Eccentrically Loaded Slip-Resistant Connections

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ALTHOUGH ECCENTRICALLY loaded connections should be avoided whenever possible, designers are frequently faced with situations where this type of joint must be used. Such cases could be the provision of crane girder brackets or beam web splices (Figs. 1a and 1b). Eccentricity is present even in a standard beam connection (Fig. 1c), although the effect of the eccentricity is usually not significant.

Considerable attention has been directed in recent years toward the assessment of the ultimate strength of eccentrically loaded connections, whether welded or fastened with high-strength bolts.[1,2,3,4] One situation which has received very little attention, however, is the eccentrically loaded bolted connection in which slip is undesirable and friction-type high-strength bolts are employed. As far as is known, no tests except those which will be reported in this presentation have been conducted on this type of connection.[5] The purpose of this report is to review the procedure recommended for the design of slip-resistant eccentrically loaded bolted connections and to compare the results obtained in this fashion with the available experimental data.

ANALYSIS OF SLIP-RESISTANT CONNECTIONS

Unlike the situation in bearing-type joints, it is reasonable to assume that each fastener in a slip-resistant joint carries the same load. This is true because the slip resistance provided by an individual bolt is the product of the slip coefficient of the faying surfaces, k_s; the number of faying surfaces, m; and the clamping force provided by the bolt, T_i; and these quantities are independent of the location of a given bolt within the joint. Calling the slip resistance R_s, this can be written as

$$R_s = mk_sT_i \tag{1}$$

Considering further that the eccentric connection can be assumed to rotate about an instantaneous center and that the individual bolt forces act perpendicular to a line between the bolt and the instantaneous center, the analysis is quite straightforward.

A single line of bolts loaded eccentrically is shown in Fig. 2. The instantaneous center of rotation (i.c.) is located by trial. It must be on the side of the connection opposite to that of the load and, if the fastener arrangement is symmetrical about a horizontal axis, it will lie on that axis. Any trial location of the instantaneous center is checked by applying the equations of equilibrium. Using the terminology of Fig. 2, these can be stated as

$$\sum_{i=1}^{n} R_s \sin \phi_i = 0 \tag{2}$$

$$\sum_{i=1}^{n} R_s \cos \phi_i - P = 0 \tag{3}$$

$$P(e + r_0) - \sum_{i=1}^{n} r_i R_s = 0 \tag{4}$$

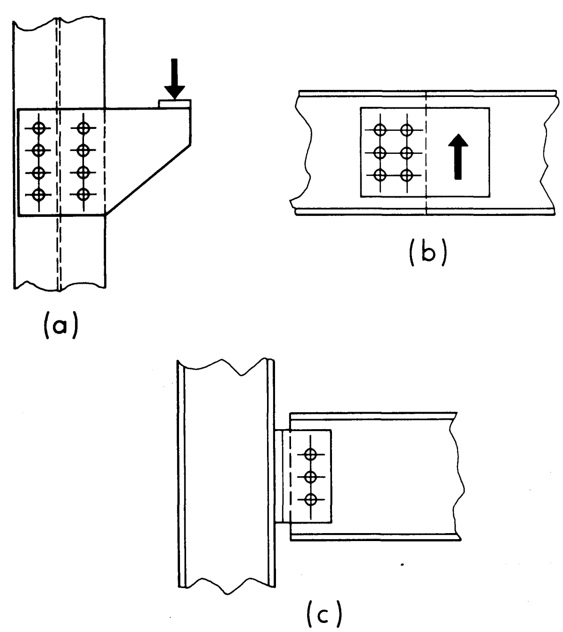

Fig. 1. Typical eccentrically loaded connections

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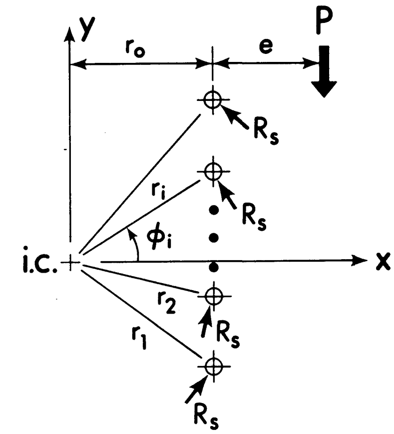

Fig. 2. Forces on eccentrically loaded slip-resistant connection

Equations (2) and (3) are more conveniently stated in terms of the *x-y* coordinate system:

$$R_s \sum_{i=1}^{n} \frac{y_i}{r_i} = 0 \tag{5}$$

$$R_s \sum_{i=1}^{n} \frac{x_i}{r_i} - P = 0 \tag{6}$$

It should be noted that Eq. (2) or (5) will be satisfied automatically for those cases in which there is no component of load in the *x*-direction.

