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HIGH STRENGTH BOLT JOINTS SUBJECT TO CYCLIC TENSILE LOADING

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SUMMARY

In this paper, the authors investigate the behaviours of axial forces in bolts used in tension joints subjected to several types of simple cyclic loadings. The factors which govern the behaviours of the joints include the additional bolt axial force and the decreases of initially induced bolt axial force. And these factors are influenced by the geometry of the joint and the flatness of contact surfaces. And a basic design criterion is also presented for structural dimensions of this type of joints.

INTRODUCTION

In Japan, friction joints with high strength bolts have gained great favor for use in structural connections of steel bridges. And it is well recognized that the high strength bolts in use have excellent quality. There is another type of high strength bolted joints such that the bolts in the connection are placed in the lengthwise direction of the connected two members and are applied longitudinal tensile loads. But this so called tension joints, which will be discussed in this paper, has rarely been used in steel bridge superstructures. Nevertheless, in the basements of maintower of suspension bridges, which are most important in the structure, this kind of tension bolts are necessarily utilized. Thus the tension joints which directly resist tensile loads have been used either in very restricted parts of steel structures or in a very few practices for other parts.

Besides the apparent fact that high tensile strength given to high strength bolts can be effectively utilized, there are following advantages in high strength bolted joints provided that considerations are made regarding to structural details so as not to cause prying action:

a) easiness to evaluate joint stiffness,
b) accurate predictability of the load which separates the contact surfaces,
c) clearness of applicable load range,
d) performance desirability against cyclic loading,
and
e) large deformability.

The performance of the tension joints having these advantages is exclusively controlled by the axial force in the bolts.

In this paper, an experimental investigation is presented about the behaviour of the axial force in the bolts used in the tension joints subjected to several types of simple cyclic loadings. A basic design criterion is also presented for structural dimensions of this type of joints.

TEST SPECIMENS AND TEST SETUP

The geometry of test specimens is shown in Fig.1. These specimens were fabricated from JIS SS41 structural steel. And JIS F8T bolts, which were installed with JIS F35 washers under JIS F10 nuts, were of 20mm nominal diameter and 580mm nominal length.

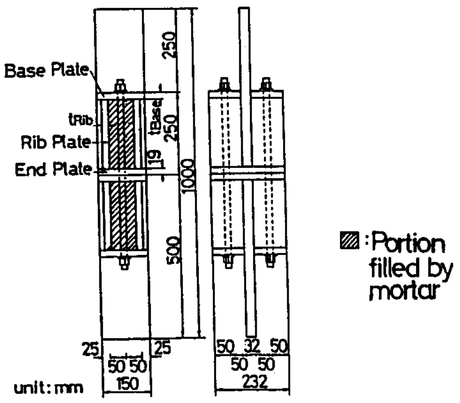

Fig.1. Geometry of test specimens

The various combinations of base plate thickness, rib plate thickness and the tensile force in the bolts and the designations of corresponding connection geometries are indicated in Table 1.

Tensile tests were performed on JIS F8T bolts, and the tensile strength was found to be 854 MPa and the Young's modulus 210 GPa. The relationship between bolt tension (as indicated on a testing machine) and average axial shank strain (as indicated by the resistant type strain gauges) was linear for values of bolt tension up to more than 97% of the ultimate tensile strength.

EXPERIMENTAL TESTS AND THOSE RESULTS

Loading patterns

Loading tests were carried out under the loads which had three loading patterns shown in Fig.2.

