13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3426

EVALUATION OF DEFORMATION CAPACITY OF H-SECTION BEAM CONSIDERING MATERIAL PROPERTY

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SUMMARY

Recently, not only mild steel but also high performance steel are used as structural materials. Generally, the material properties are specified in terms of yield stress and/or ultimate strength. However, the characteristics of the material are not defined by only these properties. Thus, the characteristics of various materials aren't reflected in present building codes, particularly on deformation capacity classification.

The purpose of this study is to make clear the influence of the material property on the deformation capacity of the H-section beam. In this study, FEM analyses are conducted to consider above issue.

INTRODUCTION

In well-designed steel frame structures, inelastic deformation under severe seismic loading is confirmed in beam plastic hinges located near the beam-to-column connections. Thus, deformation capacity of the plastic hinge and resilience of the connections are essential for good plastic behavior and expected energy dissipation in steel frame structures. This essential plastic behaviour at the hinge is strongly influenced by the difference of material properties. Generally, the material properties are specified in terms of yield stress and/or ultimate strength. However, the characteristics of the materials are not defined by only these properties. Thus, the characteristics of various materials aren't reflected in present building codes, particularly on deformation capacity classification.

In 1977, Suzuki and Ono [1] have established deformation capacity equations considering yield stress and gradient of moment. In 1980, Mitani and Makino [2] proposed deformation capacity formula for beam columns considering yield stress and distance between plastic hinges. In 1992, Spangemacher and Sedlacek [3] [4] have led an empirical deformation equation considering moment gradient, flange and web slenderness and yield ratio. In 1998 and 2000, White and Barth [5], and Barth [6] have developed a model for moment-plastic rotation which gives maximum moment and decreasing start of plastic deformation. However, these equations proposed or developed in previous study are only considering yield stress and/or ultimate strength. The plastic behaviour of beam is the behaviour of the strain-hardening of its material.

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Therefore, it is important to consider the strain-hardening properties when we consider the plastic behaviour of the structure.

The purpose of this study is to make clear the influence of the material property on the deformation capacity of the H-section beam. In this paper, firstly, a new material index considering the full stress-strain curve is proposed, and the validity of this new index is shown. Secondly, finite element analyses are conducted to the cantilever beams, and the influence of material properties to the deformation capacity are investigated. Finally, an equation, which can calculate the deformation capacity of H-section beam in various kind of material, is proposed.

MATERIAL PROPERTIES

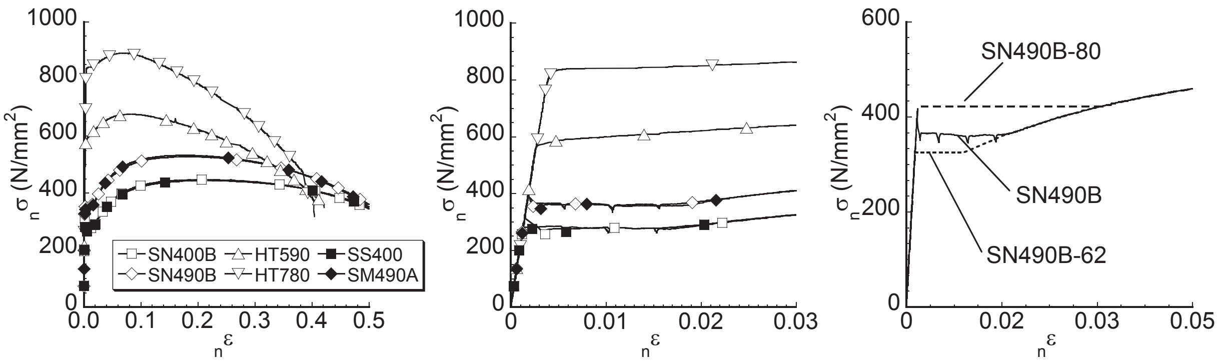
In this study, 8 types of structural steel, commonly used in the real practice, are applied in the analysis. The stress-strain relationships of the materials are shown in Figure 1, and the characteristics of the materials are listed in Table 1. Full-curves of stress strain relationships are shown in figure 1(a). Enlargement of figure 1(a) in vicinity of yield points are shown in figure 1(b). SN490B-62 and SN490B-80 listed in table 1 are the materials which are obtained from changing its yield stress of SN490B. The difference of SN490B, SN490B-62 and SN490B-80 are shown in figure 1(c).

