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EFFECT OF MANUFACTURING ERRORS UPON MECHANICAL PROPERTIES OF FRICTION-TYPE BOLTED JOINTS[*]

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1. INTRODUCTION

At the present time, as for the method of field joint for steel structural members, the friction-type bolted joint is the most popular and reliable. It defies all other comparison, especially, as for the method to connect thick plates of high strength steel in such case as the members of long span bridges. Including such joints of members of the bridges, there are some questions left to be solved in the friction-type bolted joints. This paper clarifies experimentally the effect of the following items out of the aforesaid questions which affect the slip resistance of the joints:

(1) errors due to faying surface,
(2) errors of plate thickness, and misalignment of steel plates, and
(3) errors in bolt hole diameter.

As to item (1), the actual conditions of scattering of slip coefficients were made clear according to the attributable factors such as fabricators, steel producers, rusted or not rusted faying surfaces and the grade of steel, etc.

Table 1 Specified Slip Coefficients in the World

Specification	Slip Coefficient for New Construction	Surface*
European Convention for Constructional Steelwork,[1] 1971	0.5 for steels of σ_B=37; 42-46 (kg/mm^2) classes, and 0.55 for 50-52 classes	a), b), c)
England,[2] 1960	0.45	mill scale off
Japan; for Bridges, 1971 for Buildings, 1970	0.40 0.45	mill scale off
U.S.A.,[3] 1964	0.35	mill scale on
West Germany,[4] 1963	0.45 for St33, 37; 0.60 for St52	a), b), c) for buildings b), c) for bridges

* a) flame cleaning, b) sand blasting, c) shot blasting

In spite of the fact that the condition of a faying surface is an important factor which directly affects the slip resistance of a friction-type joint, the slip coefficient to be applied to the design shows considerable difference in values, as in Table 1, between the field of the bridge and building frame construction, or by the grade of steel in some specifications, at home and abroad. It goes without saying that these values are established through numerous tests.

This study intended to bring to light new facts

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about the matters of no informations as yet, such as the individual variations among fabricators, in the organization of committee.

In item (2), it is clarified how the slip resistance of a flange joint in a girder will be affected by a manufacturing error in the girder height, besides a common difference of plate thickness.

A previous study⁵⁾ showed a decrease of about 10% or so in the slip resistance of a joint caused by a difference of plate thickness by 2 mm. In that case, the tapering to a butt end of the plate made effective as a countermeasure. As other procedures available, it was likely that, the more the edge distance or number of lines of bolt increased, the more the slip resistance strengthened. In this experimental study, the actual conditions such as the order of bolt installation and the joint aligned eccentrically were added thereon to take into consideration.

As regards item (3), it is natural to consider, in the general, to compose the joint of bolt holes over standard size diameter, i.e. the joint with oversize holes, as well as the intention to improve on the efficiency of the erection work in the field, which induced to examine the slip resistance of such bolted joint with oversize holes, especially from the side of the fatigue strength.

As the study of the bolted joint with oversize holes with the intention of improving the efficiency of construction work, there are the works of Chesson and Munse,⁶⁾ Allan and Fisher,⁷⁾ Tajima and others,⁸⁾ and Shoukry and Haish,⁹⁾ etc., which seemed to show, through all of them, to have no decreasing effect upon the slip resistance of the joint, in cases of the difference between the bolt shank and the hole up to 3/16 in., in some cases up to 1/4 in., for the bolts of 22-24 mm diameter. In the present study, further attempts were made to examine not only from the side of the static strength but also from that of the fatigue strength, considering also an eventual slip of the hole of plate to be seen in the actual construction.

2. SCATTERING OF SLIP COEFFICIENTS

(1) Test Series

The extensive slip load tests were performed on two series of tests: Series I and II. The objective of the former series is to get informations on the scattering of slip coefficients due to difference in surface treatments among fabricators. To eliminate the effect expected from the difference in mechanical properties of steel itself, the plates for test specimens were supplied by a designated producer. The grade of steel was JIS SM50A for which the properties are specified as shown in Table 2. The test specimens were

Table 2 Specified Values for Various Steels

Steel	Plate Thickness (mm)	Mechanical Properties			Chemical Composition (%)						
		σ_y (kg/mm^2)	σ_B (kg/mm^2)	Elongation (%)	C	Si	Mn	P	S	Cu	Cr
SM41A	≤16 $16<t\leq40$	25≤ 24≤	41-52	19≤ 22≤	≤0.23	—	2.5 ×C≤	≤0.040	≤0.040	—	—
SM50A	≤16 $16<t\leq40$	33≤ 32≤	50-62	18≤ 21≤	≤0.20	≤0.55	≤1.30	≤0.040	≤0.040	—	—
SMA50A	≤16 $16<t\leq40$	37≤ 36≤	50-62	16≤ 19≤	≤0.19	≤0.75	≤1.40	≤0.040	≤0.040	0.20~ 0.70	0.30~ 1.20
SM50YA, B	≤16 $16<t\leq40$	37≤ 36≤	50-62	16≤ 19≤	≤0.20	≤0.55	≤1.50	≤0.040	≤0.040	—	—
SM53B, C	≤16 $16<t\leq40$	37≤ 36≤	53-65	16≤ 19≤	≤0.20	≤0.55	≤1.50	≤0.040	≤0.040	—	—
SM58	≤16 $16<t\leq40$	47≤ 46≤	58-73	19≤ 26≤	≤0.20	≤0.55	≤1.50	≤0.040	≤0.040	—	—
SMA58	≤16 $16<t\leq40$	47≤ 46≤	58-73	19≤ 26≤	≤0.19	≤0.75	≤1.40	≤0.040	≤0.040	0.20~ 0.70	0.30~ 1.20
H.T. 80	$6\leq t\leq50$ $50<t\leq100$	70≤ 68≤	80-95 78-93	$6\leq t\leq16$: 16≤ $16\leq t\leq20$: 22≤ $20\leq t$: 16≤	≤0.14 ≤0.17	≤0.55	≤1.50	≤0.030	≤0.030		

prepared by eleven fabricators, numbered from 1 through 11, by means of their own procedure of surface treatment.

