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EVALUATION OF THE CHARACTERISTICS OF EXTERNAL DIAPHRAGM CONNECTIONS WITH STEEL CHS COLUMNS AND WIDE-FLANGE STEEL BEAMS

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ABSTRACT

Evaluation equations of external diaphragm connection with steel circular hollow section columns and wide-flange steel beams, to include initial stiffness, yield strength, post yield stiffness and maximum strength, were deduced from regression analysis. Finally, the verification of the estimations with typical frames was conducted. As a result, the evaluation equations were useful to trace the behavior of the semi-rigid steel frame with external diaphragm connections.

Introduction

It is well known that local deformation occurs in columns in which the section is hollow, and is caused by force at the height of the beam flange in beam-to-column connections stiffened by an external diaphragm. The local deformation causes reduction of stiffness and yield loading capacity of over-all frames consisting of such hollow section columns and connections. The characteristics of semi-rigid beam-to-column connections need to be obtained for structural design of frames with such connections.

Nowadays, the CAE tool such as the finite element analysis program is popular in structural engineering for research of behavior of structures. When a well-controlled analytical technique is obtained, laborious experiments do not need to be carried out by researchers, saving both time and money. The authors tested the ability of the finite element analysis program Marc with an experimental test result. After that, a lot of numerical work was conducted for the induction of the characteristics of semi-rigid beam-to-column connection of the external diaphragm connection.

Subassemblages for Finite Element Analysis

Moment-resisting frames with semi-rigid connections behave as softened or weakened frames rather than what we call rigid frames. However, semi-rigid connections vary over a wide range from nearly pinned to almost rigid. The information about such connections is usually obtained through a series of experiments.

In this research, another way was taken to achieve the information using a computer aided engineering tool, the Marc program. This program is a useful tool for virtual experiments that are performed in a computer, instead of actual experiments. This way ensures that uncertainty, which is an adhering thing for the experiment, is excluded from the test results.

Finite Element Analysis Model

Three dimensional finite element analysis models were prepared for numerical work, as shown in Fig. 1. The model as the subassemblage consists of steel circular hollow section columns and wide-flange steel beams. The beams are connected to the columns in external diaphragm type with which the columns are not cut at the height of beam flange. All finite elements that form the model type 75, which has 4 nodes at the corners on a thick shell rectangular element. The lengths of the column and the beam are 1000 mm and 1350 mm, respectively.

Suitable boundary conditions are applied to the model for keeping the consistency where the subassemblage is taken out of an overall frame. The subassemblage is subjected to increasing lateral force

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and constant axial force at the top of the column to simulate the overall frame which is under lateral force like an earthquake or in wind. The lateral force direction is measured as θ shown in Fig. 1.

Analyses

The yield condition of material as von Mises and the radial return method accounting for swell of yield surface are taken in FE analyses. This is the most popular method in non-linear static analysis of steel structures.

