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# Elastic-Plastic Behaviour and Design of Beam-to-Column Connections Reinforced by Increased Thickness of Columns

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## 1 Introduction

In recent years, it has become general practice to use rectangular hollow section columns (hereinafter referred to as "RHS") in low-and medium-rise buildings.

Two types of beam-to-column (RHS) connections are available, the exterior-diaphragm type and the through diaphragm type (**Fig. 1**-(a)). However, the exterior diaphragm type is seldom adopted for design reasons and the through diaphram type that is most frequently used poses problems, such as requiring too many man-hours for fabrication and assembly and an excessive amount of welding.

Reinforcement of the connection by increasing the plate thickness without using a diaphragm (hereinafter referred to as "increased thickness type," Fig. 1(b)) provides an excellent method for reinforcement because it reduces the man-hours required for fabrication and assembly, makes the execution of work easier, etc. and permits substantial rationalization of the fabrication and assembly of steel structures.

Because this type, however, resists external force by the strength in out-of-plane bending of the plate, a decline in strength and stiffness is expected compared with the horizontal diaphragm type. In using this increased thickness type in design, therefore, it is necessary to accurately evaluate the strength and stiffness of beam-to-column connections.

This report describes the results of these examination.

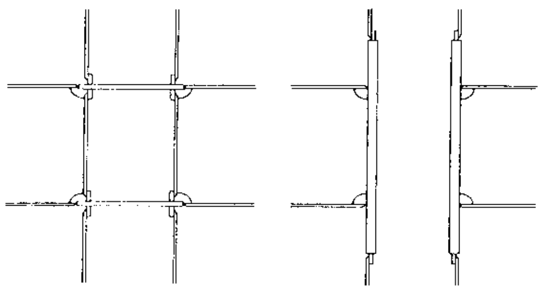



Fig. 1 Connection types

## 2 Beam-to-Column Sub-Assemblage Tests

### 2.1 Test Program

Test specimens have the shape and size shown in **Fig. 2**, being cruciform specimens of a sub-assemblage in

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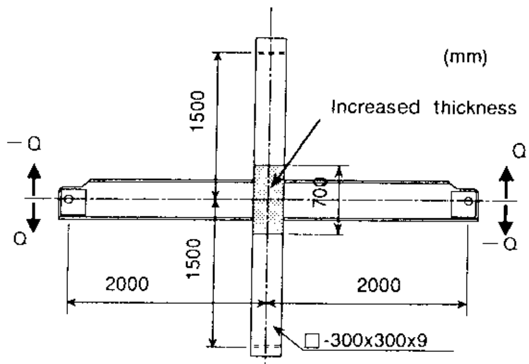


Fig. 2 Test specimens

Table 1 Parameter of sub assemblage tests (mm)

| Specimens | Beam | Part of increased thickness |
|---|---|---|
| No. 1 | BH-400×200×6×12 | □-300×300×19 |
| No. 2 | BH-400×250×6×12 | □-300×300×19 |
| No. 3 | BH-400×200×6×12 | □-300×300×32 |

Table 2 Mechanical properties of materials

| Plate thickness (mm) | Yield point (MPa) | Tensile strengrh (MPa) | Elongation (%) |
|---|---|---|---|
| t6 | 285 | 446 | 25.4 |
| t12 | 290 | 456 | 31.2 |
| t19 | 283 | 446 | 31.7 |
| t32 | 271 | 454 | 34.8 |
| t9 | 429 | 516 | 32.6 |

which H-beams are connected with RHS. The test parameters are beam width and the thickness of the increased part, as shown in **Table 1**. The mechanical properties of the materials are shown in **Table 2**. The top and bottom ends of the column were supported with pins, and loads were applied to the right and left beam ends using antisymmetric increasing amplitudes.

Table 3 Results of sub-assemblage test and analysis (kN)

| | Experimental strength | | | | Analytical | |
|---|---|---|---|---|---|---|
| | $P_y$ | $P_u$ | $P_{py}$ | $P_{ny}$ | $_jP_{ny}$ | $P_{ny}/_jP_{ny}$ |
| No. 1 | 106 | 158 | 107 | 109 | 110 | 0.97 |
| No. 2 | 129 | 186 | 129 | 126 | 132 | 0.96 |
| No. 3 | 176 | 218 | — | — | 140 | — |

## 2.2 Test Results

Relations between load and overall deformation (vertical displacement of beam end) are shown in **Fig. 3**. All the hysteretic curves show a stable fusiform stability characteristic, and it is apparent that this connection has sufficient energy absorbing capacity.

**Table 3** shows the results of the test as yield strength $p_y$, maximum strength $p_u$, yield strength of panel $p_{py}$, and local yield strength of column flange $p_{ny}$, as well as the calculated value of the local yield strength $_jp_{ny}$ found by yield line theory by supposing a collapse mode[1] composed of the yield lines shown in **Fig. 4**. The experimental value of each yield strength was determined from a synthetic curve of the monotonous loading type based on the cumulative rule of thumb[2] by the General Yield Point method.

