MECHANICAL BEHAVIOR OF HIGH STRENGTH BOLTED TENSILE JOINTS FOR STEEL BOX MEMBERS SUBJECTED TO TENSION AND BENDING

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(Received October 15, 2001)

Synopsis

Most of the past studies on high strength bolted tensile joints have dealt with parts of connections, such as split tee joints subjected to only tension, due to simplicity. However, in order to apply these joints to bridge structures, the mechanical behavior of overall connections of this type of joints must be made clear under actual loading state. In this study, therefore, the loading tests for connections using this type of joints for box cross sections are carried out, paying attentions to the mechanical behavior of the connections subjected to combined load, i.e. both bending and tension simultaneously. Based on the experimental results, the mechanical behavior is discussed in detail considering bolt arrangements and its applicability to the connections of bridge structural members.

KEYWORDS: high strength bolted tensile joint, box cross-section, combined load, bolt arrangements

1. Introduction

High strength bolted tensile joints are superior to welding joints because of their good characteristics, such as high rigidity, high fatigue durability for bolts, easiness of erection without using special facilities, and so on. Recently, in Japan, some application examples of this type of joints can be seen in some connections of steel bridge structures, such as connections of towers of suspension bridges[1)], connections of main girder and crossbeam of bridges which have a few main girders[2)], and so on. However, most of them are not used to connect primary members. And some of them connect primary members, but they are subjected to large compressive load not tensile load.

As for this type of joints, Recommendation for the Design of High Strength Bolted Tensile Joints for Bridge Structures (draft) [3)] has been provided by Japanese Society of Steel Construction (JSSC) in 1993. In this recommendation, there is no information on multiple bolt arrangements like friction type joints, nevertheless the load transferring capacity of the joints with only one low bolt arrangement is not enough for connections of primary members. In addition, the JSSC recommendation doesn't give enough information on the rigidity of this type of joints.

Therefore, various studies[4)-7)] on high strength bolted joints are carried out both experimentally and analytically to investigate the effects of multiple bolt arrangements and their rigidity. In these studies, partial joints like split tee joints are used as experimental and analytical models, and these models are subjected to only tension because of simplicity. And it is found that multiple bolt arrangement is very effective. Accordingly, the mechanical behavior of not only partial but also overall connections should be made clear under combined load to investigate the usefulness of high strength bolted tensile joints for connecting primary members of steel bridge structures.

In this paper, therefore, loading tests are carried out for specimens with box cross sections connected by using tensile joints subjected to tension and bending simultaneously as combined load.

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2. Experiment

2.1 Specimens

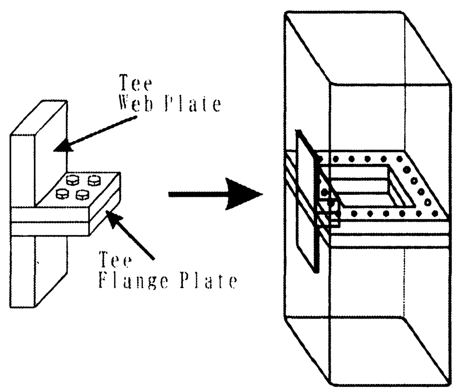
In this study, 7 specimens shown in **Fig. 1(b)** are prepared in order to investigate the influence on their mechanical behavior caused by the arrangement of the bolts at the flange plate and the thickness of the flange plate. Cross sections of these 7 specimens are shown in **Fig. 2**. First character of the specimen names means the pattern of bolt arrangements, and the following number denotes the thickness of tee flange plates in mm.

By the way, according to the past studies[5), 7) - 9)], connections using high deformability bolts with waisted shank such as illustrated in **Fig. 3** at the first row in the tensile side are stronger and more ductile than connections with normal bolts. In this experiments, A-34w specimen uses high deformability bolts at the first row of the tensile side.

