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Behavior of Slip-Resistant Bolted Joints

Comportement des assemblages boulonnés résistant par frottement

Verhalten von Reibungsverbindungen

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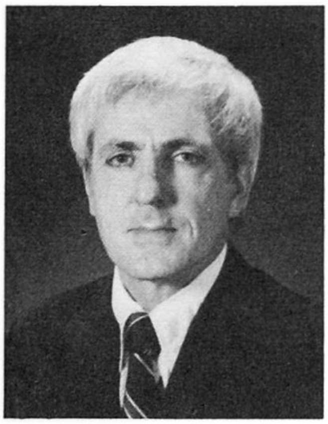

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SUMMARY

A slip-resistant joint (also called friction-type joint) is one which has a low probability of slip at any time during the loading for which it was designed. It is used where any occurrence of major slip would endanger the serviceability of the structure. For a given number of slip planes and bolts, the slip load will be proportional to the product of the slip coefficient and the bolt preload force. The influence of various effects on these controlling features is presented and design rules are proposed.

RÉSUMÉ

Un assemblage boulonné est appelé «résistant par frottement» si la probabilité de glissement relatif des pièces assemblées est faible pendant toute la durée d'application des charges pour lesquelles il a été dimensionné. On l'utilise lorsque l'apparition d'un glissement important met en danger l'aptitude au service de la structure. Pour un nombre donné de plans de glissement et de boulons, la charge qui provoque le glissement est proportionnelle au produit du coefficient de frottement par la force de précontrainte appliquée sur les boulons. L'article présente l'effet de différents paramètres qui peuvent influencer la résistance au glissement et propose des règles de dimensionnement.

ZUSAMMENFASSUNG

Eine Reibungsverbindung (auch schlupffreie Verbindung genannt) liegt vor, wenn die Wahrscheinlichkeit einer Verschiebung der verbundenen Teile infolge der Bemessungslast klein ist. Sie wird verwendet, wenn jegliche Verschiebung das Verhalten des Bauwerks im Gebrauchszustand gefährden würde. Für eine vorgegebene Anzahl Schrauben und Reibungsflächen ist die Last, die eine Verschiebung bewirkt, proportional zum Produkt aus Reibungskoeffizient und Vorspannkraft der Schrauben. Der Einfluss von verschiedenen Parametern wird dargestellt, und Bemessungsregeln werden vorgeschlagen.

1. INTRODUCTION

A slip-resistant joint (also called friction-type joint) is one which has a low probability of slip at any time during the loading for which it was designed. It is used where any occurrence of major slip would endanger the serviceability of the structure and where slip therefore has to be avoided. It should be emphasized that, in general, the slip-resistant connection is used to meet a serviceability requirement. Thus, in load factor design, the design of a slip-resistant connection is to be carried out under the working loads, not the factored (ultimate) loads; the joint must not slip in service. (The term "working load" is used throughout this paper to represent that load specified by the authority having jurisdiction for the structure. The terms "characteristic load" or "specified load" are often used elsewhere to mean the same thing.) However, it must also be noted that some jurisdictions require slip-resistant connections in cases where slip at the ultimate load level might produce changes in geometry affecting stability. This would be an unusual situation.

In a slip-resistant joint, the externally applied load usually acts in a plane perpendicular to the bolt axis. The load is completely transmitted by frictional forces acting on the contact area of the plates fastened by the bolts. (The term "plates" is used here to mean not only plates but any connected parts such as angles, channels and so on.) This frictional resistance is dependent on the bolt preload and slip resistance of the contact surfaces. The capacity is assumed to have been reached when the frictional resistance is exceeded and overall slip of the joint occurs that brings the plates into bearing against the bolts.

Slip-resistant joints are often used in connections subjected to load reversals, severe stress fluctuations, or in any situation wherein slippage of the structure into bearing would produce intolerable geometric changes or where fatigue due to fretting is a consideration.

In the following sections, the different factors influencing the slip load of an axially-loaded connection are discussed. When discussing specific grades of high-strength bolts, reference will usually be to ASTM grades A325 or A490. In Europe, the comparable bolts are those meeting ISO R898, Grades 8.8 and 10.9. The mechanical properties of the comparable bolts are very similar. Section 9 of the report presents design recommendations.

2. BASIC SLIP RESISTANCE

The slip load of a simple tension splice, as shown in Fig. 1, is given by

$$P_{slip} = k_s \, m \sum_{i=1}^{n} T_i \tag{1}$$

where k_s = slip coefficient
m = number of slip planes
$\sum_{i=1}^{n} T_i$ = sum of the bolt preloads

The bolt preloads usually can be assumed to be equal in all bolts. Equation 1 therefore reduces to

$$P_{slip} = k_s \, m \, n \, T_i \tag{2}$$

where n represents the number of bolts in the joint.

Equation 2 shows clearly that for a given number of slip planes and bolts, the slip load of the joint depends on the slip coefficient and bolt preload force. For a given geometry, the slip load of the connection is proportional to the product of the slip coefficient k_s and bolt preload T_i.

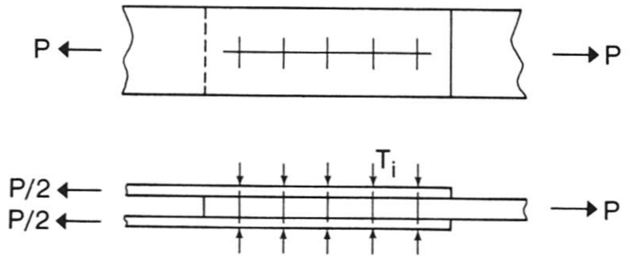

Fig. 1 Symmetric Shear Splice

Both the slip coefficient k_s and the clamping force T_i show considerable variation from their mean values. The slip coefficient varies from joint to joint and, although a specified minimum preload is usually prescribed, bolt preloads are also known to vary considerably, generally exceeding the prescribed minimum value. These variations in the basic parameters describing the slip load must be taken into account when developing criteria for joint design.

3. EVALUATION OF SLIP CHARACTERISTICS

The slip coefficient k_s corresponding to the surface condition can only be determined experimentally. In the past, slip tests have usually been performed on symmetric butt joints loaded in tension until slip of the connection occurs. The bolt preload, induced by the tightening process, is determined before the test is started. Once the slip load of the connection is known, the slip coefficient can be evaluated from Eq. 2:

$$k_s = \frac{P_{slip}}{m\ n\ T_i} \tag{3}$$

Most of the work done to determine the slip coefficient has been on symmetric butt joints of the type shown in Fig. 2. Both a two bolt specimen, type A, and a four bolt specimen, type B, have been used. The two standard test specimens with dimensions given in Fig. 2 are recommended for use with A325 as well as A490 bolts. Nearly identical specimens have been recommended by the European Convention for Constructional Steelwork [1]. Of course, in fabricating and preparing the test specimens, care must be taken to ensure that the material and surface conditions of the test joints are representative of conditions that occur in the field.