The calculated values of local yield strength based on

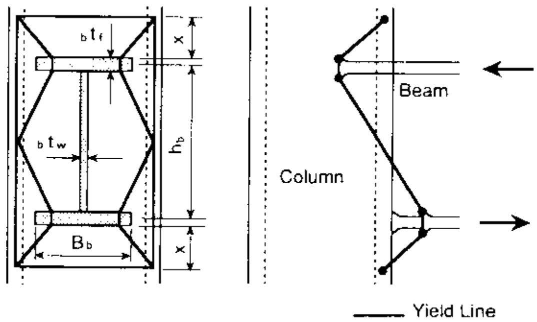


Fig. 4 Yield mechanism

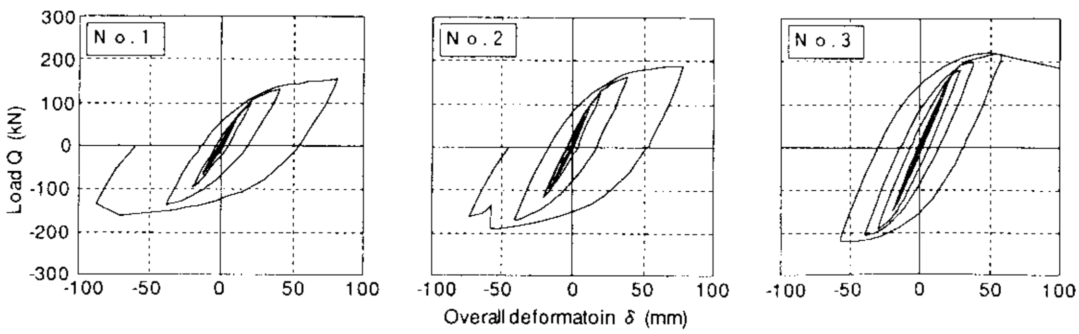


Fig. 3 Relations between load and overall deformation

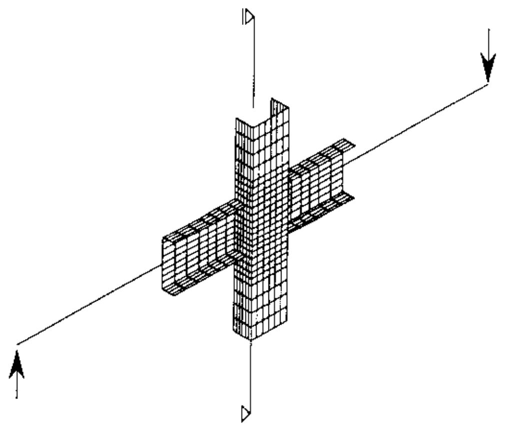

Fig. 5 Model for FEM

Table 4 Parameters of FEM analysis (mm)

| | |
|---|---|
| Increased thickness type | |
| Width of beam | 150, 200, 250, 300 |
| Thickness of increased plate | 12, 16, 19, 22, 25, 28, 32 |
| Extra length of increased plate, $h_s$ | 50, 100, 150, 200, 300 |
| Through diaphragm type | |
| Width of beam | 150, 200, 250, 300 |
| Thickness of increased plate | 9 |
| Thickness of diaphragm | 16 |

the yield line theory agree well with the experimental values obtained when the column flange undergoes out-of-plane local yield, and the ratio of the two shows good correspondence. Therefore, it is apparent that the local yield strength based on the yield line theory can be predicted with good accuracy.

## 3 Elastic-Plastic Analysis by FEM

### 3.1 Outline of Analysis

As shown in **Fig. 5**, the analysis model was obtained by modeling the sub-assemblage frame. A 1/2 model was adopted in consideration of the symmetry of shape and load conditions. As shown in **Table 4**, the overhang length $h_s$ from the flange face of the beam in the part reinforced by an increased thickness (hereinafter referred to as "the extra length") shown in **Fig. 6** was selected as another analytical parameter in addition to the width of the beam and the plate thickness of the part of increased thickness.

