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# Studies on the Application of High-Strength Bolted Joints to Bridges

*Recherches sur l'utilisation, dans les ponts, d'assemblages réalisés avec des boulons à haute résistance*

*Untersuchungen über die Verwendung von hochfest verschraubten Stößen im Brückenbau*

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## 1. Introduction

This paper is concerned with the experimental investigations into static and fatigue tests on full-scale welded girders with high-strength bolted joints. In the static tests, the deformations and the strain distribution around the joint were investigated up to the failure of girders.

Furthermore, girders with riveted joints were made by replacing the bolts of the bolted girders by rivets for the purpose of comparing the properties in different types of girders. Fatigue tests were also performed in order to ascertain the fatigue behaviour of the girders.

## 2. Test Girders and High-Strength Bolts

### *a) Test Girders*

The test girders illustrated in Fig. 1 are made of high strength steel which has a tensile strength of 50.5 kg/mm$^2$ and a yield tensile strength of 32.9 kg/mm$^2$.

Since the test girders were loaded at two symmetric points, as in Fig. 1, the part of the girder between the loading points was subjected to bending moment only.

Assuming the allowable tensile stress of the steel to be 1,900 kg/cm$^2$, the loads at which the fibre stress in the lower flange plate will reach the allowable stress can be estimated as $P = 43.5$ tons for the gross section and 34.8 tons for the net section. The load that will cause yielding of the lower flange plates will be 75.6 tons for the gross section and 60.5 tons for the net section.

### *b) High-Strength Bolts*

Four types of high-strength bolts ($\varnothing$. 22 mm) were used. They have almost the same mechanical properties, as is evident from Table 1, and have the chemical compositions indicated in Table 2.