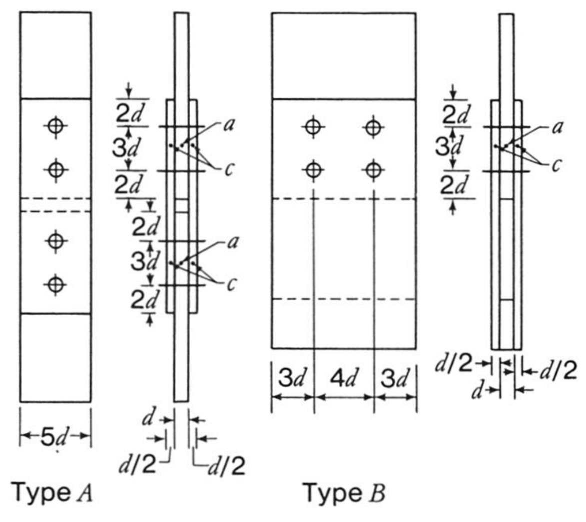

Fig. 2 Test Specimens for Determining Slip Coefficient (d = bolt dia. = hole dia. + 1/16 in.)

It is apparent from Eq. 3 that the value of the bolt preload T_i is of prime importance when determining the value of the slip coefficient k_s. Since the early stages of high-strength bolting, much attention has been directed to determine the force in a bolt installed in a joint. Up to the time of publication, no precise method is available. The best available method is to calibrate the bolts used in the test specimens [2]. This requires that each bolt be calibrated prior to installation in the test joint. The bolt clamping force should be within the elastic range if an accurate evaluation is made. Consequently, the bolts can be used more than once as long as the grip length is not altered. If the bolts are tightened beyond the elastic limit load, permanent plastic bolt deformations will occur. In such cases an average bolt preload versus elongation curve for the lot to be used in the test joints has to be determined from a representative sample of bolts. The elongations of the bolts in the test joint can be related to the bolt preload through this average bolt calibration curve. Because of inelastic deformations, the bolts can only be used once.

Load-indicating devices, such as tension-control bolts and load indicating washers, are available for establishing that the bolt preload meets or exceeds the specified minimum value. Whether such devices would provide a sufficiently accurate measure of the preload for purposes of the slip test would have to be evaluated on a case-by-case basis.

More recently, the Research Council on Structural Connections (RCSC) has approved a standard test for determination of the slip coefficient when coatings are used in bolted joints. The "standard" specimen in this case is a three-plate specimen (one main plate and two lap plates) loaded in compression and containing a single fastener. The fastener described in the test method is actually a threaded rod and nut arrangement which permits application of a known load by means of a centerhole ram. Alternative means of applying the clamping force are permitted, including use of a high-strength bolt, as long as the magnitude of the force in the bolt can be established to within ± 1%. A tension-type test is also permitted, and the specification provides rules for establishing the performance of connections under sustained loads (creep). Details of this test are available in Reference 3.

Regardless of which type of specimen is used to carry out the slip test, in a short-term static test the test specimens are subjected to gradually or incrementally increasing tensile loads. The displacements between points a and c (see Fig. 2) should be recorded at selected intervals of loadings.

In most slip tests on specimens without a protective coating on the slip surfaces, a sudden slip occurs when the slip resistance of the connection is reached. Coated specimens often do not exhibit sudden slip; the slipping builds up continuously, as evidenced by cumulative microslips. In these situations, the load corresponding to a prescribed amount of slip can be used to define the slip load. In North American practice, 0.02 in. (0.50 mm) has been used to provide this definition.

Other than major slip, creep of a connection might also impair the serviceability of a joint. A creep test can be performed to evaluate the influence of sustained loading levels on the displacement of a joint. A constant load level is applied for a long period in a creep test and the observed displacements are evaluated. The RCSC specification for determination of slip loads can be consulted for details of a suitable creep test.

4. EFFECT OF JOINT GEOMETRY AND NUMBER OF FAYING SURFACES

The effects of joint geometry have been examined in numerous experimental studies. The significance of the influence of factors such as number of bolts in a line and whether the bolts are arranged in compact patterns has not been determined. An analysis of the slip coefficient in large bolted joints having clean mill scale surfaces yields an average slip coefficient of 0.33 with a standard deviation of 0.07. For small joints, these values were 0.34 and 0.07, respectively. In this comparison, a large bolted joint was defined as having at least two lines of bolts parallel to the direction of the applied load with each line consisting of at least three bolts. Based on the results of this analysis, it was concluded that the number of bolts in a joint does not have a significant influence on the slip coefficient.

The slip resistance of a bolted joint is also proportional to the number of faying surfaces. Hence, a multilap joint can resist slip with great efficiency. However, tests have shown that the slip coefficient is not affected by the number of faying surfaces [4].

5. JOINT STIFFNESS

In slip-resistant joints the main plate and lap plates are compressed laterally by the initial clamping force. No relative displacement of the contact points on the surfaces takes place, and the joint may be considered equivalent to a solid piece of metal with a cross-section equal to the total area of the main and lap plates.

The stiffness of the joint, characterized by the slope of the load versus deformation curve, will decrease significantly if yielding occurs in either the net or gross cross-section. Yielding will not occur under working load levels because the working load is much less than the yield load of the connection. Since, under either allowable stress design or load factor design, the slip-resistant connection is designed using the working loads, its stiffness will not be affected by yielding up to the load levels for which the design is applicable.

6. EFFECT OF TYPE OF STEEL, SURFACE PREPARATION, AND TREATMENT ON THE SLIP COEFFICIENT

One of the significant factors influencing the slip resistance of a connection is the slip coefficient k_s, as defined by Eq. 3. Because of its significant influence, much research has been done in the United States, Europe, Japan and elsewhere to determine the magnitude of k_s for different steels, different surface treatments, and surface conditions [5-26]. The results of these studies have been used to evaluate the slip coefficient for a number of surface conditions.

It is clear that in order to determine a reliable value of the slip coefficient k_s, an accurate estimate of the initial clamping force must be known. Therefore, only tests where the actual clamping force in the bolts was measured were considered in the following analysis. Data obtained from tests in which bolts were installed using torque control were not considered.

