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The Use of High-Strength Bolted Joints in Railway Bridges

Utilisation des boulons précontraints dans les ponts-rails

Die Verwendung von HV-Verbindungen bei Eisenbahnbrücken

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1. Introduction

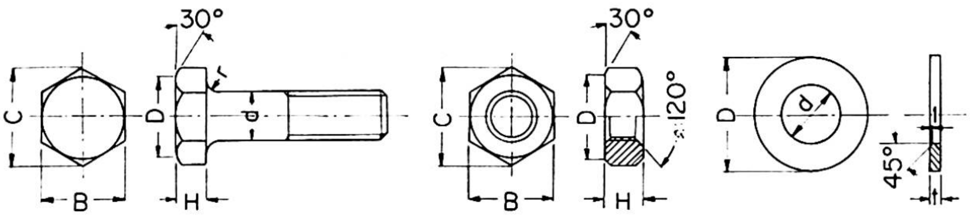
The first use of high-strength bolted joints for steel structures in Japan was for a temporary truss (span 62.4 m, through type, single track) for the Japanese National Railways in 1954. The laboratory tests and field observations began with this bridge construction. Many experiments have been carried out and the study was pushed forward to clarify the characteristics of the friction joints for use by structural engineers. Nowadays, high-strength bolted joints are applied to hundreds of railway bridges. The new head office of the J.N.R. and the new Osaka Station building on the new Tokaido Line were also constructed with this method of jointing.

2. Bolts, Nuts, Washers and Tightening of Bolts

In railway bridges the standard size of bolts is $^7/_8$ in dia., but $^3/_4$ in. or 1 in. dia. are also used. The shapes of bolts, nuts and washers comply with the Japanese Industrial Standard most nearly concerned, and new specifications for high-strength bolts, nuts and washers will be provided in the near future. Table 1 shows the shapes of bolts, nuts and washers. The mechanical properties of the bolts are shown in Table 2. The material used for class 8 T or 9 T bolts is medium carbon steel, and for class 11 T bolts it is low alloy steel. The threads of the bolts are turned before or after heat treatment, and in the former case no oxygen furnace is normally used. Class 8 T bolts are now employed for railway bridges and 9 T bolts are used in buildings. In the new JIS, 9 T and 11 T bolts will be specified for structural use.

The bolt tensions used in design work are shown in Table 3. Bolts are tightened with a hand torque wrench or a torque-controlled impact wrench in the initial tensioning to nearly 10% above the designed bolt tension. The torque coefficient of the bolts used for railway bridges is 0.14—0.15 or about 0.18. In the former case, specially lubricated washers are used under the nuts.

Table 1. Dimensions of Bolts, Nuts and Washers



Bolt	$w\,^3/_4$	$w\,^7/_8$	w 1
d	19.05	22.22	25.40
r	1.0∼1.5	1.0∼1.5	1.0∼1.5
H	13	15	18
B	32	35	41
$C\approx$	37	40.4	47.3
$D\approx$	31	33	39

Nut	$w\,^3/_4$	$w\,^7/_8$	w 1
H for $8T$	16	18	20
H for $11T$	19	21	25
B	32	35	41
$C\approx$	37	40.4	47.3
$D\approx$	31	33	39

Washer	$w\,^3/_4$	$w\,^7/_8$	w 1
d	21	24	28
D	40	44	52
t	4.5	6	6

Table 2. Mechanical Properties of Bolts (min. value)

Class of bolt	Yield point (kg/mm²)	Tensile strength (kg/mm²)	Elongation G.L. 50 (%)	Reduction of area (%)
8 T	65	80	16	40
9 T	70	90	14	35
11 T	95	110	14	35

Table 3. Permissible Shear Load

Size of bolt	Min. bolt tension (t)		Permissible shear load (t)	
	8 T	11 T	8 T	11 T
$w\,^3/_4$	10	15	2.222	3.333
$w\,^7/_8$	14	21	3.111	4.667
w 1	19	28.5	4.222	6.333

An unbiased estimate of the standard deviation of the torque coefficient is that it is not more than 5% when the manufacture and the tightening of the bolts are carefully controlled.

