Reliability of Rotational Behavior of Framing Connections

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INTRODUCTION

Recent studies have pointed to the behavior of beam-column connections as having an important effect on stiffness and strength of steel frames,[1,2] and considerable work has been done to develop analysis methods intended to include not only member, but also connection behavior.[3,4]

Design methods as outlined in the AISC Allowable Stress[5] and LRFD[6] Specifications authorize inclusion of connection effects under the heading of "Type 3" in the former, and "Partially Restrained" (PR) in the latter.

In both analysis and design including connection effects, connection behavior must be known. For typical beam-to-column connections of building frames, voluminous, if fragmentary, data are available.[7,8,9] Attempts at rational prediction of connection behavior have been less than successful, but empirical expressions, based on test data, of the relation between the applied moment M and the resulting connection rotation θ are available. Among these, the most commonly used are those of Frye and Morris,[10] shown in Fig. 1.

The deterministic moment-rotation curves shown in Fig.1, and others similar, are often based on one single test, and do not account for the scatter which may inevitably be expected of connection behavior, specially if field-bolted. Little is available in the way of replicate tests which might provide a database necessary for statistical prediction of connection behavior. Until such information about reliability of connection behavior is provided, its inclusion in design or analysis rests, at best, on a shaky basis.

This paper reports a study the aim of which is to provide a statistical database for the purpose of establishing the degree of reliability of strength and stiffness for one connection type. To this end, nominally identical framing connection specimens from different sources were tested under identical conditions. The individual moment-rotation curves obtained from these tests form the database for probabilistic determination of the reliability with which specified behavior of these connections can be expected.

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TEST PROGRAM

Specimens

Six fabricators volunteered to provide double-web angle connection specimens fabricated according to the drawing and specifications shown in Fig. 2. Two identical specimens were provided with untensioned bearing-type bolts (B-bolts), and two with friction-type bolts (F-bolts) tensioned according to shop practice of the individual fabricator, for a total of 12 specimens for each bolt type. Since each specimen contained

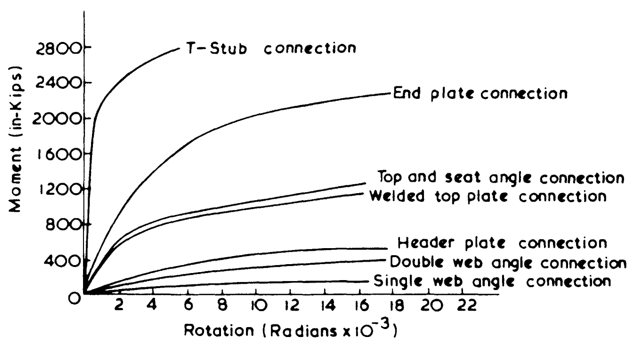

Fig. 1. Connection moment-rotation curves.[10]

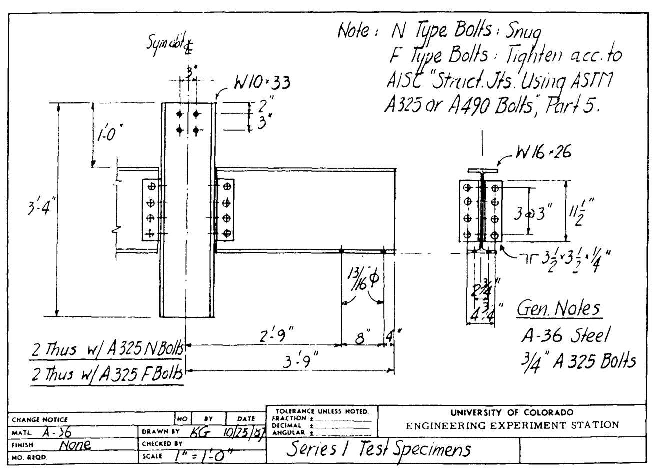

Fig. 2. Test specimen.

