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Investigation on the validity of connection classification system

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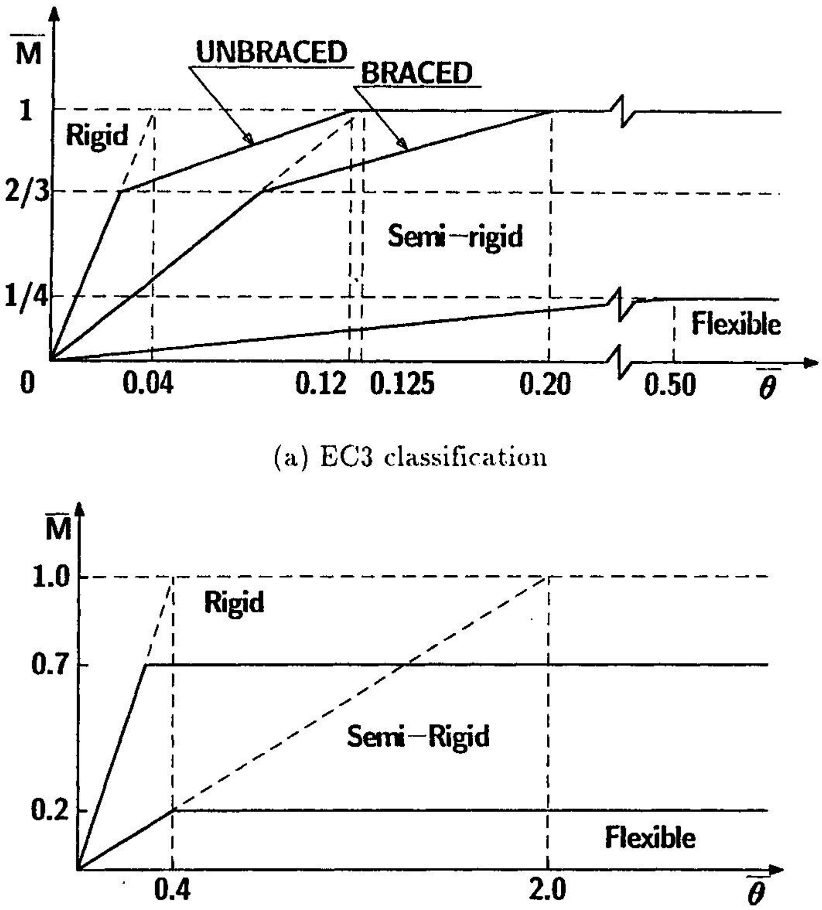
Summary

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 is shown by performing frame analysis that this rationale is plausible but does not produce satisfactory results. Therefore, this study stems the rationale and shows the necessity of having a classification system which reasonably reflects the proper contributions of the connection components on connection behavior.

1. Introduction

In steel construction, beam-to-column connections are commonly classified into three categories: (i) rigid connection, (ii) semi-rigid connection, and (iii) flexible 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 other hand, as a unified effort in Europe, a systematic connection classification scheme was introduced in their EC3 (1992) code. Among other contemporary efforts on connection classification, 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 non-dimensionalized 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 regarding 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 those obtained from the classification schemes are used. The frame responses obtained by applying the experimental moment-rotation curves are compared with the results correspond to the classification schemes. From the comparison, the validity of the classification schemes, with reference to initial connection stiffness, has been examined.



(a) EC3 classification

(b) Bjorhovde et al.'s classification

Fig. 1. Connection classification systems

2. Connection classification systems

The non-dimensional moment-rotation classification system as per the EC3 (1992) and Bjorhovde et al. (1990) are illustrated in Fig. 1. 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 reference 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: $\theta_p = M_p/(EI/L)$ (3)

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

where L and d are 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 rigid and semi-rigid connections (Fig. 1a). On the other hand, same boundary line is provided between semi-rigid and flexible connections for both types of frames.

2.1 Initial connection stiffness as per classification systems

The boundary values of 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 Fig. 1 are listed in Table 1. The major drawbacks of the classification systems are well manifested in this table: the initial connection stiffness, instead of depending on the properties of connection elements, completely depends on the physical and material properties of the connected beam. For the same connection configuration, as per the 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.