The trial location of the instantaneous center corresponds to the true location when the equations of equilibrium are satisfied. The solution gives both the location of the instantaneous center, which is of no direct interest to the designer, and the value of the eccentric load *P*, which corresponds to the chosen slip resistance per bolt.

In order to proceed with a solution, the slip resistance of an individual bolt, R_s, must be evaluated. Usual practice has been to put Eq. (1) into terms of an equivalent shear resistance, even though the friction-type bolt is not actually acting in shear. At present, the AISC Specification permits an equivalent allowable shear stress of 15 ksi for A325 bolts and 20 ksi for A490 bolts.[6] The recently published *Guide to Design Criteria for Bolted and Riveted Joints*[5] has suggested shear stress values corresponding to various probabilities of slip, a procedure that tells the designer a good deal more about the potential behavior of the structure. For example, a slip probability level of 5% on A36 steel with clean mill scale corresponds to equivalent allowable shear stress values for A325 and A490 bolts of 17.8 ksi and 20.7 ksi, respectively.

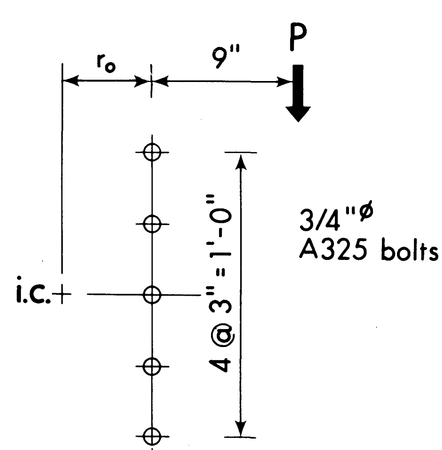

Fig. 3. Connection of design example

DESIGN EXAMPLE

Consider the connection shown in Fig. 3, where five ¾-in. dia. A325 bolts are used in a connection which is loaded by a force 9 in. from the center of gravity of the bolt group. The bolt resistance will be taken as that corresponding to the equivalent allowable shear stress level of 17.8 ksi.

$$R_s = 17.8 \text{ ksi} \times 0.442 \text{ sq. in.} \times 2 \text{ faying surfaces}$$
$$= 15.7 \text{ kips}$$

The results of the last trial are:

$$\text{Try: } r_0 = 1.00 \text{ in.}$$
$$\text{Then: } r_1 = r_5 = \sqrt{1^2 + 6^2} = 6.08 \text{ in.}$$
$$r_2 = r_4 = \sqrt{1^2 + 3^2} = 3.16 \text{ in.}$$
$$r_3 = 1.00 \text{ in.}$$

Solving Eq. (6) for *P* gives:

$$P = 15.7\left[\left(\frac{1.00}{6.08} + \frac{1.00}{3.16}\right) 2 + 1.00\right] = 30.9 \text{ kips}$$

Solving Eq. (4) for *P* gives:

$$P(9.00 + 1.00) = 15.7[(6.08 + 3.16)2 + 1.00]$$
$$P = 30.6 \text{ kips}$$

Although the values of *P* so obtained are not identical for this trial, they are in close enough agreement.

TEST PROGRAM

Three full-size specimens were tested in order to examine the behavior of slip-resistant eccentrically loaded connections. Considering the variables in the problem, for example the condition of the faying surfaces and the variation in the bolt clamping force, a greater number of specimens would have been desirable. However, these tests do give a reasonable insight into the behavior of such connections and allow a comparison between actual slip loads and predicted values as well as with allowable loads.