3. Slip Load of Joints

The nominal coefficient of friction is affected by various factors, and consequently a number of tests were conducted to determine the coefficient of friction for our designs.

The factors that seem to affect the slip load of joints significantly and the effect of these factors are as follows:

1. Condition of faying surface: The coefficient of friction depends significantly on the condition of the faying surface. However, for the same description of the condition of the faying surface, the value of the coefficient of friction ranges between the following limits:

Red lead	0.05—0.2	Flame cleaning	0.2—0.5
Galvanized	0.1 —0.3	Rusty	0.4—0.7
With millscale	0.2 —0.4	Shot blasted	0.4—0.7

2. Strength of bolted plate: In the results of slip tests for joints with 40 kg/mm^2, 50 kg/mm^2 and 60 kg/mm^2 class steel, we were unable to find any difference between 40 kg/mm^2 class steel and 50 kg/mm^2 class steel. Joints made with 60 kg/mm^2 class steel had a coefficient of friction that was greater by not less than 20%.

3. Type of joints: Butt type and lap type joints, consisting of plates only, have the same slip coefficient. In cases where the joint is assembled with one plate and one angle and the total length of the test specimen is not great, the slip load decreases considerably compared with the joint having zero or slight excentricity of load.

4. Size of joints and arrangement of bolts: The size of the joints may not greatly affect the slip load, that is to say, a series of tests with several set of joints which had the same bolt arrangement (series of 1×1, 1×2, 1×3, 2×2, 2×3 bolts), but a different edge distance, pitch and gauge, showed nearly the same value for the coefficient of friction. The slip load of joints where the bolts were arranged in one line of not more than six bolts was proportional to the number of bolts. But in the tests with an 8-bolt or 10-bolt specimen, the slip coefficient decreased slightly when the number of bolts was increased to 8 or 10. In this case both joints had the same cross sectional area, so that stress at the slip load in the 10-bolt joint was higher than in the 8-bolt joint. Because of this fact a crosswise reduction of area might affect the slip coefficient. We shall explain the relationship between slip stress and slip coefficient in the next paragraph.

5. Relationship between slip coefficient and slip stress: When the normal stress of the bolted plate is increased by tensile load, the thickness of the plate decreases gradually by Poisson's ratio and the initial bolt tension decreases accordingly. Therefore, the slip load does not increase proportionally to the initial bolt tension in cases where the slip load exceeds some limiting load. Fig. 1 shows the relation between σ_{sn}/σ_y and μ. σ_{sn} is the stress at the slip load based on the net sectional area of the bolted plate and σ_y is the yield stress of the plate. From this figure, it is found that μ does not seem to be affected by σ_{sn}/σ_y when σ_{sn}/σ_y is 0.8 or less, but when σ_{sn}/σ_y exceeds 0.8, μ decreases proportionally. In these tests the test specimens had the same condition of faying

surface and were assembled with 6-bolts (3 lines $\times$ 2 rows) or 9-bolts (3 lines $\times$ 3 rows).

6. Effect of relaxation on the slip load of the joint: The effect of relaxation was investigated on more than 300 test specimens of the compression type with 2 bolts whose grip thicknesses were 90 mm and whose dia. were $^7/_8''$.

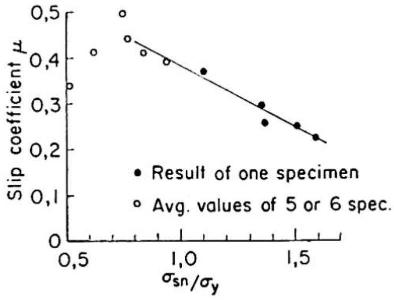


Fig. 1. Relationship between slip coefficient and slip stress.