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 rigid connection or maximum R_{ki} of semi-rigid connection	$R_{ki} = \frac{25EI}{L}$	$R_{ki} = \frac{8EI}{L}$	$R_{ki} = \frac{EI}{2d}$
minimum R_{ki} of semi-rigid connection or maximum R_{ki} of flexible connection	$R_{ki} = \frac{EI}{2L}$		$R_{ki} = \frac{EI}{10d}$

3. Methodology

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

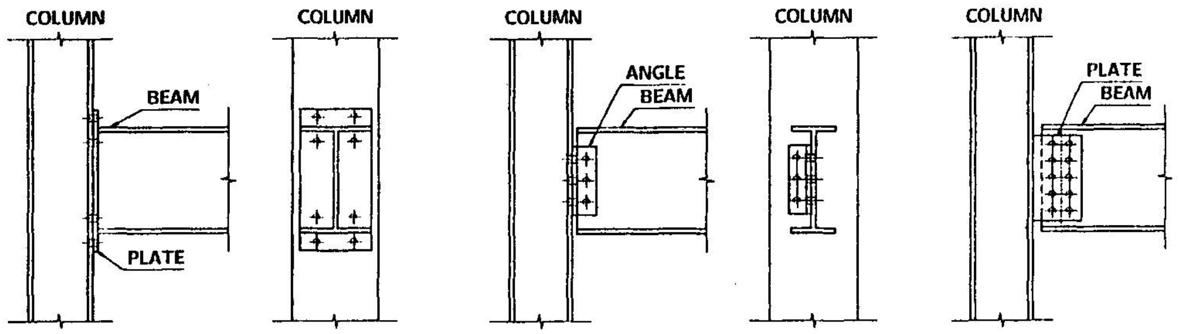
3.1 Minimum initial connection stiffness of a rigid connection

Extended end-plate connection, a typical of which is shown in Fig. 2(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. To this end, a second-order elastic analysis program considering non-linear connection stiffness (Goto and Chen, 1987) is used to calculate the frame responses (beam end moments and frame drift). Calculated values for real connections are normalized by the corresponding values for rigid connections i.e.,

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

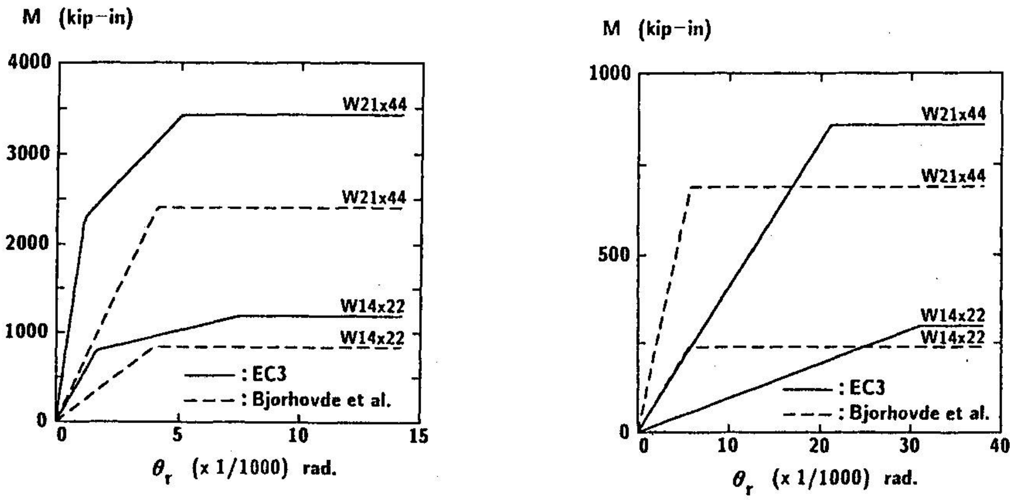
$$\text{normalized frame drift, } d^* = \frac{\text{drift for extended end-plate connection}}{\text{drift for fully rigid connection}}$$

Normalized beam end moment m* and normalized frame drift d* 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, as shown in section 4. Frame analyses are executed by using portal; two-bay two-story and four-bay two-story frames as shown in Fig. 4. In these frames, W21×44 for floor beam and W14×22 for roof beam are used. The moment-rotation relations for these beam sections correspond to each classification systems are shown in Fig. 3(a).



