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STRENGTH REQUIREMENT FOR BEAM END CONNECTIONS TO ABSORB PLASTIC STRAIN ENERGY

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SUMMARY

Earthquake induced energy for steel frames with weak beams is absorbed mainly in the plastic zone of beams which gradually expands from the beam ends toward the middle of the beams. The expansion of the plastic region causes an increase in the moment of the beam ends. Therefore, the beam end connections must have the strength necessary to expand the plastic zone of the beams. Through carrying out response analyses with the variation in the natural period, the vertical load on the beam and the kind of seismic wave and its intensity, a method for determining the strength required for the beam ends of the steel moment resisting frames with weak beams was proposed.

INTRODUCTION

The plastic energy of beams is absorbed by their plastic zone, which gradually expands toward the middle of the beams. The expansion of the plastic region causes an increase in the moment of the beam ends. Therefore, the beam end connections must have the strength necessary to expand the plastic zone of the beams.

In this paper, the relationship between the amount of plastic energy dissipation and the strength of the joint connection of beam ends is clarified for the case in which the plastic energy dissipation ability of beams for steel frames with weak beams is limited by the fracture of the beam ends. Then, a design method for the beam end connections is studied.

RELATIONSHIP BETWEEN BEAM END MAXIMUM MOMENT AND ABSORBED ENERGY

Method

The maximum moment of the beam end and the amount of plastic energy absorption are indicated using the maximum strength coefficient of α and the cumulative plastic ductility ratio of η, both of which can be obtained from the following equations.

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$$\alpha = \frac{M_{\max}}{M_p} \quad (1)$$

$$\eta = \frac{W_p}{2W_e} \quad (2)$$

Where $M_{\max}$: Maximum moment of a beam end
M_p : Full plastic moment of a beam
W_p : Plastic strain energy that a beam absorbs
W_e : Elastic strain energy that a beam absorb in the case of full plasticity caused by monotonic loading

If the shape of the beam and the stress-strain relation of steel are provided, the relationship between α and η during monotonic loading can theoretically be obtained. Usually, the input energy by an earthquake is absorbed on both positive and negative sides due to cyclic loading. Therefore, when the value of η is the same in both cases of an earthquake response and monotonic loading, the value of α in the former case is smaller than that in the value in the latter case. The relationship between α and η during earthquake responses differs due to the structural characteristics and input ground motion characteristics.

In this study, through carrying out inelastic earthquake response analyses for a number of models all with different natural periods, pattern of the vertical load on the beams and input ground motions, a method for easily estimating the relationship between α and η is derived from the analysis results

Frame Model for Analyses

In the inelastic earthquake responses, P-Δ effects cause the concentration of the plastic deformation in one direction. The degree of this deviation can be estimated using the method shown in Ref. [1]. There is a possibility that the plastic deformation for frames which are greatly influenced by the P-Δ effects occurs almost in one direction. In this case, the relationship between α and η is the same as that in the case of monotonic loading. The frame for which the influence of the P-Δ effects can be ignored is subject to the analyses in this study.

With regard to middle or low storied steel frames with weak beams for which the influence of the P-Δ effects can be ignored, the relationship between α and η for the beams of each story of the frame is not greatly different from the relationship between α and η for the beams of the one degree of freedom system. Therefore, the relationship between α and η is obtained using a one degree of freedom system model in this study.

Fig. 1 shows the frame models used for the analyses. Since the vertical load on the beam has influences upon the relationship between α and η, three kinds of frames (frame 1 ~ frame 3) with different load patterns are used. No vertical load acts on the beam of frame 1. All frames have weak beams. The beam and column sections of the frames are shown in the figure.

The amount of the vertical load can be expressed using the following parameter of γ.

$$\gamma = \frac{M_0}{M_p} \quad (3)$$

Where M_0: Maximum moment caused by the vertical load for a simple beam

Analyses are carried out in the case of the value of γ being 0.5 and 0.8 for frames 2 and 3. In the case of γ=0.8 for frame 3, plastic hinges occur at one end and the middle part of the beam when the frame attains to yield mechanism. In other cases, plastic hinges occur at both ends of the beam.