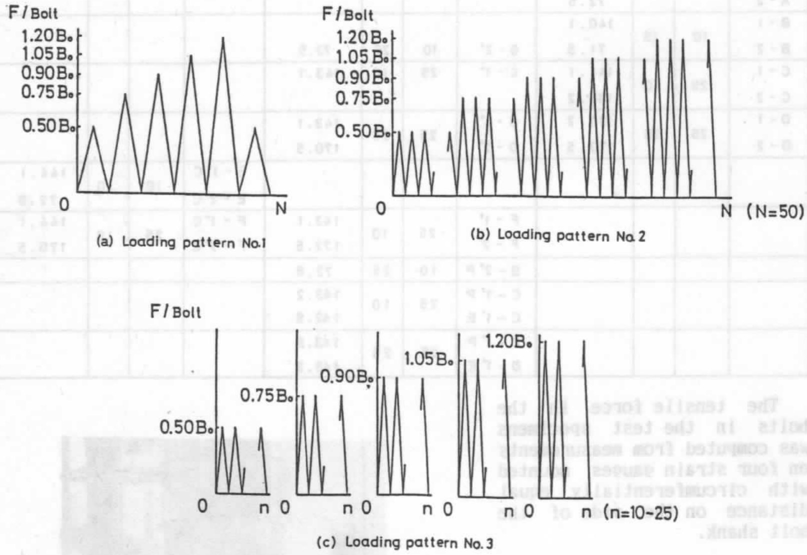

Fig.2. Loading patterns

The external force which is sustained by a joint is in equilibrium with the tensile force introduced to the bolts and the compressive force caused by them between contact surfaces. Accordingly, until the external force reaches the bolt tensile force, the additional bolt axial force is theoretically proportional to the external force and the rigidity of the joint does not vary. From this point of view, the behaviours of a joint have to be investigated under two cases. One of them is the case that the maximum load is less than the initial bolt axial force, and the other case has the maximum load over the initial bolt axial force. In this paper, the external force of 50%, 75% and 90% of the initial bolt axial force was applied in the former case. And the amount of 105% and 120% was applied for the latter case.

Experimental relations between load and tensile force in bolts

Fig.3 to Fig.7 show some test results about the bolt axial force in joints caused by the loading with the loading pattern shown in Fig.2. As classified in Table 1, specimens are grouped according to the conditions of contact surfaces.

Table 1. Designations of test specimens

Specimens without mortar								Specimens filled by mortar			
Contacting surface not finished				Contact surface finished							
Test Specimen	tBase (mm)	tRib (mm)	Bolt initial axial force Bo(x10³N)	Test Specimen	tBase (mm)	tRib (mm)	Bolt initial axial force Bo(x10³N)	Test Specimen	tBase (mm)	tRib (mm)	Bolt initial axial force Bo(x10³N)
A-1	10	10	139.2								
A-2			72.5								
B-1	10	25	140.1								
B-2			71.5	B-2'	10	25	72.5				
C-1	25	10	141.1	C-1'	25	10	143.1				
C-2			186.2								
D-1	25	25	139.2	D-1'	25	25	143.1				
D-2			170.5	D-2'			170.5				
								E-1'C	10	10	144.1
								E-2'C			72.5
				F-1'	25	10	143.1	F-1'C	25	10	144.1
				F-2'			172.5	F-2'C			170.5
				B-2'P	10	25	72.8				
				C-1'P	25	10	143.2				
				C-1'E			142.8				
				D-1'P	25	25	143.9				
				D-1'E			143.9				

The tensile force in the bolts in the test specimens was computed from measurements on four strain gauges mounted with circumferentially equal distance on the side of the bolt shank.

The test setup is shown in Photo 1.

The designations " C1'-P " and " D1'-P " shown in Table 1 mean that the bolts in the corresponding specimens were carefully tensioned that bending due to eccentricities may not take place in the joints. The tensioning were controlled through measurements of strain in the bolt shank and other parts of the joints. While " C1'-E " and " D1'-E " mean the specimen of which bolts were tensioned giving some eccentricities.

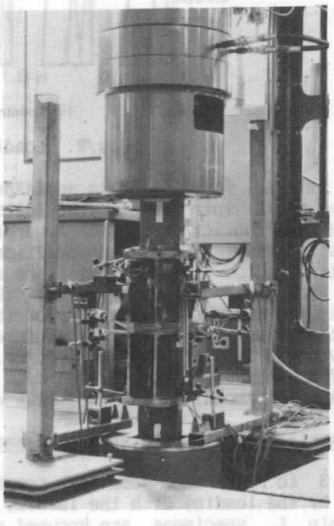

Photo 1. The test setup

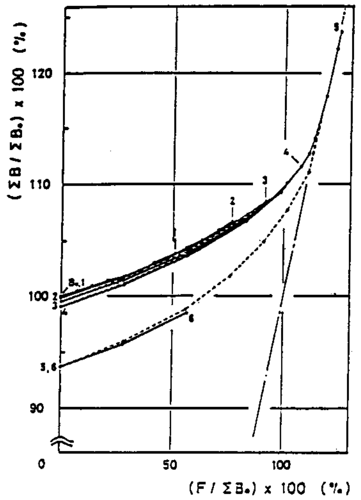

Fig.3. Relation between bolt axial force and external force (specimen C-1)

