Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

CORRELATION BETWEEN PLASTIC DEFORMATION CAPACITY AND HYSTERESIS ENERGY FOR H-SHAPED BEAMS

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ABSTRACT

In general, the seismic capacity of H-shaped beams with local buckling is estimated by two main structural factors. One of them is plastic deformation capacity in the skeleton curve, and the other is the cumulative hysteresis energy in cumulative hysteresis loops. Based on reported test results, their correlation has not been shown even though each one has been individually used as the seismic capacity of beams. In this paper, the approximation of the energy absorption by the Bauschinger effect is suggested, considering the loading history and the expansion of application. The approximation estimates correlate the plastic deformation capacity and the cumulative hysteresis energy.

Introduction

There are some seismic design methods in present Japanese code provision. One of them is the plastic design method and another is the energy method. The seismic characteristics for H-shaped beams with local buckling are also estimated by two main structural properties, which are the plastic deformation capacity and the cumulative deformation capacity. The plastic deformation capacity is defined as the rotation of the beams divided by their yield rotation at the maximum load, and the cumulative deformation capacity is defined as the area of load–deformation curves until the maximum load. The area is then divided by the unit energy, which is the plastic moment multiplied by the yield rotation. The relationship has not been clarified by experimental results, even though each parameter is represented in Japanese design code provision.

It is shown that the load–deformation curves for H-shaped beams were able to approximate the experimental skeleton curves with their width-thickness ratio, slenderness ratio and yield strain in past research (Kato and Akiyama, 1989), but it is not enough to compare between the approximation of the skeleton curves and those from the experimental results under cyclic loads.

In this paper, the experimental results such as the load-deformation curve in cyclic loads are investigated in previous papers, in addition to the above research, and are compared to the proposed curves. From the results, it is shown that some of the experimental results are approximated well, but the others are not. As such, the proposed method is not considered with the cyclic number and the amplitude. Based on the proposed methods, the approximation for load-deformation curves is fixed with cyclic number and amplitude. Following this, it is shown that most of the experimental results are fixed well. The relationship

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between the plastic deformation capacity and the cumulative deformation capacity is also estimated with this approximation.

Summary of Investigation for H-Shaped Beams

Fig. 1 shows the relationship between the width-thickness ratio of flange, b/t_f and web, d/t_w for H-shaped beams in the past experimental tests. There are 28 specimens in 11 papers, and the range of b/t_f is applied from 5 to 11, and that of d/t_w is applied from 20 to 70. The lines indicate the upper limit of width-to-thickness ratio for flange and web of H-shaped beams by Design Code for Steel Structure (AIJ, 2005) in Japan. These lines show the limitation for SS400, which of the flange and the web are 16 and 70, respectively.

Fig. 2(a) through (d) show the examples of the displacement history for loading protocol in past experiments carried out on H-shaped beams as the cantilever. δ/δ_p or δ/δ_y is the ratio of the displacement divided by the full plastic displacement or the yield displacement at the loading point.

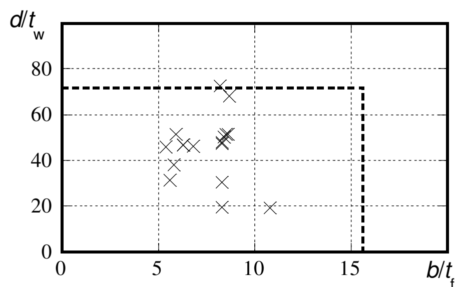

Figure 1. Width-to-thickness ratio.

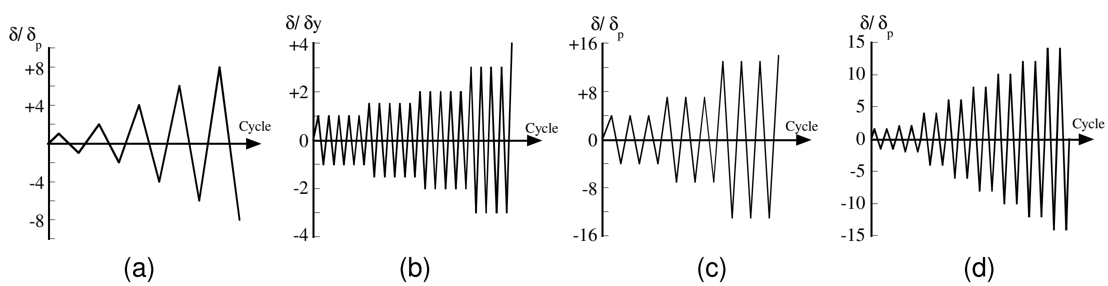

Figure 2. Examples of loading pattern.