The objective of Series II was to obtain informations on the difference of slip coefficients among different grade of steels. To eliminate the error due to the difference of surface treatment among fabricators, a designated fabricator was selected to prepare the test specimens in this series. The steel plates for the specimens were supplied by four steel producers numbered I, II, III, and IV, each of which offered several grade of steels as shown in Table 2. The faying surfaces of the specimens were blasted in the same way as in Series I.

Through both test series, faying surfaces were either as-blasted or rusted. To obtain rusted surfaces, the plates were exposed one-month in the yard of the fabricator. Table 3 shows the number of tests in Series II. All of the tests were conducted at Kobe University.

Table 3 Kinds and Number of Tests in Series II

Steel Producer	I		II		III		IV	
Surface Condition*	S	R	S	R	S	R	S	R
SM41A	3	3	3	3	3	3	3	3
SM50A			3	3				
SM50YA	3	3	3	3	3	3		
SM50B	3	3	3	3	3	3		
SM58	3	3	3	3	3	3	3	3
SMA50A	3	3	3	3	3	3		
SMA58					3	3		
H.T. 80	3	3	3	3	3	3		

* S: As-Blasted by Shot, Sand, or Grit; R: Rusted

(2) Test Specimens

Fig. 1 shows the test specimens for Series I and II. The materials for blasting were different among fabricators as shown in Table 4 according to their own custom. The blasting conditions to prepare the test specimens for Series II were as followings:

50-micron for the roughness of faying surfaces;
60-mesh for the grading of sand;
5 kg/cm^2 for the air-pressure;
30-50 cm for the length of blast; and
12 mm for the diameter of a nozzle.

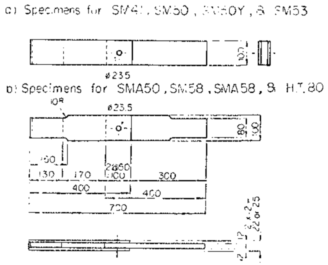

a) Specimens for SM41, SM50, SM50Y, & SM53
b) Specimens for SMA50, SM58, SMA58, & H.T.80

Fig. 1 Test Specimens

Table 4 Details of Blasting*

Fabricator No.	Materials for Blasting
1	Grit
2	Sand
3	Grit
4	Shot
5	Grit
6	Sand
7	Grit
8	Shot
9	Grit
10	Shot
11	Grit

* Designated surface roughness of plates: 50S

(3) Test Procedure

Prior to the slip test, the roughness of faying surfaces of each test specimen was measured before assembling plates by means of a center-hole type oil jack (cap. 30 t) which will behave as a substitute of high-strength bolt of F9T × W7/8. The pretension was 17.0 t, which cornensponds to the specified standard value of the above bolt; however, there were two exceptions in Series I for the test specimens prepared by the fabricator Nos. 3 and 11 for which the pretension was 23.1 t. The circumstance of clamping by an oil jack is shown schematically in Fig. 2. For rusted plates, the surfaces were cleaned by a wire blush before assembling.

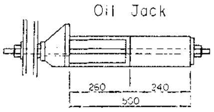


Fig. 2 Circumstance of Tightening by an Oil Jack (cap. 30 t)

During the tests, the bolt pretension was kept constant. The major slip load was distinguished by a sudden drop of the load indication of a testing machine, or by a sound when the slip occured, or by the indication of dial gauges attached to the test specimen when the former two methods were ineffective.

(4) Test Results and Considerations

1. *Series I.* The test results in this series are plotted in Fig. 3, from which the following considerations will be made:

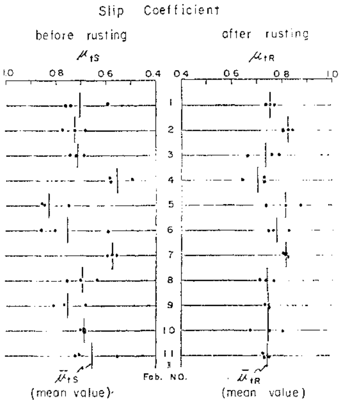


Fig. 3 Test Results of Series I

(1) Through comparison among the mean values of slip coefficients μ_t defined by the ratio of the major slip load and the bolt pretension, $\bar{\mu}_t$, of each fabricator, it may be recognized that there are comparatively wide scattering among them. The difference of μ_t among fabricators will decrease on an average through rusting, and the decrease in the range of scattering in a fabricator is explicit after the rusting of surfaces.

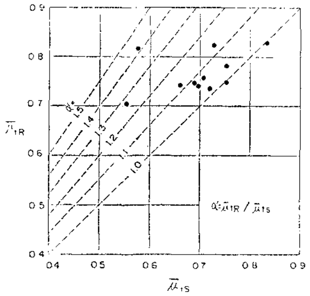


Fig. 4 Correlation between $\bar{\mu}_{tR}$ and $\bar{\mu}_{tS}$; Series I

(2) The evident increase of μ_t values through rusting of the faying surfaces may be recognized by plotting as shown in Fig. 4. The rate of increment, α, defined by the ratio of the mean values $\bar{\mu}_{tR}/\bar{\mu}_{tS}$, where the suffices S and R show before and after rusting respectively, varied in the range from 1.0 to 1.4, and the most of them were in the range from 1.0 to about 1.1.