Semi complementary energy ratio (S.C.E./${}_n\sigma_y$) listed in Table 1 is the new index which indicates the capability to absorb energy in its material, where it is defined in Figure 2. This is the important index used in this study.

Table 1. Material Properties

Materilal	E (N/mm^2)	${}_n\sigma_y$ (N/mm^2)	${}_n\sigma_u$ (N/mm^2)	${}_n\varepsilon_u$ (%)	Y.R.	S.C.E./${}_n\sigma_y$
SS400	2.12E+05	281	443	20.6	0.63	3.20E-02
SM490A	2.09E+05	361	532	18.4	0.68	2.50E-02
SN400B	2.13E+05	275	446	21.3	0.62	3.31E-02
SN490B	2.14E+05	366	527	18.1	0.70	2.09E-02
HT590	2.17E+05	585	676	7.89	0.87	1.64E-03
HT780	2.10E+05	838	890	7.09	0.94	5.93E-04
SN490B-62	2.14E+05	325	527	18.1	0.62	2.50E-02
SN490B-80	2.14E+05	422	527	18.1	0.80	1.52E-02

E: Young's Modulus, ${}_n\sigma_y$: Yield Stress, ${}_n\sigma_u$: Ultimate Strength, ${}_n\varepsilon_u$: Ultimate Strain
Y.R.: Yield Ratio, S.C.E./${}_n\sigma_y$: Semi Complementary Energy Ratio



(a) Full curves **(b) vicinity of yield point** **(c) SN490B,-62,-80**

Figure 1. Stress-Strain curves

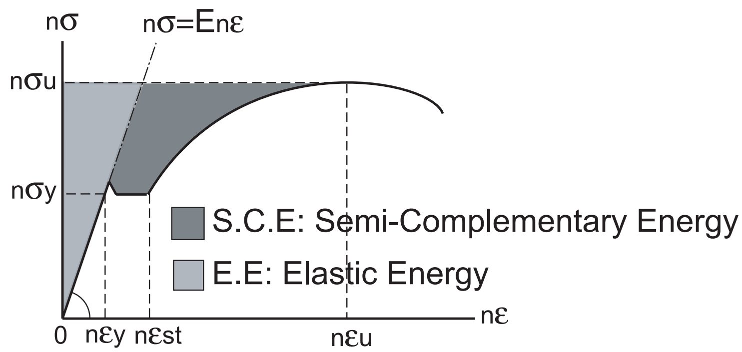


Figure 2. Definition of Semi-Complementary Energy Ratio

PLATE ELEMENT ANALYSIS

Plate element analyses are conducted to evaluate the effect of the material index, *Semi complementary energy ratio*, defined in the previous chapter. Analysis model is shown in figure 3. This plate is the model of the beam flange segment where the compressive stresses are acting. The model has one free edge and three hinge-supported edge. And the uniformly distributed forces are applied in one direction. Shell elements were used to represent the plate. The dimensions of the plate are shown in the figure. The parameters for the analysis were set by the difference of material properties. In this analysis, two types of width-to-thickness ratio (b/t), b/t=6.0 and 8.3, were selected. To analyze the plate element behaviors, FEM program, MARC2000, was used.

The correlations between deformation capacity (δmax) and *yield ratio* (Y.R.) are shown in figure 4(a). And in figure 4(b), the correlations between *Semi complementary energy ratio* (S.C.E./${}_n\sigma_y$) are also shown. Deformation capacity (δmax) shown in figure 4(a) and (b) are the values when the applied load reached its maximum (Pmax). As shown in figure 4(a) and (b), *yield ratio* and *semi complementary energy ratio* have a good correlation between deformation capacity. Moreover, *semi complementary energy ratio* has a more good correlation between deformation capacity than yield ratio. Therefore, it is possible to say that the semi complementary energy ratio (S.C.E./${}_n\sigma_y$) is an useful index to evaluate the deformation capacity.