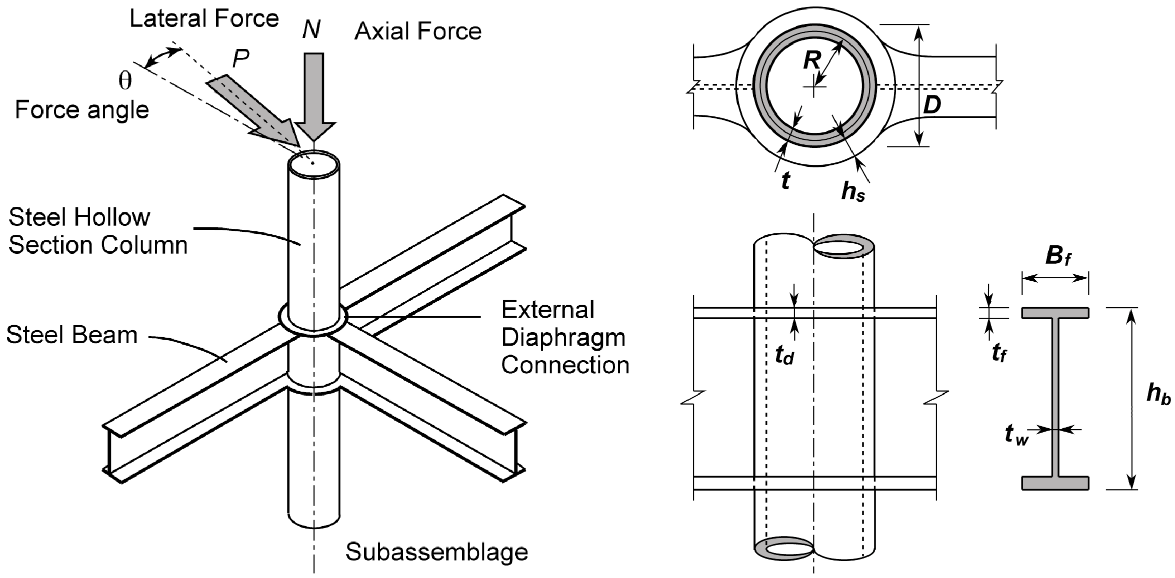


Figure 1. Subassemblage with external diaphragm subjected to increasing lateral force and constant axial force at the top of the column.

A series of numerical models which consists of 32 frames was applied in this research. Before the performance of the series of numerical work, some pilot tests with the FE program were conducted for exact tracing for real experimental results.

Six geometrical parameters that rather strongly affect the stiffness and the loading capacity of the connection are taken to deduce the evaluating equations for the characteristics of such semi-rigid connections referred to in the next chapter. Each parameter varies, covering the practical range.

Table 1. Geometrical parameters for structural analyses of subassemblages.

Geometrical Parameter	**Range**	
	Minimum	**Maximum**
R / t	6.26	23.53
$R / (t + Hs)$	1.79	5.43
D / B_f	1.24	2.16
H_b / B_f	1.70	2.70
R / t_d	8.35	13.02
B_f / t_f	11.11	19.44

Restoring Force Characteristics of Connection

It is useful for structural designers that the necessary equations for frame design are prepared. Moreover those should be expressed in an explicit form. The real load-deformation relationship curve is generally drawn smoothly. However, dealing with smooth curves is not always convenient for easy calculations or structural design. In particular, it is difficult to find the apparent yield point on the curve. In this research, a multi-linear expression of load-deformation relationship should be suitable for the problem.

Fig. 2 shows the definition of some physical notes for expressing a tri-linear load-deformation relation of a connection. K_{L0} , P_{Ly} , K_{L2} and P_{Lmax} are respectively the initial stiffness, the yield loading capacity, the secondary stiffness and the maximum loading capacity of a connection. The yield load represents the general yield load when the gradient of the tangent line reaches one third of the value of the initial stiffness. Secondary stiffness is determined by the least square method over the sampling range in Fig. 2. The estimation of quantity of those is obtained when the force angle shown in Fig. 1 is zero because the characteristics are independent from the force direction, and when the axial load on the top of column member is zero.

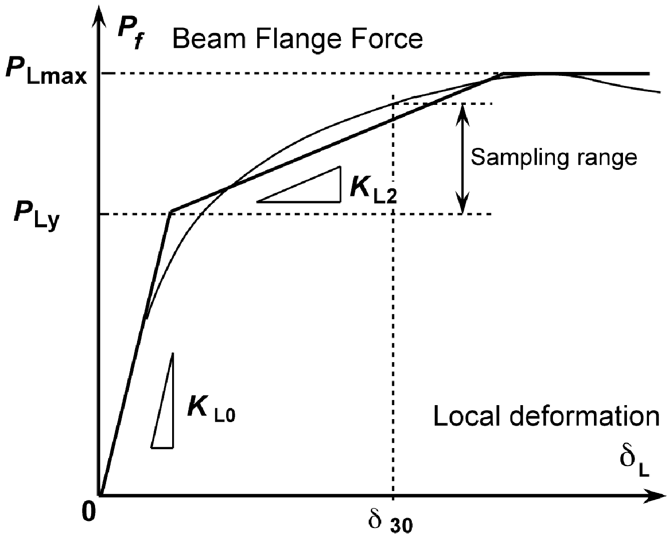


Figure 2. Tri-linear force-deformation relationship of connection.