(3) The so-called slip coefficient should be lower about 5% than the value obtained through the present tests; therefore, the design value 0.40 in the current specifications for steel bridges will be 0.42, which is surpassed sufficiently by the minimum value obtained from the present test.

2. *Series II.* Figs. 5 and 6 are the plotting of the test results, from which the following conclusions may be allowed:

(1) The plotting shows explicitly the trends in variation of μ_t in a same kind of steel among steel producers: wide for as-blasted surfaces and less for rusted ones.

(2) The variation of μ_t among different steels is remarkable even in a same steel producer for as-blasted surfaces, however, the variation is lesser for rusted ones.

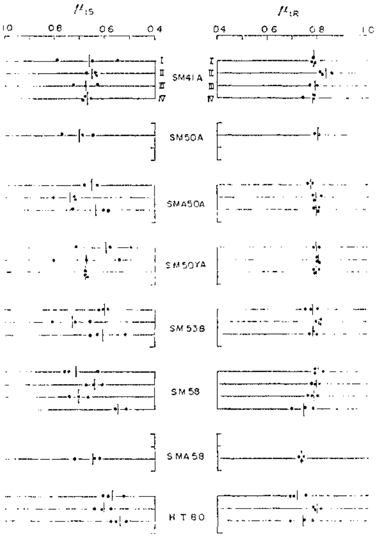


Fig. 5 Test Results of Series II

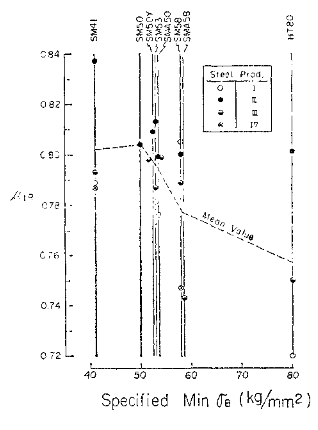


Fig. 6 μ_{tR} of Various Steels

(3) The increase in $\bar{\mu}_t$ values through rusting is clear for all kinds of steels; especially for H.T. 80, for which the average rate of increase was $\alpha=1.31$.

(4) Slip coefficient showed a trend to decrease according to the increase of the tensile strength of the plate as shown in Fig. 6.

3. EFFECT OF ERRORS DUE TO THE PLATE THICKNESS

(1) Scope of Tests

In this section, the mechanical behavior of the joint between different thickness plates was clarified, and the methods to improve the strength of the joint were examined. The following are the main items which should be clarified through the tests on specimens:

(1) the influence of the order of tightening bolt in a joint to the slip resistance of the joint,

(2) the variation of decrease in the bolt pretension compared with that of the joint between same thickness plates,

(3) the improvement of the slip resistance of the joint between different thickness plates by using filler plates, and

(4) the influence of the thickness of splice plates and the edge distance on the slip resistance of the joint.

(2) Test Specimen

The test specimens used for this test series are shown in Fig. 7, including 12 kinds of test specimens classified into several groups as shown in Table 5 according to the factors investigated.

Steel plates for test specimens were JIS SM50 steel except for the filler plates for which JIS SS41 steel was used. The faying surfaces were sand-blasted, and the specimens were fabricated immediately after the blasting. High-strength bolts for the test specimens were JIS F9T × W7/8; the pretension was 18.3 t, and the bolt holes were drilled to a standard diameter 23.5 mm.

The installation of bolts was carried out by means of a torque wrench by two steps: the preliminary tightening was done according to the predetermined order until the pretension in the bolt reached at 80% of the final value, and the final tightening was conducted to complete the installation according to the same order as the preliminary one.