Table 1. Test Program					
Test Series	No. of Fabricators	Connection Type	No. of Specimens	No. of Connections	Angle Thickness
1	6	B-Bolt	12	24	¼
2	6	F-Bolt	12	24	¼
3	1	F-Bolt	6	12	⅜

two web-angle connections, we had in fact a sample of 24 of each connection.

In addition, one fabricator supplied us with a set of six specimens with ⅜-in. thick web angles with F-bolts, attached to previously tested members. Table 1 summarizes the test specimens. This program gave us the opportunity to assess the following factors:

- Scatter of connection behavior
- Comparison of B-bolt versus F-bolt behavior
- Influence of connection stiffness
- Effect of applied load history.

The ratio of moment to shear transmitted by the connection might have considerable influence on its behavior, but was not a variable in our study. It was held constant at the value of shear span shown in Fig. 2.

It should be noted that these double web-angle connections are commonly used as shear connections. Our discussion only concerns their rotational characteristics and therefore none of the conclusions should be interpreted as addressing their reliability in transmitting shear. We are here only concerned with the way in which they can be expected to rotate under applied moment.

The test configuration used in this study, consisting of beams and column stub as shown in Figs. 2 and 3, should not be construed as suggesting that web angles should be used to provide lateral resistance for unbraced frames. This specimen type was used here only to provide a simple connection test setup.

Test Method and Instrumentation

The specimens were mounted as shown in Fig. 3 in a 1000 kip MTS universal testing machine with load and displacement control. Instrumentation consisted of rotation meters and strain-gaged links to determine applied moments. The former, also shown in Fig. 3, consisted of an aluminum frame mounted on the beam, with linear variable differential transducers (LVDTs) bearing against the column flange. Each link support shown in Fig. 3 was instrumented for measurement of reactions in order to determine the connection moment.

Test Procedure

All tests were carried out under load control. Two types of load history were applied: A cyclic regime (C-Type) consisting of three cyclic reversals each up to moments of 80, 160, and 240 kip-inches for Test Series 1 and 2, and 160, 320, and 480 kip-inches for Series 3, followed by load increase up to a rotation of about 0.06 radians which would entail contact between beam and column flanges. For comparison, some of the specimens were subjected to a monotonic load increase (M-Type) up to maximum connection rotation.

During tests, data were collected by a ten-channel data acquisition system at specified time intervals, and significant events were recorded. In some tests, the shock caused by sudden bolt slip was sufficient to cause displacement of the LVDTs; corrections were made to the readings in such cases.

TEST RESULTS

All test results will be presented in the form of monotonically increasing moment-rotation curves. These were obtained from the cyclic tests by drawing envelope, or spline, curves circumscribing the cyclic response. Comparison with curves from monotonic tests, described in greater detail in Ref. 11, was in general good.

Test results will be described separately for the different series specified in Table 1.

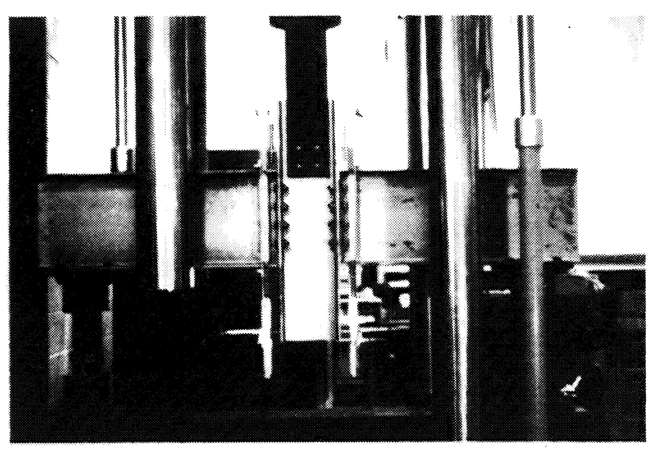

Fig. 3. Test setup.

Series 1

Figure 4 shows monotonic moment-rotation curves obtained from 24 connections in 12 specimens obtained from six different fabricators. As might be expected of connections with non-tensioned bolts of random location within $\frac{1}{16}$-in. oversize holes, the range of rotational behavior is vast. These results are sufficiently unpredictable that no reliance whatever can be placed on the rotational resistance of such web-angle connections with bearing bolts. No further reference will be made to the results of Test Series 1.