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

Fig. 2. Practical connections used in frame analysis



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

Fig. 3. Moment-rotation curves as per classification system

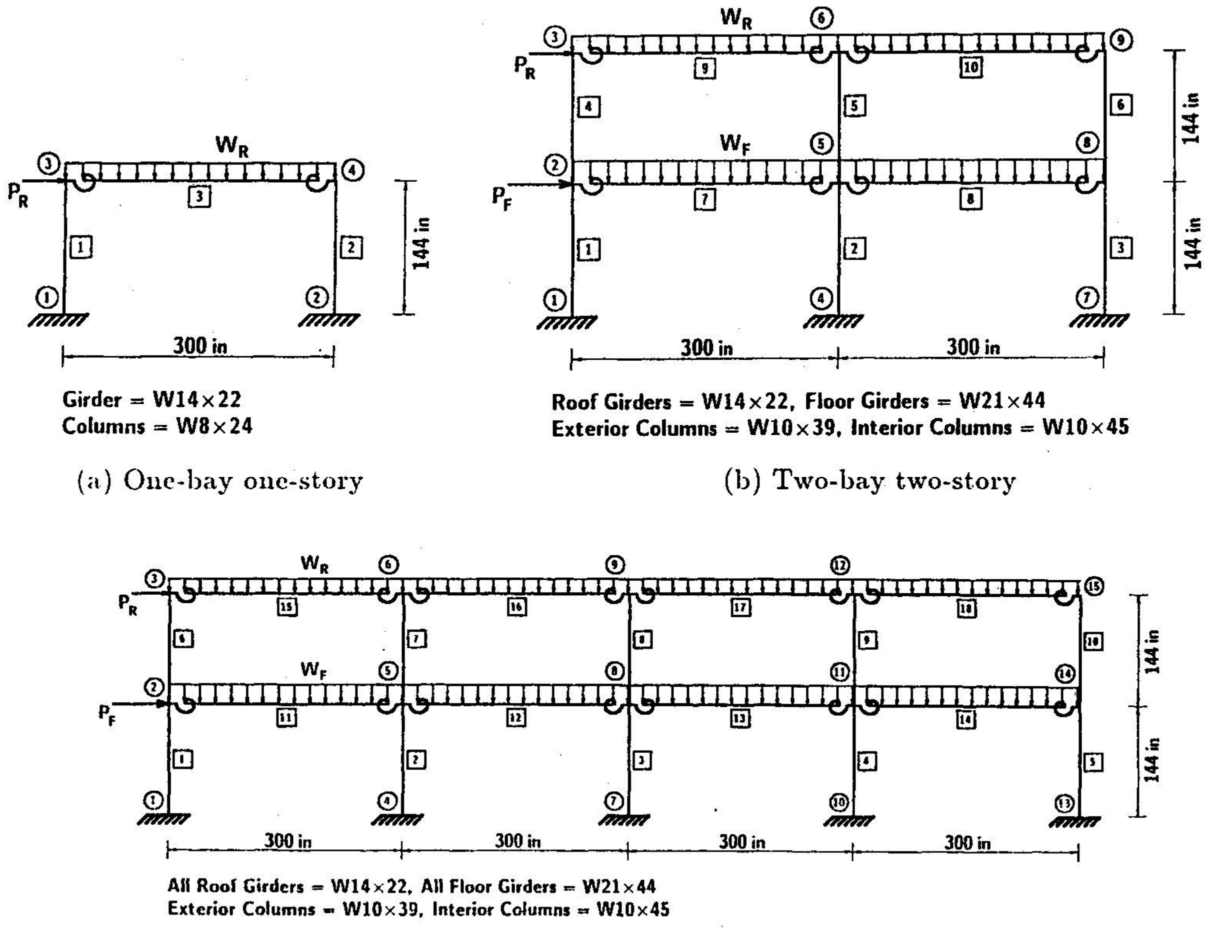
3.2 Maximum initial connection stiffness of a flexible connection