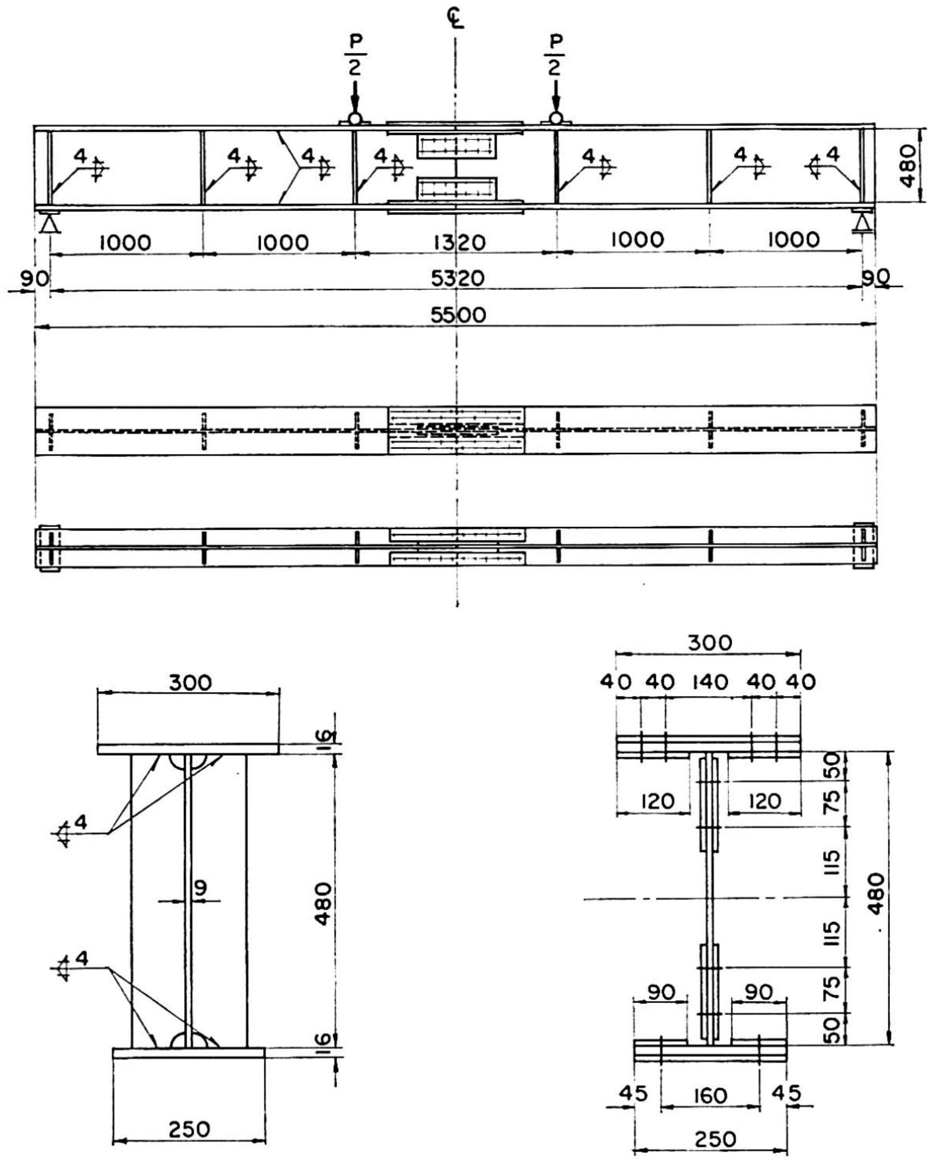


Fig. 1.

*Table 1. Mechanical Properties of Bolts*

| Item | Yield Tensile Strength ($kg/mm^2$) | Ultimate Tensile Strength ($kg/mm^2$) | Elongation (%) | Reduction of Area (%) | Charpy Impact ($kg\text{-}m/cm^2$) |
|---|---|---|---|---|---|
| A | 104.6 | 109.5 | 16.8 | 53.3 | 4.5 |
| B | 99.6 | 110.7 | 15.8 | 52.0 | 12.0 |
| C | 103.4 | 113.3 | 15.3 | 48.0 | 12.0 |
| D | 97.0 | 107.0 | 20.4 | 56.8 | — |

Each bolt was tightened by means of a torque-wrench. To obtain a given pre-load on the bolts of 24 tons, the necessary torque to rotate the nuts, namely 97 kg m, was estimated by using the torque coefficient 0.183. This pre-load causes a tensile stress of 8,000 $kg/cm^2$, and it corresponds to 82% of the yield stress of the material.

*Table 2. Chemical Composition of Bolts (%)*

| Item | C | Si | Mn | P | S | Cr | V | Mo | Al | |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.50 | 0.34 | 0.96 | 0.009 | 0.011 | 1.15 | 0.14 | — | 0.020* | 0.012** |
| B | 0.41 | 0.31 | 0.90 | 0.002 | 0.012 | 0.95 | 0.10 | — | 0.019 | 0.011 |
| C | 0.43 | 0.35 | 0.74 | 0.010 | 0.019 | 1.20 | — | 0.248 | 0.018 | 0.011 |
| D | 0.43 | 0.28 | 0.88 | — | — | 0.95 | — | 0.20 | — | — |

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Torque value tests were performed prior to clamping off the bolts of the girders. The experimental relationships between the values of the pre-load on the bolts, $P_v$, and the values of the torque, $M_a$, were approximately linear, from which the torque coefficient $k$ was obtained as

$$k = M_a/P_v d = 0.183 \text{ (mean value)},$$

where $d$ signifies the nominal diameter of the bolts.

## 3. Static Test and Discussion of the Results

### *a) Remarks on the Tests*

The tests were carried out on four test girders, two of which had a joint made with high-strength bolts, while the others had a riveted joint. The former will be referred to as the "bolted girder", while the latter will be termed the "riveted girder" in this paper.

These tests were intended to investigate the following properties: (1) the deflection of the girders at midspan, (2) the relative displacement between the lower flange plates, and (3) the strain distribution in the plate around the midspan joint.

For investigation (3), the strains were measured by means of electrical-resistance type strain gauges. For investigation (2), small steel balls for a contact-type strain indicator were pressed at the gauge points on to the side faces of the flange and the splice plates of the bolted girders. Throughout the tests, measurements were made for every 5 or 10 ton increment of the test load. The same methods were used for the two riveted girders.

All the tests were conducted at the Department of Civil Engineering, Kyoto University, using the Kyoto University Structural Testing Machine.

### *b) Deflection at the Midspan of the Test Girders*

The deflection at the midspan of the test girders was measured by dial gauges. The results are shown in Fig. 2. The deflections of the riveted girder are about 10% greater than those of the bolted girder.

