I－12 DISCUSSION ON CONNECTION CLASSIFICATION SYSTEMS BASED ON FRAME ANALYSIS

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1. INTRODUCTION

In steel construction, beam-to-column connections are commonly classified in to three groups: (i) rigid connection, (ii) semi-rigid connection, and (iii) flexible (pinned) connection. In North American codes, this classification is described in general terms without explicitly defining the connections in terms of connection strength or stiffness. On the contrary, as an unified effort in Europe, a systematic connection classification system was introduced in the EC3 (1992) code. Among other contemporary efforts on classifying connections, Bjorhovde et al.'s (1990) classification system received keen attention. In both classification systems, moment axis is non-dimensionalized with reference to the plastic moment of the connected beam. The rotation axis is nondimensionalized with reference to the stiffness either of the full length or of a reference length of the beam. These appear to be the contrary to the common experimental evidences that the moment-rotation behaviors of steel connections are mainly dependent on the characteristics of the connection elements (such as: geometric and material properties of angle, plate, fastener, column flange etc.) rather than the properties of connecting beam.

In this study, these skepticisms on the validity of the classification systems (EC3 and Bjorhovde et al.) have been examined by conducting frame analysis. To this end, a second-order elastic analysis program which considers non-linear connection stiffness is used. In the frame analysis, a good number of experimental moment-rotation curves as well as the moment-rotation curves obtained from the classification schemes are used. The frame responses obtained from the experimental curves are compared with those of the classification systems. From the comparison, the validity of the classification systems has been examined.

2. CONNECTION CLASSIFICATION SYSTEMS

The non-dimensional moment-rotation classification system as per EC3 (1992) and Bjorhovde et al. (1990) are illustrated in Figs. 1 and 2. Main features of the classification systems can be listed as:

1) The moment axis is non-dimensionalized with reference to plastic moment of the connected beam M_p, i.e.,

$$\overline{m} = M/M_p \tag{1}$$

(2) The rotation axis is non-dimensionalized with reference to plastic rotation θ_p, i.e.,

$$\overline{\theta} = \theta/\theta_p \tag{2}$$

where plastic rotation is defined as the beam stiffness either of full length (EC3) or of a reference length (Bjorhovde et al.), i.e.,

EC3: $$\theta_p = M_p/(EI/L) \tag{3}$$

Bjorhovde et al.: $$\theta_p = M_p/(EI/5d) \tag{4}$$

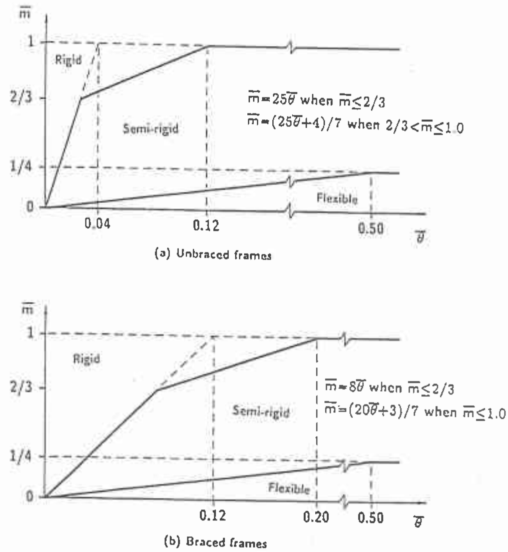


Fig. 1. EC3 Classification System

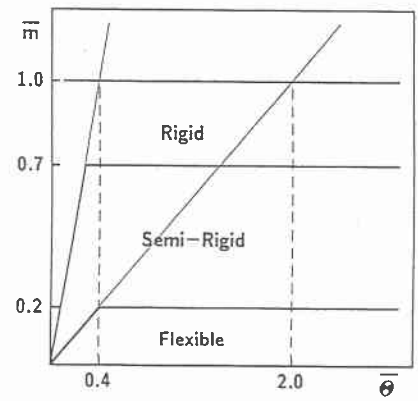


Fig. 2. Bjorhovde et al.'s Classification System

where L and d is the beam length and depth, respectively.