The initial Stiffness

A mathematical model was prepared for estimating the initial stiffness of a connection using FE analysis results. Assuming all the data lay on a lognormal distribution, Eq. 1 is deduced by multiple regression analysis.

$$\frac{{}_{c}K_{L0}R^{3}}{EI} = 1.466 \times 10^{3}\left(\frac{R}{t}\right)^{2.383}\left(\frac{2R+h_{s}}{2R}\right)^{2.835}\left(\frac{B_{f}}{D}\right)^{0.409}\left(\frac{t_{d}}{R}\right)^{0.692} \tag{1}$$

where ***E*** and ***I*** are Young's modulus of steel diaphragm and moment inertia of the cross section with one unit width and the thickness of column plate, respectively.

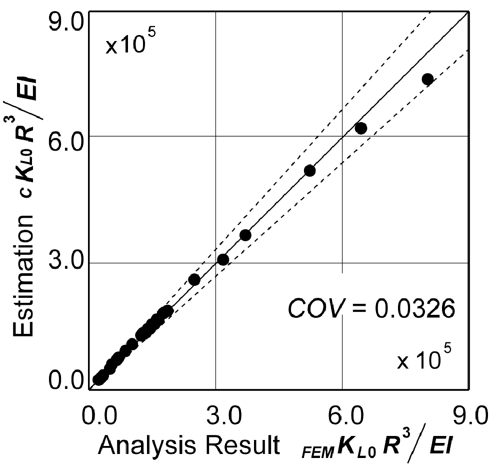


Figure 3. Estimation of initial stiffness of connection.

Fig. 3 shows the result of the estimation of the initial stiffness of connection and Eq. 1 provides good fitting. ***COV*** means the coefficient of variance on all data.

The yield Load

A mathematical model was prepared for estimating the yield load of connection using FE analysis results as well as the initial stiffness. Assuming all the data lay on a lognormal distribution, Eq. 2 is deduced by multiple regression analysis.

$$_cP_{Ly} = 3.042\left(\frac{t}{R}\right)^{0.421}\left(\frac{t+h_s}{R}\right)^{0.434}\left(\frac{B_f}{D}\right)^{0.254}\left(\frac{t_d}{R}\right)^{0.695} R^2 s_y \tag{2}$$

where s_y is yield strength of a steel diaphragm.

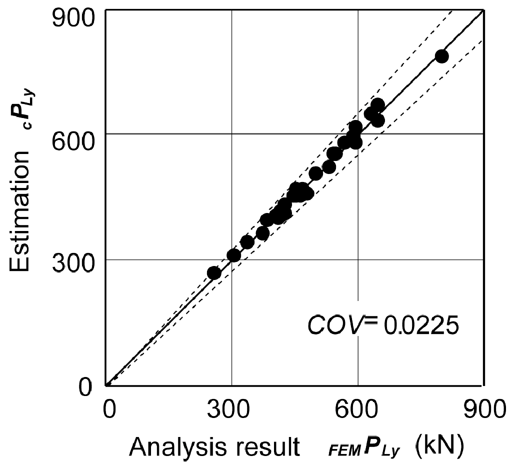


Figure 4. Estimation of yield load of connection.

Fig. 4 shows the result of the estimation of the yield load of connection and Eq. 2 provides good fitting. ***COV*** means the coefficient of variance on all data with respect to yield load.

The Secondary Stiffness

A mathematical model was prepared for estimating the secondary stiffness of connection using FE analysis results as well as the initial stiffness. Assuming all the data lay on a lognormal distribution, Eq. 3 is deduced by multiple regression analysis.

$$\frac{_cK_{L2}R^3}{EI} = 1.117\ x\ 10^3\left(\frac{R}{t}\right)^{2.330}\left(\frac{t+h_s}{R}\right)^{0.612}\left(\frac{B_f}{D}\right)^{1.225}\left(\frac{t_f}{B}\right)^{0.985} \tag{3}$$