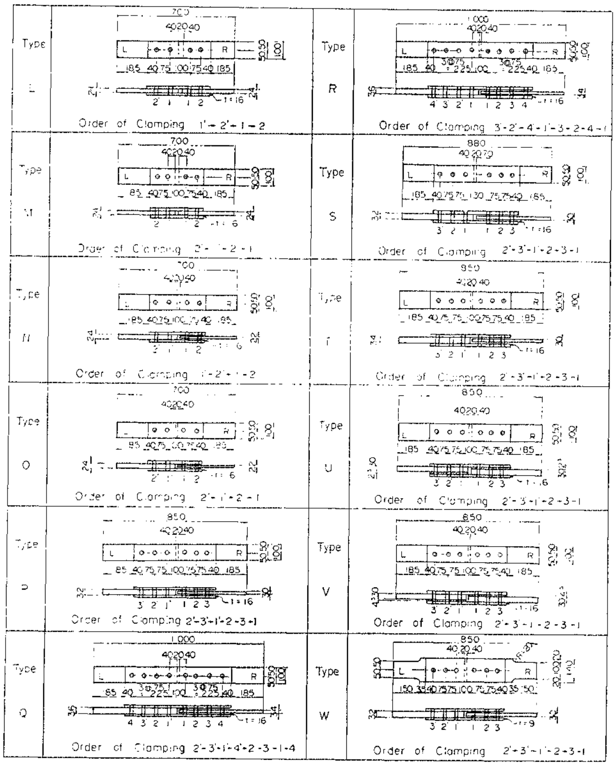


Fig. 7 Types and Detail of Test Specimens

Table 5 Summary of Test Specimens and Measured Slip Coefficients

Factor	Corresponding Types of Specimens	Difference	Slip Coefficient, Mean of 3 Tests	Notes
Order of Clamping	L	Bolt 1→2	0.685	Number of Bolts: 2
	M	2→1	0.686	Clearance : None
	N	1→2	0.585	Number of Bolts: 2
	O	2→1	0.558	Clearance : 2 mm
	Q	2→3→1→4	0.602	Number of Bolts: 4
	R	3→2→4→1	0.582	Clearance : 2 mm
Edge Distance	P	40 mm	0.558	Number of Bolts: 3
	S	70 mm	0.635	Clearance : 2 mm
Clearance	P	2 mm	0.558	Number of Bolts: 3
	T	4 mm	0.563	Clearance : 2 mm
Use of Filler Plate	P	2 mm Clearance	0.558	Number of Bolts: 3
	U	2.3 mm Filler Plate	0.695	
	T	4 mm Clearance	0.563	Number of Bolts: 3
	V	4.5 mm Filler Plate	0.696	
Thickness of Splice Plates	P	Two 16 mm Plates	0.558	Number of Bolts: 3
	W	Two 9 mm Plates	0.618	Clearance : 2 mm

(3) Test Procedure and the Results

1. *Bolt Pretension*

The bolt pretension induced by a torque wrench was measured by electric resistance wire strain gauges set on the bolt shank. The measurements were performed twice: the first was done at the final tightening and the second at the tension test. The torque at the final tightening was recorded for reference. Without regard to the result of the second measurement, the tightening to adjust the lower pretension to the specified value was not performed. The rate of decrease in bolt pretension detected by the above two measurements are shown in Fig. 8, in which the intervals for 95% confidence for the mean values were shown, too. The correlation between the decrease of bolt pretension and the slip coefficient are summarized in Table 6.

Table 6 Correlation between the Decreases of Bolt Pretension and Slip Coefficient

Correlation	Notable		Uncertain	None	
Combination of Test Specimens Compared	L&N L&O M&N M&O Q&R	S&U S&V T&U T&V T&W U&W	L&M P&T S&W U&V V&W	N&O P&S P&U P&V	P&W S&T
Number of Cases	11		5	6	

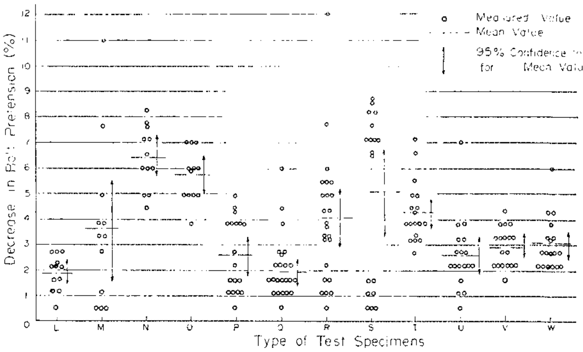


Fig. 8 Decrease in Bolt Pretension

2. *Tension Test*

The tension tests were performed by using an Amsler type oil pressure testing machine, which has a capacity of 200 tons. The elongation of a test specimen during a test was measured by means of dial gauges. Fig. 9 shows a plotting of the test results, in which the slip coefficients were calculated by using the bolt pretension obtained at the first measurement. Fig. 10 shows the envelopes to the load vs. deformation curves for various test specimens. Slip between plates under test load occured at the thinner plate side for all of the test specimens with clearance, Types N, O, P, Q, R, S, T, and W; however, about 30% of these specimens showed larger rate of decrease in pretension of the bolts on the thicker main plate which is shown in the left hand side in Fig. 7.

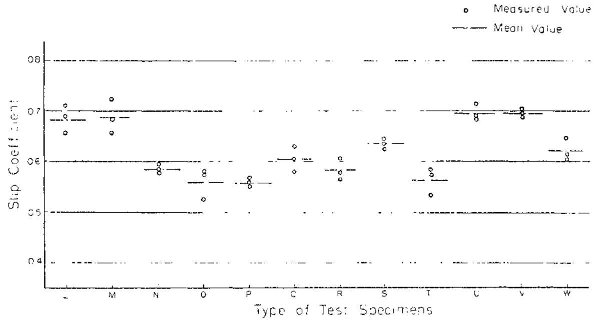


Fig. 9 Slip Coefficients Based on the Pretension Immediately after Clamping.

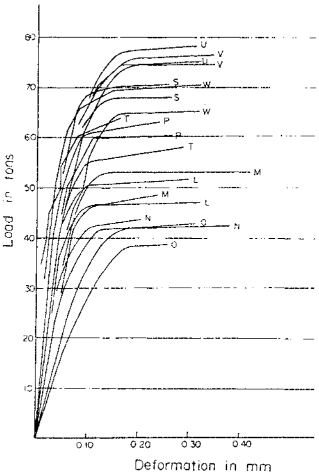


Fig. 10 Envelopes to the Load vs. Deformation Curves for Each Type of Specimens. →

(4) Considerations

From the results obtained through the present tests, the following considerations may be done:

(1) Based on a comparison between the slip coefficients of the corresponding test specimens, as shown in Table 5, the effect of the order of tightening will be as follows:

a) The clearance due to a difference in thickness of main plates decreased the slip coefficient of friction-type bolted joint as shown by a comparison in Table 5: Specimen Types L and M, and Types N and O.

b) There was no explicit effect of the order of tightening on the 2-bolt specimens of same thickness plates: Types L and M.

c) For the 2-bolt or 4-bolt specimens of 2 mm-clearance, slightly higher slip coefficients were obtained for the specimens Types N and Q in which the bolt arranged at the farthest position from the butt end of the plate was tightened in a final turn. This fact may be explained as the bolt mentioned above will make more tight contact between plates than the other bolt.