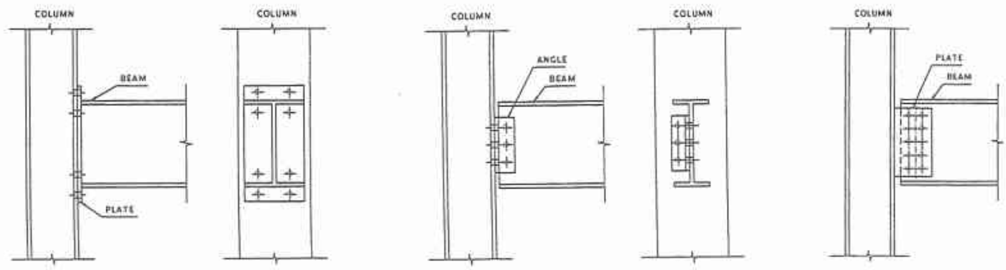
(3) The EC3 classification system recognizes different semi-rigid action depending upon the type of the structure, i.e., braced or unbraced frame and provides different boundary lines between semi-rigid and rigid connections (Figs. 1(a) and (b)). On the other hand, same boundary line is provided between semi-rigid and flexible connections for both types of frames.

Table 1. Boundary Values of Initial Connection Stiffness of Different Connections

Initial Connection Stiffness (R_{ki})	EC3		Bjorhovde et al.
	unbraced	braced	
minimum R_{ki} of a rigid connection or maximum R_{ki} of a semi-rigid connection	$R_{ki} = \frac{25EI}{L}$	$R_{ki} = \frac{25EI}{3L}$	$R_{ki} = \frac{EI}{2d}$
minimum R_{ki} of a semi-rigid connection or maximum R_{ki} of a flexible connection	$R_{ki} = \frac{EI}{2L}$		$R_{ki} = \frac{EI}{10d}$

3. INITIAL CONNECTION STIFFNESS AS PER CLASSIFICATION SYSTEMS

The initial connection stiffnesses of the rigid, semi-rigid and flexible connections can be calculated from the primary slopes of the boundary lines among the three connection categories as shown in Figs. 1 and 2. The boundary values of the initial connection stiffness of rigid, semi-rigid and flexible connections are listed in Table 1. The major drawbacks of the classification systems are well manifested in this table: the initial connection stiffnesses are all expressed in terms of beam stiffness of a certain length and no relation was shown with the connection elements characteristics. For the same connection configuration, as per EC3 classification system, a change in beam length causes a change in initial connection stiffness. Similarly, Bjorhovde et al.'s classification suggests that a change in beam depth results in a variation in the value of initial connection stiffness without referring to connection details or properties of connection elements. These, obviously, do not pertain to the reality. Therefore, the validity of the classification systems is not beyond question and requires examination.



(a) extended end-plate (b) single web-angle (c) single plate

Fig. 3. Practical Connections Used in Frame Analysis

4. METHODOLOGY

As evident from Table 1, two primary slopes could be identified as: (i) minimum initial connection stiffness of a rigid connection and (ii) maximum initial connection stiffness of a flexible connection. These two theoretical boundary values are examined by comparing with the experimental boundary values obtained from frame analysis.

4.1. Minimum Initial Connection Stiffness of a Rigid Connection

Extended end-plate connection, a typical of which is shown in Fig. 3(a), consists of a end-plate profile welded to the beam-end, bolted to the column flange and extended beyond the beam flange. This type of connection is commonly used to sustain high moment and is generally regarded as rigid connection. Therefore, a total of 112 experimental moment-rotation curves of this connection stored in the updated data base (Hasan et al., 1995) are utilized to determine the experimental minimum initial connection stiffness of a rigid connection. A second-order elastic analysis program considering non-linear connection stiffness (Goto and Chen, 1987) is used to calculate the frame response (end moment). Calculated values for real connections are normalized by the corresponding values for rigid connections i.e.,

$$\text{normalized moment, } m^* = \frac{\text{end moment for extended end-plate connection}}{\text{end moment for fully rigid connection}}$$

Normalized end moments m^* are then plotted against initial connection stiffness R_{ki}. Relative locations of the data correspond to the EC3 and Bjorhovde et al. classification systems are also shown in these figures by black star and triangular marks, respectively. Frame responses correspond to the connection classification systems are calculated utilizing the moment-rotation curves for floor beam (W21×44) and roof beam (W14×22) as shown in Fig. 4(a). These beam sections are adopted in the frames studied here (Fig. 5).