In many cases structural members are bolted together without special treatment of the contact surfaces. A natural contact surface is provided by clean mill scale. Only the loose mill scale and dirt is removed by hand wire brushing. Grease originating from the fabrication process is removed with a solvent. An analysis of the available data shows that the clean mill scale condition for ASTM steels A7, A36, and A440 yields an average slip coefficient k_s of 0.33 with a standard deviation of 0.06. (Steel manufactured in accordance with ASTM A7 is no longer available, but many of the early test results for slip coefficient were obtained using this steel. The slip characteristics of joints made using A7 steel are considered to be comparable to those obtained using A36 steel.) Tests performed in Europe on Fe37 and Fe52 steels, comparable to A7, A36, and A440 steels, exhibited similar results. If all the available data on A7, A36, Fe37, A440, and Fe52 steel are considered, an average value of k_s equal to 0.33 is obtained. The standard deviation is 0.07. Figure 3 shows the frequency distribution of the slip coefficient as derived from the 327 tests. Some slip test results are available for a newer steel, ASTM A588, a weathering steel used mainly for bridge structures [26]. The data from 31 tests show that the slip coefficient for this steel in the clean mill scale condition is 0.23, with a standard deviation of 0.03. These test results fall on the low side of the scatter shown in Fig. 3. However, the results do not differ significantly from other studies contained within Fig. 3. For example, Ref. 7 reported a mean slip coefficient of 0.25 and a standard deviation of 0.04 for A440 steel specimens. In Ref. 22, the slip coefficient reported for A36 steel was 0.27, with a standard deviation of 0.05.

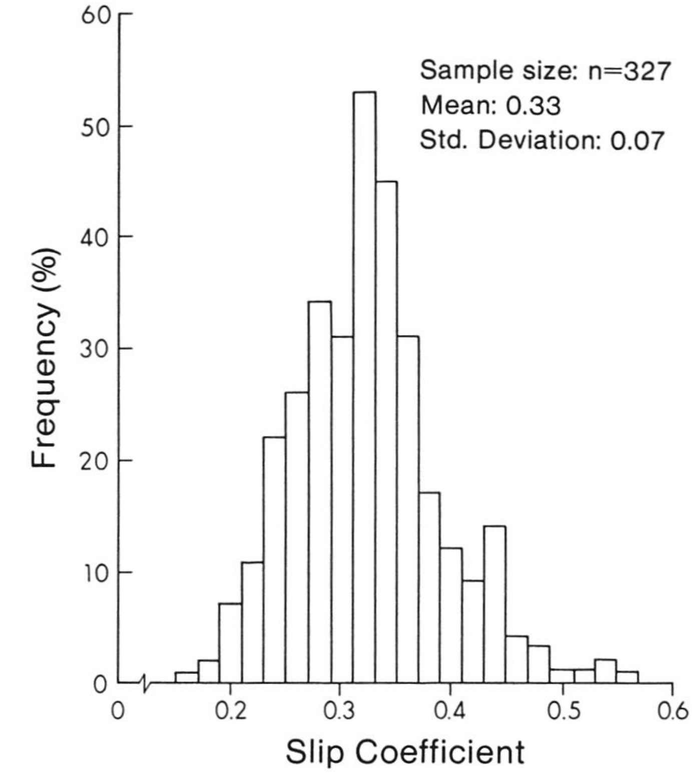

Fig. 3. Slip Coefficients for Clean Mill Scale Surfaces (A7, A36, A440, Fe52 Steels)

If the mill scale is removed by brushing with a power tool, a shiny clean surface is formed that decreases the slip resistance. Joints tested at Lehigh University with such semi-polished surfaces indicated a decrease in friction resistance of 25 to 30% as compared with normal hand-brushed mill scale surfaces [6]. This decrease is mainly due to the polishing effect of the power tool; the surface irregularities, which are essential for providing the frictional resistance, are reduced, causing a decrease in k_s.

Many tests have shown that blast-cleaning with shot or grit greatly increases the slip resistance of most steels as compared with the clean mill scale condition [12] [18]. An analysis of available data yielded an average value k_s equal to 0.51 for A7, A36, and Fe37 steels with blast-cleaned surfaces. The frequency distribution of the test results is shown in Fig. 4. It is apparent that the frequency distribution is somewhat skewed. This is reasonable, since the higher values could be influenced by yielding of the steel. The friction coefficient for blast-cleaned A440 and Fe52 steel should not differ from the value reported for blast-cleaned A7, A36, and Fe37 steel surfaces.

The magnitude of k_s for shot-blasted surfaces is greatly affected by the type and condition of grit or material that is employed to clean the surface. The condition of the cleaning material determines whether the surfaces are polished or left with a rough texture that is more slip-resistant.

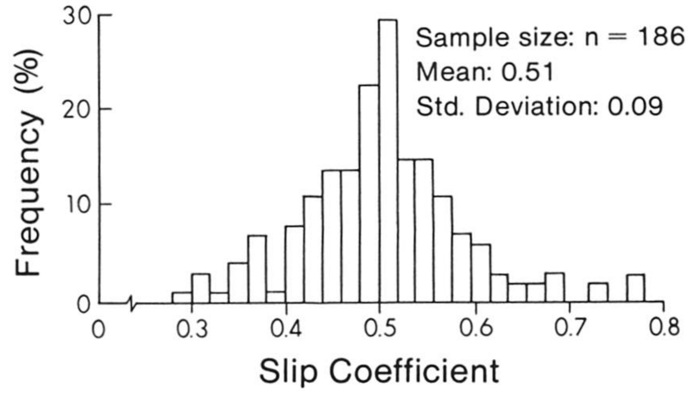

Fig. 4 Slip Coefficients for Blast-cleaned Surfaces (A7, A36, Fe 37 Steels)

The mean slip coefficients of the three studies contained within Fig. 4 varied from 0.49 to 0.55, with standard deviations of between 0.06 and

0.09. A limited study using Fe52 steel yielded a mean slip coefficient of 0.65 and a standard deviation of 0.08. Differences in the slip resistance from the different studies may be due to different blast-cleaning procedures in use at the time the studies were undertaken. It should also be noted that the standard deviation of the blast-cleaned surfaces does not differ appreciably from the variation observed for clean mill scale surfaces.

Tests on ASTM A514 constructional alloy steel showed an average slip coefficient of 0.33 for steel grit-blasted surfaces [19]. Although not much experimental evidence is available, these results show that grit-blasting of quenched and tempered alloy steel as compared with lower strength steel has less effect on the slip coefficient. This indicates that the hardness of the surface influences the roughness achieved by the blast-cleaning.

In most field situations, structural members are exposed to the atmosphere for a period of time before erection. During this period, unprotected blast-cleaned surfaces are highly susceptible to surface corrosion. To simulate this field condition, tests were performed in which the blast-cleaned surfaces were stored in the open air for different periods before being assembled and tested [18]. These test specimens were bolted up without wire brushing or otherwise disturbing the rusted surfaces. The results indicated that the relatively high slip coefficient obtained by shot or grit blasting is decreased with increased exposure time. After 12 months exposure to a humid, industrial atmosphere, the slip coefficient was about the same as the high end of the test results for clean mill scale. Removing the rust by wire brushing improved the slip resistance. If it can be ensured that the blast-cleaned surfaces will be exposed only for a short time, the relatively high slip coefficient of 0.51 (see Table 1) can be used for steels like A36, Fe37, and Fe52.