(2) The effect of a clearance in a joint on the decrease in bolt pretension will be apparent from Fig. 8. Comparing Types L and M with Types N and O; Types S and T with Types U and V, the slightly higher rate of decrease in bolt pretension may be expected to the joint of different plate thickness.

(3) Correlations between the decrease in bolt pretension and the slip coefficient may be summarized basing on Figs. 8 and 9, as shown in Table 6. One may conclude from the table that the decrease in bolt pretension is one of the causes for the decrease in the slip coefficient, and a higher rate of decrease in a joint of different plate thickness may be caused by higher decrease in bolt pretension.

(4) The rate of decrease in the slip coefficient for a joint with a smaller clearance than 4 mm showed a lesser value than 20% compared with that for the specimens with filler plates. This fact will be introduced through comparisons between Type U and Type P; V and T; L and N; and M and O. Comparing the slip coefficient for U with that for V, the effect of a clearance on the slip resistance of the joint may be disregarded when the clearance is smaller than 4 mm and the filler plates are applied to the specimen.

(5) The thickness of splice plates had an apparent effect on the slip resistance of a joint:

Comparing the slip coefficients of Type P with that of Type W, both have a same difference of main plate thickness but have different thickness of splice plates, the specimens of thinner splice plates showed a higher slip coefficient than thicker ones as shown in Table 5. From the table, comparing Type P with Type S, a higher slip coefficient will be expected for the joint with a longer edge distance when the difference of the plate thickness will be same.

4. EFFECT OF ERRORS IN THE DIAMETER OF BOLT HOLES

(1) Scope of Tests

In a joint with oversize bolt holes aligned eccentrically, it is suspected that the creep in a highly stressed part caused by the bolt tightening will reduce the bolt pretension, and, as a consequence, decrease the frictional resistance of the joint. The plate thickness should be considered as a predominant factor for the creep.

From the previous reports on the fatigue test of friction-type bolted joints with standard size holes, it is apparent that the strength will be affected by many factors: the ratio of the net area to the gross one, the number of bolt in a load direction, the width of the test specimen, the thickness of the plate, the edge distance, etc. In case of the joints with oversize holes, the same situation will be expected for the reduction in the fatigue resistance of the joint.

From the above viewpoint, the following tests were made for the test specimens with oversize bolt holes:

(1) Static Tests
- a) Series I. The Effect of the Diameter and the Eccentricity of Bolt Holes on the Slip Load
- b) Series II. The Effect of Plate Thickness on the Slip Load

(2) Fatigue Tests

(2) Static Tests

1. *Series I*

(1) Test Specimens and Test Procedure

Fig. 11 shows the test specimens used for this series. They were designed to cause slip under a load lower than the yield point of the plates of JIS SM50 which has a specified yield point of greater than 32 kg/mm². High-strength bolts JIS F9T × W7/8 were used for the specimens by a pretension of 17.0 t. The ordinary hole diameter 23.5 mm for W7/8 bolt was adopted as a standard size, while a hole diameter 28.5 mm was adopted as an oversize one. The bolt pretension was measured by means of electric resistance wire

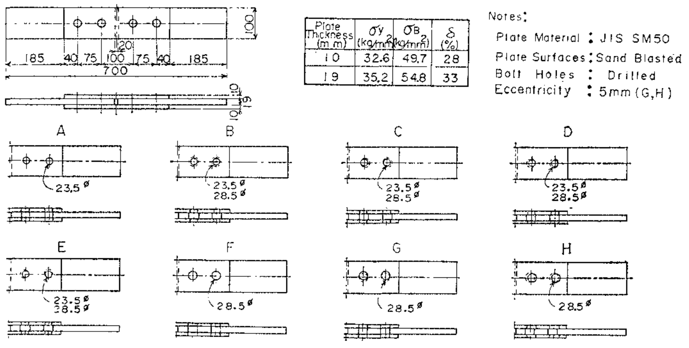


Plate Thickness (m m)	σ_y (kg/mm²)	σ_B (kg/mm²)	δ (%)
10	32.6	49.7	28
19	35.2	54.8	33

Notes:
Plate Material : JIS SM50
Plate Surfaces : Sand Blasted
Bolt Holes : Drilled
Eccentricity : 5mm (G,H)

Fig. 11 Test Specimens—Series I

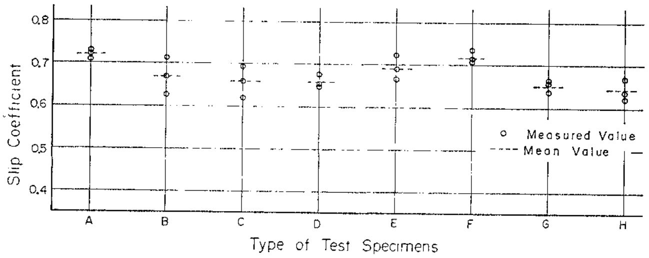


Fig. 12 Slip Coefficients—Series I

strain guages set on the bolt shank.

The plate surfaces of the specimens of this series were treated by sand blasting, and the test was conducted in as-blasted condition, in which the slip coefficient was taken as 0.5 for estimating a slip load.

(2) Test Results and Considerations

The slip coefficient obtained by dividing the slip load by the bolt pretension is plotted in Fig. 12. Each test was repeated three times to cope with expected scattering of values in test results. From Fig. 12, it may be stated that the specimen with normally assembled bolt holes belonging to Types A and F clearly exhibited higher slip coefficients than those with eccentrically assembled bolt holes; the slip coefficient was 0.72 for Types A and F and from 0.64 to 0.69 for the other types.