To examine the validity of classification systems with reference to stiffness of flexible connection, same procedure is followed as described in the sub-section **3.1**. 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 connections. These connections use only one angle/plate in the web of the beam as shown in Figs. 2(b) and (c). The frame responses (mid-span moment and frame drift) obtained from frame analysis are normalized as follows:

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

$$\text{normalized frame drift, } d^* = \frac{\text{drift for single web-angle/plate connection}}{\text{drift for flexible connection}}$$

For moment analysis, mid-span moments are considered because the end moments of a beam element are almost zero when it is connected to the column with flexible connections. 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. The same frames (Fig. 4) used for rigid connection analysis are used here. The moment-rotation curves as per classification systems for floor beam (W21×44) and roof beam (W14×22) are shown in Fig. 3(b), respectively.



(a) One-bay one-story

(b) Two-bay two-story

(c) Four-bay two-story

Fig. 4. Frames used in analysis

4. Frame analysis

Three frames: one-bay one-story, two-bay two-story and four-bay two-story, as shown in Fig. 4 are analyzed. Beam and column sections, floor heights and beam spans used 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 48 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 drift and end/mid-span beam moments are obtained for service load combination (D+L+W) and factored load combination (1.2D+0.5L+1.3W), respectively, as per AISC-LRFD specification (1994). The frame spacing is taken as 300 inch.

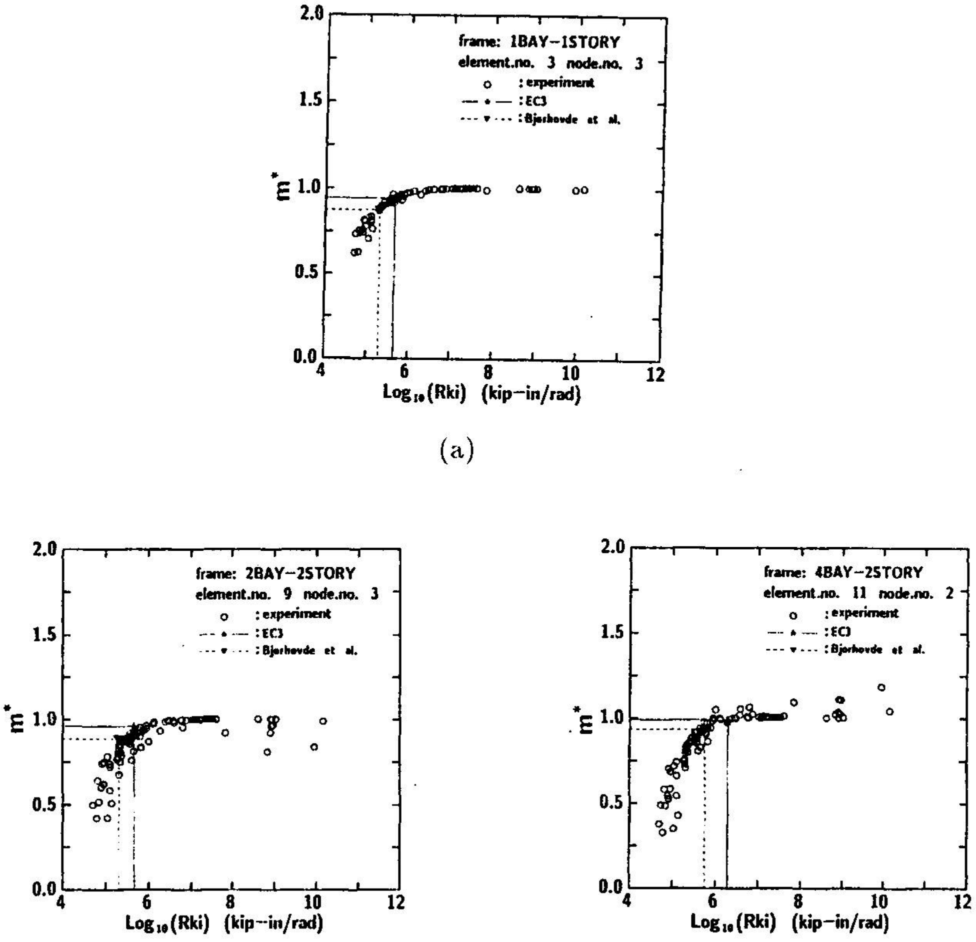
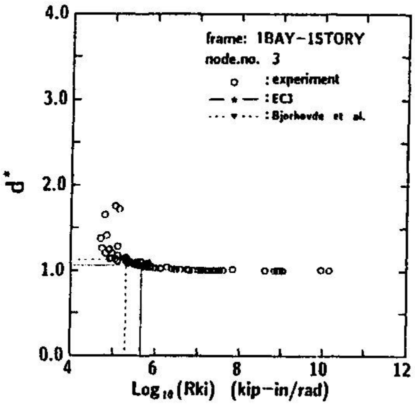


