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Analytical Study on Mechanical Behavior of High Strength Bolted Tensile Joints with High Strength and High Ductility Bolts

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Synopsis

In this study, in order to investigate in detail the mechanical behavior of the high strength bolted tensile joint with high strength and high ductility bolts, focusing on the failure modes of the joint and the effectiveness of the high strength and high ductility bolt, F.E. analysis has been carried out for some cases varying the thickness of the flange plate. Discussed herein are different failure modes corresponding to the thickness of the flange plate through comparing with the joints using normal high strength bolts. And it is concluded that the joint with high strength and high ductility bolts is effective with respect to deformability.

KEYWORDS: High Strength and High Ductility Bolt, Tensile Bolted Joint, F.E. Analysis

1. Introduction

This study is to improve the deformabilty of tensile high strength bolted joints of short connection type by using high strength and high ductility bolts. The high strenghth and high ductility bolt has waisted shank as shownn in **Fig. 1**. The effectiveness of the high strength and high ductility bolt is reported by the refference 1). The bolt with appreciate diameter of the shank shows high strength and high deformability. If this type of bolts are used for the high strenghth bolted tensile joints of short connection type, it is expexceted to change the failure mode from brittle to ductile by controling the maximum load carrying capacity. As a result, the application of the high strength bolted joints will become wider and more various. For example, this type of the joint will be expexted to be adopted to the joint of structural members, such as the joint of main truss girders and lateral struts, as an energy absorption device. One of the merits of this type of the joint is the easy and quick replace of the bolts and recovery of the performance of an joint even after the large deformation. The schematic figure of one of the application examples is show in **Fig. 2**. This is the joint between the strut and the column in a bridge.

In this study, the split tee type joint with two bolts as shown in **Fig. 3** are dealt with as the simple high strength bolted tensile joints. And F.E. analysis is carried out for such joints considering geometrical and boundary non-linearity, that is, contact/non-contact condition between two flange plates.

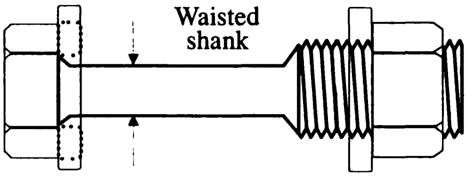

Fig. 1 High strength and high ductility bolt

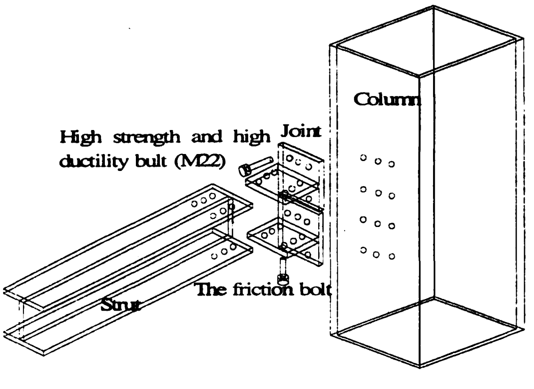

Fig. 2 Application example

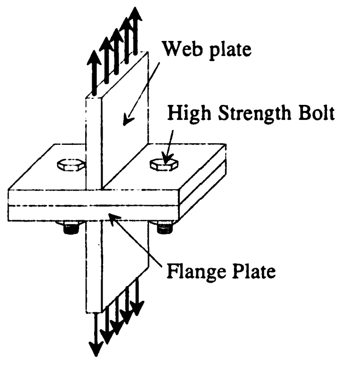

Fig. 3 Typical type of split tee joint

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First of all, the validity of the F.E models is checked through comparison with experimental results obtained from the experiment for the same type of joints carried out by authors in advance. After then, the mechanical behavior of the joints is examined through the F. E. analysis.

2. Analytical Model

The analytical model used in this study is shown in **Fig. 4**. The geometrical configurations of the model are determined as same as those of the experimental specimens as shown in **Fig. 5**. The geometrical configurations of the high strength and high ductility bolts used in this analysis are shown in **Fig. 6**.