A distinction must be made in some cases between surfaces blast-cleaned with shot or grit and those cleaned by sand-blasting. Quenched and tempered steels, like A514, which have a low coefficient of slip if they have been cleaned using shot, display a much higher coefficient if sand has been used. The test results for sand-blasted A572 and A514 steels can be included with A7 and A36 test results. As seen in Table 1, the average slip coefficient for this group is 0.52, with a standard deviation of 0.09.

If rust forming on the blast-cleaned faying surfaces cannot be tolerated, a protective coating can be applied to the surfaces. These protective treatments alter the slip

Table 1. Summary of Slip Coefficients

Type of Steel	Treatment	Average	Std. Dev.	Number of Tests
A7, A36, A440	Clean mill scale	0.32	0.06	180
A7, A36, A440, Fe37, Fe52	Clean mill scale	0.33	0.07	327
A588	Clean mill scale	0.23	0.03	31
Fe37	Grit blasted	0.49	0.07	167
A36, Fe37, Fe52	Grit blasted	0.51	0.09	186
A514	Grit blasted	0.33	0.04	17
A36, Fe37	Grit blasted, exposed (short period)	0.53	0.06	51
A36, Fe37, Fe52	Grit blasted, exposed (short period)	0.54	0.06	83
A7, A36, A514 A572	Sand blasted	0.52	0.09	106
A36, Fe37	Hot dip galvanized	0.18	0.04	27
A7, A36	Semi polished	0.28	0.04	12
A36	Vinyl wash	0.28	0.02	15
	Cold zinc painted	0.30	-	3
	Metallized	0.48	-	2
	Galvanized and sand blasted	0.34	-	1
	Sand blasted and treated with linseed oil (exposed)	0.26	0.01	3
	Red lead paint	0.06	-	6

characteristics of bolted joints to varying degrees. Tests have been performed to evaluate the behavior of bolted joints in which the faying surfaces were galvanized, cold zinc painted, metallized, treated with vinyl wash or linseed oil, or treated with rust-preventing paint [14][16][18][20][28]. The results of these tests are summarized in Table 1. Some of the values listed in this summary were determined from a rather small number of tests. They provide only an indication of the magnitude of the slip coefficient.

7. EFFECT OF VARIATION IN BOLT CLAMPING FORCE

Besides the slip coefficient k_s, the initial bolt preload T_i is one of the major factors governing the slip load of a connection, as is apparent from Eq. 2. A variation in the initial clamping force provided by the preload directly affects the slip load of the connection. Experience has shown that the actual bolt tensions in a joint usually exceed the minimum tension required by specifications. This results from different tightening methods and from variations in the mechanical properties of the bolts.

North American practice in the past has been to install high-strength bolts by either a turn-of-nut method or with calibrated wrenches. Although the current (1980) RCSC Specification [29] only prescribes the turn-of-nut method, the effects of both types of installation will be treated herein in view of the large number of installations that have been made in the past using calibrated wrenches. European practice varies. Eurocode 3, for example, permits installation of high-strength bolts by torque measurement (calibrated wrench), turn-of-nut, or a combination of the two [30]. The descriptive material which follows will generally refer to North American practice.

The turn-of-nut is primarily based on an elongation control, whereas the calibrated wrench method is based on controlling the applied torque. The two methods do not necessarily yield the same bolt tension, as illustrated in Fig. 5. Here the influence of the tightening method on the bolt tension achieved is shown for two bolt lots having different mechanical properties. When the calibrated wrench method is used, the bolt tension T_{iC} is about the same for both lots since the wrench is adjusted for each lot. However, if the turn-of-nut method is employed the average elongation of the bolts will be about the same for both lots. Consequently, the bolt tensions T_{iA} and T_{iB} will differ, as illustrated in Fig. 5.

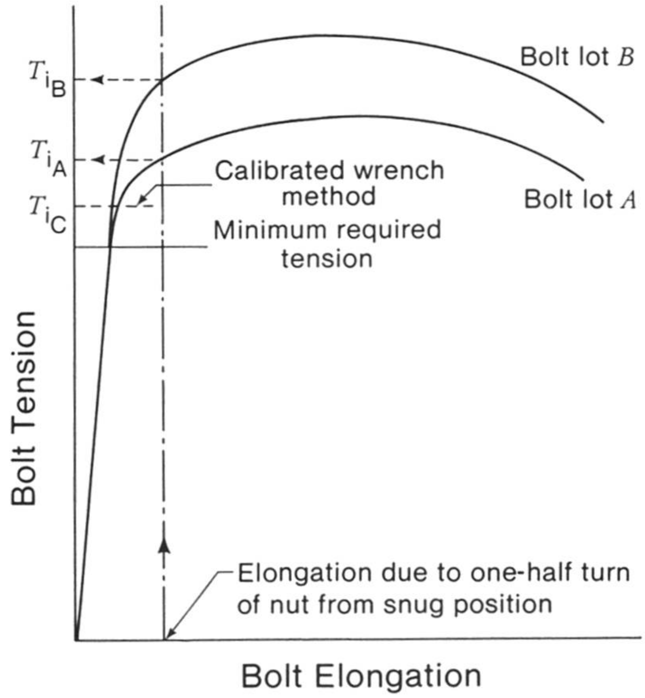

Fig. 5. Influence of Tightening Method on Bolt Preload

7.1 Turn-of-the-Nut Method.

Figure 5 illustrates that the tensile strength of the bolt is a significant factor influencing the induced bolt tension when the turn-of-nut method is used. An increase in tensile strength leads to an increase in initial bolt tension in an installed bolt. An analysis of the data obtained from several bolt lots used in joints and calibration tests at Lehigh University indicates that the relationship between the tensile strength and initial bolt tension can be approximated by the straight line relationship given in Fig. 6. The tensile strength of a bolt was determined from static tension tests on representative samples. The induced bolt tension at one-half turn from the snug position can be derived from the measured average tensile force in bolts installed in joints or by torquing the bolts in a hydraulic calibrator. Based on a least square fit of all the data plotted in Fig. 6, the relationship between σ_i and σ_u was determined as

$$\sigma_i = 0.80\, \sigma_u \tag{4}$$

The data plotted in Fig. 6 show clearly that torquing a bolt one-half turn from the snug position in gripped material, such as a joint, leads to a higher tension stress than obtained by torquing the bolt one-half turn in a hydraulic calibrator. This is mainly due to the difference in stiffness of the gripped material as compared to the hydraulic calibrator [31]. Hence, including the above data tends to yield a conservative estimate of the average bolt tension in a joint based on the average tensile strength of the bolts.