Fig. 5. Beam end moment for extended end-plate connections

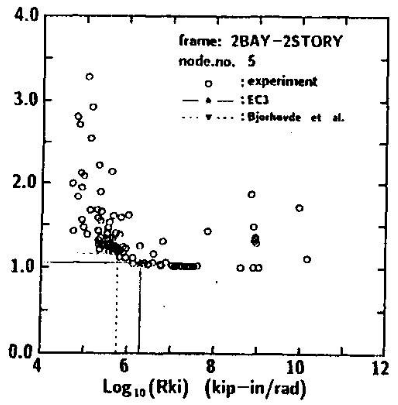
5. Discussions on results of frame analysis

5.1 Minimum initial connection stiffness of a rigid connection

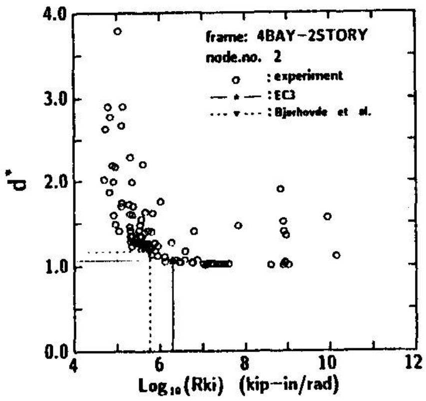
Three illustrative examples of m^*-$\log_{10}R_{ki}$ for the three frames are shown in Figs 5(a)~(c). Figures 5a, b, and c show the distributions for node 3 of element 3 (one-bay one-story frame), node 3 of element 9 (two-bay two-story frame) and node 2 of element 11 (four-bay two-story), respectively. One most distinct observation can be made from the $m^*-\log_{10}R_{ki}$ distribution is that: almost all data are clustered in the vicinity of $m^*=1$ when their $Log_{10}R_{ki} \geq 6$. 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. Again, this observation will be found equally valid for drift calculation i.e., $d^*=1$ when $Log_{10}R_{ki} \geq 6$ (refer examples in Figs 6a~c). This, therefore, substantiate the previous conclusion. A detail discussion regarding this general conclusion can be found in Hasan et al. (1995).



(a)



(b)



(c)

Fig. 6. Frame drift for extended end-plate connections

Table 2. R_{ki} and m^* in the illustrative examples (Figs. 5a~c) for moment analysis

Frame Type	Node	Beam	Min. R_{ki} of a rigid conn. in kip-in/rad.			m^*	
			Present study	EC3	Bjorh.	EC3	Bjorh.
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 5(a~c) are listed in Table 2. The boundary values of initial connection stiffnesses for the roof beam (W14×22) and the floor beam (W21×44) are largely different e.g., 0.48×10^6 kip-in./rad. and 2.04×10^6 kip-in/rad., respectively, as per the