For the purpose of reference, the deflection at midspan under the same loading for a welded girder without joints was computed as 11.70 mm, assuming

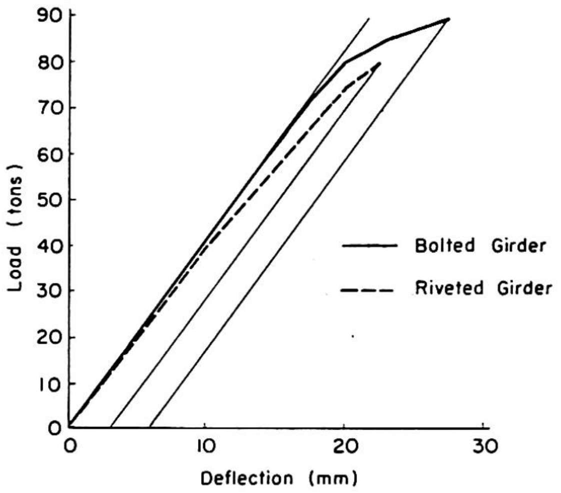


Fig. 2.

the moduli of elasticity of the steel to be $E = 2.1 \times 10^6$ kg/cm$^2$ and $G = 0.81 \times 10^6$ kg/cm$^2$. The experimental results of the deflections are 12.54 mm for the riveted girder and 11.33 mm for the bolted girder.

From the above result, it can be concluded that the flexural behaviour of the bolted girder will be similar to that of the welded girder without joints.

### *c) Relative Displacement Between the Lower Flange Plates*

Measurements of the relative displacement between the lower flange plates at their joint were made by using dial gauges attached to their lateral edges.

The relative displacement obtained for the riveted girder is nearly twice as great as that for the bolted girder.

On the other hand, the relative displacement between the flange and the splice plate was investigated by means of contact-type strain indicator. Based on the measurements of the gauge length of 20 mm, which was set inclined at 30 degrees to the direction slip, of the amount of displacement was determined as shown in Fig. 3 for the bolted girder and Fig. 4 for the riveted girder. The displacement measured in the present test for the bolted girder consists of three components: extensional deformation of the plates, shearing deformation due to friction between the plates, and slip between the plates.

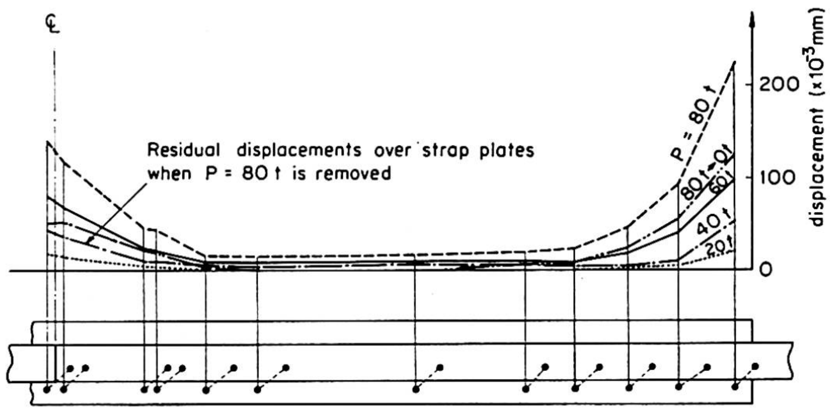


Fig. 3.

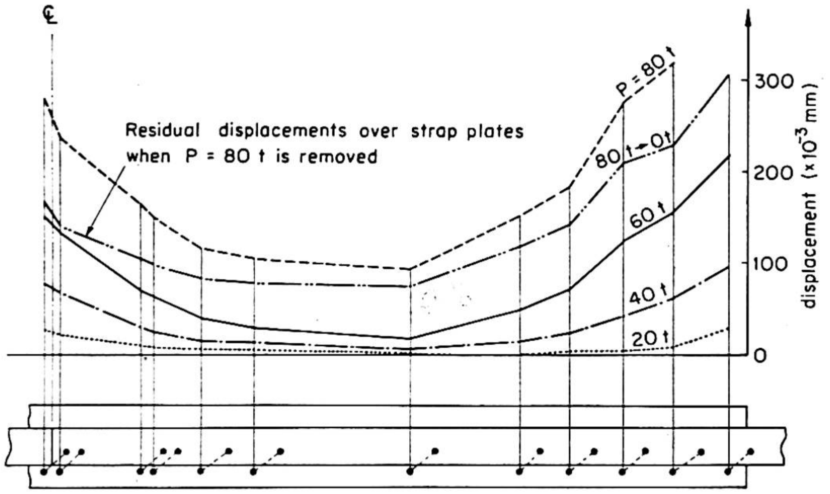


Fig. 4.

In conclusion, from these two kinds of displacement measurements, the superiority in flexural rigidity of the bolted girder to the riveted girder is well established.