These two series of tests, covering different intervals of time of one year and six months, respectively, were plotted by means of measurements of the slip load of the test specimens. The induced bolt tension was about $0.6\,\sigma_y$, $0.8\,\sigma_y$ and σ_y plus. The stress of the bolt was calculated as a combination of normal tensile stress and shearing stress due to torque by means of the formula $\sigma_v = \sqrt{\sigma^2 + 3\,\tau^2}$ based on the effective area of the bolt threads. σ_y is the yield stress of the bolt employed, when tested on machined specimens. Consequently, in cases where the bolt tension was $0.6\,\sigma_y$ no reduction of slip load occurred. In cases where it was about $0.8\,\sigma_y$ the effect of relaxation is a low percentage of reduction and may be negligible. When the bolt tension exceeds the yield strength of the bolt, the decrease in the bolt tension seems to be 10—20% or more. However, in most cases the friction of the assembled joints will increase as a result of rust due to exposure to the atmosphere, so that the slip load of joints in actual structures may not show as great a decrease as that measured in the laboratory tests under dry conditions.

Having regard to the many factors above-mentioned which affect the slip load and the variance of the slip load due to an error in the bolt tension, we take 0.4 as the coefficient of friction for use in design in the case of shot blasted faying surfaces. The safety factor for the slip load is 1.8. This value is the same as that of structural steel for tension stress. Table 3 shows the permissible load per bolt in one faying surface.

4. Sectional Area of the Joint Used in Calculating the Stress

The ratio of the stress of the joint, calculated on the gross sectional area of the bolted plate, to the elongation is nearly equal to the Young's modulus of the steel materials, but in riveted joints the ratio is about one-third of that of a bolted joint. However, if we take into consideration the value of 0.2% offset, the stress calculated on the net sectional area of the bolted plate is nearly equal to the yield stress of the base plate, and the breaking load of a bolted joint does not differ from that of a riveted joint, except in a few cases. Consequently, it may be better to calculate the stress of the bolted plate with respect to the net sectional area of the bolted plate.

Table 4 shows a comparison between the average measured stress obtained from the stress distribution diagram as measured with wire strain gauges and the average stress calculated from an applied load. In this table the σ/σ_n values of 2-bolt joints are about 0.8. However, when the number of bolts is increased σ/σ_n also increases and in cases where there are more than 6 bolts, σ/σ_n is nearly equal to 1.0.

Fig. 2 shows examples of the stress distribution of bolted joints. When the number of bolts is small, the extent of the stress concentration at the bolt holes is 2.0—2.5 and the stress does not reach the yield point at the permissible load on the joint, but when the number of bolts becomes large, the stress exceeds the yield point at the permissible load.

Table 4. Average Measured Stress and Average Calculated Stress

No.	Arrangement of bolts	Pitch of bolts (mm)	$\frac{b_n}{b}$	Slip load (t)	$A_n \cdot \sigma_y$ (t)	Load (t)	Measured avg. stress σ (kg/mm²)	$\frac{\sigma}{\sigma_n}$	$\frac{\sigma}{\sigma_g}$
1	1×2	66	$\frac{96}{120}=0.80$	26.3	31.8	15 30	9.6 20.7	0.80 0.86	0.99 1.07
2	1×2	66	$\frac{96}{120}=0.80$	24.5	31.8	15 30	9.1 21.2	0.75 0.88	0.94 1.09
		110		24.5<		15	9.8	0.81	1.01
3	1×2	66	$\frac{56}{80}=0.70$	18.7	34.6	15	9.7	0.84	1.20
4	1×4	66	$\frac{96}{120}=0.80$	34.4	63.6	30 50	11.2 20.3	0.84 0.92	1.05 1.15
5	1×6	66	$\frac{95}{120}=0.79$	94.7	81.8	40	11.5	0.87	—
		110					13.4	1.02	—
6	1×6	66	$\frac{95}{120}=0.79$	79.5	72.3	40	17.9	0.94	—
		110		74.8			20.1	1.05	—
7	1×8	66	$\frac{95}{120}=0.79$	116.0	103.4	50	17.6	1.05	—
8	1×10	66	$\frac{106}{130}=0.82$	113.5	112.3	60 100	17.2 29.1	0.95 0.99	— —
		110		119.8		60 100	15.8 29.4	0.88 0.99	— —