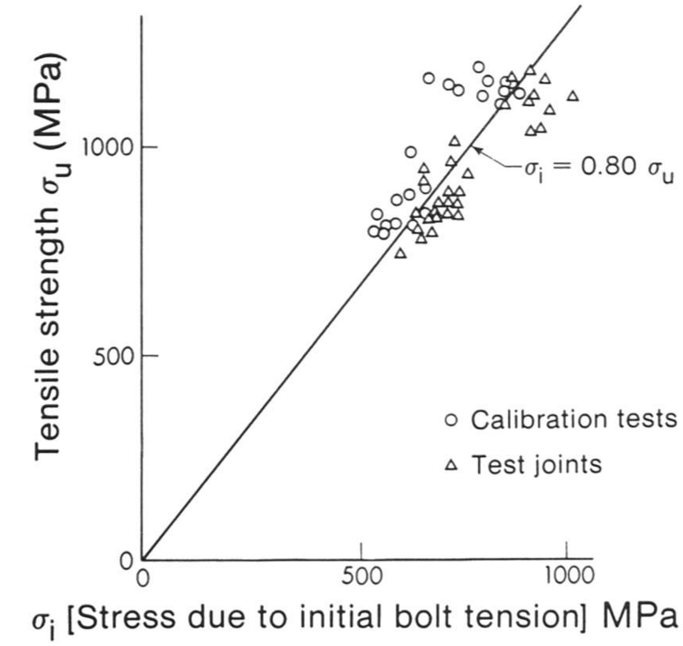

Fig. 6. Tensile Strength vs. Initial Bolt Strength

The actual bolt tension using the turn-of-nut method may exceed substantially the required minimum tension. This is illustrated in Fig. 7 where test data obtained from joints assembled with A325 bolts installed to 1/2-turn from snug are shown. The bolt tension on the horizontal axis is plotted as a percentage of the specified minimum required bolt tension. The average bolt tension in these joints was about 20% greater than the required minimum tension. In joints assembled with A490 bolts installed to 1/2-turn from snug, an average bolt tension of 26% greater than the required minimum tension was observed. The bolts used in these tests were purposely ordered to minimum strength requirements of the applicable ASTM specification. Although the actual tensile strength of the bolts exceeded the required tensile strength (3% for A325 and 10% for the A490 bolts), it was less than the average tensile strength of production bolts.

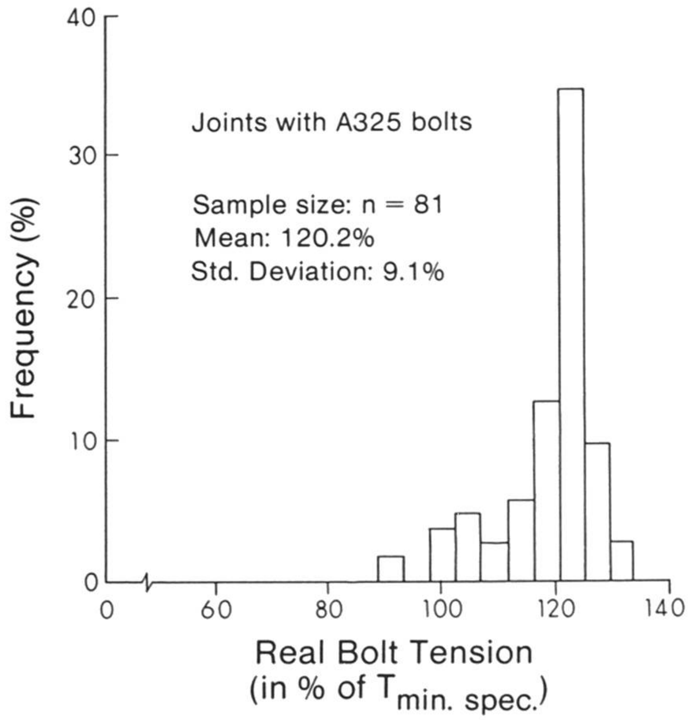

Fig. 7. Initial Bolt Preload: 1/2 Turn-of-Nut Installation

Since the average tensile strength of A325 bolts is

$$\sigma_{u\ real} = 1.183\ \sigma_{u\ specified}$$

and the average clamping force is about 80% of the actual tensile strength, it follows that the installed bolt tension σ_i is about equal to $0.95\sigma_{u\ specified}$. North American specifications require the minimum bolt tension to equal or exceed 70% of the specified tensile strength. Hence, the average actual bolt tension will likely exceed the required minimum bolt tension by approximately 35% when the turn-of-nut method (1/2-turn from snug) is used to install the bolts. (Eurocode 3 requires that the minimum bolt tension be 80% of the specified yield strength; this is equivalent to about 65% of the specified ultimate strength.)

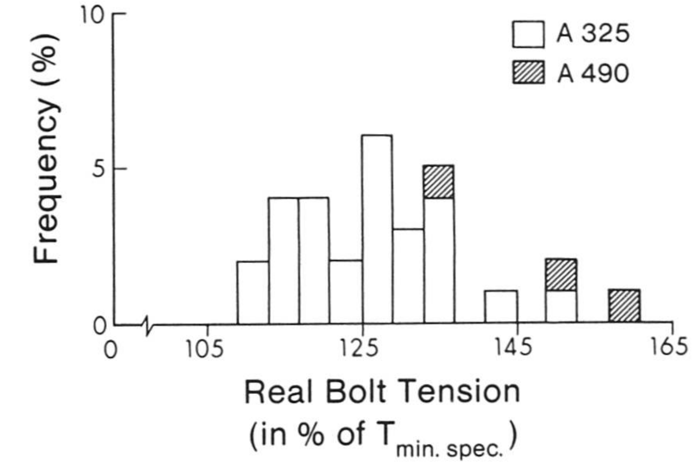

Fig. 8. Initial Bolt Preload: 1/3 Turn-of-Nut Installation

Tests on short grip length high-strength bolts installed to 1/3-turn from snug yield similar values [32]. The results are shown in Fig. 8. The average bolt tension for short-grip A325 bolts was 26% greater than the required minimum tension. The results for short-grip A490 bolts show an even greater increase, but the number of data is very small. Other tests on short-grip A325 bolts installed to 1/3-turn from snug in coated joints indicated an average bolt tension 20% greater than that required [3].