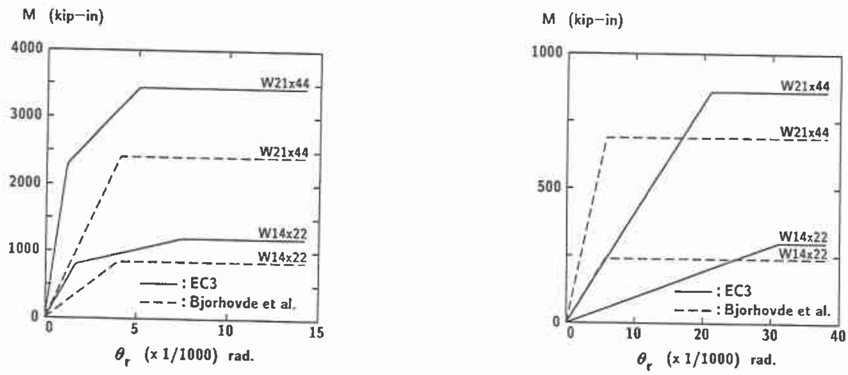
4.2. Maximum Initial Connection Stiffness of a Flexible Connection

Same procedure is followed as described in the sub-section 4.1. The practical connections used for this purpose are: (i) single web-angle connection and (ii) single plate connection, because they are generally regarded as flexible connection. These connections use only one angle/plate in the web of the beam as shown in Figs. 3(b) and (c). In this case, mid-span moments are considered because end moments of a beam element are always zero when it is connected to the column with flexible connections. The frame responses (mid-span moments) obtained from frame analysis are normalized as follows:

$$\text{normalized moment, } m^* = \frac{\text{mid-span moment for single web-angle/plate connection}}{\text{mid-span moment for flexible connection}}$$

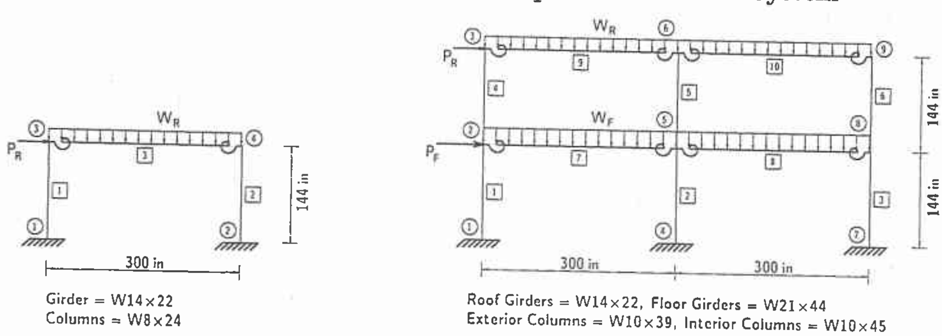
A total of 54 experimental moment-rotation curves stored in the updated data base

(Hasan et al., 1995) are utilized to calculate frame responses correspond to real connections. And to calculate frame responses correspond to the connection classification systems, the moment-rotation curves for floor beam (W21×44) and roof beam (W14×22) (as per classification systems) used in the frame analysis are shown in Fig. 4(b).