Specimens are summarized in **Table 1**. The mechanical properties of the materials and the bolts used in the experiments are shown in **Table 2** and **Table 3**, respectively.

The specimens are made in accordance with the JSSC recommendation, and the ultimate state of the connections is defined by breaking of bolts. Therefore, the geometrical dimensions of the joint, such as thickness of a flange plate, the arrangement of the bolts in the flange plate are determined as to prevent a flange plate from the fracture before some one bolt reaches to the ultimate limit state.

The specimens are made at a scale of 1/2 of connections of a real structure considering the loading capacity of the test system. The size of the bolts used in the test is M12; the nominal diameter of the bolt is 12mm. And the diameter of the shank of the high deformability bolts is 10mm by referring to the past studies[8), 9)].



(a) Partial model (b) Overall model (specimen)

Fig. 1 Connection of members with box cross sections using high strength bolted tensile joint

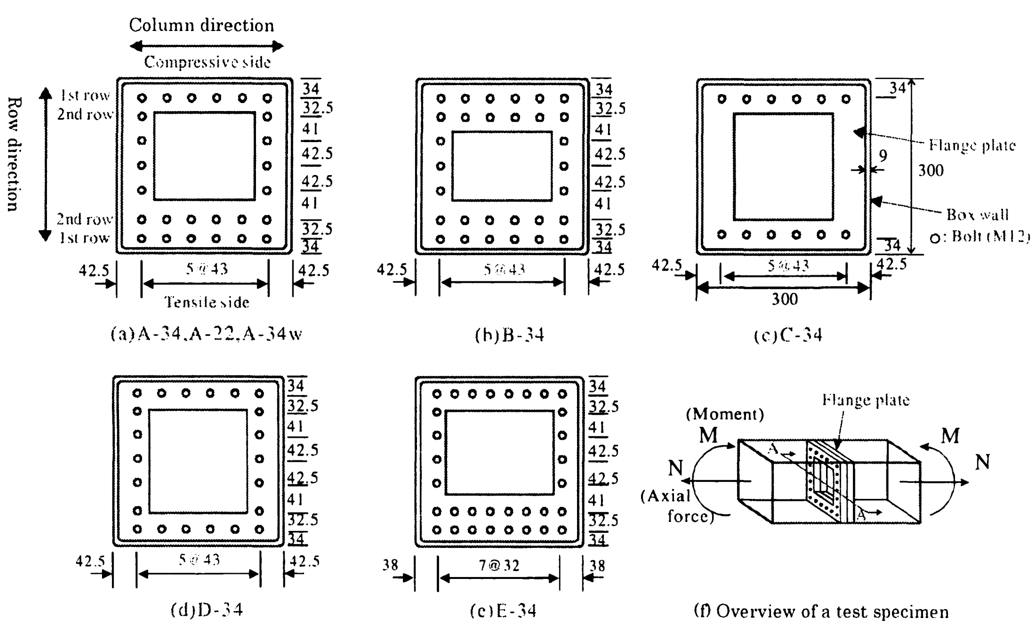


Fig. 2 Cross sections of connections of specimens (unit: mm)

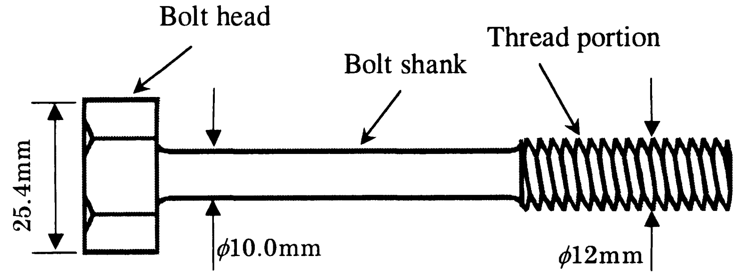


Fig. 3 High deformability bolt used in the tests (M12)