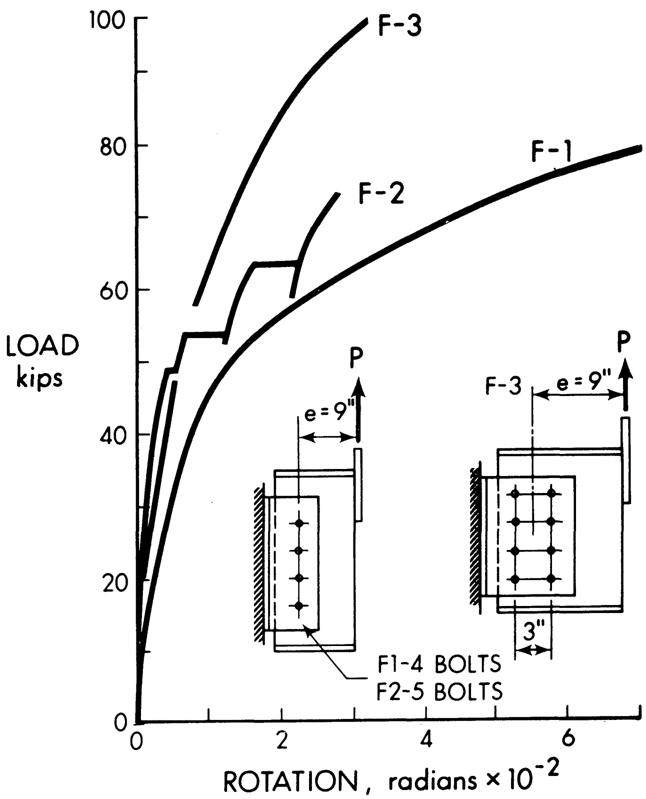

Fig. 4. Test specimens and load-rotation behavior

The configuration of the test pieces is shown in the inset to Fig. 4. All specimens used ¾-in. dia. A325 bolts and all bolts were from the same production lot. Steel parts used were carbon steel corresponding to ASTM A36. All faying surfaces were clean mill scale and standard shop procedures were used in forming the holes, etc. Bolts were installed in the laboratory, using the turn-of-nut method.[6] However, actual clamping forces induced during installation were measured so that slip loads might be predicted more accurately. No particular attempt was made to install the bolts in the centers of their holes and it could be expected that some bolts might initially be in bearing, just as would be expected in real structures. The average clamping force in these bolts was about 42 kips, substantially above the specified minimum load of 28 kips.[6] Tests on specimens using single bolts and loaded axially were also conducted, in order to determine the slip coefficient of the faying surfaces. It was established that the slip coefficient of the material used in the eccentrically loaded specimens was 0.27. Using all of these data, and measured rather than prescribed dimensions, the loads at which slip should theoretically have occurred were computed. These are shown in Table 1.

Neither Specimen 1 nor Specimen 3 showed any abrupt slip as the connection was loaded. Specimen 1 did show an increased rate of rotation starting at a load level of about 50 kips. Specimen 2 had an initial slip at a load level of about 48 kips, compared with the predicted value of 44.1 kips. Further slips occurred at 53 kips and 63 kips. (The geometry of Specimen 2 corresponds to the connection used in the Design Example.)

Table 1

Specimen	Slip Loads (kips)			Factor of Safety	
	Theoretical	AISC (Ref. 7)	"Guide" (Ref. 5)	AISC (Ref. 7)	"Guide" (Ref. 5)
1	30.0	14.2	19.4	2.11	1.55
2	44.1	20.9	29.3	2.11	1.51
3	63.3	29.4	42.0	2.15	1.51

DESIGN RECOMMENDATIONS

At the present time, design of slip-resistant connections would probably be based on the method prescribed in the AISC *Manual of Steel Construction.*[7] Although that procedure is fundamentally developed for bearing-type eccentrically loaded connections, it is based on the use of a constant resistance for each bolt and is therefore a satisfactory approach for the slip-resistant case. (In this method, rotation about the center of gravity is assumed, however, and the method is not identical to the procedure described in this paper.)

The allowable loads (AISC) are also shown in Table 1. These are calculated on the basis of 15 ksi allowable equivalent shear stress and the actual rather than an "effective" eccentricity. The introduction of the latter quantity arose out of tests on bearing-type connections and is not appropriate for slip-resistant connections. The factor of safety obtained by comparing the theoretical slip loads with the AISC allowable values is about 2.1 for these specimens.

The *Guide to Design Criteria for Bolted and Riveted Joints* also recommends allowable loads for eccentrically loaded slip-resistant connections.[5] They use equivalent allowable shear stresses corresponding to 5% or 10% slip probabilities in combination with coefficients developed by the writer.[3] Allowable loads by this method and corresponding to the 5% slip probability level (17.8 ksi for A325 bolts) are also given in Table 1. Comparing these loads to the theoretical slip loads, it is seen that the factor of safety is reduced to about 1.5.

SUMMARY AND CONCLUSIONS

Tests of typical slip-resistant eccentrically loaded connections have shown that the actual behavior of the joint may or may not exhibit slip. If slip does not occur, it is likely due to the fact that one or more fasteners is already in bearing or comes into bearing soon after the load is applied.

The prediction of allowable loads based on either current standard practice (AISC *Manual of Steel Construction*) or recently recommended procedures (*Guide to Design Criteria for Mechanically Fastened Joints*) will produce safe designs. The factor of safety provided by the former method is probably higher than is necessary. The latter method, even at a slip probability method of 5%, produces a design incorporating a reasonable factor of safety.

ACKNOWLEDGMENTS

The work described in this report was conducted with the assistance of N. M. Holtz and M. J. Perlynn and their contribution is gratefully acknowledged. The study was carried out in the Department of Civil Engineering at the University of Alberta.

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