Series 2

Moment-rotation curves from 22 connections of 11 specimens of Series 2, obtained either from monotonic, or as envelope curves from cyclic tests, are shown in Fig. 5. Although showing considerable variation, a systematic random pattern is seen here for both stiffness and strength. Non-linearity is mainly due to yielding of the outstanding angle legs, and bolt slip occurs only under rotations well in excess of admissible values.

Series 3

The 12 moment-rotation curves for these $\frac{3}{8}$-in. web angle connections furnished by one fabricator are shown in Fig. 6, indicating consistency in the initial stiffness, but considerable scatter in the occurrence of bolt slip which accounted for the onset of softening of these connections.

Descriptive Parameters of Connection Response

The parameters used to describe the connection response in the statistical analysis which follows were the secant modulus K_{sec}, the elastic limit moment M_{el}, and the moment under permissible rotation M_s, as shown in Fig. 7.

The secant modulus K_{sec} was based on the moment corresponding to a rotation of 0.002 radians, well within the elastic range. M_{el} was obtained visually as the moment corresponding to the onset of softening of the M-θ curve. M_s was the moment corresponding to the end rotation of a uniformly loaded simple beam under allowable midspan deflection $L/360$, computed as 0.009 radians.

Tables 2 and 3 show the values of these parameters for the right and left connection of each of the 12 specimens of Series 2, and of the six specimens of Series 3. In these tables, fabricator, test number, and loading type, parameter values, and tension control are shown. These values furnish the database for the statistical study of the next section.

STATISTICAL ANALYSIS

The purpose of our study is to assess the reliability with which strength and stiffness of these web angle connections can be predicted. To this end, we will subject the strength parameters M_{el} and the stiffness parameter K_{sec}, defined in Fig. 7, to statistical analysis with the aim of predicting their minimum values which may be expected with specified probability, or confidence level. In addition, we will try to extract

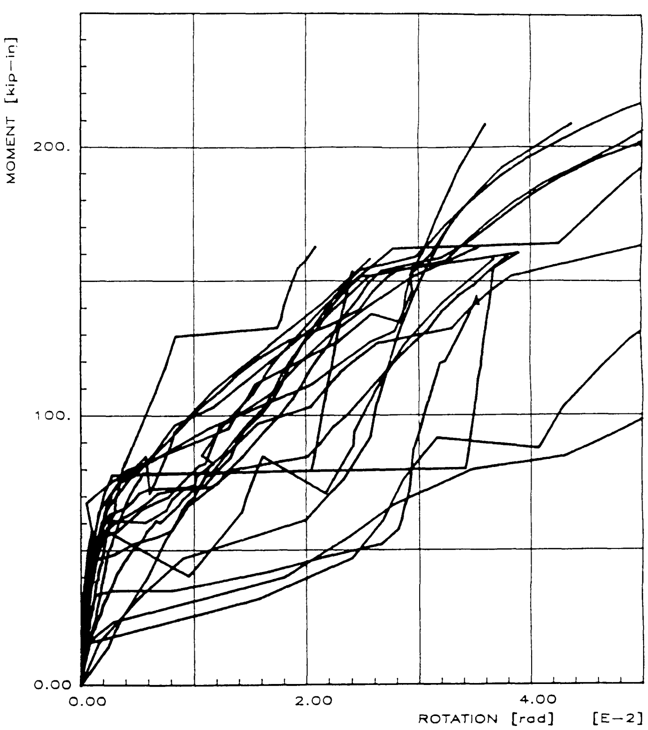

Fig. 4. Bearing-type bolt connection response.

