Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 7 (1964)

Artikel: Experiment on tensile joints using high-strength bolts

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DOI: https://doi.org/10.5169/seals-7852

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Experiment on Tensile Joints using High-Strength Bolts

Essais sur des assemblages HR sollicités à la traction

Versuche an zugfesten Stößen mit hochfesten Schrauben

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To obtain necessary data for the design and construction of Kobe Port Tower, an extensive experimental study was carried out as reported by Dr. B. KATO in his paper "Stress Analysis and Tests on a One-sheet Hyperboloidal Tower" (Id) submitted to this Congress. The tests herein reported, which were conducted to provide a basis for the specification for field assembly of the tower members, constitute a part of the said study.

Figs. 1 and 2 show the typical connections actually used for the tower construction. The vertical tension acting on the connections is carried by long

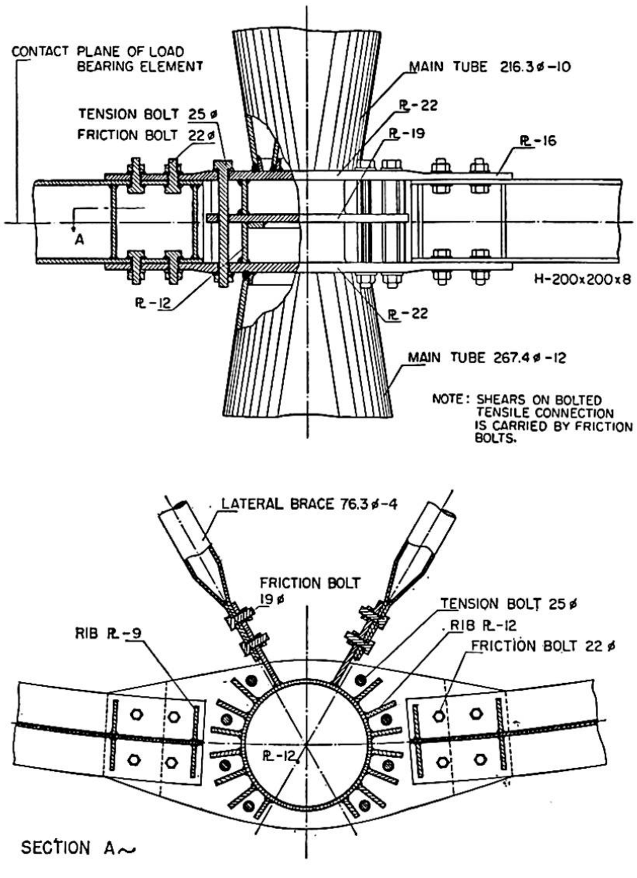


Fig. 1. Detail of connection in the outer net (at Point F shown in Fig. 1 of the paper submitted by Dr. B. KATO).

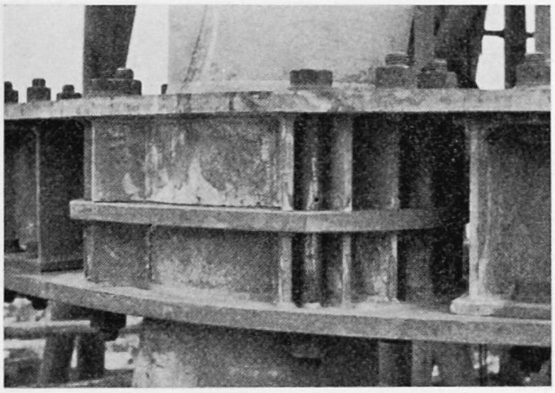


Fig. 2. Typical connection.

tension bolts while horizontal shear is taken care of by short friction bolts. In this paper, emphasis will be put on the tension bolts which present a number of new problems. These tension bolts were used to increase the rigidity of connections and for this purpose they were given a pre-load comparable with the design stresses. The chemical and mechanical properties of the bolts used are given in Table 1.