In Fig. 12, the value of bolt pretension to calculate the slip coefficients was taken to be the value measured immediately after tightening the bolt.

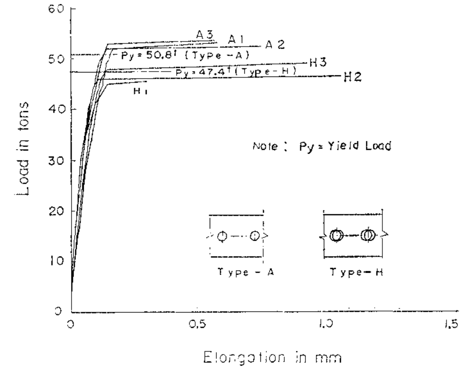


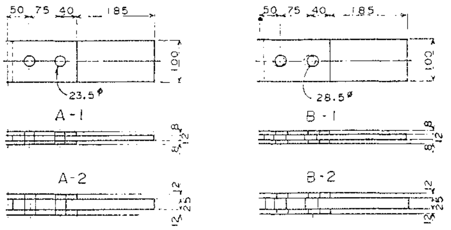
Fig. 13 Load-Joint Elongation Relationship for Specimens—Series I

In Fig. 13 are shown the load-deformation curves of the typrs A and H which showed relatively large difference.

2. *Series II*

(1) Test Specimens and Test Procedure

In this test series, the specimens were fabricated in various total thicknesses. A measurement was made on the variation of bolt pretension in relation to the duration before testing. Fig. 14 shows the geometrical layout and the materials of the specimens. The faying surfaces were treated by grit blasting, which differes from the preceding test series I treated by sand blasting. In Fig. 14, Types A-1 and A-2 correspond to Type A shown in Fig. 11, while Types B-1 and B-2 to Type H.



Mechanical Properties of Plates

Distinction	Thickness (mm)	σ_y (kg/mm^2)	σ_B (kg/mm^2)	δ (%)
Main	12	39.8	57.9	24
	25	37.1	57.5	22
Splice	8 or 12	32.8	49.9	28

Notes:

Plate Material : JIS SM 50
Plate Surfaces : Grit Blasted
Bolt Holes : Drilled
Splice Plates : Machined from 14 mm thick Plate
Eccentricity : 5mm (B-1, B-2)

Fig. 14 Test Specimens—Series II

(2) Test Results and Considerations

The obtained slip coefficients were plotted as shown in Fig. 15. Fig. 16 shows the load-deformation relationship. For the thin plates specimens, Types A-1 and B-1, the amount of slip increases gradually after surpassing the yield point, and the increase in joint deformation considerably lags as compared with the thick plate specimens, Types A-2 and B-2. After the major slip, the load indications of the testing machine dropped about 20% in the thin plate specimens

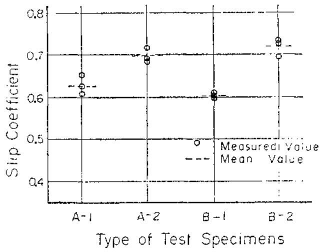


Fig. 15 Slip Coefficients—Series II

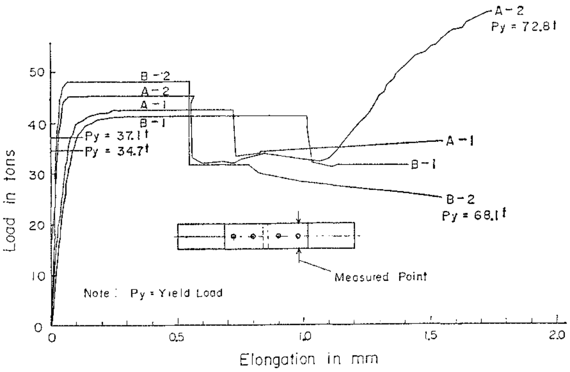


Fig. 16 Load-Elongation Relationship for Specimens—Series II

and about 30% in the thicker ones, after which the load did not vary. No significant difference was noticed between the specimens with oversize and standard size holes.

3. *Variations of Bolt Pretension*

The measurement of the bolt pretension during long period after installation of bolt are very important from a practical point of view to secure the safety against slip. Fig. 17 shows the rate of decrease of bolt pretension, and Fig. 18 the variation of pretension after installation. It is clear that there are considerable scattering of values in the rate of decrease in bolt pretension; however, it may be seen that the pretension decreases evidently in the specimens of Types G, H, and B-2 provided with greater holes and eccentricity while specimens of Types A, A-1, and A-2 having standard size holes does not exhibit significant decrease. The rate of decrease in the remainder lies roughly between those of two groups.