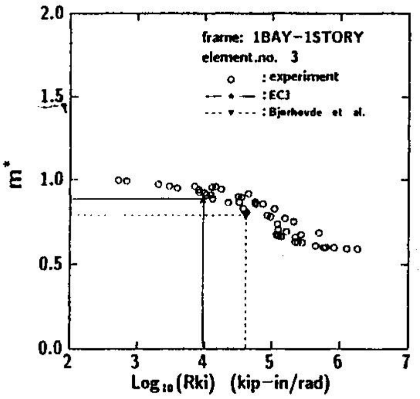
EC3 classification system. This obviously, exposes the inconsistency of the classification systems. The normalized moments correspond to the EC3 classification system are 0.941, 0.957 and 0.987, while their counter-figures for Bjorhovde et al.'s classification system are 0.873, 0.884 and 0.930 for the one-bay one-story, two-bay two-story and four-bay two-story frames, respectively. Therefore, with reference to the normalized moment, both systems of connection classification give conservative results, particularly, Bjorhovde et al's classification system.

The numerical values of the initial connection stiffness and normalized drift correspond to the EC3 and Bjorhovde et al.'s classification systems of the three examples in Figs 6(a~c) are tabulated in Table 3. As evident in these three examples, normalized drifts are somewhat equal to unity, however, the EC3 connection classification system performs better than Bjorhovde et al.'s classification system.

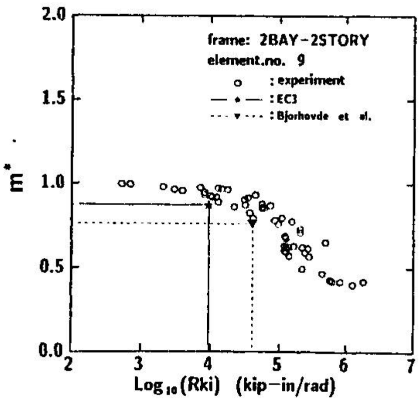
Table 3. R_{ki} and d^* in the illustrative examples (Figs. 6a~c) for drift analysis

Frame Type	Node	Beam	Min. R_{ki} of a rigid conn. in kip-in/rad.			d^*	
			Present study	EC3	Bjorh.	EC3	Bjorh.
1-bay 1-story	3	W14×22	1.0×10^6	0.48×10^6	0.21×10^6	1.058	1.125
2-bay 2-story	5	W21×44		2.04×10^6	0.59×10^6	1.046	1.152
4-bay 2-story	2	W21×44		2.04×10^6	0.59×10^6	1.057	1.161

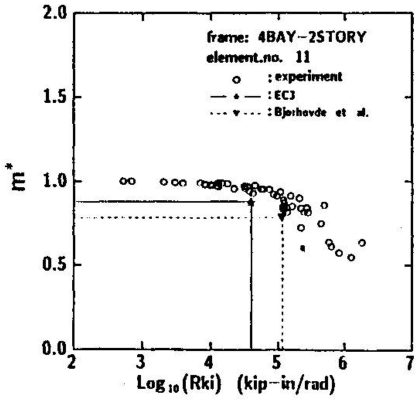
5.2 Maximum initial connection stiffness of a flexible connection



(a)



(b)

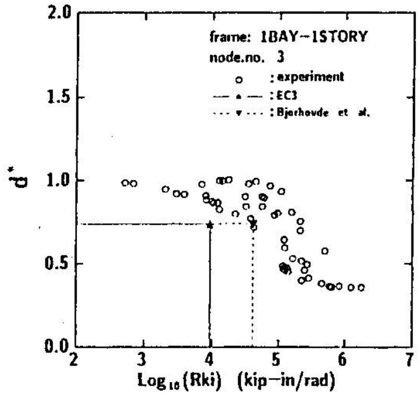


(c)