### 3.2 Analysis Results

The relations between load and overall deformation are shown in **Fig.7** in comparison with the test results. The analytical values are in good agreement with the test results, although the experimental values in specimens No.1 and No.2 are slightly higher than the loads of

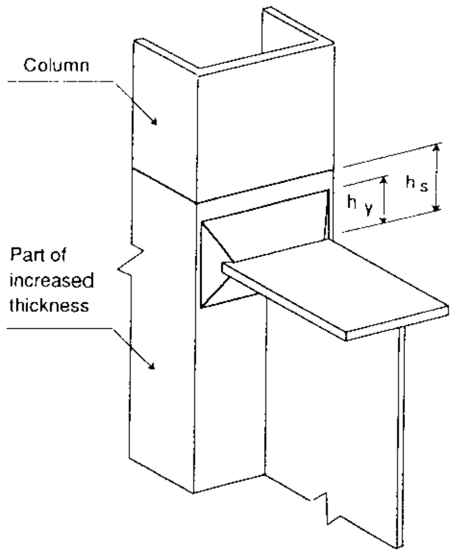


Fig. 6 Extra length $h_s$

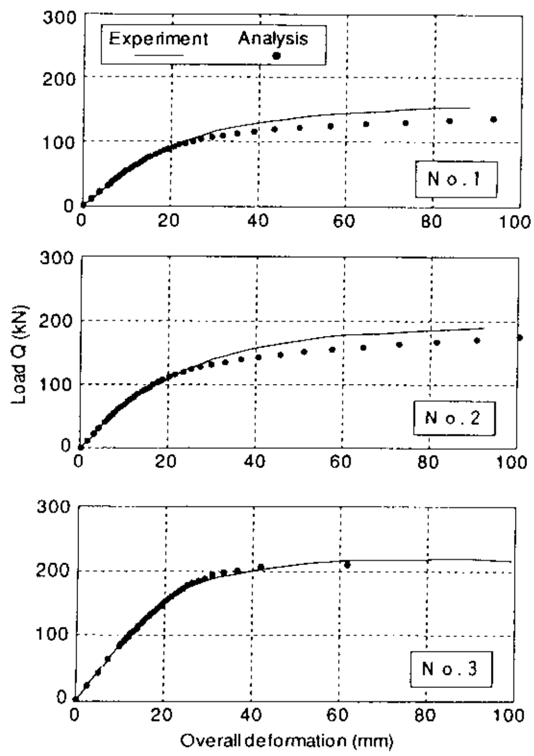


Fig. 7 Load vs. overall deformation curves

analytical value in the large deformation region. When the error that may occur in converting the hysteretic curve in the experiment into a synthetic curve is considered, it is judged that in all the three specimens an analysis can be made up to yield strength with very high accuracy as a whole. Therefore, it is possible to predict the actual behavior of the beam-to-column connections in the elastic region with high accuracy by FEM analy-

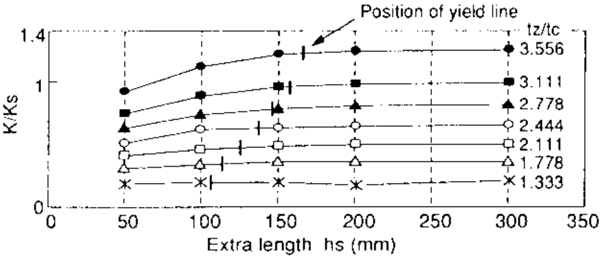


Fig. 8 Relation between stiffness of connection and extra length ($t_c$, thickness of column; $t_z$, thickness of increased part)

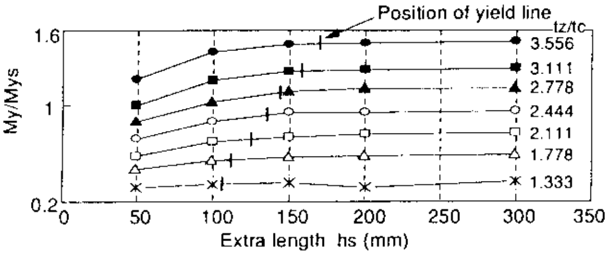


Fig. 9 Relation between strength of connection and extra length

sis, and an reasonable approximation can also be obtained in the plastic region.

**Figure 8** shows the relationship between the extra length and the rotational stiffness of the beam end. In the figure, the ordinate is the rotational stiffness $K$ made dimensionless by being divided by the rotational stiffness of diaphragm type $K_s$. A model of the connection of the column flange to the beam flange was analyzed by the yield line theory and the distance $h_y$ shown in Fig. 6 from the position of beam flange to the yield line is shown by longitudinal bars in Fig. 8. Neither the amount of increase in thickness nor beam width is related, and it is apparent that the rotational stiffness is not affected if the extra length $h_s$ is longer than the distance $h_y$. Although the yield line theory is based on the assumption that the material is in the plastic condition, it might be said that the out-of-plane deformation of the column flange is based on the position of the yield line even if the connection is in the elastic region.

The relationship between the extra length and the local yield moment of the connection is shown in **Fig. 9**. The ordinate is the local yield moment of connection $M_y$ made dimensionless by being divided by the yield moment of a connection of diaphragm type $M_{ys}$. It is apparent that as with the rotational stiffness, the yield moment of connection is not affected by decrease of strength if the extra length $h_s$ is longer than distance $h_y$.