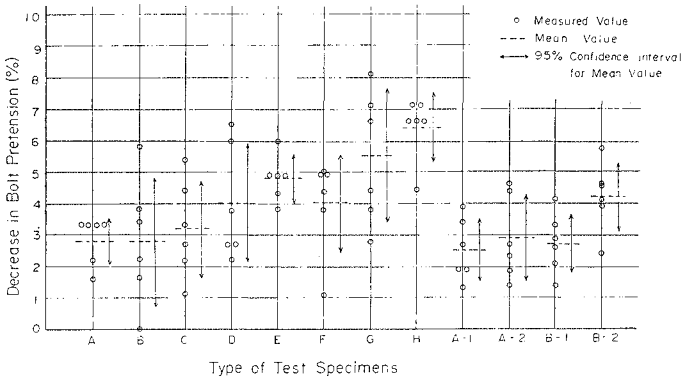


Fig. 17 Decrease in Bolt Pretension

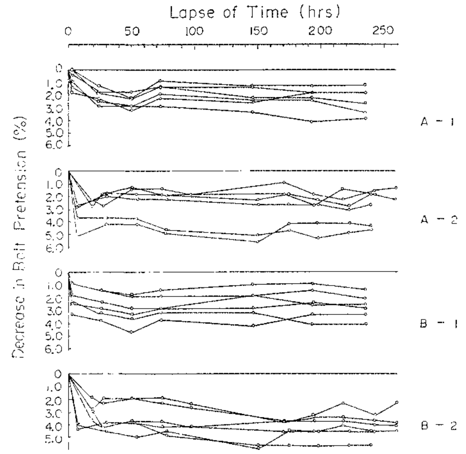


Fig. 18 Decrease in Bolt Pretension after Tightening

4. *Summary for the Static Test*

Considering the results obtained through the static test, the relationship between the slip coefficients and the stress ratio defined by the stress on the net area divided by the yield stress are plotted as shown in Fig. 19. From the figure, it may be indicated that the specimens of standard size holes kept the slip coefficient unchanged until the stress ratio reached 1.0. For the specimens of eccentrically assembled oversize holes, the slip coefficient tends to decrease when the stress ratio approaches to 1.0. The decrease in the slip coefficient was explicit when the stress ratio reached at about 1.1 for the both groups of specimens. From these test results, it is apparent that the coefficient never dropped below 0.6, which was attained when the stress ratio reached 1.2.

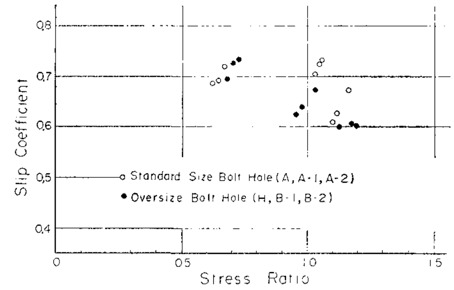
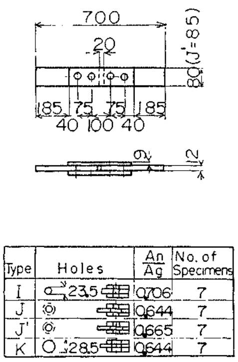


Fig. 19 Relations between Stress Ratio and Slip Coefficient

(3) Fatigue Test

1. *Test Specimens and Test Procedure*

The test specimens for this test series are shown in Fig. 20, which are comprised of 4 kinds of specimens including Type I which has ordi-



Type	Holes	$\frac{An}{Ag}$	No. of Specimens
I	23.5	0.706	7
J		0.644	7
J'		0.665	7
K	28.5	0.644	7

Fig. 20 Fatigue Test Specimens

nary holes. The material for the specimens was JIS SM50 for steel plates, and JIS F9T×W7/8 for bolts, which were tightened by pretension of 18.3t. Both sides of the specimens were machined to avoid a stress concentration under fatigue loading, and the bolt holes were drilled to the specified dimension. The surfaces of the plates were sand blasted with the particle of 60 mesh at a jet pressure of 5 kg/cm^2.

Fatigue tests were conducted by an Amsler type fatigue testing machine of 50 t in capacity under a pulsating load with minimum load of 1.0 t at 400 c.p.m.

2. *Test Results and Discussions*

The results of fatigue tests are shown in Table 7. Fig. 21 shows so-called S-N diagrams, in which the number of loading cycles to failure are plotted against the stress calculated on the basis of a net area or of a gross area of the specimen, and the straight lines in the diagram are fitted to the test results by a method of least square. From the figure, the fatigue strength at loading cycles of 2×10^5 and 2×10^6 are obtained as shown in Table 8. Based on the fatigue strength at 2×10^5 loading cycles, it is apparent that the strength on the basis of a gross area for various kind of test specimens are I>J'>J>K. This fact corresponds with the theoretical expectation that the strength will be lower for the specimens with oversize holes than those with the ordinary size ones. However, comparing the strength of specimens at 2×10^6 cycles, there is no appreciable difference of strength between the specimens.

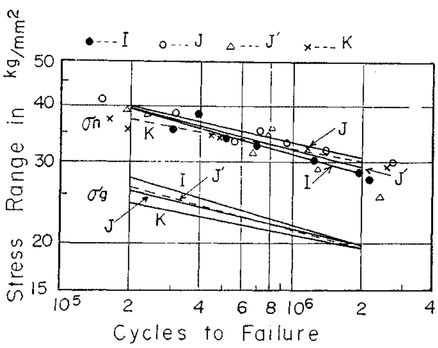


Fig. 21 S-N Diagrams

Table 7 Fatigue Test Results

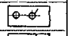
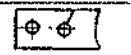
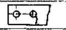
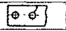
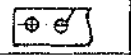
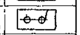
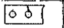
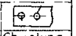
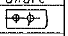
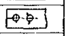
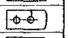
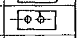
Type	Net Stress Range in kg/mm^2	Cycles to Failure x 10^4	Failures Conditios
I - 1	35.2	29.3	Chucking Portion
2	38.2	39.0	
3	33.4	45.7	
4	32.2	68.9	Chucking Portion
5	30.1	125.8	
6	28.2	195.6	
7	27.0	212.9	Chucking Portion
J - 1	41.7	15.1	
2	38.5	25.5	
3	33.6	54.7	
4	35.5	73.6	
5	32.9	92.5	
6	31.8	137.5	
7	30.0	268.7	Chucking Portion
J'- 1	39.0	19.2	
2	37.8	23.6	
3	31.4	67.5	
4	35.0	78.4	
5	35.7	81.4	
6	28.4	130.2	Chucking Portion
7	25.5	240.0	Non Failure
K - 1	43.6	6.1	
2	37.2	16.3	
3	35.5	19.5	
4	34.4	42.5	
5	33.8	49.4	
6	32.8	117.9	
7	29.4	255.4	Chucking Portion