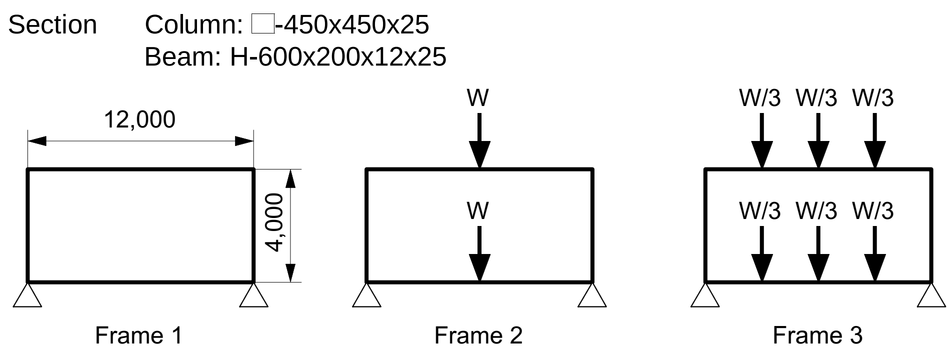

Fig.1 Frame model

Steel Characteristics

The stress-strain relation of the steel used in this study is determined based on Ref. [2] as a standard model for steel of 490N/mm^2 class. Fig.2 shows the model of the stress-strain relation. The nominal stress-nominal strain relation for compression, that for tension and the true stress-true strain relation are shown using a solid line, broken line and dash-and-dotted line respectively.

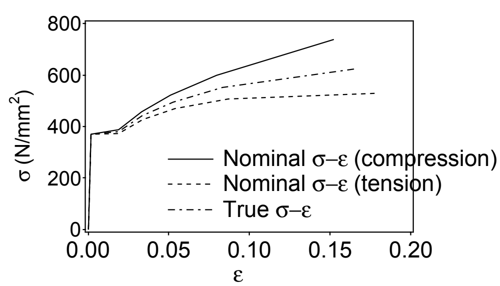

Fig.2 Stress-strain relation

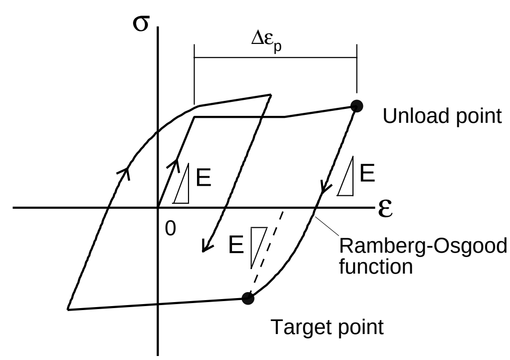

Fig.3 Hysteresis model

Response Analyses

Inelastic response analyses are carried out using the member model shown in Ref. [3]. The member is divided into minute elements. The cyclic hysteresis characteristics of the spring of each minute element is evaluated by using the Takanashi-Ohi model [4] made with consideration to the Bauschinger's effect of steel (See Fig.3). The analytical conditions are summarized as follows:

1) Frame model: Frame 1, Frame 2, Frame 3 (See Fig.1)
2) Amount of vertical load: γ=0, 0.5, 0.8
3) Natural period: 0.5, 1.0, 2.0, 3.0(sec)
4) Damping factor: 0.02
5) Input wave: JMA-Kobe 1995 (NS), El Centro 1940 (NS), Hachinohe 1968 (NS), Yokohama (artificial seismic wave)
   The time-history of ground motion and velocity response spectra (damping factor 2%) for each input wave are shown in Figs.4 and 5.

