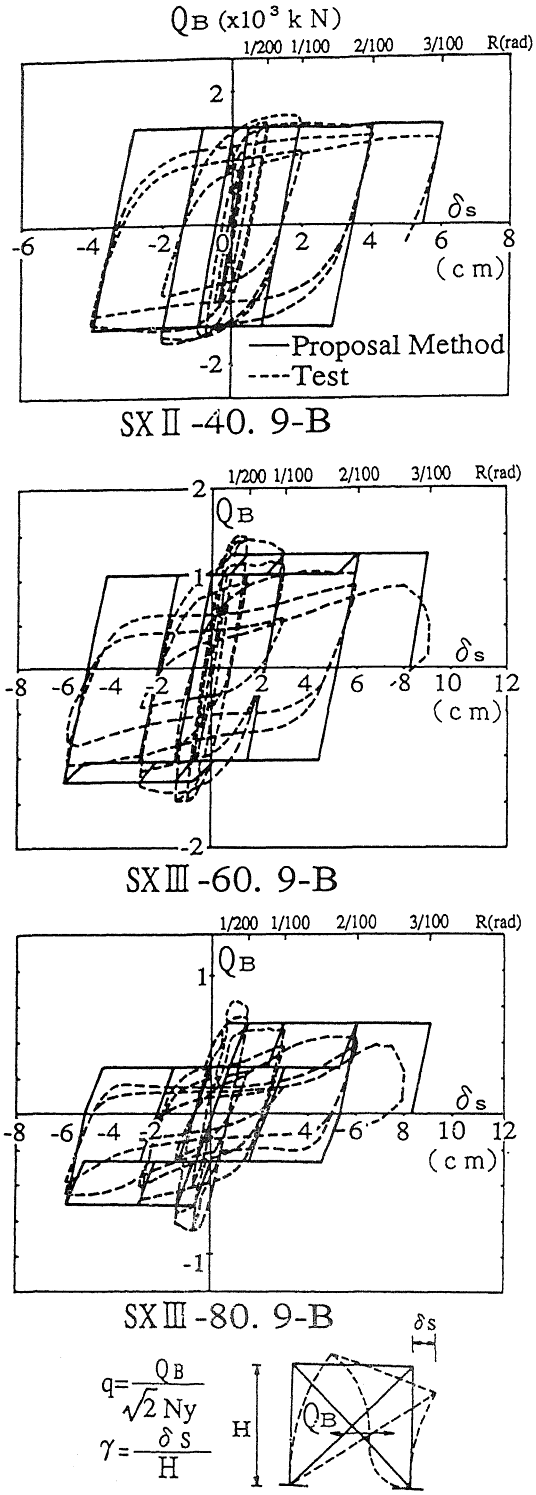


Figure 8. Comparison of Test Results and Results Produced by Proposed Analytical Method

The proposed q-γ model thus appears to be appropriate for use in the dynamic analysis of steel X-braces.

5 CONCLUDING REMARKS

X-braces are the principal earthquake-resistant elements in the steel frames of nuclear power station buildings. Based on test results, a simple and practical q-γ model composed of perfect elasto-plastic and pinched hysteresis curves whose distribution ratio is obtaind from a generalized slenderness ratio was proposed for use in designing X-braces.

We will perform further dynamic analyses on X-braced frames to compare the analytical model proposed here to more accurate hysteresis models and to confirm that the model proposed here is useful for analyzing the dynamic response of nuclear power station buildings.

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