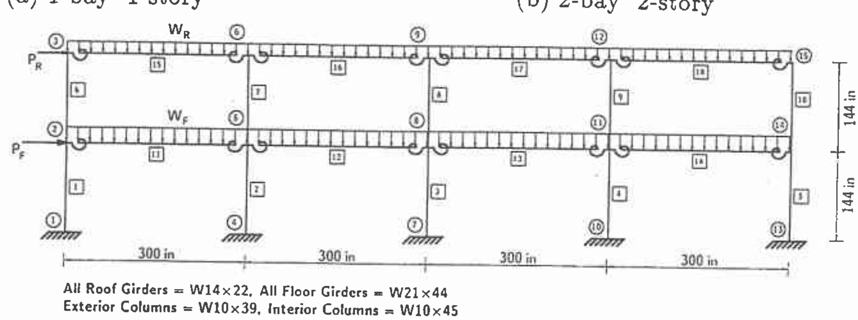


(a) curves for rigid connection (b) curves for flexible connection

Fig. 4. Moment-Rotation Curves as per Classification System



(a) 1-bay 1-story (b) 2-bay 2-story



(c) 4-bay 2-story

Fig. 5. Frames Used in Frame Analysis

5. FRAME ANALYSIS

Three frames: one-bay one-story, two-bay two-story and four-bay two-story, as shown in Figs. 5(a)~(c), are analyzed. Beam and column sections, floor heights and beam spans used in this study are shown in their corresponding figures. Element nos. are shown in boxes while node nos. are shown in circles. The frames are loaded with 68 and 40 psf load as floor dead (D) and live (L) load, respectively. The intensity of roof dead

(D) and live (L) load , and wind (W) load are of equal magnitude: 20 psf. Frame moments are obtained for factored load combination (1.2D+0.5L+1.3W), as per AISC-LRFD specification (1994). The frame spacing is taken as 300 inch.

6. DISCUSSIONS ON RESULTS OF FRAME ANALYSIS

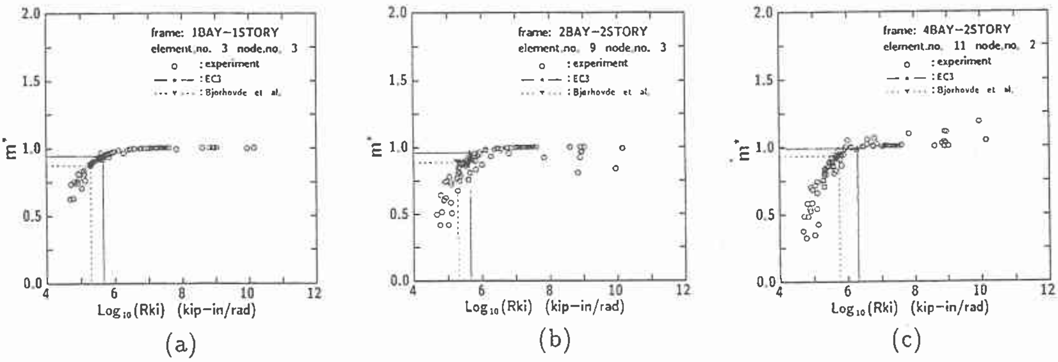


Fig. 6. Results of Moment Analysis for Extended End-Plate Connection

6.1. Minimum Initial Connection Stiffness of a Rigid Connection

Three illustrative examples of m^*-$\log_{10}R_{ki}$ for the three frames are shown in Figs. 6(a)~(c). One most distinct observation can be made from the $m^*-\log_{10}R_{ki}$ distribution patterns is that: almost all data are clustered in the vicinity of $m^*=1$ when their $\mathrm{Log}_{10}R_{ki}\geq 6$. This observation is found valid for all cases (i.e., for all nodes of all frames analyzed). Therefore, this leads to a general conclusion that: the minimum initial connection stiffness R_{ki} for a rigid connection can be assumed to be 10^6 kip-inch/radian.

Table 2. R_{ki} and m^* in the illustrative examples (Figs. 6(a)~(c)) for moment analysis