Table 1 a. Chemical Properties of Bolts

Steel Quality (JIS)	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
SCM 4 (Bolts)	0.42	0.29	0.76	0.026	0.019	0.07	1.14	0.27	0.19
S 45 C (Nuts)	0.44	0.26	0.70	0.012	0.015	0.022	0.032	—	0.09
S 35 C (Washers)	0.36	0.29	0.74	0.015	0.017	—	—	—	0.14

Table 1b. Mechanical Properties of Bolts

	Yield Strength kg/mm²	Tensile Strength kg/mm²	Elongation %	Reduction of Area %	Hardness H. B.	Quenching Temp. °C	Tempering Temp. °C
Bolts	114—119	120—130	16—19	52—60	331—356	860	580
Nuts	62—70	86—91	22—29	59—65	230—254	850	620

Note: Bolts and nuts are threaded to the precision requirements prescribed in JIS BO 210 for Whitworth Threads (Class 2).

There are two basic problems that should be given careful consideration in the design of tensile connections using high-strength bolts. They are:

1. Proper design of load bearing elements and possible constructional errors in these elements resulting from the variations in effective sectional area and quality of finish of contact surfaces and in precision of bolts threads, base plate, etc.
2. Selection of proper method to obtain the required bolt tension for the bolts tightened on the construction site.

A. Tension Test of Bolted Connections

Within the load range not causing the splitting of the parts in contact, the bolt tension may be computed from the following formula:

$$P = P_0 + \frac{A_B}{A_B + A_L} T\alpha, \tag{1}$$

Where P = bolt tension (tons),
P_0 = bolt pre-load (tons),
A_B = effective sectional area of bolt across shank (cm²),
A_L = effective sectional area of contact surface (cm²),
T = applied tensile force (tons),
α = form factor determined from the degree of contact and shape of load bearing elements.

The variation in bolt tension as observed during the test shown in Fig. 5; the theoretical values of bolt tension; and the values of form factor α computed from the comparison of observed and theoretical values are all given in Table 2.

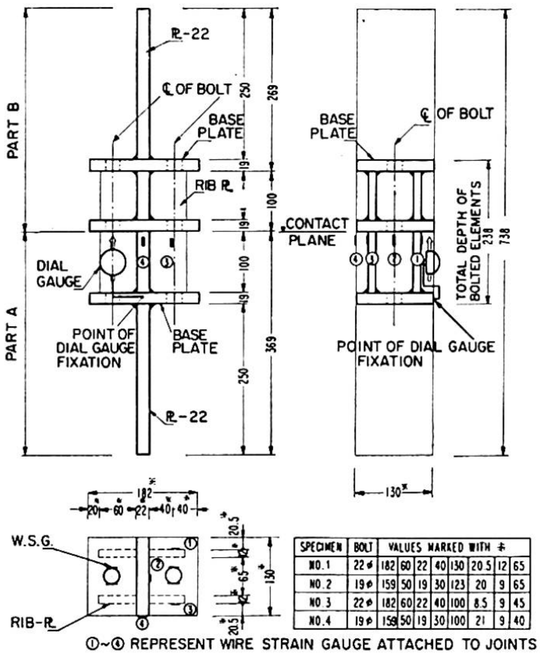
Table 2. Variation of Values of Bolt Tension and α for Tensile Load of 10 tons

Specimen No.	A_B cm²	A_L cm²	P_0 t	$P-P_0$ (if $\alpha=1$)	$P-P_0$ (experimental)	α
			42.8		0.60	0.63
No. 1 (22 ∅)	6.10	57.4	31.0	0.96	0.65	0.68
			16.6		0.60	0.63
No. 3 (22 ∅)	6.10	43.6	44.8	1.22	0.60	0.49
			33.7		0.60	0.63
No. 2 (19 ∅)	4.40	41.4	24.5	0.96	0.65	0.68
			12.6		0.70	0.73
No. 4 (19 ∅)	4.40	37.0	34.0	1.06	0.60	0.57

Figs. 3 and 4 show the test specimens and the test set-up. To minimise the deviation from the actual conditions, these specimens were prepared in the same size and shape as the actual connections except that fewer bolts were used because of the limited capacity of the testing machine.