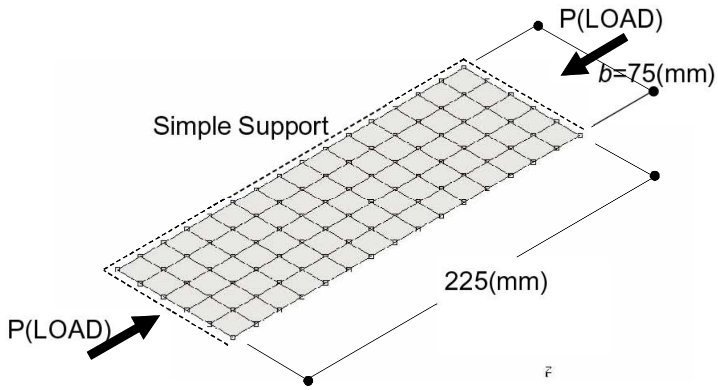
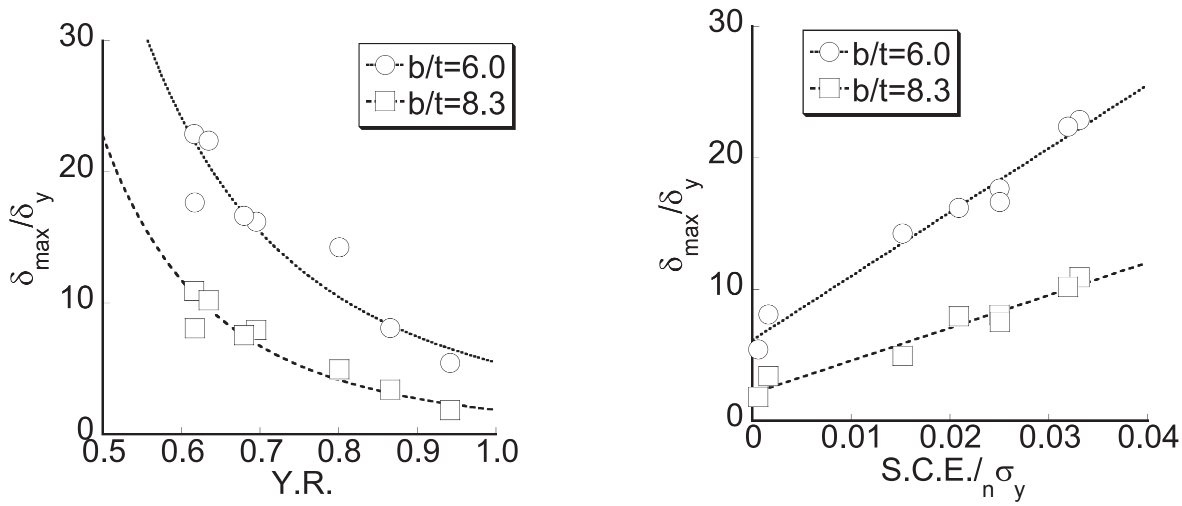


Figure 3. Plate Element Model



(a) Y.R. **(b) S.C.E./$_n\sigma_y$**

Figure 4. Correlation between deformation capacity and material properties

DEFROMATION CAPACITY OF H-SECTION BEAM

Description of the finite element model

Nonlinear finite element analyses were used to investigate the influence of the material property and the difference of the shape of H-section beam on the deformation capacity of the H-section beams. Beam finite element model is shown in Figure 5. Similarly to chapter 3, MARC2000 was used to create three-dimensional finite element models of beam subassemblies. The materials were modeled using an isotropic hardening rule with the Von Mises yield criterion. The material nonlinearities were combined with geometric nonlinearities, using a finite strain formulation in order to capture the effects of local buckling and subsequent strength degradation. The initial imperfections in the members were included in the compression side flange and were based on a proportion of the amplitude of the first elastic buckling mode of the model [Ono & Yoshida, 1998][7]. It is assumed that the flange is restrained against buckling by a torsional spring that represents the effect of web. Therefore, in-plate buckling is considered in this analysis.

The parameters for the analysis were the difference of material property and width-to-thickness ratio of the flange (b/t_{bf}). In this study, the thickness of flange, t_{bf}=9, 12, 15(mm), were selected for the parameter. The other dimensions of the beam are shown in figure 5, and take the constant value. Beam height, D, is 350(mm), beam width, B, is 150 (mm), web thickness, t_{bw}, is 9.0 (mm) and beam length, L, is 2060(mm), respectively. Beam depth, d, is calculated from ($D-2*t_{bf}$).