Table 8 Fatigue Strengths

Stress Range in kg/mm^2

Type		On Net Area		On gross Area	
	n =	2×10^5	2×10^6	2×10^5	2×10^6
I		38.8	27.9	27.4	19.7
J		39.7	30.5	25.6	19.6
J'		39.1	29.0	26.0	19.3
K		37.2	30.0	24.0	19.3

From an investigation of the fatigue strengths calculated basing on a net area, it is obvious that the strength for Type K is lower than that of Type I at smaller loading cycles than 5×10^5; however, at larger cycles, the strength for Types J, J', and K are superior to that of Type I. These facts explain that the joints with oversize holes are not inferior to that with ordinary ones in fatigue strength at a larger number of loading repetitions. Some experimental works[10)] show that the fatigue strength based on the net area will be larger when the rate of reduction of area by bolt holes becomes larger. The above fact was proved by the present test in which the fatigue strengths at 2×10^6 loading cycles were $J \fallingdotseq K > J' > I$. In other words, this is corresponding to that the fatigue strength based on the gross area will approach to that of the plain plate specimens irrespective of the rate of reduction of area by bolt holes, and the fact will be understood by the S-N curves based on the gross area in Fig. 21.

The decrease in the pretension in a bolt was estimated by the difference between the values measured at the installation and the fatigue testing. The average decrease in pretension were 5.3% for I, 4.0% for J, 5.6% for J′, and 8.4% for K; and it was confirmed that the decrease in pretension does not significantly affect the fatigue strength.

The slip resistance of the fatigue specimens under static loading may be sufficiently larger than the corresponding load for the fatigue strength which is 27.5 t at maximum, as will be expected from the slip load for Types A and F which have similar configurations as the fatigue specimens; therefore, the slip during the fatigue testing will not be expected in the present tests. Through inspection of the failed specimens, no slippage was detected between plates except for a portion where fatigue crack started.

The features of fatigue failure are shown in Table 7, which shows that the fatigue crack caused by a large number of loading repetitions started through a bolt hole at a section shifted to a grip end of the plate and not at the minimum cross section. The difference in the crack initiation between the oversize and the ordinary ones was not clear in these tests.

5. CONCLUSIONS

From the present tests, the following may be allowed to conclude on the effect of various manufacturing errors for the mechanical properties of friction-type bolted joints:

(A) On the Effect of Errors due to the Condition of Faying Surfaces

1) The slip coefficients between plates for friction-type joint of same kind of steel, JIS SM50A, blasted by the peculiar method to each of the eleven fabricators varied in mean values. The scattering of three tests for each fabricator decreased appreciably through rusting, and at the same time, the mean value explicitly increased.

2) The slip coefficients varied remarkably among steel producers even in a same kind of steel; however, the difference decreased through rusting of the faying surfaces. A remarkable variation of slip coefficients was recognized among kinds of steels in a same producer. The coefficients showed a trend to decrease according to the increase of the strength of the plate. The increase in the coefficient through rusting of faying surfaces were remarkable in all kinds of steels, especially in H.T. 80, for which 1.31 was obtained as a mean value for the steel supplied by several producers.

(B) On the Effect of Errors due to the Plate Thickness

1) The coefficients decreased apparently by the existence of a clearance due to the difference in thickness of main plates, say 2 mm. Improvements may be attained ① by changing the order of tightening bolt so that the farthest bolt from the butt end of the joint in a final turn; ② by making the edge distance of the joint larger than the ordinary one; and ③ by applying filler plates to the clearance of the joint.

2) No distinct difference was recognized between the slip coefficients of the specimens with clearances of 2 mm and 4 mm.

3) The rate of decrease in the coefficient for a joint with a smaller clearance than 4 mm showed lesser values than 20% which is smaller than that for the specimen with filler plates.

(C) Effect of Errors in the Diameter of Bolt Holes

1) From the static tests, the coefficients for the test specimens of concentrically assembled holes were higher than those of eccentrically assembled ones irrespective of the diameter of holes: 23.5 mm for the ordinary one and 28.5 mm for the oversize one.

2) The coefficients for various types of specimens were sufficiently high as compared with the specified value 0.4 of the current specifications. The effect of the oversize in holes on the slip coefficient was not explicit.

3) The bolt pretension decreased clearly in the test specimens with oversize and eccentric holes, while decreased slightly in the specimens with standard size bolt holes.

4) From the fatigue tests, the strength calculated based on the gross area at the loading cycles of 2×10^5 was 27.4 kg/mm² at the maxi-

mum for the specimen with standard size bolt holes, and 24.0 kg/mm^2 at the minimum for the one of oversize bolt holes; however, the differences in strength became less at 2×10^6 cycles and the extreme values were 19.7 and 19.3 kg/mm^2.

5) The fatigue strengths calculated based on the net area were higher for the specimens with oversize holes than for those with standard size holes under a larger number of loading repetitions, 30.0 kg/mm^2 and 27.9 kg/mm^2 for 2×10^6 cycles, respectively.

6) The fatigue crack caused by a larger number of loading repetitions started through a bolt hole at a section shifted to a grip end of the plate and not in a net section. The difference in the trend of crack initiation between the oversize and the ordinary holes was not clear.

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