Definition of Plastic Deformation Capacity and Cumulative Deformation Capacity

Plastic deformation capacity is defined as the rotation at maximum load, θ_{max} divided by the plastic rotation, θ_p when members have the plastic moment, and cumulative deformation capacity is defined as the non-dimensional area of the load–deformation curves until the maximum load.

Fig. 3 shows the example for the hysteresis loops under cyclic load with Fig. 2(d) in the past experiment. It can be divided into skeleton parts, Bauschinger parts and unloading parts. The skeleton part is defined as where it reaches specific stress for the first time.

Fig. 4 shows the skeleton curves divided from the hysteresis loops on Fig. 3. In this diagram, two parameters are defined. One of them is the plastic capacity, ${}_{I}\mu_{max}$ at the point of the maximum load and the other is the cumulative deformation capacity, ${}_{I}\eta_{max}$ for skeleton curve until the maximum load. The three lines are calculated from the proposed approximation (Kato and Akiyama, 1989), and it consists of three lines with the elastic region, the strain hardening region and the region of the degradation. The approximation and the experimental result are almost same.

Fig. 5 shows the cumulative deformation curves divided from the hysteresis loops on Fig. 3. The area for the cumulative hysterisis loops is placed to $\alpha_B{}^*{}_I\eta$. The parameter, α_B is the ratio of the total area for the load-deformation curves of H-shaped beams under cyclic load to the area for that of the skeleton.

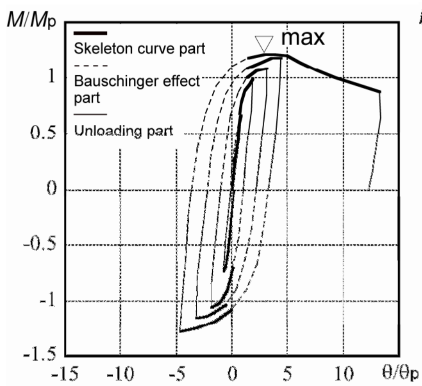

Figure 3. .Load-displacement curve.

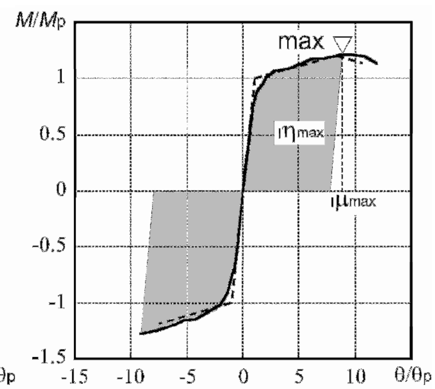

Figure 4. Skeleton curve.

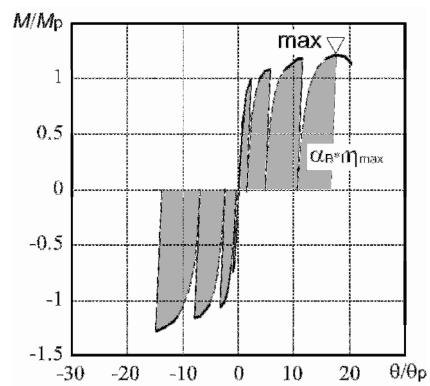

Figure 5. Cumulative hysteresis loops.