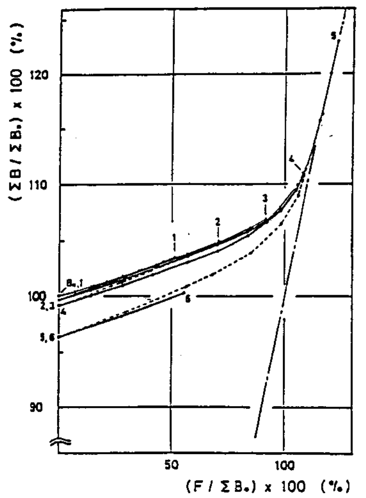

Fig.4. Relation between bolt axial force and external force (specimen D-1)

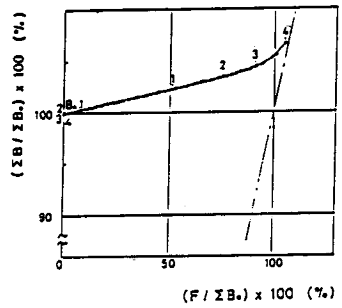

Fig.5. Relation between bolt axial force and external force (specimen C-1'P)

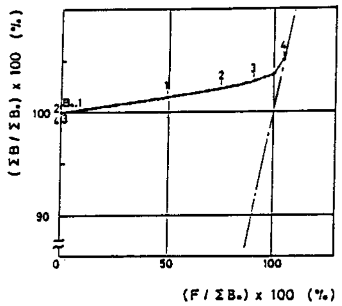

Fig.6. Relation between bolt axial force and external force (specimen D-1'P)

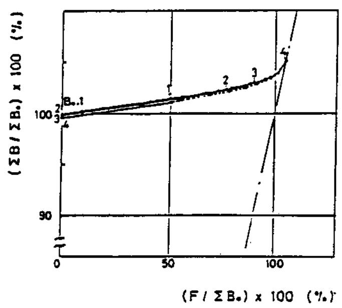

Fig.7. Relation between bolt axial force and external force (specimen D-1'E)

Table 2. Additional bolt axial force and variation of initially induced bolt axial force

Test Specimen	A.B.A.F.C.		Variation of Initial Bolt Axial Force								
	$F/\Sigma B_0$ =		$F/\Sigma B_0$ = 50(%)			90(%)			120(%)		
	50(%)	90(%)	max	min	total	max	min	total	max	min	total
A 1	0.067	0.060	※1.2	※-0.2	1.4				20.5	-100.0	120.5
A 2	0.043	0.057	2.1	-0.4	2.5	3.8	-1.6	5.4	12.6	-12.0	24.6
B-1	0.065	0.092	3.2	-0.3	3.5	5.0	-5.6	10.6	21.0	-90.0	111.0
B-2	0.083	0.100	4.0	-0.2	4.2	7.5	-1.3	8.8	14.8	-4.0	18.8
C-1	0.077	0.107	3.9	0	3.9	8.4	-0.5	8.9	23.7	-6.2	29.9
C-2	0.050	0.066	2.5	-0.6	3.1	4.0	-2.4	6.4			
D-1	0.069	0.081	3.4	0	3.4	7.0	-0.3	7.3	23.3	-3.6	26.9
D-2	0.074	0.096	3.6	-0.3	3.9	6.4	-3.3	9.7	17.4	-48.9	66.3
B-2′	0.030	0.036	1.3	0	1.3	2.8	-0.2	3.0	16.3	-1.8	18.1
C-1′	0.044	0.050	2.1	-0.2	2.3	4.1	-0.4	4.5	16.9	-1.8	18.7
D-1′	0.030	0.035	1.5	-0.1	1.6	2.9	-0.3	3.2	20.0	-3.2	23.2
D-2′	0.030	0.037	1.4	-0.2	1.6	2.7	-0.8	3.5	20.6	-81.3	101.9
F-1′	0.046	0.057	2.2	-0.1	2.3	4.7	-0.5	5.2	23.6	-3.2	26.8
F-2′	0.040	0.047	2.0	-0.3	2.3	3.4	-1.3	4.7	19.1	-90.6	109.7
B-2′P	0.031	0.040	1.5	0	1.5	3.4	0	3.4			
C-1′P	0.045	0.048	2.3	0	2.3	4.4	0	4.4			
C-1′E	0.046	0.049	2.3	0	2.3	4.4	0	4.4			
D-1′P	0.030	0.034	1.5	0	1.5	3.1	0	3.1			
D-1′E	0.030	0.035	1.5	0	1.5	3.0	-0.1	3.1			
E-1′C	0.016	0.035	0.7	-1.0	1.7	1.2	-2.6	3.8	19.5	-12.8	32.3
E-2′C	0.028	0.040	1.5	-0.2	1.7	2.7	-1.0	3.7	16.2	-3.5	19.7
F-1′C	0.028	0.041	1.4	-0.2	1.6	3.1	-0.7	3.8	18 2	5 3	23 5
F-2′C	0.028	0.035	1.4	-0.5	1.9	2.1	-1.4	3.4	20 5	94 2	144 7