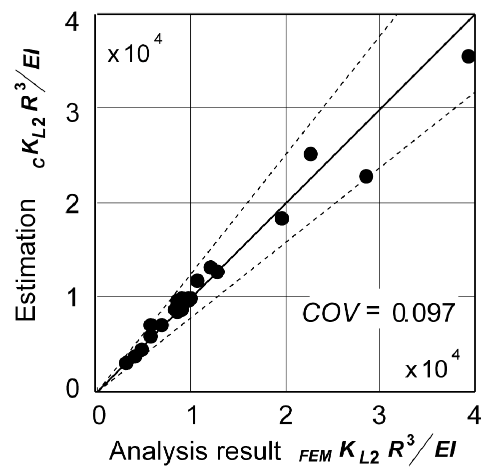


Figure 5. Estimation of the secondary stiffness of connection.

Fig. 5 shows the result of the estimation of the secondary stiffness of connection and Eq. 3 provides good fitting. ***COV*** means the coefficient of variance on all data.

The Maximum Load

A mathematical model was prepared for estimating the yield load of connection using FE analysis results as well as the initial stiffness. Assuming all the data lay on a lognormal distribution, Eq. 4 is deduced by multiple regression analysis.

$$_cP_{L\,max} = 3.934\left(\frac{t}{R}\right)^{0.653}\left(\frac{t+h_s}{D}\right)^{0.297}\left(\frac{B_f}{D}\right)^{0.161}\left(\frac{t_d}{R}\right)^{0.443} R^2 s_y \tag{4}$$

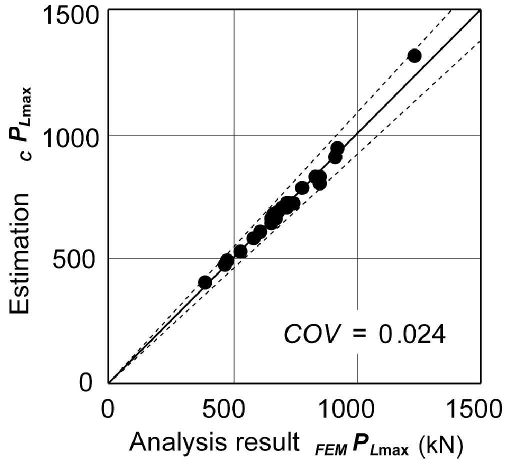


Figure 6. Estimation of maximum load of connection.

Fig. 6 shows the result of the estimation of the maximum load of connection and Eq. 4 provides good fitting. ***COV*** means the coefficient of variance on all data with respect to maximum load.

Discussion

The estimation was successfully conducted by the systematic method and under the clear-cut approach as mentioned above. The deduced equations provide well-fitted load-deformation curve. Therefore these are useful for the calculation of frame analysis and structural design.

Influence of Axial Load in Column to Frame Behavior

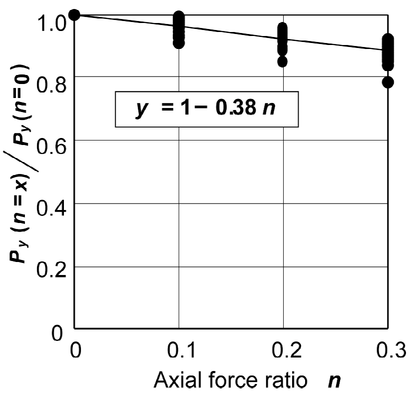
As shown Fig. 1, the subassemblage is subjected to not only lateral force but also axial load at the top of the column. It is well known that the axial load affects the behavior of the overall frame such as the P-delta effect. So as to examine the effect of the axial load to the frame with semi rigid connection, more numerical work was conducted.

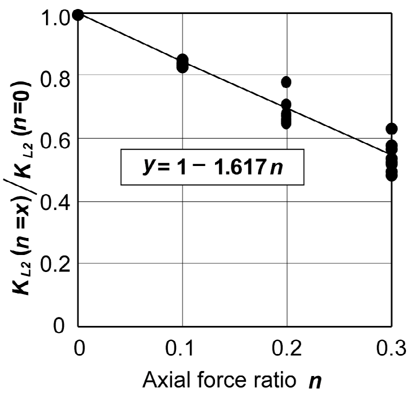
Here, the axial load ratio n is introduced for the examination of influence of the axial load to frame behavior.

$$n = N / N_y \qquad (5)$$

where N and N_y is the axial load and the yield load of column respectively.