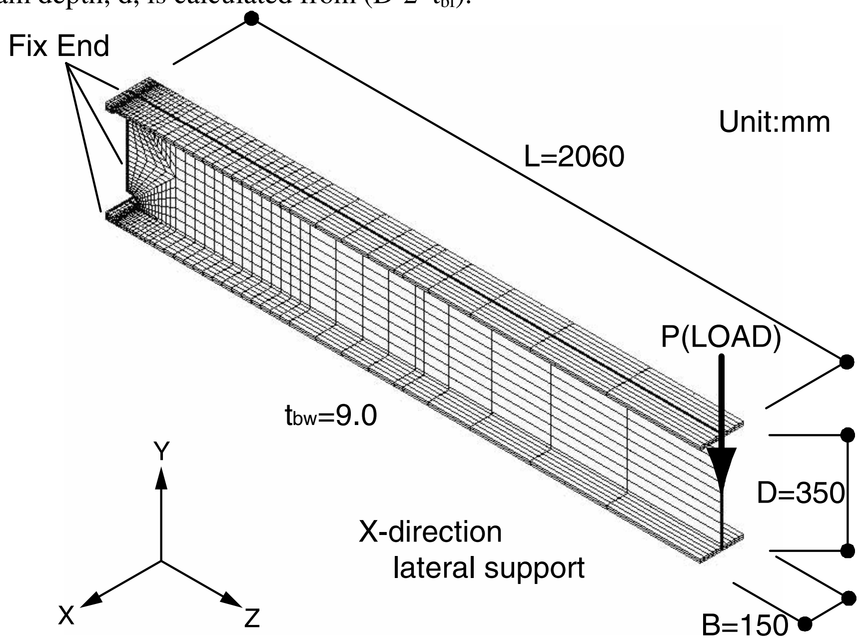


Figure 5. Finite element beam model

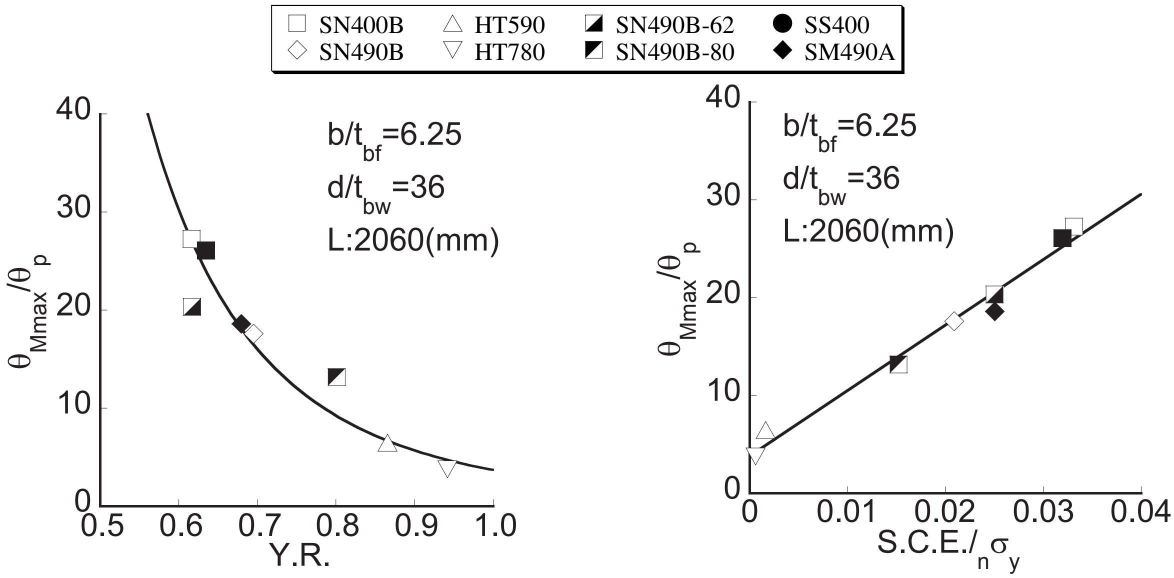
Influence of Material Property

Deformation capacity of the H-section beam defined by the degradation of strength is strongly influenced by the difference of material property, as shown in figure 6. In figure 6, the correlation between deformation capacity (θ_{Mmax}/θ_p) and material properties are illustrated. Available deformation capacity of the beam is defined as the deformation when the strength of the beam reaches its maximum strength (Mmax). In figure 6(a), the correlations between deformation capacity (θ_{Mmax}/θ_p) and *yield ratio* (Y.R.) are shown. And in figure 6(b), the correlations between *Semi complementary energy ratio* (S.C.E./$_n\sigma_y$) are also shown. As shown in figure 6(a) and (b), *yield ratio* and *semi complementary energy ratio* has a good correlation between deformation capacity (θ_{Mmax}/θ_p). Moreover, semi complementary energy ratio has a more good correlation between deformation capacity than yield ratio. Therefore, it is possible to say that the semi complementary energy ratio (S.C.E./$_n\sigma_y$) is an useful index to evaluate the deformation capacity of H-section beam.

The correlation between deformation capacity (θ_{Mmax}/θ_p) and material property, studied in this paper, are all illustrated in figure 7. As shown in the figure, not only in one width-to-thickness ratio but also in other width-to-thickness ratio, we can have good correlations. The regression lines drawn by using the method of least squares, solid and dotted lines in the figure, can be expressed by the following equation.