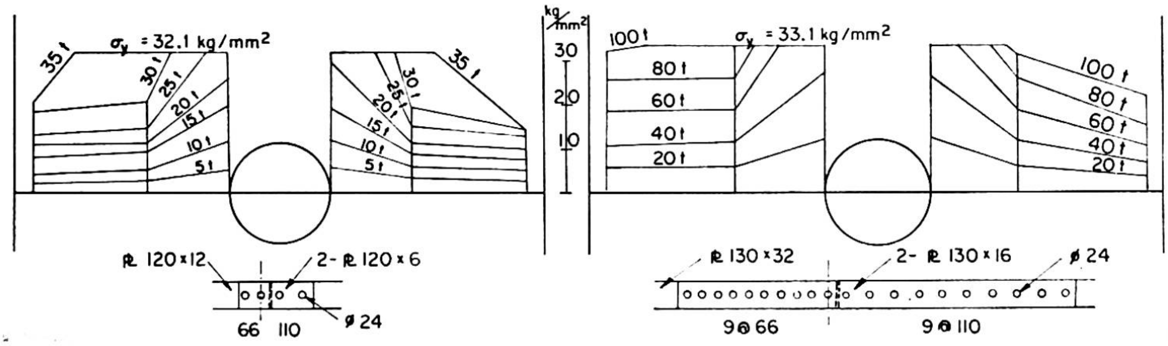


Fig. 2. Stress distribution of joints.

5. Fatigue Strength of the Joint

The slip coefficient and the number of bolts in the direction of the load affect the fatigue strength of the joint significantly. Fig. 3 shows the relation-

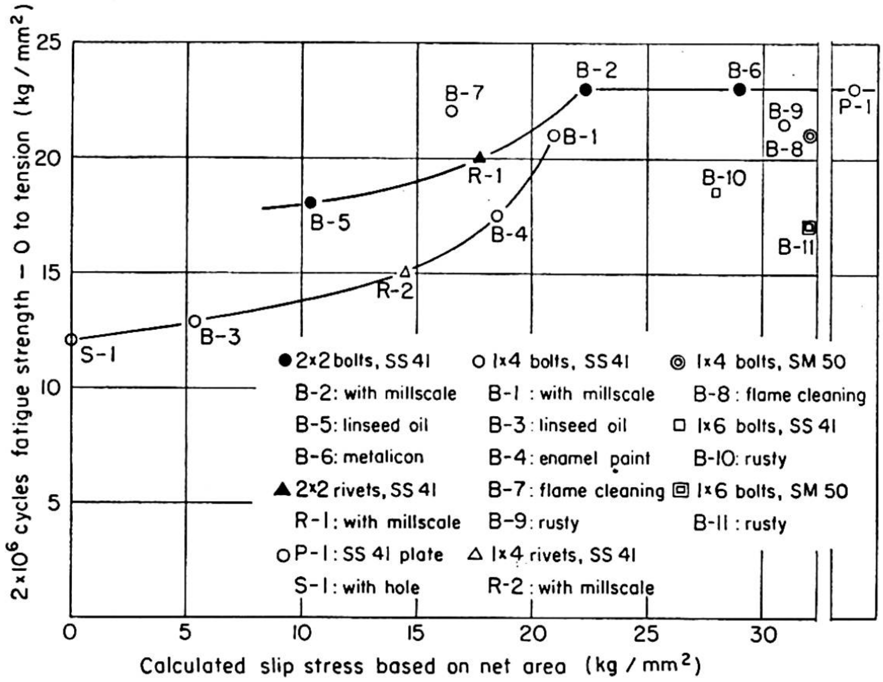


Fig. 3. Relation between fatigue stress and slip stress.

ship between the slip stress and the fatigue strength for 2×10^6 cycles under a repeated load varying from zero to tension.