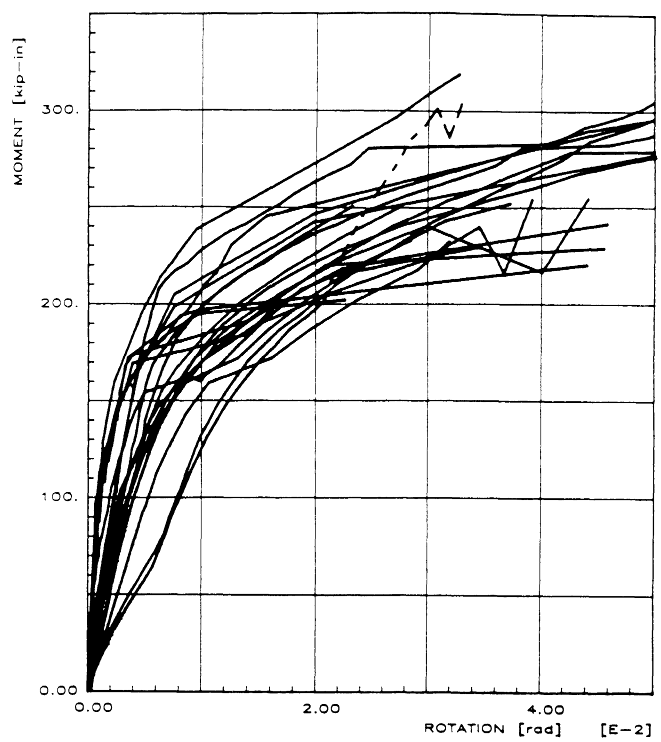

Fig. 5. Friction-type bolt connection response, Series 2.

Table 2. Sample Data for Series 2									
Fabricator	Test No.	Loading Type	K_{sec} (kip-in./radian)		M_{el} (kip-in.)		M_s (kip-in.)		Tension Control Method
			is	rs	is	rs	is	rs	
1	1	C	30,000	33,000	168	182	183	200	Calibrated wrench
	15	C	46,500	52,000	100	167	110	185	Specified tension
2	11	C	80,000	72,500	175	240	172	212	not available
	14	M	59,500	39,500	160	218	200	220	
3	23	C	69,000	74,000	140	179	135	179	Twist-off
	24	M	75,000	66,000	150	195	133	195	
4	13	C	40,000	50,000	168	200	210	225	Turn-of-nut
	8	M	—	—	—	—	—	—	(no data recorded)
5	3	M	35,000	34,000	120	135	172	175	Twist-off
	4	C	37,000	32,500	140	142	155	160	
6	6	M	47,500	35,000	175	185	150	118	Twist-off
	16	M	24,242	25,806	130	165	161	183	

Table 3. Sample Data Test Series 3									
Fabricator	Test No.	Loading Type	K_{sec} (kip-in./radian)		M_{el} (kip-in.)		M_s (kip-in.)		Tension Control Method
			is	rs	is	rs	is	rs	
3	25	M	95,000	115,000	338	338	345	345	Twist-off
	26	C	135,000	89,000	265	270	280	280	
	27	C	89,500	112,500	395	350	360	340	
	28	M	95,000	115,000	265	230	243	280	
	29	C	105,000	130,000	360	325	370	335	
	30	M	99,000	100,000	370	365	370	378	

information about systematic differences between products of different fabricators in order to obtain insight into problems of quality control.

Statistical Methods

The value of any characteristic will vary among the specimens tested. The total of these specimens is called the sample. The individual values can be plotted in the form of a histogram. We assume that this histogram can be matched under increasing sample size by a continuous bell-shaped curve containing an area of value unity, as shown in Fig. 8, representing a normal distribution. This curve displays the character of the population of an infinite number of such specimens, of which the sample is assumed to be a part. The shape of this curve can be defined by just two parameters, the mean X and the standard deviation S, defined in Fig. 8. The coefficient of variation S/X indicates the degree of scatter of results among nominally identical specimens.

The probability P of exceeding any particular value of the parameter x is given by the area under the bell curve (shown shaded in Fig. 8) which is to the right of that value, and which can range from zero to unity.

The probability P can be found for a distribution with given X and S for any value of x by integration, or from available tables.[12] In this way, we will determine the minimum strength and stiffness which can be expected at a specified level of confidence—say, 95 times out of the next 100 specimens, as will be assumed in what follows.