Relationship between Plastic Deformation Capacity and Hysteresis Energy

Empirical equations for the skeleton curves were approximated in the reference (Kato and Akiyama, 1989), so that the values of plastic deformation capacity ${}_I\mu_{max}$. , ${}_I\mu_{0.95}$ and hysteresis energy ${}_I\eta_{max}$,${}_I\eta_{0.95}$ in skeleton curve are calculated as followings:

$$ {}_I\mu_{\max} = 1 + \frac{(\tau_m - 1)}{0.03} \tag{1}$$

$$ {}_I\mu_{0.95} = {}_I\mu_{\max} + \frac{0.05\tau_m}{\kappa_d} \tag{2}$$

$$ {}_I\eta_{\max} = \frac{1-\tau_m^2}{2} + \frac{(\tau_m + 1)({}_I\mu - 1)}{2} \tag{3}$$

$$ {}_I\eta_{0.95} = {}_I\eta_{\max} + \left(0.04875 + \frac{0.475}{\kappa_d}\right)\tau_m^2 \tag{4}$$

Here, the subscript 0.95 means the point of the load reduced until 95% of the maximum load beyond the peak, so that and ${}_I\mu_{0.95}$ and ${}_I\eta_{0.95}$ are the plastic deformation capacity at 95% of the maximum load and the cumulative deformation capacity until 95% of the maximum load beyond the peak, respectively.
τ_m is the stress ratio. It is calculated from the followings. It is selected from the larger value between those of Eqs. (5) and (6), and its lower limitation is 1.0. Based on the equation in the reference, a new parameter in Eq. (5) is add and improved.

$$ \tau_m = 1.46 - \sqrt{\frac{\lambda_y}{70}}\,\{0.63\frac{b}{t_f} + 0.053\frac{d}{t_w} + 0.02\left(\lambda_y - 50\right)\}\sqrt{\varepsilon_y} \tag{5}$$

$$ \tau_0 = 1 + \left\{\left(0.0403 - 0.0744\frac{b}{t_f}\sqrt{\varepsilon_y}\right)^2 - \left(0.00024\frac{d}{t_w}\sqrt{\varepsilon_y} - 0.00025\right)\right\}\frac{1}{\varepsilon_y} \tag{6}$$

κ_d is the slope after maximum load, and is selected from the smaller value between the vales of Eqs. (7) and (8).

$$\kappa_d = -0.355\left(\frac{d}{t_w}\right)\varepsilon_y \tag{7}$$

$$\kappa_d = -\left\{-1.33 + \left(10.6\frac{b}{t_f}\sqrt{\varepsilon_y} - 2\right)\left(0.63 + 0.33\frac{d}{t_w}\sqrt{\varepsilon_y}\right)\right\}\sqrt{\varepsilon_y} \tag{8}$$

where b/t_f : width-to-thickness ratio of flange, d/t_w : width-to-thickness ratio of web, λ_y : slenderness ratio

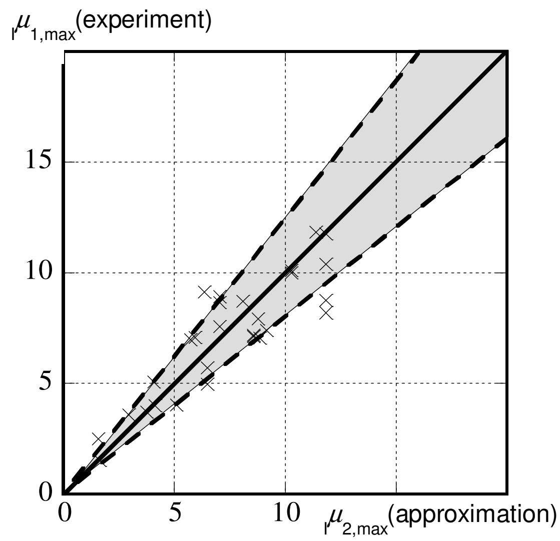

Figure 6. Plastic deformation capacity–plastic deformation capacity of experimental result and approximation at maximum load.

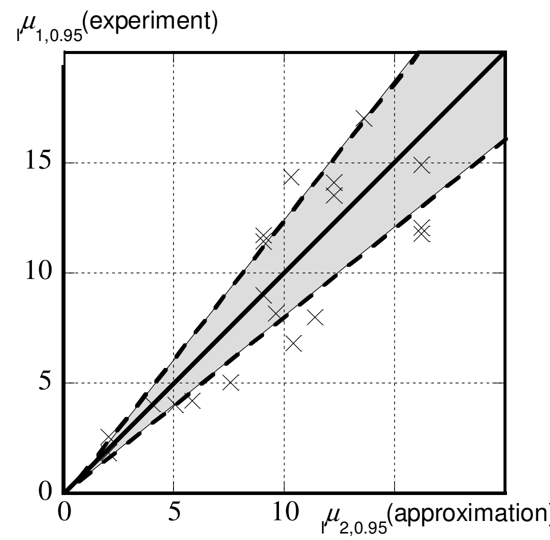

Figure 7. Plastic deformation capacity–plastic deformation capacity of experimental result and approximation at 95% of maximum load.