6) The intensity of input ground motion

The intensity of ground motion is determined so that the following conditions can be satisfied.

$$Q_p / Q_{e_{\max}} = 1/4,\ 1/8,\ 1/12$$

Where Q_p: Full plastic story shear force without vertical loading

$Q_{e_{\max}}$: Response maximum shear force in the case of the model being elastic

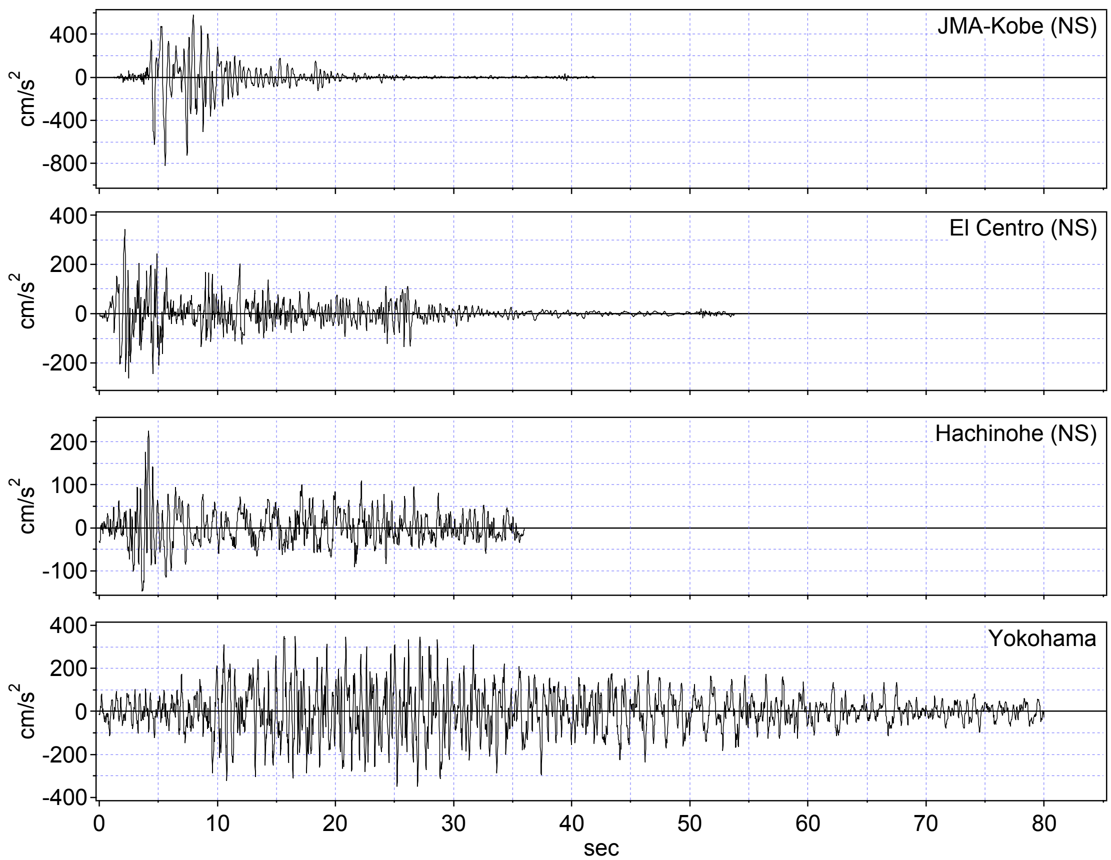

Fig.4 Time history of input waves

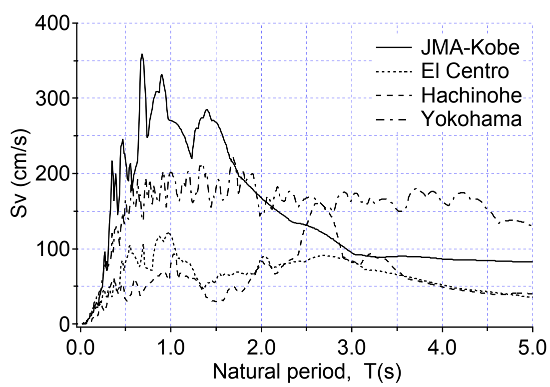

Fig.5 Velocity response spectra (damping factor 2%)