The methods just described depend on the premise that all specimens belong to the same population. However, the techniques of different fabricators could be so different that their products might not belong to one population. Such conditions are determined by an analysis of variance (ANOVA).[12] An occurrence of this type will be discussed below in connection with the stiffnesses of Series 2.

These techniques were applied to the test data in the following sequence: the strengths M_{el} and M_s, and the stiffness K_{sec} of Series 2 and 3 were first subjected to an analysis of variance to determine the likelihood of their belonging to one or more populations to within the 95 percent level of confidence, using the F-Test described in Ref. 12.

For each population, the values X and S of the normal distribution were computed, and the minimum value of each parameter which might be expected within 95 percent confidence level was calculated.

Series 2

Strength

The strengths M_{el} and M_s, defined in Fig. 7, were subjected to the statistical treatment outlined, and the results are summarized in Table 4. An ANOVA showed to within a 95 percent confidence level that the strength of all 22 specimens belonged to one population, whose characteristic values X and S are shown in Table 4, and that one might expect 95 out of the next 100 specimens to have strengths in excess of M_{el} = 89 kip-inches and M_s = 99 kip-inches.

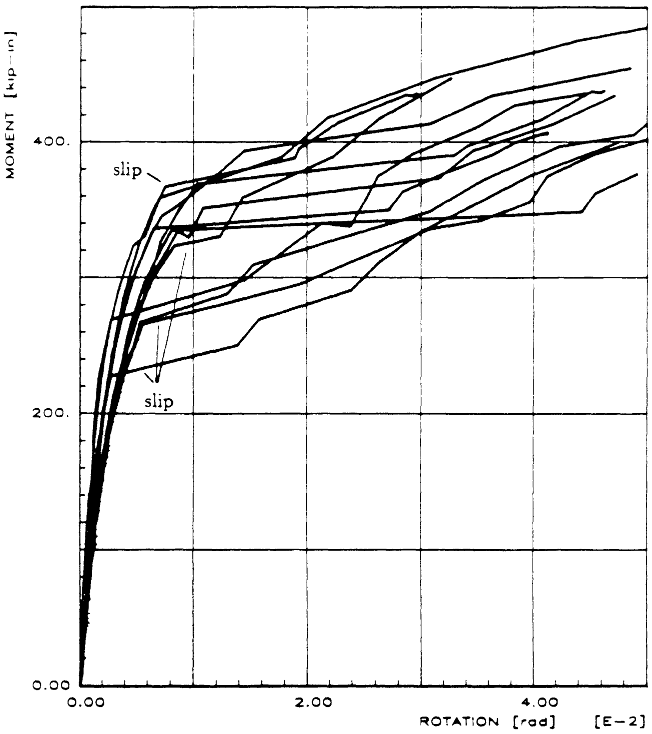

Fig. 6. Friction-type bolt connection response, Series 3.

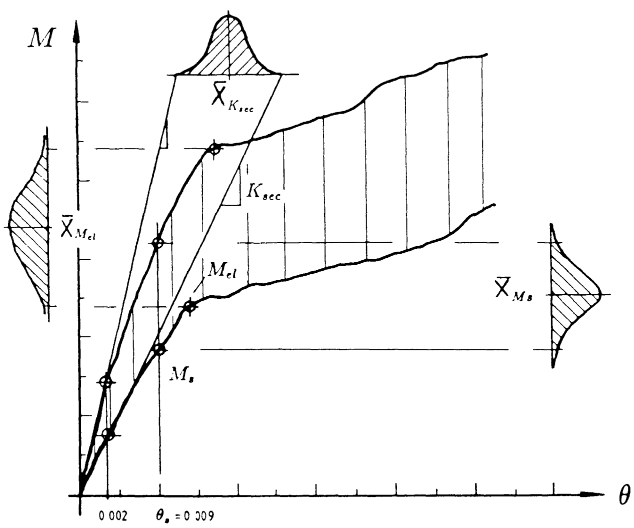

Fig. 7. Descriptive parameters of connection response.