Table 1 Summary of comparison between specimens

Specimen	Thickness of flanges (unit : mm)	Comparing items					
		Effect of High deformability bolts	Influence of thickness of flange	Effect of 2nd row bolts in compressive side	Effect of 2nd row bolts in tensile side	Effect of bolts in web side	Influence of distance between bolts
A-34	34	○	○	○	○		○
A-34w*	34	○					
A-22	22		○				
B-34	34			○			
C-34	34					○	
D-34	34				○	○	
E-34	34						○

*A-34w has high deformability bolts in the 1st row in the tensile side

Table 2 Material properties of specimens used in the experiments

Material	Yield strength (N/mm^2)	Ultimate strength (N/mm^2)	Young's modulus (N/mm^2)	Poisson's ratio
SM490Y(22mm)	354.2	530.2	2.09×10^5	0.293
SM490Y(34mm)	341.5	524.1	2.07×10^5	0.288
STKC490	526.4	600.6	1.94×10^5	0.296

Table 3 Material properties of bolts used in the experiments (M12)

Bolt type	Length (mm)	Yielding stress (N/mm^2)	Ultimate stress (N/mm^2)	Yielding axial force (kN)	Ultimate axial force (kN)
Normal Bolts	70	1034	1136	87.2	94.6
	95	1086	1139	91.5	95.3
High deformable Bolts	95	1086	1139	85.3	89.4

2.2 Loading procedure

The test system used in this experiment is illustrated in **Fig. 4**. The loading procedure is shown in **Fig. 5**. Applying the load, namely, tension and bending is operated by using two vertical actuators through 2 steps. At the first step, only tensile force is loaded by controlling the load of two actuators equally. At the second step, the load of actuator I increases, and the load of actuator II decreases at the same rate. And, the bending moment increases monotonously until the joint will be broken.

The tensile load is applied to the specimens up to 20% of total introduced bolt-axial force of all bolts. This amplitude of the tensile load is determined considering that the specimen is subjected to as large as tensile load in the range of loading capacity of the test setup.

In this experiment, the applied force, the strain on the box wall, bolt-axial force and the gap between tee flange plates are measured automatically using the computer on-line instrumentation system. The measurement position of the gap between tee flange plates and the strains on the box wall are shown in **Fig. 6**.