### *d) Deformation Properties of the Flange Plate Joint*

To investigate the mechanism of stress transmission in the flange plate joint, strains in the upper and lower flange plates and the spice plates were measured by electrical resistance strain gauges at every 10 tons of test loading up to 90 tons for the bolted girder and up to 80 tons for the riveted girder.

The results showed that the surface strains in both flange plates, at some little distance from the joint, were greater at the middle of the width, where the web plate was welded.

In the joint of the flange plates, the surface strains in a transverse section of the plate at both ends were greater than those in the middle. Based on the strain measurement in a transverse section through the first row of bolts or rivets, the strain for the bolted joint was less than that for the riveted joint. This fact shows that the transmission of stress for the bolted joint will depend on the friction between the connected plates. Strain distributions measured along the edge of the lower flange plates in bolted and riveted girders show similar properties to the slip distributions described in (c).

The strain distributions along the edge of the lower flange plates in the bolted girder and the riveted girders were as follows: for the bolted girder subjected to comparatively small test loads, the longitudinal strain at the middle of the jointed portion were distributed uniformly, and gave a lower value than at the ends of the joint, and the range of uniform strain distribution was rather wide. This shows that the stress transmission under comparatively small test loads will contribute to the frictional resistance at the ends of the joint on bolted connections and will scarcely exist between the flange plate and the splice plates at the middle part of the joint. With increase in the test load, the range of uniform strain distribution tends to diminish, i. e., the range where the frictional resistance is effective, extends towards the middle part of the joint. On the other hand, for the riveted girder, the range of uniform strain distribution was narrower than that for the bolted girder and vanished when the test load reached 60 tons. This shows that each of the six rivets took a part of the stress transmission almost uniformly upon itself. Incidentally, the behaviour of the riveted girder under low test loads was similar to that of the bolted girder.

### *e) Elastic Behaviour of the Web Joints*

In order to investigate the elastic behaviour of the web joints, the strains at 23 selected points on the web joint were measured for each riveted and bolted girder. The measurements were conducted under the test loads; 20, 40, and 80 tons. The results show a remarkable difference between the bolted girder and the riveted girder in regard to the strain distribution on the moment plates. They indicate that these differences are caused by the contact between the connected plates at the upper flange and at the upper part of the web. That is to say, the contact of the web plates will develop more easily for a riveted connection than for a bolted connection.

## 4. Fatigue Tests and Discussion of the Results

### *a) Remarks on the Tests*

Fatigue tests were made on three bolted girders, No. 1, No. 2, and No. 3, and on one riveted girder, using the same testing machine as in the static tests. The alternating loads were selected in the range of 8 to 36 tons during all the tests. The lower flange stresses computed for the gross section are from 350 to 1570 kg/cm$^2$. The machine was operated at an alternating speed of about 270 cpm throughout the tests.

### *b) Discussion of the Results*

The results are summarised in Table 3: the bolted girder No. 2 was subjected to $2 \times 10^6$ loading repetitions without showing any noticeable failure, but the riveted girder and bolted girders No. 1 and No. 3 failed after loading repetitions of less than $2 \times 10^6$ cycles. Bolted girder No. 1 failed at the section of the applied load after $1.84 \times 10^6$ cycles as a result of tensile fatigue as shown in Photo. 1. The fatigue crack started from the fillet weld connecting the lower flange and the web plates and spread into both the flange and the web plates. The principal stress at the point where fatigue failure occurred was calculated as 1,518 kg/cm$^2$.

In bolted girder No. 2, the failure occured at the same position as in girder No. 1, and in bolted girder No. 3 failure started from a bolt hole in the lower strap plate in the first transverse row nearest to the midspan.

*Table 3. Results of Fatigue Tests*

| Girders | Cycles to Failure | Remark on Failure |
|---|---|---|
| Bolted No. 1 | $1.84\times10^6$ | Photo. 1 |
| Bolted No. 2 | $2.48\times10^6$ | same as Photo. 1 |
| Bolted No. 3 | $1.95\times10^6$ | crack at the edges of bolt holes |
| Riveted | $0.75\times10^6$ | Photo. 2 |

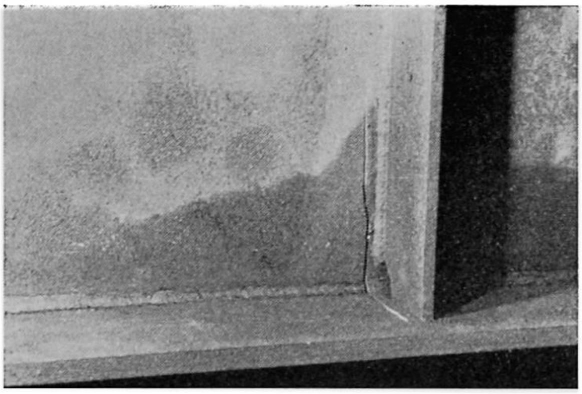

Photo 1.