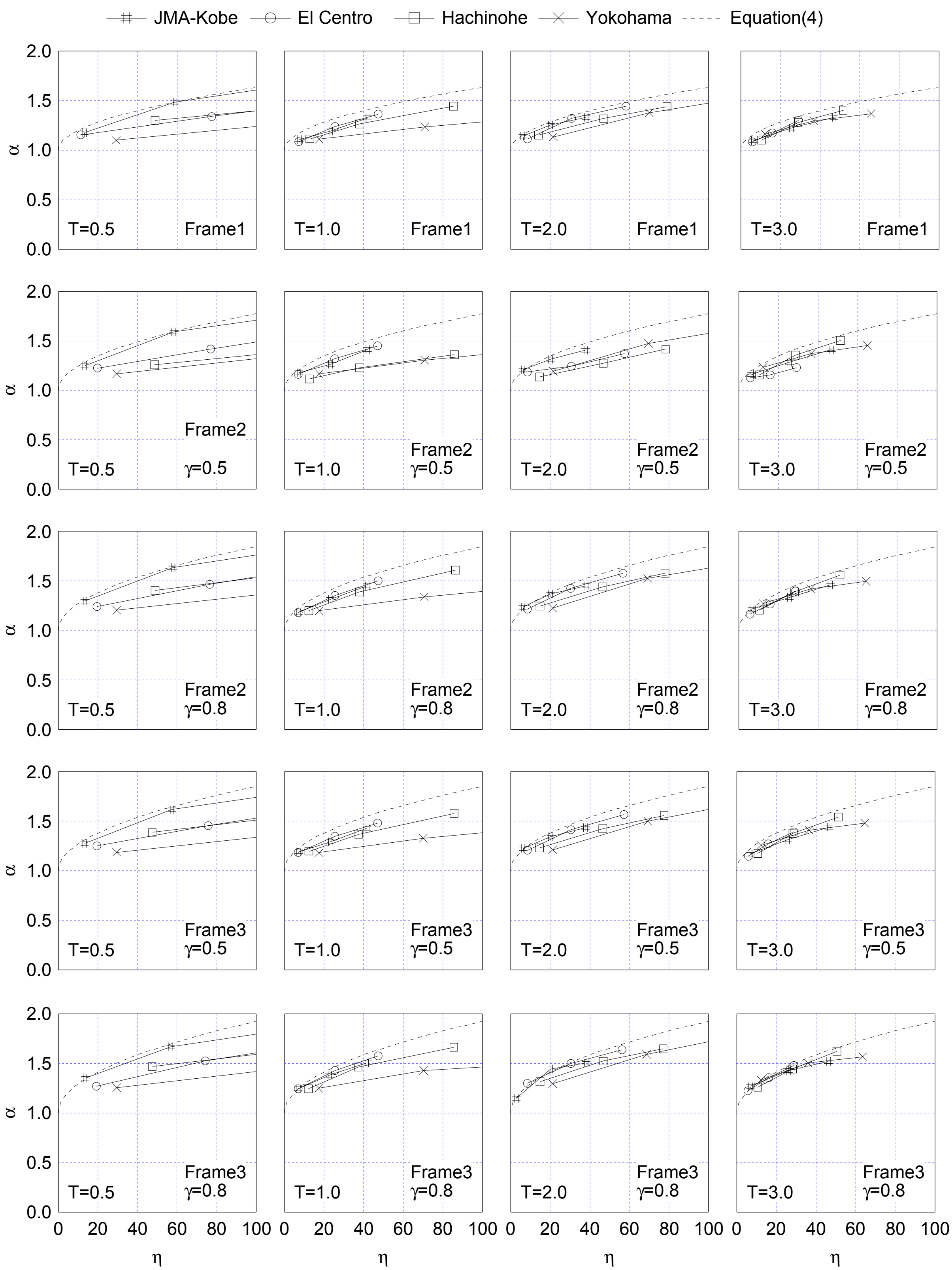

Fig.6 α-η relation

Analysis Results

Fig.6 plots the relationship between α and η when the intensity of the ground motion is changed.