In order to characterize the frequency distribution of the ratio $T_i/T_{min.spec.}$, both the standard deviation and the average value of the ratio are required. These have been estimated for both A325 and A490 bolts from test results. Data obtained at the University of Illinois, Lehigh University, and the University of Texas showed that the standard deviation of the ratio $T_i/T_{min.spec.}$ from average values was between 6% and 12% for A325 and A490 bolts. By assuming a normal distribution, the frequency distribution curve of the ratio $T_i/T_{min.spec.}$ can be defined. Figure 9 shows these curves for A325 and A490 bolts. The figure illustrates that bolts installed by the turn-of-nut method will provide a bolt tension which exceeds the minimum required tension.

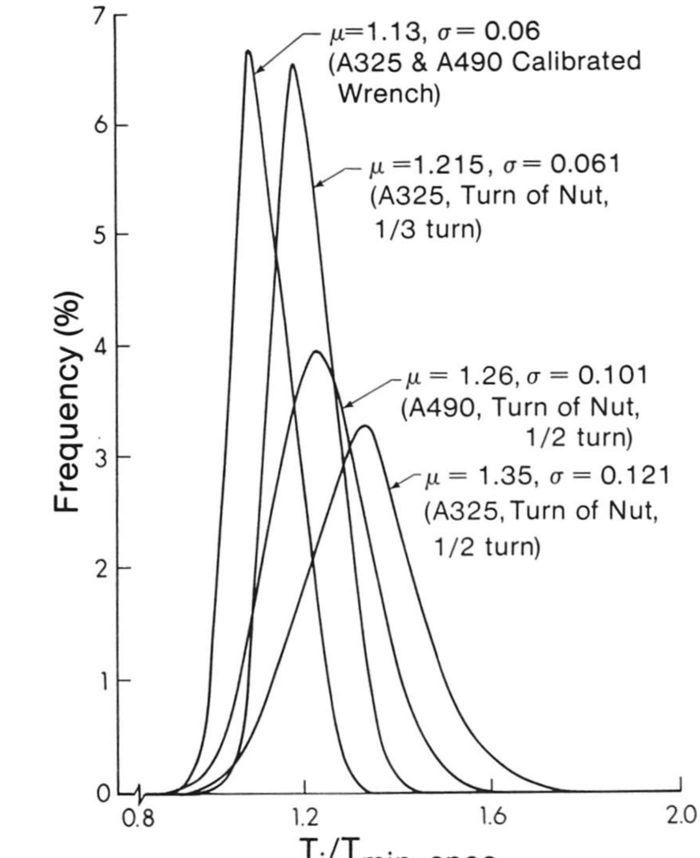

Fig. 9. Initial Bolt Preload for Various Installation Procedures

It was noted earlier that the average tensile strength of production A325 bolts exceeds the required tensile strength by approximately 18%. This was observed for bolt sizes up to 1-in. diameter. For A325 bolts greater than 1 in. dia., the range of actual tensile strength over specified minimum ultimate strength is even more favorable. The extra strength of bolts larger than 1 in. diameter was not considered.

7.2 Calibrated Wrench Method.

A variation in mechanical properties of bolts does not affect the average installed bolt tension when the calibrated wrench is used. However, since this method is essentially one of torque control, factors such as friction between the nut and the bolt and between the nut and washer are of major importance. An analysis of 231 tests in which single bolts were subjected to a constant predetermined applied torque showed that the standard deviation of the recorded bolt tension equaled 9.4% of the recorded value [33] [34]. It was observed that the variation of the average clamping force for a joint decreases depending on the number of bolts in the joint. For a joint having five bolts, the standard variation of the average bolt clamping force becomes 5.6% of the required mean value.

Because variations in bolt tension do occur as a result of variations in thread mating, lubrication, and presence or absence of dirt particles in the threads, specifications usually require that the wrench be adjusted to stall at tensions 5 to 10% greater than the required preload.

Tests have indicated that installing a bolt in a joint leads to a higher bolt tension as compared with torquing the bolt in a hydraulic calibrator. This difference is about equal to 5.5%. Consequently, the average clamping force in a five-bolt joint, with bolts installed by the calibrated wrench with a setting 7.5% greater than the required preload is equal to

$$(0.7\sigma_u)(107.5)(1.055) = 0.796\sigma_u$$

or $1.13\sigma_u$ specified. The standard deviation is equal to about 6%. The corresponding frequency distribution curve of the ratio $T_i/T_{min.spec.}$ for bolts installed by the calibrated wrench method is also shown in Fig. 9.

7.3 Alternate Bolts.

The use of alternate bolts, load-indicating washers, or other non-standard methods for introducing and monitoring the bolt preload will not necessarily lead to the same levels and distributions of preload as described here for bolts installed by turn-of-nut or calibrated wrench methods. Data are available for tension-control type bolts and results are shown in Fig. 10 for 3/4-in., 7/8-in., and 1-in. dia. A325 quality bolts

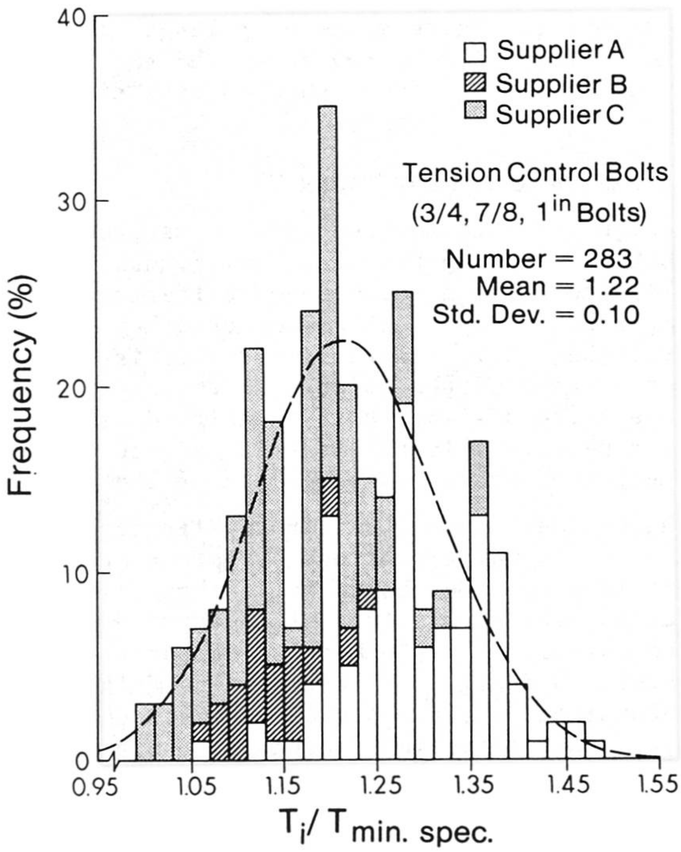

Fig. 10. Intial Bolt Preload for A325-Quality Tension-Control Bolts

obtained from three different suppliers. (Tension-control bolts, designed for installation by working from only one side, feature an extension of the bolt beyond its threaded length. The extension contains both a spline used for holding the bolt during installation and a circumferential groove designed to produce twist-off of the extension when the desired preload has been reached.) Distinct differences in the ratio of real initial tension to specified minimum tension can be seen, depending upon the supplier. Using all the test results, the mean value of the ratio is 1.22, about the same as that for A325 bolts installed to 1/3-turn from snug tight. The standard deviation from the mean is slightly larger for the tension-control bolts than for the normal A325 bolts.