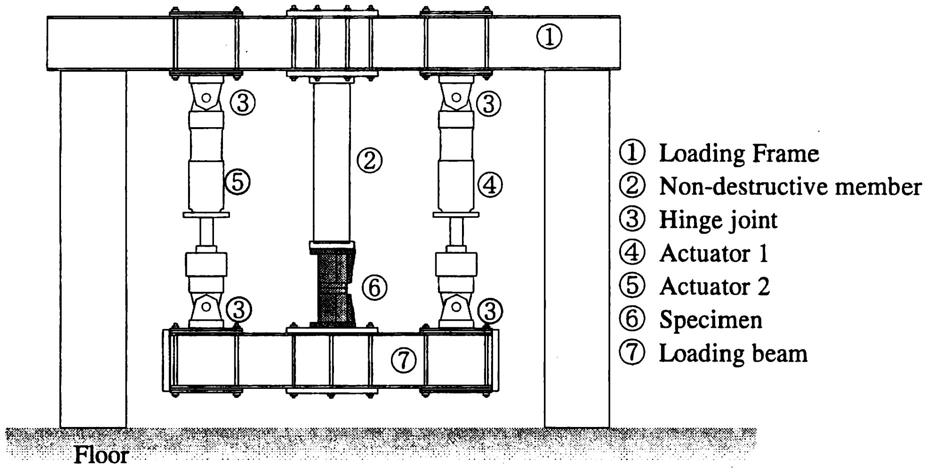
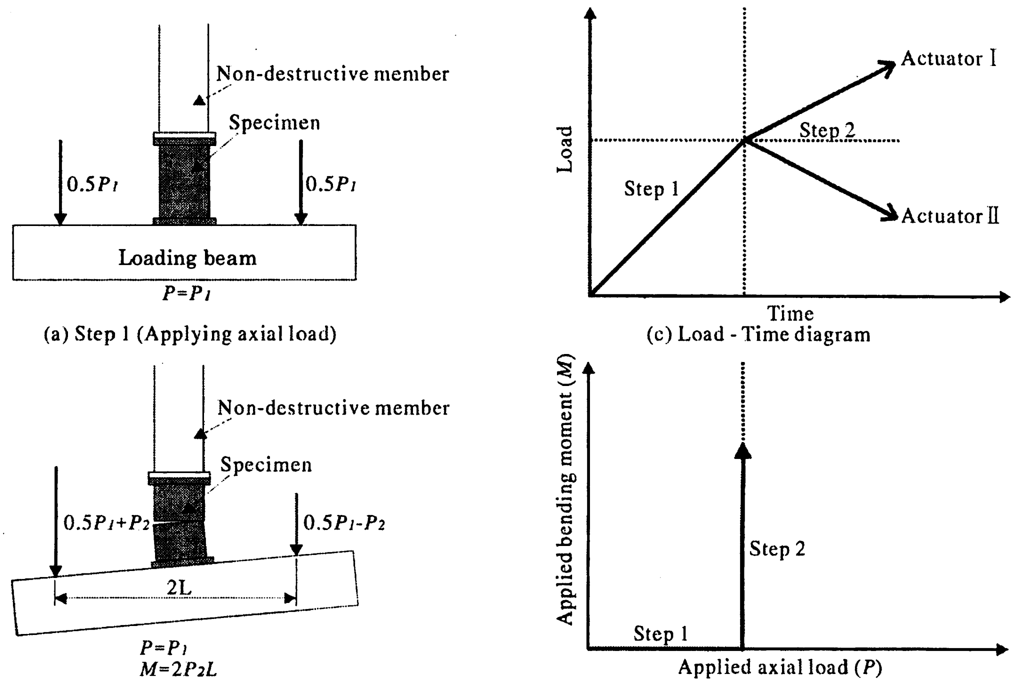


Fig. 4 Test setup



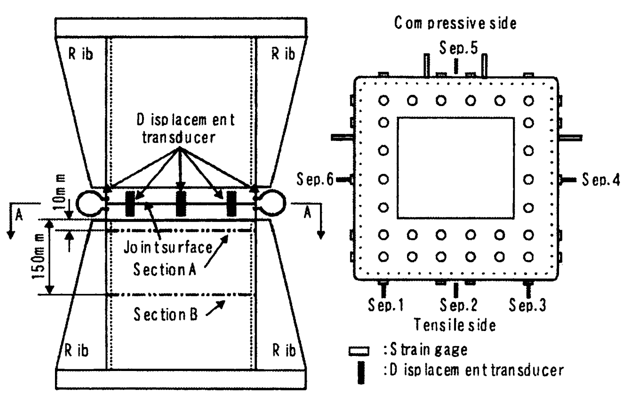
(a) Step 1 (Applying axial load)

(c) Load - Time diagram

(b) Step 2 (Applying bending moment)

(d) Moment - Axial load diagram

Fig. 5 Loading procedure



(a) Overview of measurement position (b) Cross section A-A

Fig. 6 Measurement position of Gap and strain

3. Experimental results and discussions

3.1 Failure mode

The ultimate state of all the specimens is breaking the bolts. As shown in **Photo 1,** the normal bolts were broken at the threaded section. On the other hand, the high deformability bolts were broken at the shank. As for the deformation of the specimen after loading, there is no significant residual deformation of the flange plates except for the specimen, A-22, which has a thin flange plate. Moreover, the residual deformation such as local buckling of the steel box wall also could not be observed for all the specimens.