$$\left(\frac{\theta_{M\max}}{\theta_p}\right) = a \cdot \left(\frac{S.C.E.}{{}_n\sigma_y}\right)^b + c \qquad (1)$$

where *a,b,c* are shape factors. The shape factors are shown in Table 2.



(a) Y.R. **(b) S.C.E./$_n\sigma_y$**

Figure 6. Correlation between deformation capacity and material properties

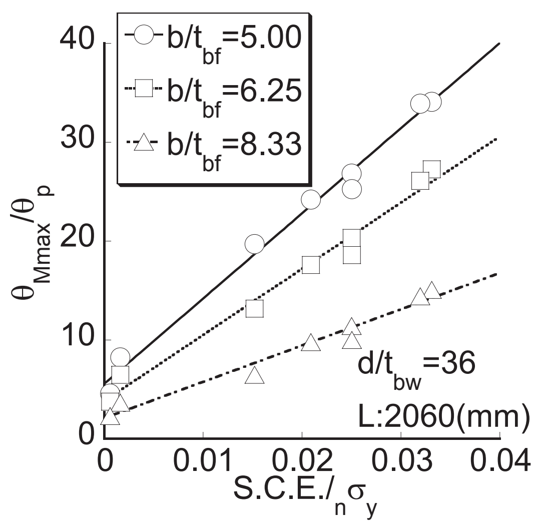


Figure 7. Deformation capacity vs. semi complementary energy ratio

Table2. Shape factor a, b, c

b/t_{bf}	a	b	c
5.00	862	1.00	5.58
6.25	669	1.00	3.82
8.33	367	1.00	2.10

b=B/2, B: beam flange width, t_{bf}: thickness of flange

Evaluation of deformation capacity

The correlations between shape factors and width-to-thickness ratio are shown in figure 8(a) and (b). As shown in these figures, shape factor shows a good correlation between width-to-thickness ratio, and takes a smaller value when the width-to-thickness ratio takes a larger value. The solid line shown in figure 8(a) and (b) are the regression lines drawn by using the method of least squares. The regression lines are expressed by the following equations.

$$a = 2.31\times10^4 \cdot \left(\frac{t_{bf}}{b}\right)^2 \tag{2}$$

$$c = 1.26\times10^2 \cdot \left(\frac{t_{bf}}{b}\right)^2 \tag{3}$$

Substituting Eq. (2), (3) and b=1.00 into Eq. (1), we obtain

$$\left(\frac{\theta_{M\,\max}}{\theta_p}\right) = \left(\frac{\Omega_B}{b/t_{bf}}\right)^2 \tag{4}$$