Fig.3 and Fig.4 indicate the test results of the specimens with unfinished contact surfaces. Fig.5 to Fig.7 show the test results of the specimens which have finished contact surfaces and the same geometry of those shown in Fig.3 and Fig.4.

With the increase of the external force, the axial force in bolts increases. Bo ,which means the amount of the initial bolt axial force, is added with the additional bolt axial force by the external force. When the joint is assumed as a spring system, the bolt axial force B after the loading of external force F is indicated by the following equation.

$$B = B_o + \frac{1}{1 + \frac{K_R}{K_B} + \frac{K_R}{K_{BASE}}} F \tag{1}$$

where K_R is the compressive stiffness of a joint in the direction of the external force to the exclusion of bolts and base plates,
K_B is the bolt stiffness for elongation of the bolts,
K_{BASE} is the stiffness for deflection of a base plate.

The coefficient of the second term in the right hand side of the Eq.1 is defined as " additional axial force coefficient". The linear relationship between B and F indicated by Eq.1 holds for values of F up to 30%~50% of Bo in the case of unfinished contact surfaces and up to 50%~70% of Bo in the case of finished contact surfaces.

The test results for α are shown in Table 2.

The bolts were tensioned to the amount of Bo which is defined as an initial bolt axial force. But in advance of the cyclic loading the bolt axial force at zero applied load was becoming less than Bo. This experimental decrease is indicated in the percentage of Bo in the column MIN of the Table 2. The values in the column MAX of the table show the additional axial force in the percentage of Bo at the beginning of unloading for each loading patterns.

Consequently, the sum of the values in both columns indicates the bolt axial force amplitude caused by loading and unloading.

ANALYTICAL STUDY

Stiffness of base plate and rib plate

Fig.1 shows that a base plate is supported along three edges,but it belongs to a thick plate and the boundary conditions for numerical evaluation of the flexural stiffness may not be clear. On the other hand the stiffness of rib plates and bolts may be able to be evaluated clearer than that of base plates, so the reference [1] introduces the coefficient concerning to the decrease of the bolt sectional area so as to evaluate the degree of unclearness in the value of base plate stiffness and shows as follows:

$$\gamma = \frac{1}{1 + \frac{K_B}{K_{BASE}}} , \qquad K_B^* = \gamma K_B \tag{2}$$

γ shown defined by the above equation is measured experimentally and the relation between the value γ and the ratio of bolt sectional area and length is shown by the group of curves of which the thickness of base plates is a parameter. Referring the figure, the estimated values of γ for the joint whose geometry is indicated in Fig.1 are tabulated in Table 3.

Table 3. Values of γ

Test Specimen	A	B	C	D
Caluculated Value	0.35	0.44	0.89	0.92
Interpolated Value	0.85	0.94	0.99	1.00

Calculated values in Table 3 are computed under the assumption that base plates are thin plates simply supported on three edges.

The tests carried on the test specimen "A" according to the loading pattern

1 brought plastic flexural deformation into the base plates. The measured deformed shape in the neighborhood of edges shows that the edges of the base plate are fixed rather than simply supported. The deformation in the type "B" was similar but the magnitude was less.

The equivalent thickness of a simply supported plate corresponding to the estimated γ value is found by the calculated γ values for simply supported plates. They are found to be about 2.2 ∼ 2.4 times for the case t_{BASE}=10mm, and about 3.0 ∼ 3.5 times for 25mm. When such multipliers are found, the approximated equivalent thickness of a base plate to evaluate the γ value may be determined. By using such equivalent thickness the γ value may be evaluated under the assumption of simply supported thin plate.