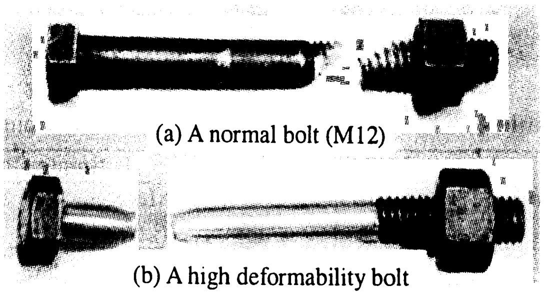


Photo 1 Breaking of the bolts

3.2 Bending moment vs. curvature curves

Bending moment (M) vs. curvature (ϕ) curves are depicted in **Fig. 7**, and the lists of the yielding and ultimate strength of all the specimens are tabulated in **Table 4**. The horizontal axis denotes the average curvature of the jointed section, and the vertical axis denotes the applied bending moment. The first yielding point of each specimen is defined by the state when a bolt will reach the yielding axial force of the bolts specified in **Table 3**. In addition, the first yielding of the box tube without joints is also shown in this figure.

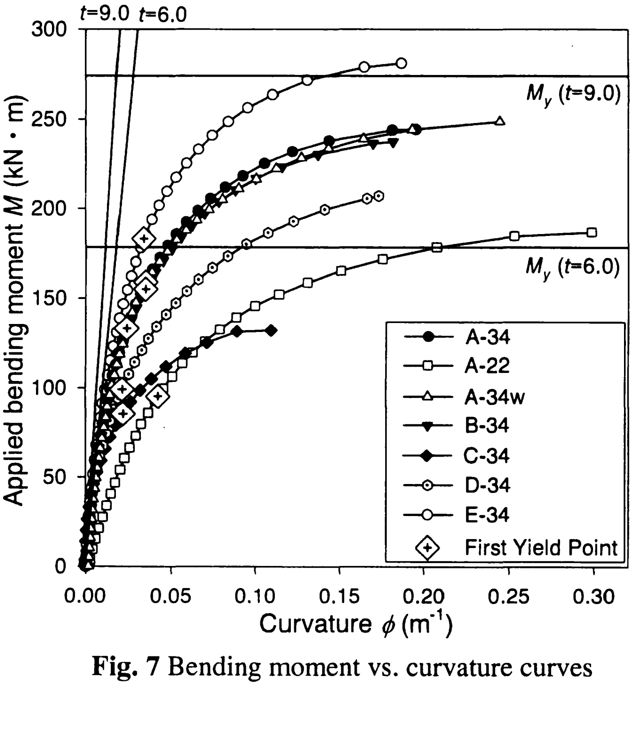


Fig. 7 Bending moment vs. curvature curves

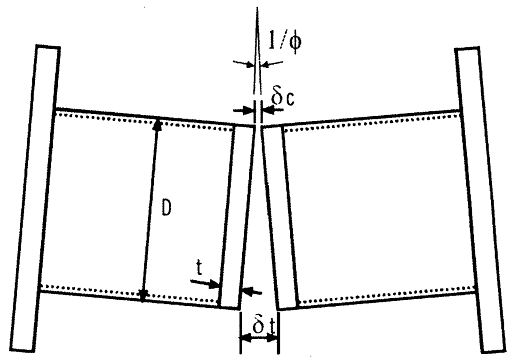


Fig.8 Definition of curvature

Table 4 Lists of the yield and ultimate limit strength

Specimen	Yielding state		Ultimate state	
	Moment (kN·m)	Gap (mm)	Moment (kN·m)	Gap (mm)
A-34	133.2	0.45	244.2	3.93
A-34w	159.1	0.66	248.8	4.93
A-22	95.4	0.52	187.3	3.61
B-34	155.1	0.70	237.5	3.68
C-34	85.6	0.42	132.3	2.19
D-34	99.2	0.40	207.2	3.44
E-34	183.2	0.68	281.1	3.79

The curvature of the joints (ϕ) is defined by the following equation.

$$\phi = \frac{\delta_t - \delta_c}{2t \cdot D} \tag{1}$$

Where, ϕ is the curvature of the joint, δ_t and δ_c are the average gap between two flange plates at the tensile and compressive side respectively, t is the thickness of flange plates and D is the diameter of the steel box tube.