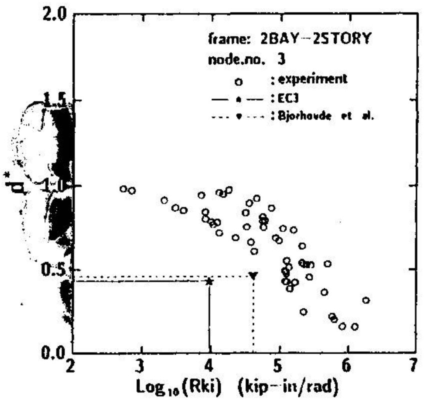
Fig. 7. Beam mid-span moment for single web angle & single plate connections

Figures 7(a)~(c) and 8(a)~(c) show examples of $m^*-\mathrm{Log}_{10}R_{ki}$ and $d^*-\mathrm{Log}_{10}R_{ki}$ distributions, respectively, obtained from frame analysis for the three frames. It is evident from the distribution pattern in these six figures that all data are closely clustered in the vicinity of $m^*=1.0$ or $d^*=1.0$ lines when their $\mathrm{Log}_{10}R_{ki}\leq4.5$. In other words, the maximum initial connection stiffness of a flexible connection can be regarded as $10^{4.5}$ kip-inch/rad. Again, likewise to rigid connection analysis, this very distinct nature of distribution is found valid for all cases.

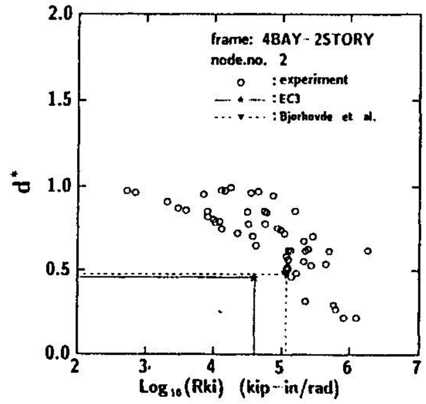
The numerical results of the Figs 7 and 8 are listed in Tables 4 and 5. The invalidity of the classification systems are obvious from these results. While frame analysis reveals that the maximum initial connection stiffness of a flexible connection is $10^{4.5}$ kip-inch/rad., the corresponding value 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 as per the EC3 classification system; and 0.42×10^5, 0.12×10^6 kip-inch/rad. for roof and floor beams, respectively as per Bjorhovde et al's classification system).



(a)



(b)



(c)

Fig. 8. Frame drift for single web angle & single plate connections

The numerical values of normalized moments m^* and normalized drifts d^* in all cases remain far below 1.0, which provides a cautious indication of unconservative design. Besides, the very low normalized frame responses, particularly for d^* (around 0.4 both for the EC3 and Bjorhovde et al.'s classification systems), raise the question of the accuracy of demarcation line between semi-rigid and flexible zone with reference to both stiffness and strength.

Table 4. R_{ki} and m* in the illustrative examples (Figs. 7(a~c) for moment analyses

Frame Type	Elem.	Beam	Max. R_{ki} of a flexible conn. in kip-in/rad.			m*	
			Present study	EC3	Bjorh.	EC3	Bjorh.
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

Table 5. R_{ki} and d* in the illustrative examples (Figs. 8a~c) for drift analyses

Frame Type	Node	Beam	Max. R_{ki} of a flexible conn. in kip-in/rad.			d*	
			Present study	EC3	Bjorh.	EC3	Bjorh.
1-bay 1-story	3	W14×22	$1.0\times 10^{4.5}$	0.96×10^{4}	0.42×10^{5}	0.732	0.735
2-bay 2-story	3	W14×22		0.96×10^{4}	0.42×10^{5}	0.428	0.458
4-bay 2-story	2	W21×44		0.41×10^{5}	0.12×10^{6}	0.452	0.473

6. Conclusion

The rationale used to devise non-dimensional connection classification systems (EC3, 1992 and Bjorhovde et al., 1990) is that the connection stiffness should be compared with that of the connected beam. The validity of this rationale is critically examined here by performing frame analysis utilizing experimental data with the perspective of real moment-rotation behavior of connections. This analysis reveals that the two classification systems have a total reliance on the properties of connected beam, even though, a rational classification system should reflect the proper role of all major connection components on connection behavior.

7. References

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