The following can be clarified from the analysis results.

1) Effects of seismic wave and natural period

Among the four kinds of input waves used for the analyses, the duration time of the main motion for JMA-Kobe is short and that for Yokohama is longer. It is thought that with the increase in the repeating number for plasticity the value of α becomes smaller for η with the same value. In the case of η being the same, the value of α in the case of Yokohama being input is smaller than that in the case of Kobe being input as a whole. This tendency is conspicuous when the period is 0.5 and 1.0sec.

The results obtained in the case of El Centro being input tend to be similar to those in the case of Hachinohe. There is a tendency in which under the same frame condition, the longer the period, the larger the value of α for η with the same value. It is thought that this is also caused by the effects of the repeating number of plastic increments. When the natural vibration period is 3sec, almost no difference caused by the seismic wave can be seen.

2) Effects of vertical load on the beam

Compared with the response results in the case of same natural period, the value of α for η with the same value for frames 2 and 3 is larger than the value of α for frame 1. The value of α in the case of γ=0.8 is larger than in the case of γ=0.5. This means, the amount of the vertical load on the beam exerts influences upon the relationship between α and η. The greater the vertical load, the larger the value of α for η with the same value.

Estimation Equation

With regard to the relationship between α and η which is the result of the response, the following equation was obtained as a simple relation which nearly corresponds to the upper limit on the conservative side.

$$\eta = 250 \cdot (\alpha - 1)^2 \cdot q \quad \cdots\cdots (4)$$

q is a coefficient indicating the influence of the vertical load on the beam and can be given by the following equation.

$$q = \frac{2M_p}{Q_1\, l}$$

Where Q_1: End shear force of the beam when the beam attains to yield mechanism (one value larger than the other), l: Beam-length

The relationship between q and γ is shown in Table 1.

The dotted line in Fig.6 shows equation (4). It is clear that equation (4) is an appropriate estimation equation for the upper limit of the response.

Fig.7 compares the relationship between α and η obtained from the shaking table test results [5] with equation (4). Equation (4) is an approximate expression corresponding well to the test results.

Equation (4) is formulated based on the analytical results obtained using the stress-strain relation of standard 490N/mm^2 class steel. Due to the fact that as for the 400N/mm^2 class steel and 490N/mm^2 class steel, there is no great difference in the strain at the beginning of strain hardening and in the strain hardening stiffness, the difference between these two kinds of steel has little effect upon the inelastic behavior of the beam with non-dimensional form. Therefore, equation (4) can also be applied to beams with 400N/mm^2 class steel.

Table 1 γ-q relation

Frame 2	$0 \le \gamma \le 1$	$q = \dfrac{1}{\gamma+1}$
Frame 3	$0 \le \gamma \le \dfrac{2}{3}$	$q = \dfrac{2}{3\gamma+2}$
	$\dfrac{2}{3} \le \gamma \le \dfrac{4}{3}$	$q = \dfrac{2}{2\gamma+\dfrac{8}{3}}$

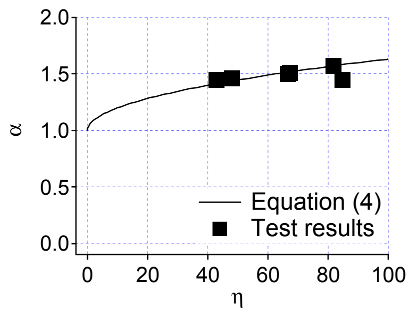

Fig.7 Comparison between shaking table test results with Equation (4)