It can be found out that the thicker the flange plate is, the higher the ultimate strength becomes. However, the strength of the specimen with the waisted shank bolt does not increase, but the corresponding curvature is improved significantly.

Comparing with A-34 and D-34, it can be also found that the second row bolts are very effective in the aspects of high strength, high rigidity, and high ductility. Moreover, from the comparison of A-34 with A-34w, it will be recognized that using the waisted shank bolts at the first row is also effective for changing the ultimate limit state from brittle to ductile. That is, the failure mode deciding the ultimate limit state of the tensile joints can change from the brittle failure to the ductile one by using waisted shank bolts. It can be seen from the relationship between the first yielding point and the ultimate strength that the ultimate strength is twice times of the first yielding strength. Therefore, if a joint is designed based on the first yield strength, the joint becomes very ductile up to the ultimate limit state. Judging from these results mentioned above, it is recognized that the high strength bolted tensile joints for box cross sections will be applicable in real bridge structures.

3.3 Change of bolt axial force

Bending moment (M) vs. bolt axial force (B) curves of A-34, A-34w, B-34, C-34 and D-34 are depicted in **Fig. 9**. The horizontal axis denotes the bolt axial force, and the vertical axis denotes the applied bending moment.

The behavior of change of the bolt axial forces was almost same between left and right side for all the specimens. Accordingly, since the load is applied to the specimens correctly, the axial force of the bolts at the right side is only shown in this figure except for D-34. The yield axial force (B_y) and the ultimate axial force (B_u) of the bolts specified in **Table 3** are also plotted in the figure.