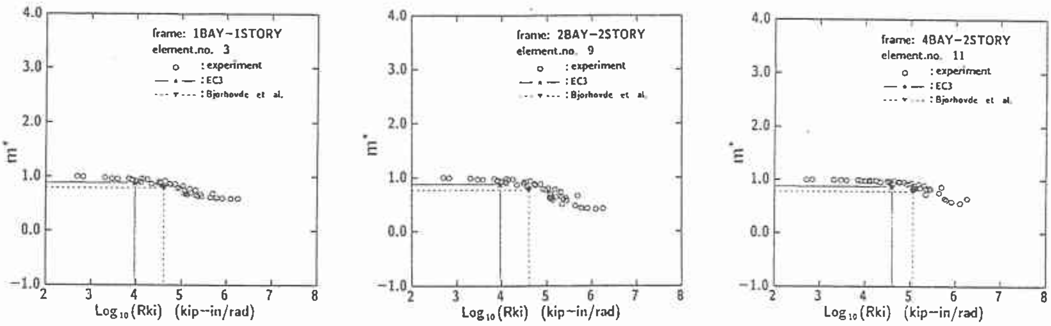
Frame Type	Node	Beam	Min. R_{ki} of a rigid conn. in kip-in/rad.			m^*	
			Present study	EC3	Bjorhovde	EC3	Bjorhovde
1-bay 1-story	3	W14×22	1.0×10^6	0.48×10^6	0.21×10^6	0.941	0.873
2-bay 2-story	3	W14×22		0.48×10^6	0.21×10^6	0.957	0.884
4-bay 2-story	2	W21×44		2.04×10^6	0.59×10^6	0.987	0.930

The initial connection stiffness and normalized moment in the three examples shown in Figs. 6(a~c) are listed in Table 2. The initial connection stiffnesses for the roof beam (W14×22) and the floor beam (W21×44) are different e.g., 0.48×10^6 kip-in./rad. and 2.04×10^6 kip-in/rad., respectively as per EC3 classification system. This obviously, raises the question of validity of the classification systems.

The normalized moments correspond to the EC3 classification system are 0.941, 0.957 and 0.987, while their counter-figures for Bjorhovde et al.'s classification system are 0.873, 0.884 and 0.930 for the one-bay one-story, two-bay two-story and one-bay three-story frame, respectively. Therefore, with reference to the normalized moment, both systems of connection classification perform well, particularly, the EC3 classification system.

6.2. Maximum Initial Connection Stiffness of a Flexible Connection

Figs. 7(a)~(c) show examples of $m^*-\mathrm{Log}_{10}R_{ki}$ figures obtained from frame analysis



(a) (b) (c)

Fig. 7. Result of Moment Analysis for Single Web-Angle and Single Plate Connections

Table 3. R_{ki} and m^* in the illustrative examples (Figs. 7(a)~(c)) for moment analyses

Frame Type	Element	Beam	Max. R_{ki} of a flexible conn. in kip-in/rad.			m^*	
			Present study	EC3	Bjorhovde	EC3	Bjorhovde
1-bay 1-story	3	W14×22	$1.0\times 10^{4.5}$	0.96×10^4	0.42×10^5	0.882	0.758
2-bay 2-story	9	W14×22		0.96×10^4	0.42×10^5	0.870	0.758
4-bay 2-story	11	W21×44		0.41×10^5	0.12×10^6	0.873	0.777

for the three frames. It is evident from the distribution pattern in these three figures that all data are closely clustered in the vicinity of $m^*=1.0$ line when their $\text{Log}_{10}R_{ki}\leq 4.5$. In other words, the maximum initial connection stiffness of a flexible connection can be regarded as $10^{4.5}$ kip-inch/rad.

The results of the examples of Figs. 7(a~c) are listed in Table 3 and the drawbacks of the classification systems are obvious here. While frame analysis reveals that the maximum initial connection stiffness of a flexible connection is $10^{4.5}$ kip-inch/rad., the corresponding value as per classification systems vary depending upon the type of the connecting beam (0.96×10^4, 0.41×10^5 kip-inch/rad. for roof and floor beams, respectively). Besides, the low normalized frame responses, raise the question of the accuracy of demarcation line between semi-rigid and flexible zone for the whole range of rotation.

7. CONCLUSION

The rationale used to devise connection classification systems (EC3, 1992 and Bjorhovde et al., 1990) is that: the connection stiffness should be compared with beam stiffness. It was shown by performing frame analysis that this rationale is plausible but not valid. Therefore, the classification systems are not free from flaws and require improvements.

8. REFERENCE

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