After the examination, it was clarified that the influence of the axial load to the behavior of frame appeared with respect to the yield load and the secondary stiffness. As for both the yield load and the secondary stiffness, the relationships in Fig. 7 show it to be almost linear.



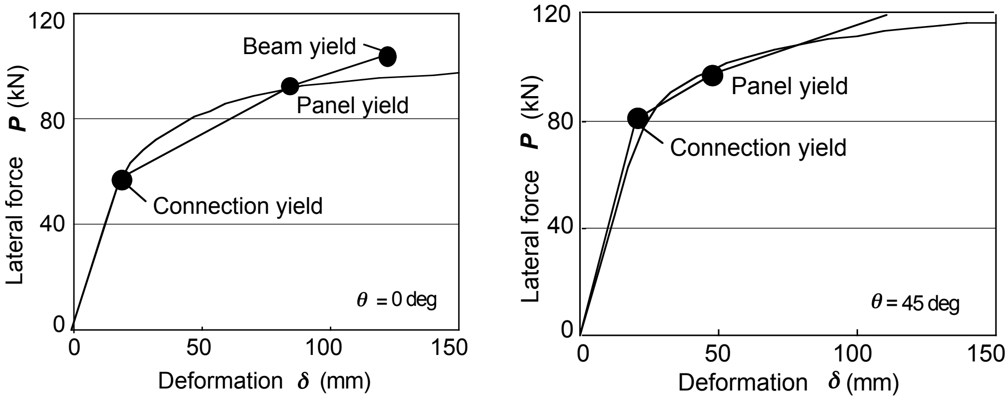


(a) Yield load ratio vs. n. (b) The secondary stiffness ratio vs. n.

Figure 7. Influence of axial load to frame behavior.

Verification with evaluation of external diaphragm connection

One of the specimens was applied for verification with the obtained equations. Fig. 8 shows the results of traced load-displacement of the frame in both conditions of 0 degree and 45 degree of load angle.



(a) Load direction: 0 deg. (b) Load direction: 45 deg.

Figure 8. Traced load-displacement relationships of subassemblage under biased lateral force.

Conclusions

Numerical work was conducted to deduce equations for the estimation of the characteristics, which specify essential features such as the initial stiffness, the yield load, the secondary stiffness, and the maximum loading of semi rigid beam-to-column connections with an external diaphragm. The equations were verified in order to consider whether they are effective for tracing a general semi rigid moment frame. Consequently, it was concluded that the evaluations of external diaphragm connections are useful in further research on frame analysis or design.

Acknowledgments

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References

Kamba, T., et al., 1982, *Tests on the Local Failures of Tubular Column to H-beam Connections in Steel Structures – A Study on the Tubular Column to Beam Connections Part 1 –*, Transactions of AIJ 322 (in Japanese), 44-51.

Lui, E. M., and Chen, W. F., 1987, *Steel Frame Analysis with Flexible Joints*, Journal of Construct. Steel Research 8, 161-202

Lindsey, S. D., 1987, *Design of Frames with PR Connections*, Journal of Construct. Steel Research 8, 251-260

Sui, W. and Yamanari, M., 2005, *A Study on Elasto-plastic Characteristics of 3D Space Steel Subassemblage under Biaxial Lateral Load and Compressive Load*, Journal of Constructional Steel 13 (in Japanese), 229-234

Yamanari, M., and Ogawa, K., et al., 1994, *Inelastic Behavior of Semi-rigid Corner Connections with RHS Columns and Wide Flange Beams*, Journal of Structural Engineering 40B (in Japanese),

Kamba, T., et al., 1983, *Empirical Formulae for Strength of Steel Tubular Column to H-beam Connections – A Study on the Tubular Column to Beam Connections Part 2 –*, Transactions of AIJ 325 (in Japanese), 67-73.

Yamanari, M., et al., 1988, Participation of Beam-to-column Connection Deformation in Hysteretic Behavior of Steel Frames, Proceedings of the 9th World Conference on Earthquake Engineering 4, 175-180