In conducting the test, the bolts were first tightened by a torque wrench to give a bolt pre-load and then the load was progressively increased until the applied tensile force per bolt became equal to the design load. Then, the load was further increased in order to observe the mode of splitting of the parts connected, the decrease of bolt pre-load and other behaviour of the bolted connection. Figs. 5, 6 and 7 show the variations in axial force acting on bolts as measured with wire strain gauges attached to bolt shanks, the deformation of part between two base-plates as measured with dial gauges, and the strain of ribs as measured with wire strain gauges placed on the rib-plates.

Evaluation of Test Results. As shown in Fig. 5, a linear relationship was observed between the bolt tension and the applied load until the load reached



SPECIMEN	BOLT	VALUES MARKED WITH *							
NO. 1	22φ	182	60	22	40	130	20.5	12	65
NO. 2	19φ	159	50	19	30	123	20	9	65
NO. 3	22φ	182	60	22	40	100	8.5	9	45
NO. 4	19φ	159	50	19	30	100	21	9	40

Fig. 3. Detail of SpecimenNo. 1.

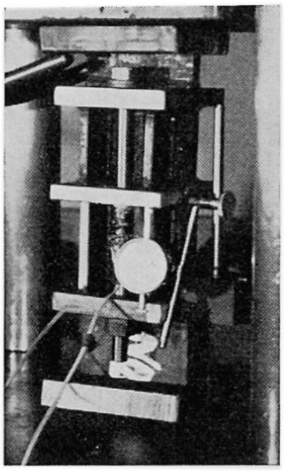


Fig. 4. Test specimen.

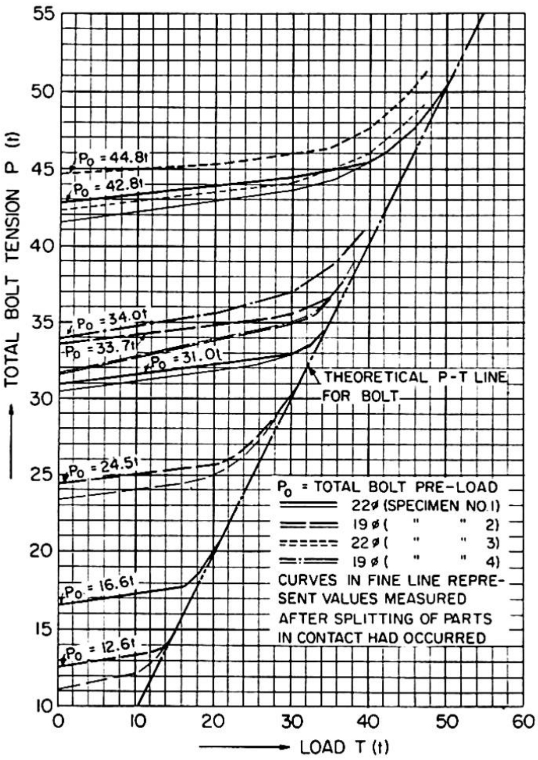


Fig. 5. Total bolt tension vs applied load — curves based on measured values.