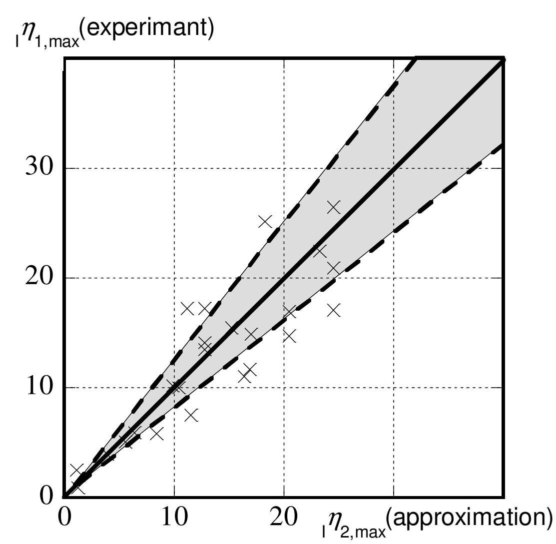

Figure 8. Cumulative hesteresis energy – cumulative hesteresis energy of experimental result and approximation until maximum load

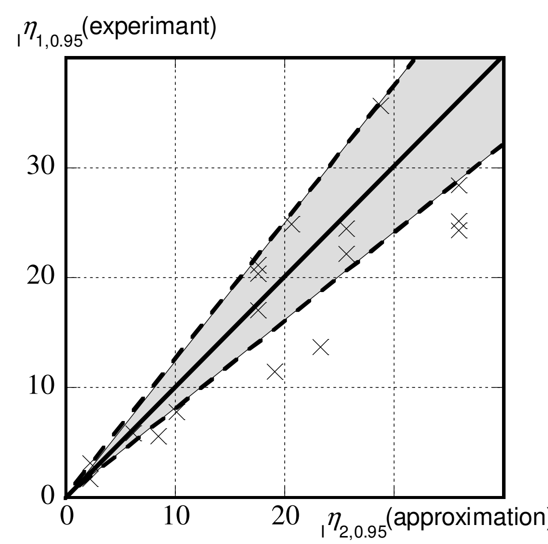

Figure 9. Cumulative hysteresis energy – cumulative hysteresis energy of experimental result and approximation until 95% of maximum load.

for week axis, ε_y : yield strain, A : sectional area, A_w : sectional area of web. ε_y is obtained from the experimental results.

Comparison of Experimental Results and Value of Approximation

Figs. 6 and 7 show plastic deformation capacities ${}_{l}\mu_{1,max}$, ${}_{l}\mu_{2,max}$ or ${}_{l}\mu_{1,0.95}$, ${}_{l}\mu_{2,0.95}$ of H-shaped beams with the local buckling. ${}_{l}\mu_{,max}$ and ${}_{l}\mu_{1,0.95}$ are plastic deformation capacities on experimental results. ${}_{l}\mu_{2,max}$ and ${}_{l}\mu_{2,0.95}$ are plastic deformation capacity on Eq. (1). In Figs. 6 and 7, and the solid lines are the lines for ${}_{l}\mu_{1,max}$=${}_{l}\mu_{2,max}$ and ${}_{l}\mu_{1,0.95}$=${}_{l}\mu_{2,0.95}$, and the broken lines show the allowable 20-percent margin of error. The plots in this diagram are the experimental results from references. A number of samples is 28 and a correlation coefficient is 0.88 in Figure 6 and 0.84 in Figure 7, respectively.

Figs. 8 and 9 show cumulative hysteresis energies ${}_{l}\eta_{1,max}$, ${}_{l}\eta_{2,max}$ or ${}_{l}\eta_{1,0.95}$, ${}_{l}\eta_{2,0.95}$ of H-shaped beams with the local buckling. ${}_{l}\eta_{1max}$ and ${}_{l}\eta_{1,0.95}$ are cumulative hysteresis energies on experimental results. ${}_{l}\eta_{2,max}$ and ${}_{l}\eta_{2,0.95}$ are cumulative hysteresis energies on Eq. (2). In Figs. 8 and 9, the solid lines are the line for ${}_{l}\eta_{1,max}$=${}_{l}\eta_{2,max}$ or ${}_{l}\eta_{1,0.95}$=${}_{l}\eta_{2,0.95}$, and the broken lines show the allowable 20-percent margin of error. A correlation coefficient is 0.87 in Figure 8 and 0.87 in Fig. 9, respectively.