Stiffness

The observed stiffnesses K_{sec} listed in Table 2 showed a great deal of scatter, indicated by the coefficient of variation shown in Table 4 and the dashed curve of Fig. 9. The ANOVA showed two distinct populations: Population A, consisting of 14 specimens from Fabricators 1, 4, 5, and 6, and Population B, of eight specimens from Fabricators 2 and 3. The statistical characteristics of each of these populations, as well as those of the composite sample of 22 specimens, are presented in Fig. 9 and Table 5. These results show that of the next 100 specimens from the first set of fabricators, 95 can be expected to have a stiffness K_{sec} in excess of 14,486 kip-in./radian, and of those from the second set of fabricators, 95 can be expected to have stiffnesses in excess of 26,438 kip-in./radian. If all 22 specimens are lumped together, then a minimum stiffness of only 6,475 kip-in./

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \; ; \quad n = \text{Sample Size}$$

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - \overline{X})^2}$$

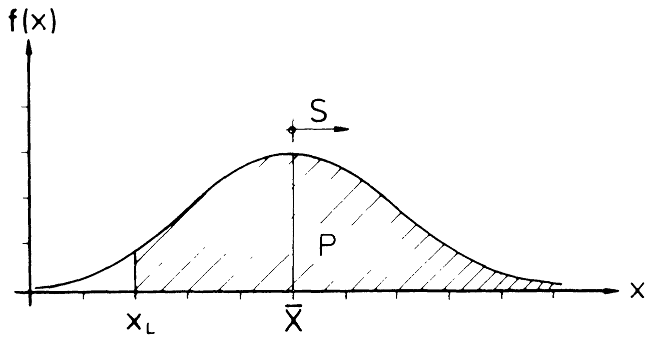

Fig. 8. Assumed population distribution.

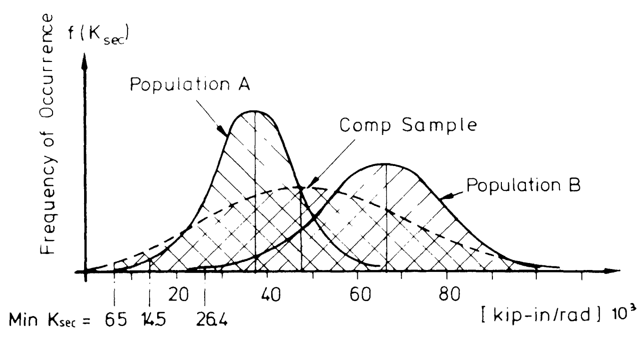

Fig. 9. Assumed distribution for K_{sec}

Table 4. Composite Sample Statistics Test Series 2

Series 2 Sample Size: n = 22	Stiffness	Strength	
	K_{sec} (kip-in./radian)	M_s (kip-in.)	M_{el} (kip-in.)
Sample mean	48,093	174	165
Standard deviation	17,710	32	35
Coefficient of variation	36.8%	18.4%	21.2%
	C = 95% Confidence Interval		
Stat. minimum P = 95%	min K_{sec} = 6,475	min M_s = 99	min M_{el} = 89

Table 5. Population Dependent Statistics Test Series 2

Series 2	Population A	Population B
	K_{sec} (kip-in./radian)	K_{sec} (kip-in./radian)
Fabricator	1, 4, 5, 6	2, 3
Sample size	n = 14	n = 8
Sample mean	37,325	66,938
Standard deviation	8,737	12,704
Coefficient of variation	23.4%	18.9%
	C = 95% Confidence Interval	
Stat. minimum P = 95%	min K_{sec} = 14,487	min K_{sec} = 26,438

Table 6. Statistics Test Series 3

Series 3 Sample Size: n = 12	Stiffness	Strength	
	K_{sec} (kip-in./radian)	M_s (kip-in.)	M_{el} (kip-in.)
Sample mean	106,667	328	323
Standard deviation	15,091	44	52
Coefficient of variation	14.2%	13.4%	16.1%
	C = 95% Confidence Interval		
Stat. minimum P = 95%	min K_{sec} = 65,377	min M_s = 208	min M_{el} = 180

radian can be assumed at the 95 percent confidence level, a value so low as to be negligible.