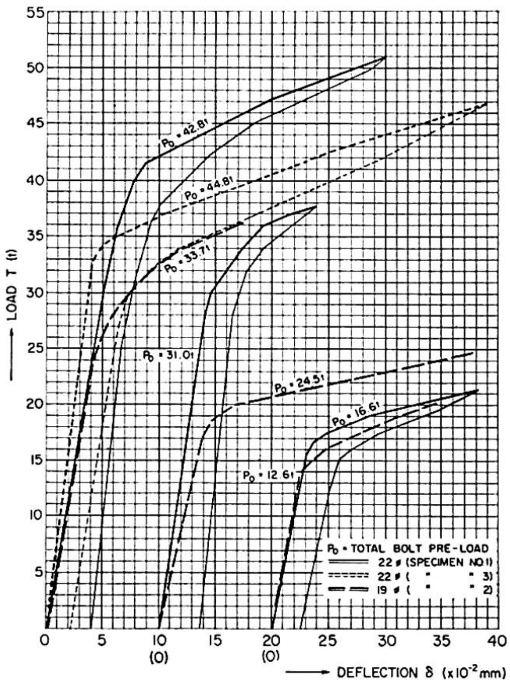


Fig. 6. Load — deflection curves based on measured values.

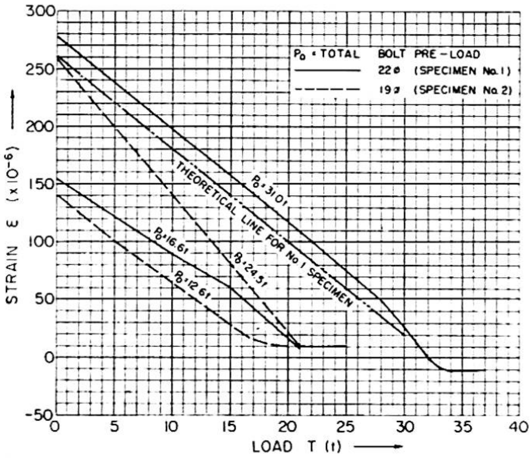


Fig. 7. Strain of rib-plates vs applied load — curves based on the values measured with wire strain gauges ($\frac{1}{3}(\epsilon_1 + \epsilon_2 + \epsilon_3)$).

a certain limit, and after this limit was exceeded the increase of bolt tension had no longer a linear relationship with the increase of applied load. After the splitting of the parts in contact had occurred the bolts behaved as if the bolts alone had been subjected to the tension test and the values of bolt tension began to show the variation in accordance with the theoretical values shown by the broken line. This tendency was observed when different bolt pre-loads were employed. This curved portion of the line representing the measured values implies that the rigidity of the bolted connection showed a continual decrease in the corresponding loading range. In other words, it means that the connection behaved as an integral unit at the early loading stage because of the tight fastening force of bolts, but as the load was further increased the compressive force acting on the parts in contact was released, resulting in the decrease of the effective sectional area of the contact surfaces. The reason why this splitting of the parts in contact took place gradually was, according to the authors' judgment, that because of unavoidable irregularities of contact surfaces it was impossible to bring the parts into perfect contact and that the stress distribution in the contact area was not uniform, thus resulting in considerable deformation of the parts in question.

The upper limit beyond which the bolt tension would not increase in linear proportion to the increase of applied load was estimated to be about 80% of the bolt pre-load, and at this loading stage the observed values of form factor α ranged approximately from 0.5 to 0.7 as shown in Table 2. It is considered that α became smaller than unity because the deformations of rib-plates and base-plates were not governed only by the axial force acting on bolts.

It was also shown during the test that inasmuch as the increase of bolt tension and the increase of applied force were in a linear relationship, the bolts did not show any decrease of fastening force upon the release of load even after the specimens had been subjected to repetitive loading. For the larger loading range, a slight decrease of bolt tension was witnessed upon removal of applied load as shown by the thin line in the graph (Fig. 5); however, it may be guaranteed from the test results that the connection using high-strength bolts show reversible behaviour under the repetitive load of nearly equal to 80% of bolt pre-load, only if the bolt tension is below the yield strength and the bolts and nuts used are manufactured with reasonable precision.