As shown in Fig. 6, therefore, the length of the increased thickness part may be so set that the extra length $h_s$ is longer than the distance $h_y$.

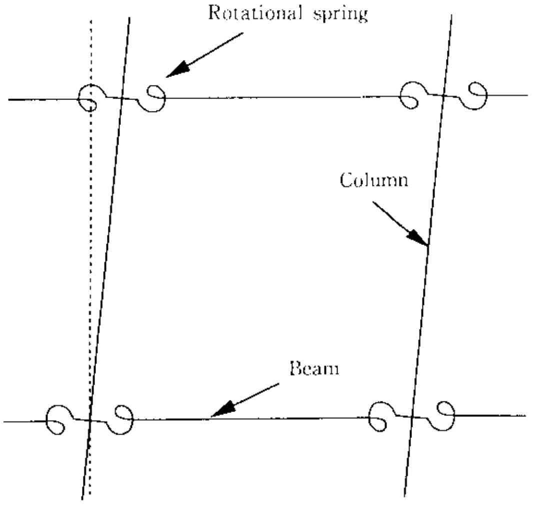


Fig. 10 Frame model with spring at the end of beams

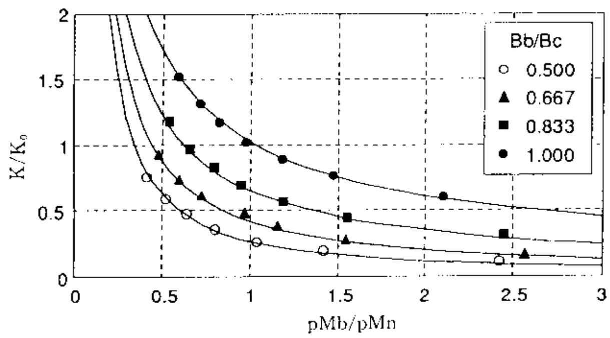


Fig. 11 Value of rotational stiffness

## 4 Design Method of structural Frame

### 4.1 Rotational Spring Model of Connection

A frame in which connections are reinforced by an increased thickness can be modeled as shown in **Fig. 10**, taking the local deformation of connections as that of rotational springs and putting such springs at the ends of the beams. Therefore, an evaluation equation that gives the stiffness of the rotational spring is derived. First, the relationship between stiffness and strength is rearranged as shown in **Fig. 11** from the results of the parametric analysis by FEM. The ordinate is the rotational stiffness $K$ made dimensionless by using the elastic shearing stiffness $K_0$ before the increase in the thickness of the connection shown in Eq. (1) as the standard value. The force equilibrium of the shear panel is based on the assumption that the shearing force of the beam and column is neglected.

$$K_0 = V_e \cdot G \quad \cdots\cdots (1)$$

$$V_e = A_c \cdot h_b / 2$$

$A_c$: Sectional area of general part of column

$h_b$: Distance of beam flange center-to-center

$G$: Modulus of rigidity

The abscissa is the plastic moment of the beam $_pM_b$ made dimensionless by being divided by the local yield strength of the connection $_pM_n$ obtained by yield line theory. In this rearrangement, an attempt was made to relate the ratio of the yield strength of the beam to the local yield strength of the connection to rotational stiffness.

The results of the FEM analysis show that the rotational stiffness of the beam end of the through diaphragm type (that due to the shearing deformation of the shear panel is dominant) $K=(0.7$ to $0.8)K_0$, although there are variations due to the effect of beam width. This suggests that as the deformation of connections is assumed to be rigid in the general design, the neglected deformation of the connections may be underestimated.

### 4.2 Equation for Evaluation of Rotational Stiffness

Eq. (2) is obtained by the least square approximation of the relationship of Fig. 11.

$$K/K_0 = a(_pM_b/_pM_n)^b \cdots\cdots\cdots\cdots (2)$$

$$a = 1.197\ (B_b/B_c)^{1.733}$$

$$b = -1.76 + (B_b/B_c)$$

$B_b$: Width of beam flange

$B_c$: Column width

The results obtained from the above equation are shown by solid lines in Fig. 11. Eq. (2) is an evaluation formula empirically obtained in the ranges of the parameters shown in Table 4. The rotational stiffness can be calculated from the specimens of connections using this equation, and subsequent designing is conducted by the same process as conventional design.

## 5 Conclusion

An experiment and FEM analysis of the beam-to-column connections reinforced by an increased thickness were carried out using a sub-assemblage model, and the following results were obtained:

(1) The connection of this type has a stable stability characteristic and sufficient deformatin capacity.

(2) The yield strength of the connection can be predicted by the yield line theory.

(3) The length of the increased thickness part should be longer than the distance to yield line calculated by the yield line theory.

(4) An equation for evaluating the rotational stiffness of beam ends was empirically obtained by a parametric analysis by FEM.

## 6 Acknowledgments

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