INVESTIGATION INTO FACTORS EXERTING EFFECTS ON ENERGY ABSORPTION ABILITY

The maximum resisting moment of the beam ends can be obtained from the following equation, where the mechanical properties of steel for the flange part and the web part are assumed to be equal to each other.

$$M_{\max} = Z_{pf} \cdot \beta \cdot \sigma_u + \gamma_w \cdot Z_{pw} \cdot \sigma_u \quad (5)$$

Where Z_{pf}: Plastic section modulus referring the flange part

Z_{pw}: Plastic section modulus referring the web part

σ_u: Tensile strength

β is the ratio of the mean normal stress to the tensile strength for the flange when the joint connection of beam ends attains to the maximum bending strength. According to previous studies, the value for the ratio in cases where the maximum bending strength is determined by the fracture of the flange is usually between 1 and 1.2. The mean value for β is about 1.1.

γ_w is the ratio of the web moment (M_w) to $Z_{pw} \cdot \sigma_u$ in the case of the joint connection of beam ends reaching the maximum bending strength. This ratio is called the reduction factor of the web. M_w can be evaluated using Ref. [6].

Based on equation (5), the maximum strength coefficient of α can be given by the following equation.

$$\alpha = \frac{M_{\max}}{M_p} = \frac{Z_{pf} \cdot \beta \cdot \sigma_u + \gamma_w \cdot Z_{pw} \cdot \sigma_u}{M_p} \quad (6)$$

Where $Z_{pf} = A_f \cdot h$

$$Z_{pw} = \frac{1}{4} A_w \cdot h = \frac{1}{4} s \cdot A \cdot h$$

$$M_p = \left(Z_{pf} + Z_{pw}\right) \cdot \sigma_y = \frac{1}{4} A_f \cdot \sigma_u \cdot YR \cdot (4 + s)$$

$YR = \sigma_y / \sigma_u$: Yield ratio

$s = A_w / A_f$

A_f : Area of the flange

A_w : Area of the web

h : Distance between each center of the flange

The following equation can be obtained by substituting the above equations for equation (6).

$$\alpha = \frac{4 \cdot \beta + s \cdot \gamma_w}{4 + s} \cdot \frac{1}{YR} \qquad (7)$$

From this, it is made clear that α is dominated by the following four parameters.

$s,\ \gamma_w,\ YR,\ \beta$

Since the relationship between α and η can be indicated using equation (4), the value of η can be determined for the given value of α.

The effects of $s,\ \gamma_w,\ YR$ and β on α and η are investigated below.

Attention must be paid to the yield ratio. The evaluation of YR based on regulation value of σ_y and σ_u ($YR(1)$ in Table 2) is regarded as an under valuation (on the unsafe side). The evaluation of YR using the upper limit value of 0.8 according to the regulation for structural steel is an overvaluation (on the conservative side). In this study, $YR(2)$ obtained by multiplying $YR(1)$ by the correction factor shown in Table 2 based on the explanation in Ref. [6] is considered to be the standard design value for the yield ratio.

Table 2 Correction of yield ratio

Steel grade	Yield strength (kgf/mm^2)	Tensile strength (kgf/mm^2)	YR(1)	Correction factor	YR(2)
SN400	23.5	40.2	0.585	1.25	0.73
SN490	32.3	49.0	0.66	1.15	0.76

Fig.8 shows the relationship between α and $s,\ \gamma_w,\ YR,\ \beta$ and the relationship between η and $s,\ \gamma_w,\ YR,\ \beta$. It is clear that $s,\ \gamma_w,\ YR$ and β have great effects upon α and η.