B. Bolt Tightening Test

The bolt tension may be computed by using either the torque coefficient or the turn-of-nut angle θ. In either case, the values should be estimated by a preliminary test because the bolt tension would vary with the designs of load bearing elements and the degrees of precision with which the threads are cut on bolts and nuts.

$$Q = k D P. \tag{2}$$

Where Q = magnitude of torque (ton-cm)
k = torque coefficient
D = nominal diameter of bolt (cm)
P = axial force acting on bolt (ton)

and

$$\theta = \frac{360}{p}(\Delta l + \Delta h)\,\alpha. \tag{3}$$

Thus, $\Delta l = \dfrac{P l}{E_B A_B}$

and $\Delta h = \dfrac{P h}{E_L A_L}$.

Where θ = turn-of-nut angle (°)
p = pitch of thread on bolt (cm)
l = effective length of bolt (cm)
h = total depth of load bearing elements to be bolted (cm)
E_B = Young's modulus of bolt (kg/cm²)
E_L = Young's modulus of load bearing elements (kg/cm²)
Other symbols are as defined elsewhere in this paper.

Fig. 8 shows the various values of torque coefficient computed from the experimental values by use of Formula 2, and Fig. 9 and Table 3 show the values of α obtained by comparison of the theoretical values of θ computed by Formula 3 with the experimental values of θ. In Figs. 8 and 9, there are also shown for reference the observed values for the short bolts for friction type connection.

The turn-of-nut method of bolt tightening gives a high degree of accuracy particularly if it is used after a certain compression has been induced in the parts to be bolted, and at this stage it has by far a supremacy over the torque

Table 3. Values of Turn-of-Nut Angle (θ) and Form Factor (α) for Axial Force of 10 tons Acting on Bolts

Bolt Size	p cm	l cm	h cm	A_B cm²	A_L cm²	θ (if α=1)	θ (expe.)	1/α	Remarks
25 ⌀ 350	0.318	33.2	31.4	4.13	11.8	50.5°	73.0°	0.69	Load Cell Test
	0.318	33.6	31.8	4.15	29.9*	42.3	71.5 (93)	0.59 (0.46)	Test on Actual Connection
	0.318	33.6	31.8	4.15	25.2⁺	43.5	71.5 (93)	0.61 (0.47)	Test on Actual Connection
22 ⌀ 280	0.282	26.3	24.8	3.05	8.2	60.8	86.0	0.71	Load Cell Test
	0.282	26.7	25.2	3.19	17.90*	51.7	97 (138)	0.53 (0.37)	Test on Actual Connection
	0.282	26.7	25.2	3.19	15.74⁺	53.0	97 (138)	0.55 (0.38)	Test on Actual Connection
19 ⌀ 280	0.254	26.5	25.2	2.20	17.55*	74.9	109 (149)	0.69 (0.50)	Test on Actual Connection
	0.254	26.5	25.2	2.20	16.02⁺	75.0	109 (149)	0.69 (0.50)	Test on Actual Connection

Note: 1. Values in parenthesis were taken from thin line curve in Fig. 11.
2. Values marked with * are the total of gross sectional areas of load bearing elements divided by number of bolts.
3. Values marked with ⁺ are the minimum values of area covered by one bolt.

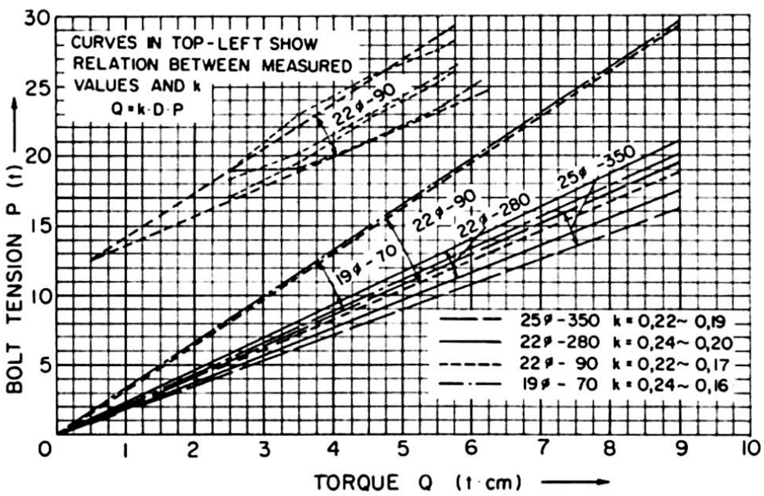


Fig. 8. Relation between torque value Q, bolt tension P and torque coefficient k — curves based on the values measured by use of load cell and torque wrench.