The expected stiffness of specimens from Fabricators 2 and 3 is about twice that of specimens from Fabricators 1, 4, 5, or 6. One might look for obvious manufacturing differences among these fabricators. The last column of Table 2 gives little clue as to causes: Three different bolt tension control methods were used by the fabricators of Population A, among whom two used the same method as one of the fabricators of Population B. The reason for these seemingly systematic differences remains unknown.

Series 3

The 12 ⅜-in. web angle specimens constituting Series 3 came from one Fabricator (No. 3). In fact, the M-θ curves of Fig. 6 show much less scatter prior to bolt slip than those of Fig. 5 for Series 2. The strength of these connections, defined by the onset of softening, was determined by bolt slip; this is in contrast to the softening of the ¼-in. angle connections which was caused by yielding of the outstanding angle legs. The uncertainty of this event seems to be about the same, no matter what the cause, as evidenced by comparison of the coefficients of variation for the strength measures of Series 2 and 3.

The statistical analysis summarized in Table 6 indicates that at the 95 percent confidence level both strength and stiffness belong to one population. Values of strength and stiffness which may be expected to be exceeded in 95 out of the next 100 specimens from Fabricator 3 are also shown in Table 6.

The coefficient of variation for the stiffness K_{sec} of the specimens of Series 3 is less than half of that of Series 2, indicating good quality control within one fabricator. For strength, Series 2 and 3 have similar scatter, indicating the difficulty of predicting bolt slip even within one shop.

DISCUSSION OF RESULTS

How will these results affect the designer who might wish to include connection restraint as provided by Type 3 Construction in the ASD, and PR Design in the LRFD Specifications? An example of this approach has been given by Lindsey[13] in an effort to optimize purlin size. In such a case, the engineer's likely recourse for the determination of connection stiffness and strength is to rely on analytical formulations such as that of Frye and Morris, which, as stated earlier, are deterministic and have in some cases[8] been found at variance with test data.

For the ¼-in. web angle connections of Series 2, the curve predicted by Frye and Morris is shown in Fig. 10, along with the range of the M-θ curves from our tests. The Frye and Morris curve is somewhat on the high side. Its initial stiffness is also shown, and the connection strength can readily be extrapolated.

If for safety's sake it is specified that these connection properties should be at the 95 percent level of confidence, then our statistical calculations would permit a serviceability moment and stiffnesses as also shown in Fig. 10, of values greatly below those given by deterministic formulation, or by any one of the test curves.

Figure 11 shows similar comparisons for Series 3: The Frye and Morris prediction is much too high (a fact which verifies the findings of Ref. 8). Because of the low scatter of the observed initial stiffnesses, the stiffness at the 95 percent confidence level is close to the measured values, but the strength under serviceability is much lower than any observed value.

It is clear that in any case the choice of either a deterministic formulation such as that of Frye and Morris, or a single test case, may lead to connection strength and stiffness grossly on the unsafe side of values in the actual structure.

CONCLUSIONS

Based on the test results and analyses which have been presented, we can draw the following conclusions for rotational behavior of the web angle connections under consideration:

1. The bearing-bolt connections showed unpredictable behavior; they are not recommended for joints intended to offer rotational constraint.
2. The friction-bolt connections exhibited a systematic pattern of behavior, whose non-linearity was caused largely by yielding for thin web angles, and by bolt slip for thicker angles.
3. The scatter of stiffness is much less for the stronger than for the weaker connections; on this basis, it may be expected that the statistical variation of joints designed as moment-resistant may be more favorable than that of the web-angle connections.
4. The strength of the connections, while showing considerable scatter, varied insignificantly among fabri-