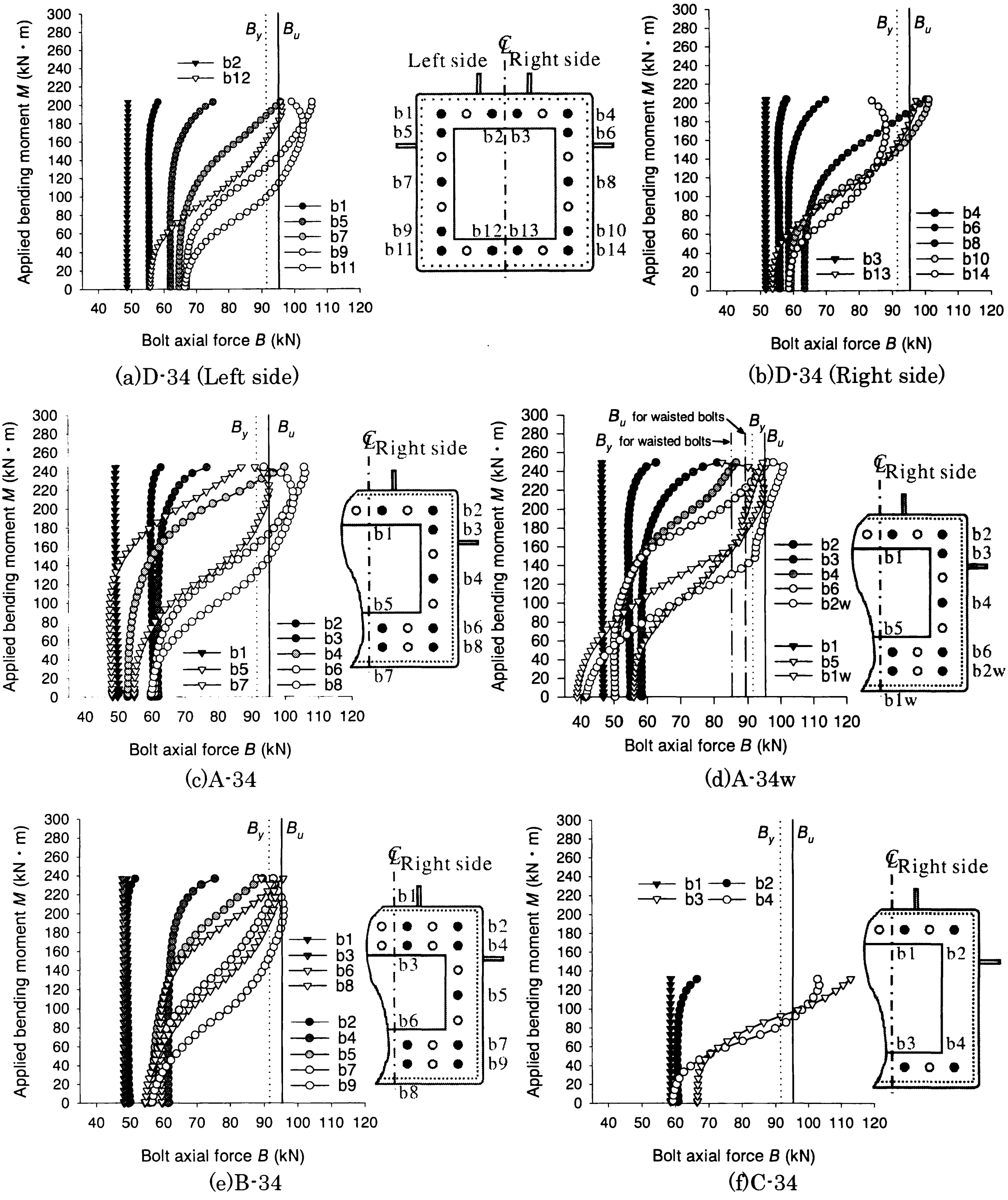


Fig. 9 The change of the bolt axial forces

From this figure, the bolt axial force of each bolt after introducing is not constant, even though the same method is used, namely the method using torque wrench. The tendency of the initial bolt axial force of each bolt is almost same among the specimens. It is considered to be depend on the order of introducing the axial force. And it is difficult to control the bolt axial force in precise by using the torque wrench method.

There are some bolts of which the introduced axial force is lower about 10% of the design value.

However, it is not a severe problem for the strength of the joint, because the strength of the tensile joints is not affected by the introduced bolt axial force. The amplitude of the bolt axial force affects on the rigidity of the tensile joints in main. Therefore, it is necessary to examine the relation between decrease of the bolt axial force and the joint rigidity in detail.

As for the tendency of increase of the bolt-axial force, the significant difference by the bolt arrangement hardly is observed.

The axial force of the bolts located at the compressive side hardly changes, even though bending moment is applied. On the other hand, the axial force of the bolt at the corner of the steel box increases at first, and then, the axial forces of the bolt located at the web side and the first row bolt at the center of the steel box increase simultaneously. This means that the second row bolts placed at the corner of the steel box are very effective. Finally, the axial force of the bolt placed in the web side begins to increase immediately, before the bolt at the tensile side yields. It is considered that the effect of placing the bolts in the web side is high. From comparison with A-34 and A-34w, it can be observed that using the high deformability bolts at the first row would contribute to increase of load transfer of the joint and further increase of the ductility of the joint.

3.4 Gap between flange plates

Bending moment (M) vs. Gap between two flange plates (δ) curves of A-34, C-34 and D-34 are depicted in **Fig. 10**. The horizontal axis denotes the average gap (separation) between two tee-flange plates, and the vertical axis denotes the applied bending moment. In this figure, Sep. 1, Sep. 2 and so on means the measured position shown in **Fig. 6**. And the first yield moments of the joints are also shown in this figure.