method. At the initial stage of tension, however, the torque method is superior to the turn-of-nut method. In consideration of these features, the laboratory tests were conducted by the use of load cell and the further tests were made on the construction site taking measurement with wire strain gauges attached

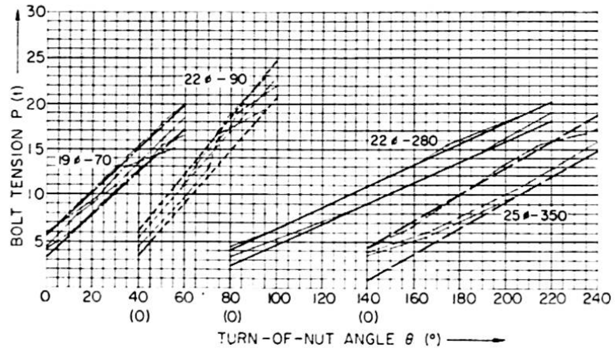


Fig. 9. Relation between turn-of-nut angle θ and bolt tension as obtained on assumption that $\theta = 0$ when $Q = 2$ tons-cm — curves based on the values measured by use of load cell.

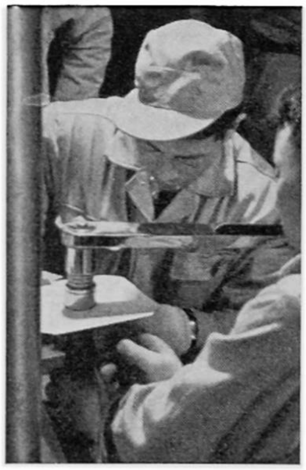


Fig. 10. Bolt tightening test by use of load cell.

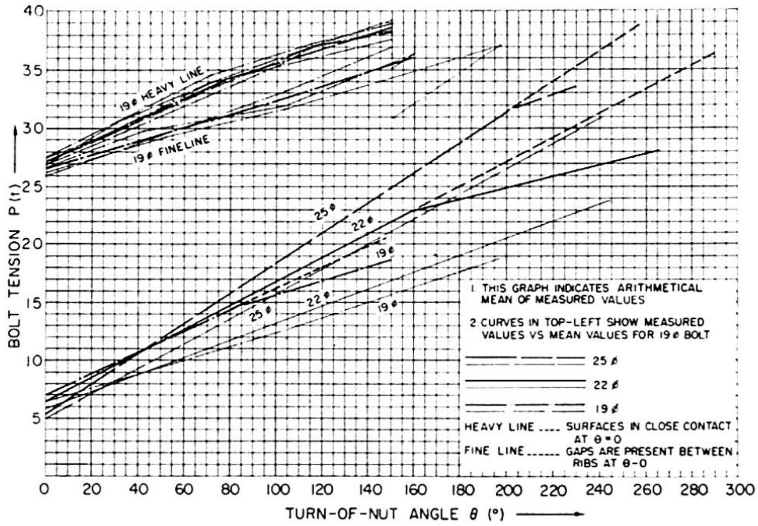


Fig. 11. Relation between turn-of-nut angle θ and bolt tension as obtained on assumption that $\theta = 0$ when $Q = 3$ tons-cm — curves based on measured values obtained by the field test on actual connections.