As for as the effect of the number of bolts in the direction of the load is concerned, the fatigue strength of joints made with 41 kg/mm² class steel, with 2, 4 and 6 bolts in one line, was 23 kg/mm², 21 kg/mm² and 18.5 kg/mm², respectively, and 31 kg/mm², 21 kg/mm² and 17 kg/mm², in the case of joints made with 50 kg/mm² class steel.

Now, in our design, the permissible fatigue strength of plates connected with friction grip bolts is as shown in the following formulas.

$$\left.\begin{array}{ll}\text{for tensile stress (based on net section)} & \dfrac{1500}{1-\frac{2}{3}k} \\ \text{for compressive stress (based on gross section)} & \dfrac{1800}{1-k}\end{array}\right\} \begin{array}{l}\leqq 1300\,\text{kg/cm}^2 \text{ for } 41\,\text{kg/mm}^2 \text{ class steel} \\ \leqq 1800\,\text{kg/cm}^2 \text{ for } 50\,\text{kg/mm}^2 \text{ class steel}\end{array}$$

$$(k = \sigma_{min}/\sigma_{max})$$

These values are the same as those of butt welded joints and of plates with longitudinal fillet welding, excluding the ends of the weld.

6. Example in Bridge Construction

Fig. 4 shows a joint in a plate girder with I section, and Fig. 5 shows a joint in a stiffening girder of a Lohse girder with a box section (span 67.2 m, load KS 18 double track, total weight of steel 400 t).

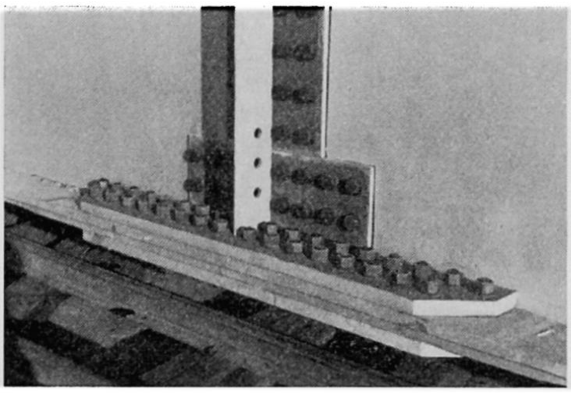


Fig. 4. Connection of a girder with I-section.

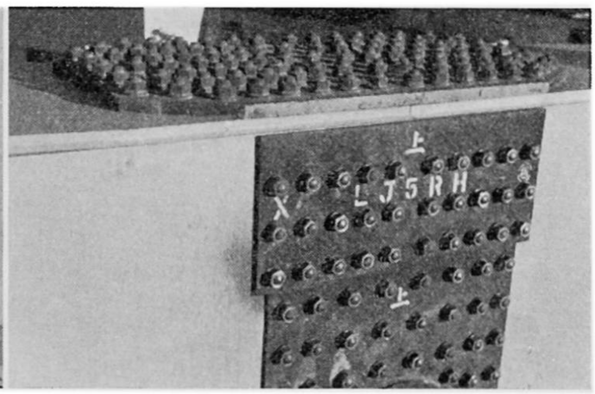


Fig. 5. Connection of a stiffening girder of a Lohse girder with box section.

Summary

In this paper tests on high-strength bolted joints and their use in railway bridges on the Japanese National Railways are described.

Résumé

Les auteurs décrivent des essais relatifs aux boulons précontraints et leur application pour les ponts-rails des Chemins de Fer Japonais.

Zusammenfassung

Es werden Versuche mit HV-Verbindungen und deren Anwendungen bei japanischen Eisenbahnbrücken beschrieben.

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