8. EFFECT OF GRIP LENGTH

The grip length of bolts does not have a noticeable influence on the behavior of friction-type joints. The only point of concern is the attainment of the desired clamping force. When the bolt length in the grip is greater than about eight times the diameter, one-half turn from the snug position may not provide the required preload. The greater bolt grip requires an increased amount of deformation. To provide this increased bolt elongation, an additional increment of nut rotation is required. The RCSC Specification requires that the turn-of-nut be increased from 1/2 turn to 2/3 turn in order that at least the minimum bolt tension be reached in bolts with long grips. Eurocode 3 requires a nut rotation beyond snug (in degrees) equal to 90 + bolt diameter (mm) + thickness of gripped material (mm).

Bolts with short grips are not likely to have less than the desired preload if installed by the turn-of-nut method. They can, however, have a reduced rotational reserve if 1/2 turn is attempted. The RCSC Specification prescribes 1/3 turn for bolts whose grip length is less than four diameters in order that the preload will be developed and the rotational reserve maintained. The Eurocode 3 rule cited above adjusts directly for grip length, of course.

9. DESIGN RECOMMENDATIONS

Design criteria for connections can be based upon performance, or strength, or both. In a slip-resistant joint, unsatisfactory behavior would result if major slip occurred, a performance criterion. The function of the structure may be impaired due to misalignment or other unsatisfactory conditions that may result from the slip. However, most slip is minor and will not be detrimental to the performance of the joint. In these cases, strength is the factor that should govern the design; it is identified as the shear stress on the fastener, the bearing stress in the material adjacent to the fastener, or as the stress on the net or gross cross-section of the member being connected.

The ultimate capacity of both slip-resistant and bearing-type bolted joints is limited by failure of one or more components of the joint. Joint strength provides an upper bound for either joint type. Hence, in working stress design, the permissible strength of a slip-resistant joint can, at best, equal the capacity of an otherwise comparable bearing-type connection. In other words, to design a slip-resistant joint, the slip resistance of the joint is determined on the basis of factors such as the surface condition, the bolt type, the tightening procedure, the number of bolts, and the number of slip planes. This slip resistance is then compared with the bolt shear capacity of the joint as based upon the number of shear planes per bolt and their location (through the shank or through the threaded part of the bolt) and the number of bolts in the joint as well as the bolt quality. Of course, the smaller value of the shear strength and the slip resistance is governing.

In load factor design, the ultimate strength of the member or connection is checked against the effect of the factored loads. The factored load is determined by multiplying the working loads by a factor which is greater than 1.0. In addition, it is necessary for the member, joint, and structure as a whole to be "serviceable" at the working load level. This means that consideration must be given to control of deflections, deformation, and fatigue of the structure at its service or working load level.

To meet the requirements of load factor design, the ultimate strength of a bearing type bolted joint is checked directly against the effect of the factored loads. Unless fatigue is a factor, the other requirements for serviceability are not operative since, by definition, any small slips that may occur are judged not to be detrimental.

On the other hand, a slip-resistant connection designed under load factor design must be checked under both service (working) load levels and factored load levels. The obvious requirement is that the connection not slip under working loads. In addition, however, it is still a requirement that the ultimate strength of the connection loads be checked under factored loads.

The basic slip resistance of a joint is best expressed using Eq. 2, in which a slip coefficient is used. This is used as the basis of the design recommendations which follow.

9.1 Slip-Resistant Joints.

If it is assumed that equal clamping forces are present throughout a joint, then the slip resistance of a connection can be expressed as

$$P_s = m\ n\ T_i\ k_s \tag{5}$$

For a given joint geometry, the slip resistance is directly proportional to the product of the initial clamping force, T_i, and the slip coefficient, k_s. Both quantities have considerable variance and this must be considered when determining design criteria for slip-resistant joints. Since the frequency distributions for k_s and T_i are known for different surface conditions, bolt types, and tightening procedures (see Sections 5 and 6), the joint frequency distribution for the product k_sT_i can be determined and suitable design expressions formulated [35].

Considering Eq. 5, it will be desirable to reformulate this expression so that deterministic values can be used for T_i and k_s. Over and above this, it will be appropriate to provide design information for different levels of slip probability (the probability that the load predicted by Eq. 5 may be exceeded) in order that the designer might have the option of selecting a slip probability level suitable for his structure. Equation 5 can be written as

$$P_s = m\ n\ \alpha\ T_{min.spec.}\ k_s \tag{6}$$

where
$$\alpha = T_i/T_{min.spec.} \tag{7}$$

and $T_{min.spec}$ is the specified minimum bolt tension. In a further step, Eq. 6 will be expressed as

$$P_s = D\ m\ n\ T_{min.spec.}\ k_{s_{mean}} \tag{8}$$

where D is a multiplier that provides the relationship between $k_{s_{mean}}$ and k_s, incorporates α, and reflects the slip probability level selected.

The frequency distribution curve for the product of the two variables in Eq. 5, that is, T_i and k_s, is shown in Fig. 11(a) for A325 bolts fastening material in the clean mill scale condition and installed by the turn-of-nut method.

Similar curves can be constructed for other fastener and faying surface conditions. A cumulative frequency curve constructed from this information is shown in Fig. 11(b). If a very high value of k_sT_i, relative to the value actually present in the joint, were to be selected by the designer, then there would almost certainly be slip. On the other hand, if a very low value of k_sT_i were selected as the design level, there would be very little likelihood of slip.

Two of the slip probability levels that might be chosen, 5% and 10%, are shown in Fig. 11(b). The 5% slip probability (or 95% confidence level) corresponds to past North American practice for slip-resistant connections. If a lower slip probability is desired, the 1% level could be chosen; if a higher slip probability can be justified, 10% could be used.

Information like that given in Fig. 11(b) can be tabulated. Table 2 gives values of D for use in Eq. 8 for either A325 or A490 bolts installed by turn-of-nut (one-half turn) and corresponding to various slip probability levels. The slip coefficients listed (mean values) are 0.20, 0.25, 0.33, 0.40, 0.50, and 0.60. The standard deviations used with these values in order to develop the table were 0.07 for mean values between 0.20 and 0.40 and 0.09 for the remainder. Table 3 gives similar information for A325 or A490 bolts installed using the calibrated wrench method. The variation in bolt clamping force is given in Figure 9 for both installation methods.