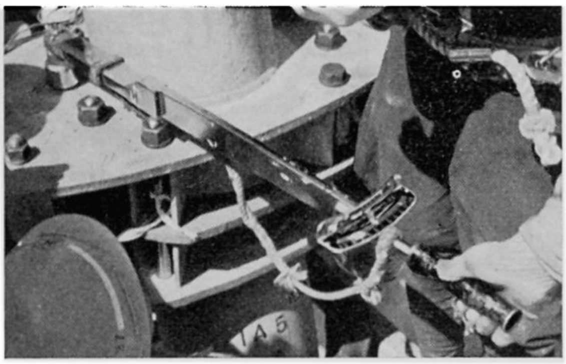


Fig. 12. Bolt tightening test at the construction site.

to the bolts actually used in the connection of the tower under construction. The preload was applied by means of a torque wrench to give the bolts a torque up to 2 tons-cm (up to 3 tons-cm in case of the field test), and these points were arbitrarily taken as zero point of the turn-of-nut angle. Then, the bolts were further tightened until the required bolt tension was produced, the measurement being made both for the torque values and for the turn-of-nut angles throughout the course of bolt tightening. The tightening test was repeated for the same bolts so as to investigate the variations of values of k and θ. Figs. 11 and 12 show the measured values taken on the site for the actual connections and a scene of the test respectively.

A comparative study of Fig. 8 and Fig. 9 indicates that for the estimation of bolt fastening force the torque values give adequate basis in low stress region while the turn-of-nut angles present better basis in high stress range.

As shown in Fig. 9, the turn-of-nut method had rather low reliability for the bolt tension ranging from 5 to 7 tons, and since the corresponding torque values for such tension range were under 3 tons-cm, this value was adopted as basic point of the turn-of-nut angle.

C. Conclusion

This experimental study has lead to the following findings.

1. As far as the applied load does not exceed about 80% of the bolt pre-load, the entire sectional area of contact surface is effectively in action.
2. The loss of bolt pre-load due to the repetitive loading is rather small.
3. As has been said, these long bolts exhibit highly reliable behaviour; however, such reliability would vary with the degrees of precision with which the contact surfaces are machined.
4. Higher reliability may be expected with regard to the fastening force of bolts if the bolt tightening is based on the turn-of-nut angle. If the errors are to be minimized, it is advisable to use torque method when the contact surfaces are not accurately finished and to use the turn-of-nut method when the contact surfaces are machined with high precision.
5. A variety of complex factors are involved in estimating the effective sectional area of load bearing elements. Particular attention should be given to the form factors of these elements if the bolt tension is to be computed according to the elastic theory.

Summary

In connection with the design of tensile joints using high-strength bolts given a pre-load, loading tests were conducted to observe the variations under test load of both bolt tension and joint rigidity so as to verify the safety of joints.

In order to determine a proper method for securing the required bolt tension, bolt tightening tests were conducted in the laboratory and on the construction site for investigation of the relationship between bolt tension, torque value and turn-of-nut angle.

Résumé

Les auteurs ont effectué des essais relatifs à la conception des attaches précontraintes HR sollicitées à la traction. Il s'agissait d'étudier, sous les charges expérimentales, la variation des contraintes dans les boulons et la rigidité de l'attache ainsi que d'en vérifier la sécurité.

Pour déterminer un procédé capable d'assurer la précontrainte requise, on a effectué des essais de serrage au laboratoire et au chantier et on a cherché la relation liant l'effort de précontrainte du boulon, le couple appliqué et la rotation de l'écrou.

Zusammenfassung

Im Zusammenhang mit dem Entwurf von zugfesten Stößen unter Anwendung vorgespannter, hochfester Schrauben wurden Belastungsversuche durchgeführt. Das Ziel der Untersuchung bestand in der Beobachtung der Veränderungen von Schraubenspannung und Steifigkeit des Stoßes in Funktion der Belastung, um so die Sicherheit des Stoßes zu überprüfen.

Zur Ausarbeitung einer günstigen Methode für die genaue Einstellung der verlangten Schraubenspannung wurden sowohl im Laboratorium als auch auf der Baustelle Anziehversuche durchgeführt. Diese gaben Aufschluß über die Beziehung zwischen Schraubenspannung, Drehmoment und Drehwinkel der Schraubenmutter.