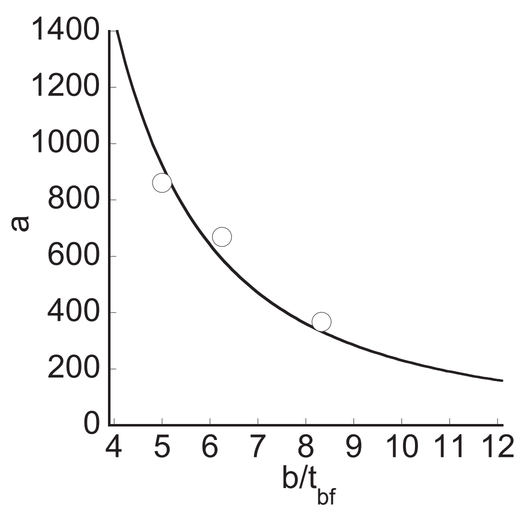
where

$$\Omega_B = \sqrt{2.31\times10^4 \cdot \left(\frac{S.C.E.}{{}_n\sigma_y}\right) + 126} \tag{5}$$

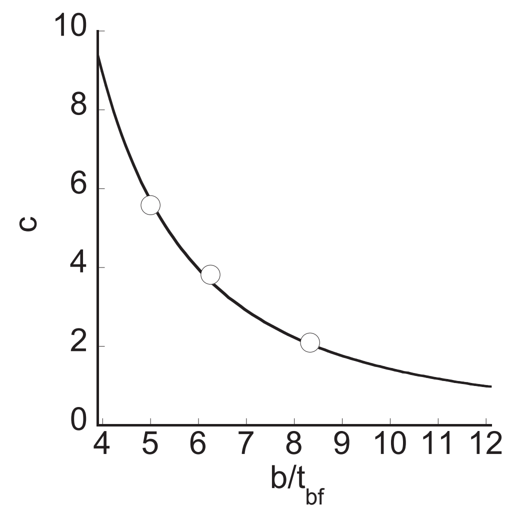
$\frac{b/t_{bf}}{\Omega_B}$: normalized width-to-thickness ratio

Equation (4) is the formula proposed to evaluate the deformation capacity of H-section beam. This proposed formula is considering the material property and the shape of the H-section beam.

The comparison between deformation capacity of beam and normalized width-to-thickness ratio are shown in Figure 9. As shown in the figure, deformation capacity and normalized width-to-thickness ratio shows a good correlation. Therefore, it is possible to say that the equation, considering material property, proposed in this paper can evaluate the deformation capacity of the H-section beam in a high accuracy.



(a) Shape factor a



(b) Shape factor c

Figure 8. Shape factors a and c vs. width-to-thickness ratio

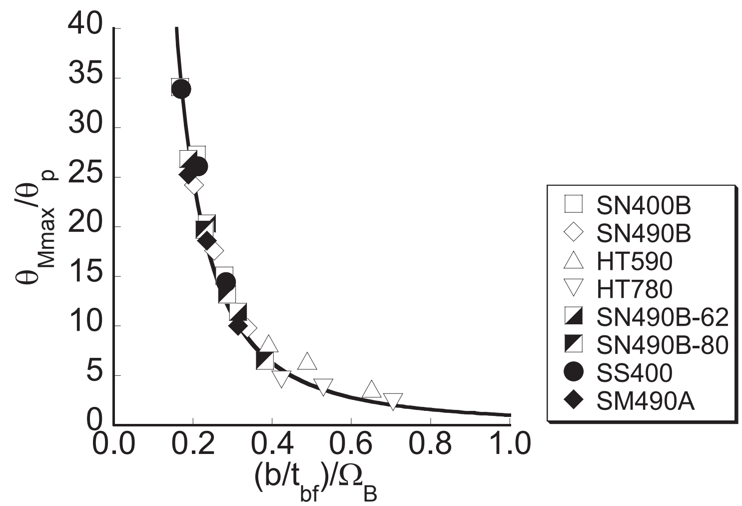


Figure 9. Comparison between deformation capacity and normalized width-to-thickness ratio

CONCLUSION

The deformation capacity of the H-section beam, which is defined by the degradation of strength, are investigated by using detailed finite element analysis. From this investigation, it is found that:

1. Semi-Complementary Energy ratio (S.C.E./${}_n\sigma_y$) is an useful material index to evaluate the deformation capacity of H-section beam defined by the degradation of strength.
2. The Equation, which can evaluate the deformation capacity of the H-section beam, was proposed. This equation is not only considering the shape of the beam but also considering material property.

The result obtained from this study will be the source of building code, based on performance design, and it will be useful and understandable for the structural designer.

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