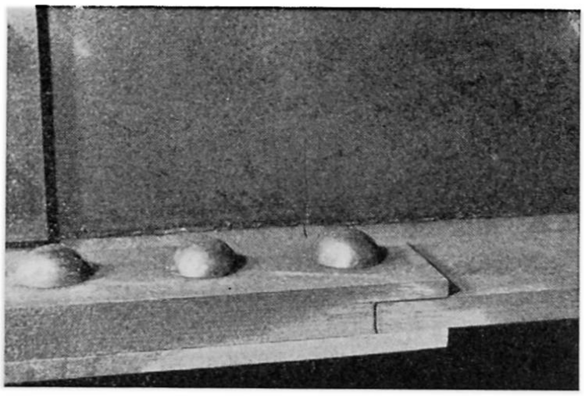

Photo 2.

Fatigue failure of the riveted girder occurred at a rivet hole in the lower flange plate in the outside row of the rivet joint as shown in Photo. 2 which corresponds in general to the weakest point of the riveted girder. The cyclic stresses at the point of failure were estimated by conventional calculations as 436—1,963 kg/cm$^2$ based on the net area.

Subsequent to the fatigue test, the torques required to release the bolts were measured in order to examine the effects of fatigue loading on the bolt tension, and it was found that there were no noticeable decreases in the bolt tension. In the case of bolted girder No. 3, however, the torque of the bolts in the failed section was a little less than that of the others.

## 5. Concluding Remarks

According to the tests, the following qualitative behaviours seem to be justified:

1. The deflection of the bolted girder did not differ from that of the all-welded girder, and was about 10% less than that of the riveted girder. The results show the superiority of the bolted girder to the riveted girder in regard to flexural rigidity.

2. The relative displacements between the main and the strap plates of the lower flange were remarkably small for the bolted girder in comparison with the riveted girder. This fact shows that the bolted girder has greater flexural rigidity than that of the riveted girder.

3. The extent of contact at the joint between the main plates under test loading was greater for the riveted girder than for the bolted girder and the neutral axis at the joint maintained a higher position for the riveted girder than for the bolted girder.

4. As can be seen from the above experiments, the stress concentration caused by the defects in the fillet weld of the flange and web plates is more intensive than that of the bolted joint, and hence it is necessary to execute the welding of structures carefully if they are to be subjected to fluctuating loads.

5. In riveted girders, stress concentration around the rivet holes governs the strength of the girder when subjected to fluctuating load. It may be concluded from the above facts that the fatigue endurance of the bolted girder is superior to that of the riveted girder.

## Summary

This paper is concerned with experimental investigations into the static and fatigue strengths of high-strength bolted joints applied to welded plate girders. The high-strength bolted joints were compared experimentally with ordinary riveted joints, and the superiority of the high-strength bolted joints in regard to both the static and fatigue strengths was made evident. Some mechanical properties of the high-strength bolted joints were investigated during the experimental studies.

## Résumé

L'auteur présente des essais concernant la résistance à la fatigue et aux efforts statiques d'assemblages réalisés avec des boulons à haute résistance sur des poutres soudées à âme pleine. Les essais effectués en vue de comparer les assemblages rivés ordinaires et les assemblages boulonnés HR, ont mis en évidence la supériorité de ces derniers tant en ce qui concerne la résistance à la fatigue qu'en ce qui concerne celle aux efforts statiques. Ils ont en outre permis d'étudier certaines propriétés mécaniques de ces assemblages boulonnés.

## Zusammenfassung

Dieser Bericht beschreibt experimentelle Untersuchungen über die Festigkeit unter statischer und wiederholter Belastung von hochfest verschraubten Stößen an geschweißten Blechträgern. In diesen Versuchen wurden die hochfest verschraubten Stöße mit gewöhnlichen, genieteten Stößen verglichen, wobei die Überlegenheit der hochfest verschraubten Lösung, sei es bei der statischen wie auch bei der Ermüdungsfestigkeit, eindeutig belegt wurde. Im weiteren wurden bei diesen Versuchen einige mechanische Eigenschaften dieser HV-Verbindungen untersucht.