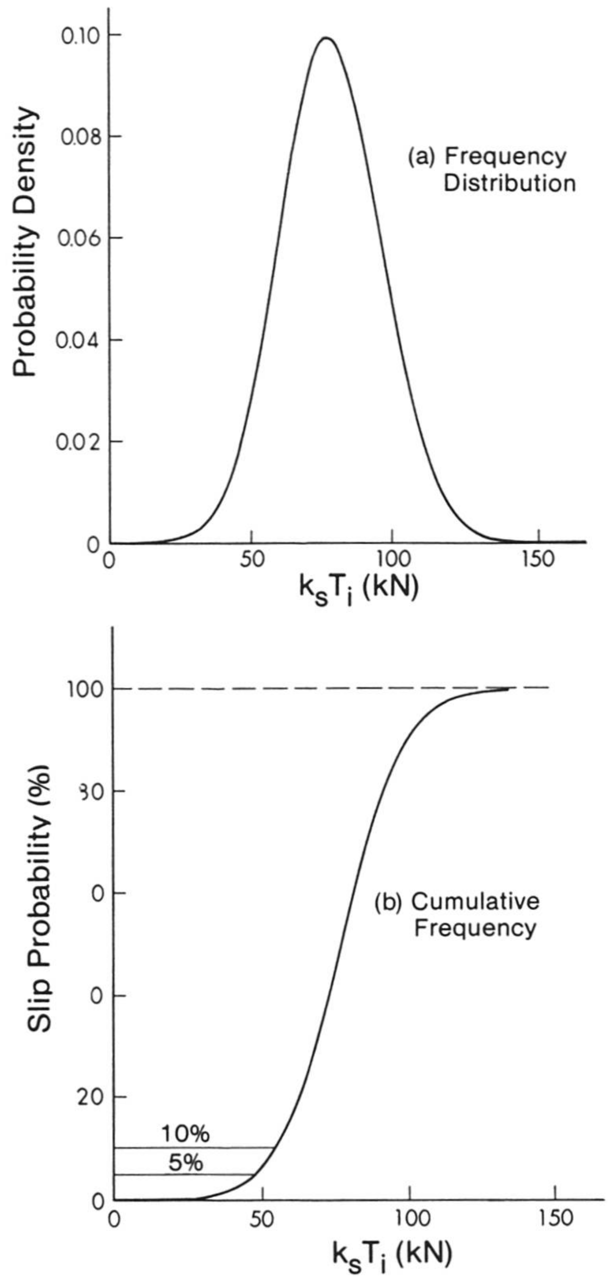

Fig. 11. Slip Resistance for A325 Bolts, Clean Mill Scale Surfaces, Turn-of-Nut Installation

A comparison of Tables 2 and 3 indicates that slip-resistant connections using bolts installed by turn-of-nut method will have a greater resistance than if the bolts are installed by calibrated wrench. For example, at the 5% slip-probability level A325 bolts installed by turn-of-nut gain a premium of about 14% over A325 bolts installed by calibrated wrench. The difference reflects the higher preloads obtained in bolts installed by the turn-of-nut method. For A325 or A490 bolts installed by calibrated wrench, α is 1.13, whereas it is 1.35 for A325 bolts or 1.26 for A490 bolts installed by 1/2 turn-of-nut, respectively.

In evaluating conditions for A325 bolts, the specified minimum tensile strength was presumed to be 120 ksi (830 MPa). The specified tensile strength for A325 bolts in sizes over 1 in. is in fact 105 ksi. Experience has shown that the actual strength of A325 bolts over 1 in. diameter usually ranges from 20% to

34% above the minimum specified tensile strength. Furthermore, the ratio of the tensile stress area of the bolt to its unthreaded area is about 0.79 for bolts over 1 in. diameter (up to 1 1/2 in. diameter), as compared to a ratio of 0.75 for bolts with diameters between 1/2 in. and 1 in.

A reduction factor must be applied to account for the effect of fabrication factors on the slip resistance of joints; for example depending on the amount of oversize of the hole or the direction of slotted holes with respect to the expected slip direction, a reduction in slip resistance may result. These details are not included in this paper.

Table 2. Slip Factor D for use in Eq. 8. Turn-of-Nut Installation

	A325 Turn-of-Nut			A490 Turn-of-Nut		
	Slip Probability			Slip Probability		
k_s (mean)	1%	5%	10%	1%	5%	10%
0.20	0.253	0.551	0.728	0.243	0.520	0.684
0.25	0.383	0.677	0.831	0.376	0.642	0.782
0.33	0.590	0.820	0.942	0.568	0.776	0.887
0.40	0.696	0.896	1.001	0.671	0.848	0.942
0.50	0.702	0.899	1.002	0.672	0.850	0.944
0.60	0.772	0.947	1.040	0.738	0.895	0.979

Note: Standard deviation of k_s (mean) taken as 0.07 for $k_s < 0.4$ and as 0.09 otherwise.

Table 3. Slip Factor D for use in Eq. 8. Calibrated Wrench Installation

	A325 <u>or</u> A490 Calibrated Wrench		
	Slip Probability		
k_s (mean)	1%	5%	10%
0.20	0.235	0.478	0.622
0.25	0.372	0.594	0.714
0.33	0.547	0.718	0.810
0.40	0.639	0.784	0.862
0.50	0.643	0.787	0.864
0.60	0.702	0.829	0.897

Note: Standard deviation of k_s (mean) taken as 0.07 for $k_s < 0.4$ and as 0.09 otherwise.

10. SUMMARY AND CONCLUSIONS

Slip-resistant connections should generally only be specified when it can be judged that, under the action of the working loads, slip into bearing would produce unacceptable geometric changes or where load reversals could result in fretting fatigue. Connections designed as slip-resistant must also be checked as bearing-type connections.

For a given geometry and number of bolts, the slip resistance of a joint will be dependent upon the slip coefficient associated with the contact surfaces and with the clamping force supplied by the bolts. Both of these quantities show considerable variation about their mean values. In order to assess slip resistance properly, the mean values and distributions of each quantity must be included in the analysis.

Slip coefficients that have been obtained by researchers in various parts of the world are summarized herein. An examination of the preloads obtained in high-strength bolts installed by various methods is also made. Using the mean values of slip and preload and their associated coefficients of variation, and assuming normal distributions, cumulative frequency curves of slip are developed. In order to present this material in a form directly useful to designers, coefficients are tabulated for use in a resistance equation. The coefficients presented cover the cases of A325 or A490 bolts installed using either one-half turn-of-nut or by means of calibrated wrenches. Six slip coefficients are included and three slip probability levels are covered.

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