Also the relationships between plastic deformation capacity and cumulative hysteresis energy are about ${}_{l}\eta_{2,max}$=1.9 ${}_{l}\mu_{2,max}$ and ${}_{l}\eta_{2,0.95}$=1.9 ${}_{l}\mu_{2,0.95}$, respectively.

Figs. 10 and 11 show the relationship between the energy absorption α_B by Bauschinger effect and the loading history and the expansion of application, which is the energy until maximum load and until 95% of maximum load, respectively. N is the number of peak load point on load-deformation curves. In Figs. 10 and 11, the broken line shows the approximation by experiment. The approximation is as the following:

$$\alpha_B = 1 + 0.4N \log(\textstyle\sum_{i=1}^{N} \mu_{xi})^{0.5} \qquad (9)$$

However, experimental results of H-shaped beams with elastic local buckling are not included ($\mu_{xi}<1$). Where i is the cycle number of loading when the beam collapsed. μ_{xi} is the amplitude at i number when the load-deformation curve. Then the correlation coefficient until the maximum load is 0.95, and that until 95% of the maximum load is 0.74. $\alpha_{B,max}$ depends on the cyclic number until maximum load and the amplitude of each cyclic hysteresis loop, and Eq. (9) and the experimental results are very fitting as would be expected.

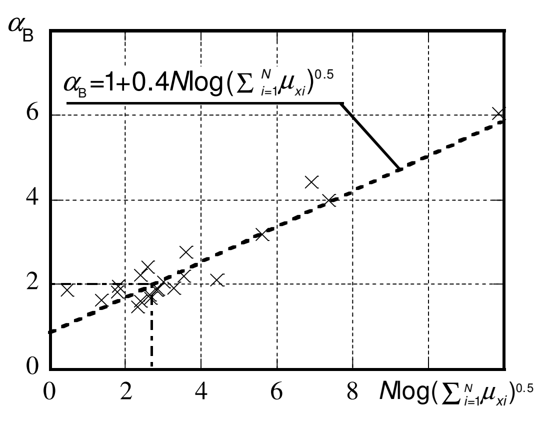

Figure 10. Relationship between cyclic number, amplitude and Bauschinger effect until maximum load.

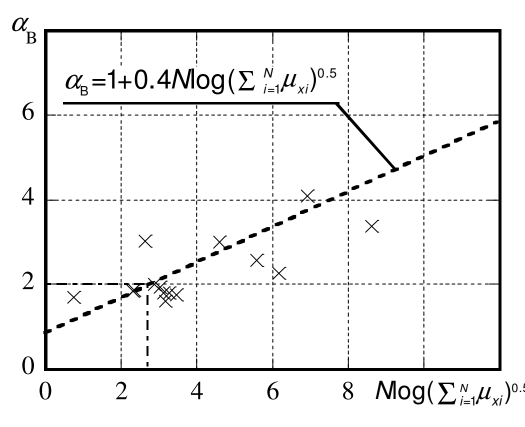

Figure 11. Relationship between cyclic number, amplitude and Bauschinger effect until 95% of maximum load.

Conclusions

In this paper, the plastic deformation capacity and the cumulative deformation capacity for H-shaped beams with local buckling are estimated and the relationship between them is investigated. From the results, the following conclusions are obtained.

1) In the case for H-shaped beams with local buckling, the skeleton curves until the maximum load or the load is reduced until 95% of the maximum load can be approximated by the improved equations, which was based on the proposed equations (Kato and Akiyama 1989).

2) The relationship between the plastic deformation capacity and the cumulative deformation capacity are estimated with Bauschinger effects $\alpha_{B,max}$ and $\alpha_{B,0.95}$. It is shown that the approximation of the energy absorption depends on the cyclic number until the maximum load or the load is reduced until 95% of the maximum load and the amplitude of each cyclic hysteresis loop.

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