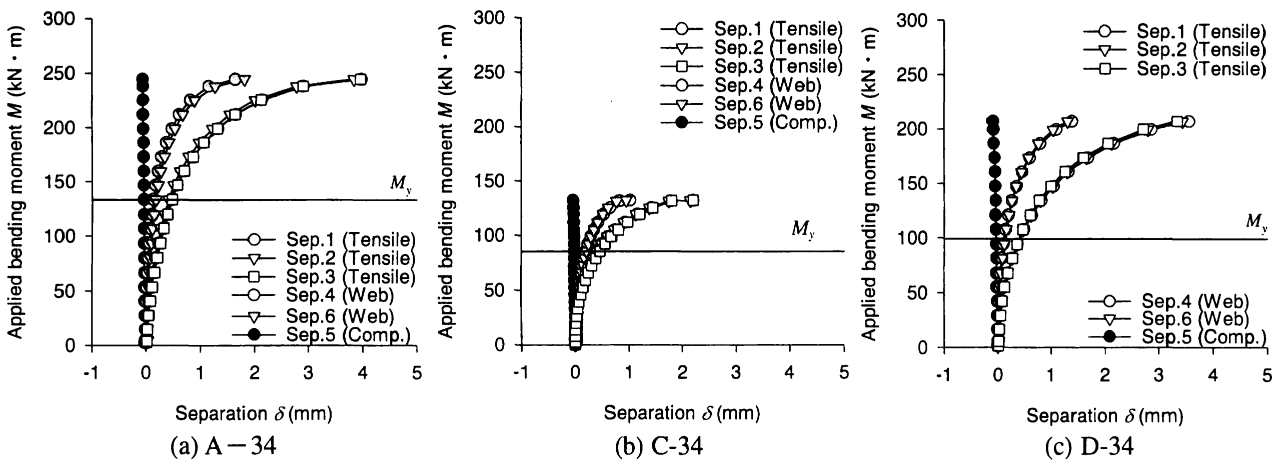


Fig.10 Bending moment vs. Gap between two tee-flange plates curves

From this figure, the behavior of applied moment vs. separation tends to be same among all specimens, and the gap gradually progresses for compressive side from the tensile side. And, the gap is very small until the joint yields.

Gap is very important factor for applying the tensile joints to the joints of bridge structures. Judging from the experimental result, the serviceability limit state of tensile joints should be defined by the yielding of some one bolts, since the gap of the connection is very small (max. 0.70mm). As a result, this type of the joints has much redundancy for the ultimate state which is the state of braking of some one bolt.

4. Concluding remarks

In this paper, experimentally investigated is the applicability of tensile joints to connecting the primary members with box cross-section of bridge structures. In the experiment, the specimens modeled as the connection of steel box tube members connected by tensile joints are subjected to bending moment and tensile force simultaneously. In particular, the effect of the bolt arrangements such as multiple row arrangements is discussed. The following results are obtained:

(1) The thicker the tee flange plate is, the more ductile the connection is and the higher the ultimate strength

becomes. The rigidity of the connection whose tee flange plates' thickness are 34mm is 3 times the rigidity of the connection with 22mm tee flange plates. And, the maximum bending moment of the connection whose tee flange plates' thickness are 34mm is 1.3 times the rigidity of the connection with 22mm tee flange plates.

(2) The bolts placed in the second row in the compressive side of the joint are not almost effective for bending and tension. On the other hand, the bolts placed in the second row in the tensile side are very effective. The strength of the connection with two-row bolt lines is about 1.2 times of that with single bolt line. And, the secant rigidity at the yield state of the connection with two-row bolt lines is about 1.3 times of that with single bolt line.

(3) The serviceability limit state of tensile joints should be defined by the yielding of the bolts. And the ultimate strength is 1.5 ~ 2.1 times of the yield strength based on the yield of bolts.

Judging from these results mentioned above, it is recognized that the high strength bolted tensile joints for box cross sections are applicable in real bridge structures.

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