In this paper, rib plates resisting together with base plates are assumed to have the function to be in equilibrium with the external force, the axial tensile force in bolts and the compressive force between contact surfaces. Therefore, the γ value is regarded as a coefficient to modify the value k_R as follows:

$$K_R^* = \frac{K_R}{\gamma} \qquad (3)$$

Test specimens are classified into two groups according to the state of contact surfaces in Table 1. This is why that the behaviours of joints are different between the case of transmitting force on full area of contact surfaces and the case of restricted area. According to the reference [1],in the case of the full area transmission it is clarified that the equivalent area of compressive elements including rib plates is 125% of the real area which is a fundamental value to evaluate the value K_R.

According to the equivalent area of rib plates mentioned above four groups of K_R^* value are evaluated from the γ value in Table 3.

Additional bolt axial force coefficient

The additional bolt axial force coefficient α defined by the coefficient of the second term of Eq.1 is as follows :

$$\alpha = \frac{1}{1 + \frac{K_R^*}{K_B}} \qquad (4)$$

The values α corresponding to each evaluated K_R^* are computed and shown in Table 4.

Table 4. Evaluated α

Test Specimen	A	B	C	D
(1) Calucuated Value	0.023	0.017	0.056	0.035
(2) Evaluated Value 1	0.054	0.035	0.062	0.038
(3) Evaluated Value 2	0.018	0.014	0.045	0.029
(4) Evaluated Value 3	0.045	0.028	0.049	0.039

The amount of "Calculated value" and "Evaluated value 1" are computed from the values in Table 3. The amount of "Evaluated value 2 and 3" are computed from the values in the rows (1) and (2) by using the equivalent area of rib plates.

The comparison of the values in Table 4 and Table 2 shows that the values measured in experiments for test specimens "C" and "D" are in good fitness to the values in the rows (3) and (4). In the case where t_{BASE} =25mm, it is feasible that the value γ may be evaluated with the same accuracy as the experimental value if it is assumed that γ is about unity and the equivalent area of the joint is 125% of the real area.

In the case that the value γ is nearly unity, Eq.4 is approximated as follows:

$$\alpha = \frac{1}{1 + \frac{A_R}{A_B}} \qquad (4)'$$

where A_R is the sectional area of the joint
A_B is the sectional area of bolts .

Accordingly, the value α is independent of the length of a joint provided that no bending arises in the joint and bolts.

In the case that the geometry of base plates is designed so as the value γ is nearly unity, the total joint area including the rib area may be estimated by the area of bolts. The values shown in Table 2 indicate that when contact surfaces are finished, even if a few eccentricities are in existence, not so large value of α can be reached.

Joints of which γ values are nearly unity may be fabricated, when the measured values shown in Table 2 are examined. According to this point of view, the upper bound for the value α of prototype joints may be kept down to 0.05 without so severe considerations regarding to design and fabrication. For the joint having γ nearly unity, the evaluation of the value α when the equivalent joint area is taken gives good fit to measured values.

Consequently, in order to realize the desired value 0.05 for α it is recommended that the joint area have to be more than fifteen times of the bolt area and the value γ is nearly unity.

Variations of bolt axial force

Loading brings the additional bolt axial force and the decrease of initially induced bolt axial force comes from unloading. Such a variation of bolt axial force composes the main parts of variations of bolt axial force. Table 2 shows both the amplitude of bolt axial force variation and the decrease of initially induced bolt axial force caused by the loading with the loading pattern 1.

That the amplitude of bolt axial force variation is less than 5% of the initial bolt axial force is obtained from the measurement under the loading being 90% of the initial bolt axial force for the specimen having finished contact surfaces.

As the desired accuracy to the initial bolt axial force in the field construction of friction joints by high tension bolts each authority or corporation in Japan usually claims ±4% ~ ±7% [2] of the bolt axial force.

The values shown in Table 2 are not so severe compared to the desired accuracy mentioned above, although it is insignificant to discuss the scattering of the initial bolt axial force and variations of bolt axial force caused by loading under the same point of view.

The variations of bolt axial force accompanied with unloading may be caused by yield in the restricted parts having stress concentration. When the external load may be less than the initial bolt axial force, the main part of the variations in axial force may be brought by irregularity between contact surfaces. Accordingly, the results of measurements for the specimens with finished contact surfaces show only slight variations in the case of loads less than 90% of initial bolt axial force as shown in Table 2. The condition of contact surfaces has great influences on the decrease of the initially induced bolt axial force.