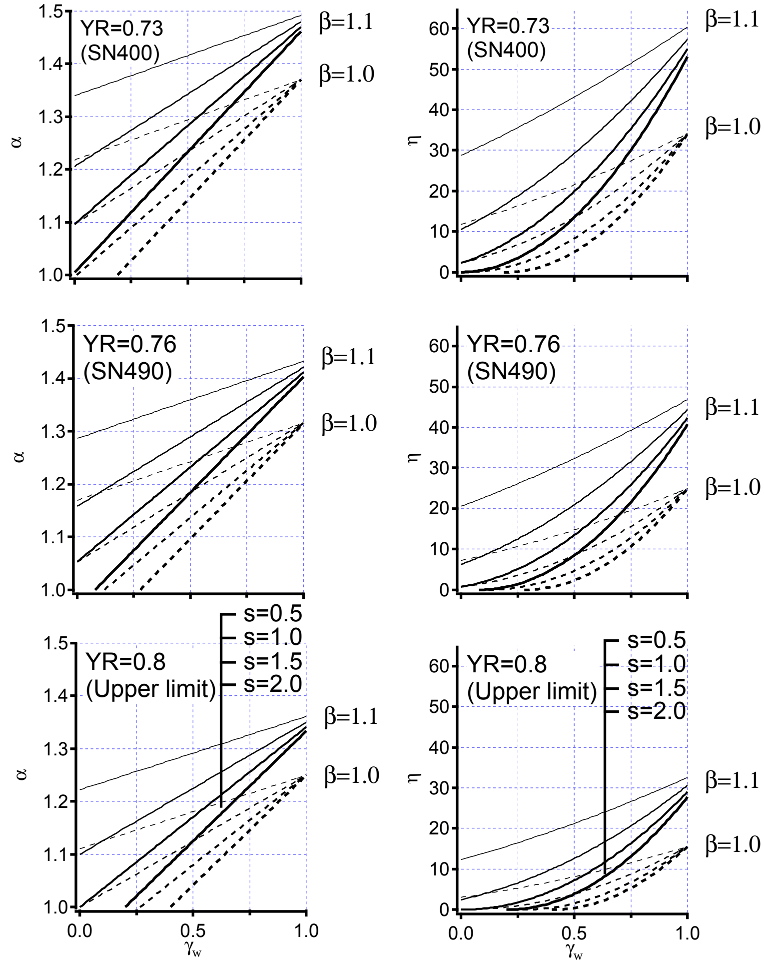

Fig.8 Relationship between α, η and β, s, γ_w, YR

DESIGN OF BEAM END CONNECTIONS

Relationship between η of the Beam and η of the Story

The relationship between η of the beam and η of the story for a frame with weak beams can be obtained from the following equation.

$$\eta_f = \frac{1}{1+k}\eta_b \quad \cdots\cdots (8)$$

$$k = {}_bK / {}_cK$$

Where η_f: η of the frame, η_b: η of the beam

${}_bK$: Rigidity of the beam, ${}_cK$: Rigidity of the column.

η in Fig.8 shows η_b. η_f can be evaluated using η_b and equation (8).

Design Method for the Beam End Connections based on Plastic Energy Absorption Ability

Once the value of η_f required for the frame is provided in a seismic design, η_b is determined using equation (8). α, which can be obtained by substituting this η_b for η in equation (4), is the required ultimate strength. This required ultimate strength of α is set as α_n. At the same time, α, which can be obtained from equation (7) based on the details of the joint connection, is set as α_r. A value in accordance with an actual condition is substituted for YR in equation (7). (For example, YR(2) in Table 2.) The design criteria for beam end connections can be expressed as follows.

$$\alpha_r \geq \alpha_n \tag{9}$$

When the assumed joint connection details do not satisfy equation (9), either (1) or (2) mentioned below is applied.

(1) The details of the connections should be changed to increase α_r.

(2) Required η_f should be lowered by increasing the yield strength of the frame to reduce α_n.

CONCLUSION

A simple estimation equation with regard to the relationship between the strength of the beam end connection and the amount of plastic energy absorption was proposed. Furthermore, a design method for the beam end connection of a frame with weak beams, in which the energy dissipation amount can be limited by the strength of the beam end connection, was studied.

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