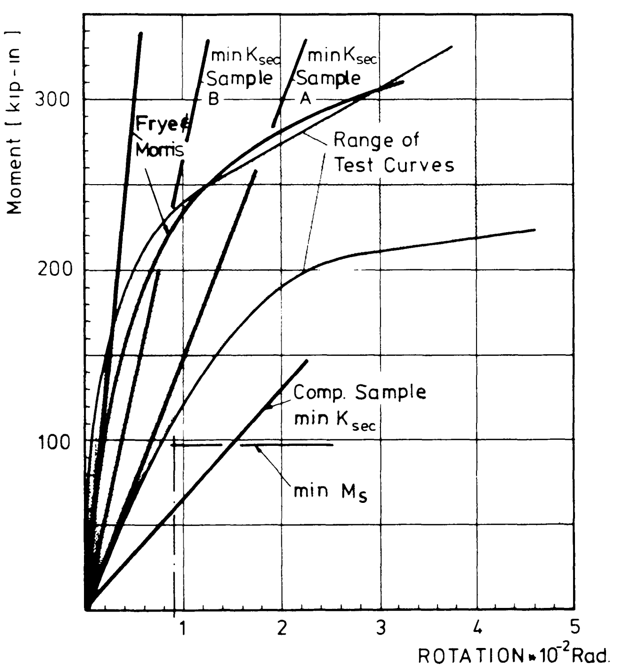

Fig. 10. Properties of Test Series 2.

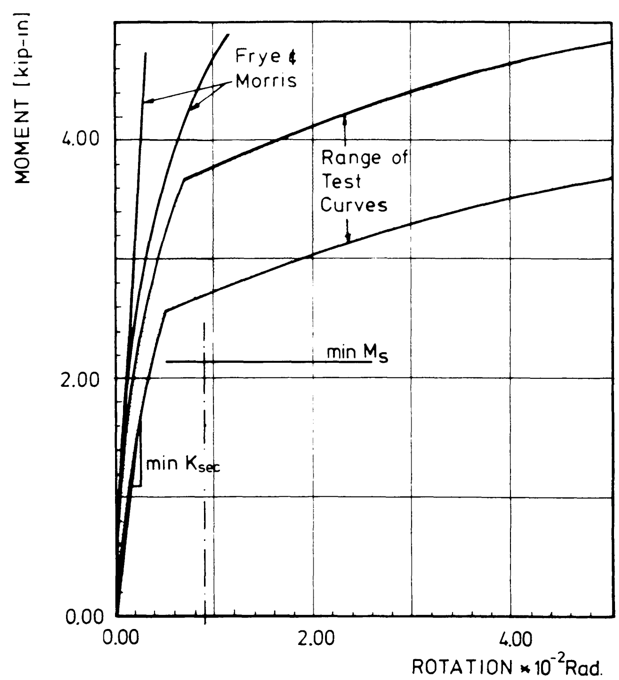

Fig. 11. Properties of Test Series 3.

cators. Statistical minimum values can be determined with a reasonable level of confidence.

5. Initial stiffness varied significantly among fabricators for the thin web-angle connections, although no physical reasons could be identified. It was not possible to assign meaningful statistical stiffness values for these specimens based on the totality of our test data. The thicker web-angle connections, from one fabricator, showed much more consistent response.
6. Deterministic predictions of connection behavior, based on either empirical formulations or single test data, are likely to overestimate reliable values of strength and stiffness. Statistically designed replicate test series are needed to establish these characteristics.

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ACKNOWLEDGMENT

This study was carried out as an M.S. thesis by the first-named author in the C.E.A.E. Department of the University of Colorado in Boulder. The following colleagues and fabricators made this work possible by furnishing specimens, equipment, funds, and, most importantly of all, enthusiasm and expert advice, for which we thank them sincerely: William Ashton, Egger Steel, Sioux City, IA; Michael Milot, Boulder Steel, Boulder, CO; Jim Roscoe, Roscoe Steel, Boise, ID; Ron Singleton, Stanley Structures, Denver, CO; Maynard Trostel, Platte River Steel, Greeley, CO; George Zimmerman, Zimmerman Metals, Denver, CO; and William Zimmerman, Zimkor Industries, Littleton, CO.