When the load beyond 105% of initial bolt axial force is sustained by the bolt shank, as the result of yield in the screwed parts of bolts the bolt axial force decreases greatly and the capacity of the joint to transmit the external force reduces considerably.

Fig.8 and Fig.9 show the decrease of bolt axial force by the loadings in the loading pattern 1. Fig.10 indicates the decreases of initially induced bolt axial force caused by loadings and unloadings in the loading pattern 1. When tensile loads were up to 105% of bolt axial force,the amount of decreases in bolt

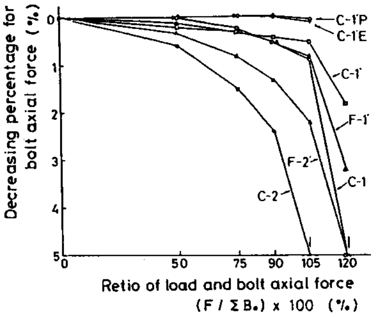

Fig.8. Rate of loads and bolt axial force (C and F type specimens)

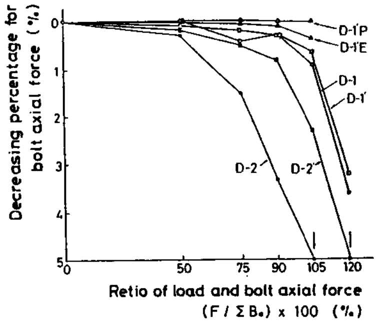

Fig.9. Ratio of loads and bolt axial force (D type specimens)

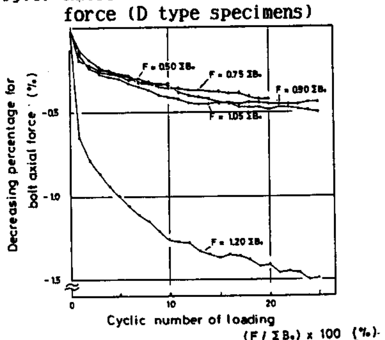

Fig.10. Decrease of initially induced bolt axial force(loading pattern 1)

axial force were less than 0.5%, and after several loading cycles no variations were observed in bolt axial force. And the total amount of the decreases were about two to three times of the decreases observed in the first path of unloadings. In a test with loading pattern 2 the bolt axial force in the specimen showed the drastic decrease when the joint was subjected to 90% or more of the bolt axial force. Noticing such a result of tests, joints may be assumed to be in normal conditions when subjected to loads under 90% of the initial bolt axial force.

<u>Additional bolt axial force and contact surfaces</u>

The flatness of contact surfaces was observed through the distribution of compressive force over the surfaces by a prescale installed between contact surfaces. The prescales installed demonstrated that the compressive force between both end plates distributed on quite restricted area for the specimen with unfinished contact surfaces. This may be a reason of larger α compared to calculated values. And the reduction of bolt axial force following the cyclic loadings and unloadings was caused by this.

Noticing the effect of flatness of contact surfaces, loading tests on specimens with the finished surfaces were carried out. Those test results indicated that α value and phenomena of the decrease in bolt axial force were improved. In Fig.11 the values α gained by measurements are plotted in the relation of the contact area. In the figure, α^{MODEL} means the calculated value under the assumption that base plates are thin plates with three edges simply supported and compressed elements are composed from a member plate and rib plates. Fig.11 shows that the values α measured are remarkably affected by the flatness of contact surfaces.

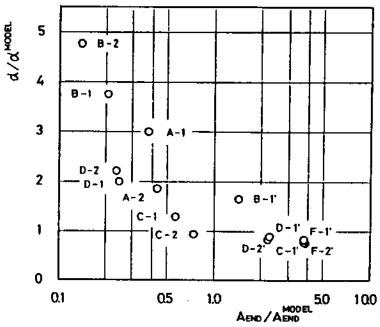

Fig.11. Relations between contact area and bolt axial force

CONCLUSIONS

The principal conclusions which were arrived at in this study on the behaviours of high strength bolted joints subjected to direct tensile loadings are as follows:

1. The factors which govern the behaviour of joint include the additional bolt axial force and the decrease of the initially induced bolt axial force.

2. The above factors are influenced by the geometry of the joint and the flatness of contact surfaces.

3. It may be feasible that α is less than 0.05 and the variation of additional bolt axial force is less than $0.05B_o$.

4. The above mentioned values are reached at in the case where γ is approximately unity, A_R is more than $15A_B$ and the contact surfaces are in good contact.

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