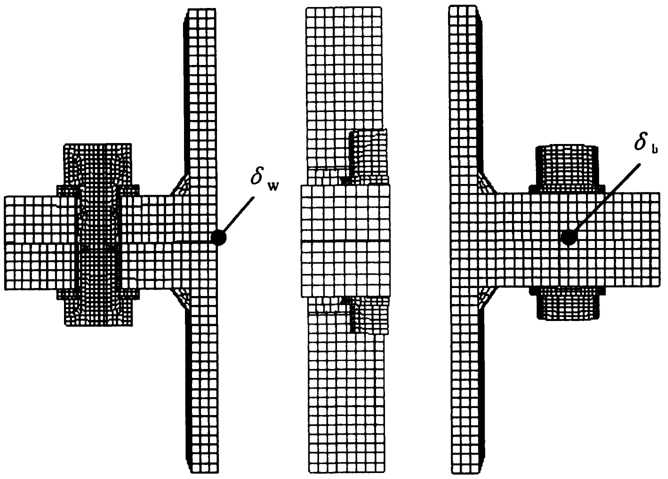
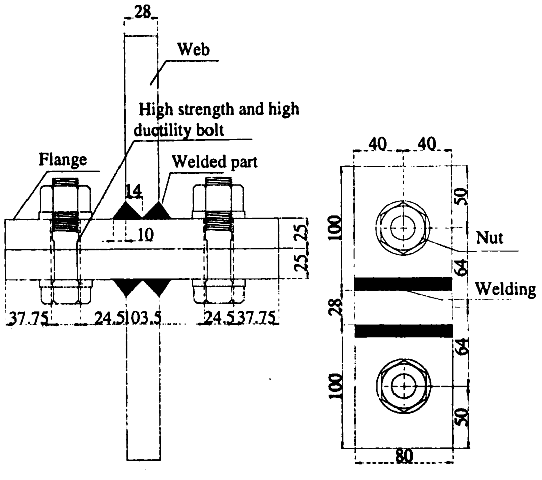
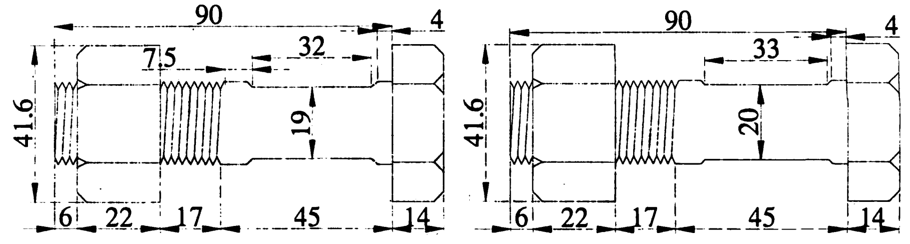


Fig. 4 Analytical model



(a)Cross sectional view (b) Plane view

Fig. 5 Geometrical configurations of test specimen (unit: mm)



(a) Analytical model T25-19 (b) Analytical model T25-20

Fig. 6 Geometrical configurations of high strength and high ductility bolts (Unit: mm)

As for the high strength and high ductility bolt, the bolt length from the head to the bottom is set to 90mm and 100mm corresponding to the total thickness of the two flange plates. But the length of the threaded portion is kept constant, 45mm. The diameter of the shank is set to be 19mm and 20mm according to the reference 1). This value is nearly equal to the effective diameter of the threaded portion specified in Japanese Industrial Standards Association, Stress Area and Bearing Area for Threaded Fasteners (JIS)[2)]. It is reported that the absorption energy of the bolt is expected to be maximal in this case.

The F.E model is 1/4 of the actual split tee joint as shown in **Fig. 4** considering structural symmetry. Geometrical configurations are determined basically following the JSSC recommendation for design of high strength tensile bolted connections for steel bridges[3)]. The structural dimensions are determined considering actual joints.

The flange plate, web plate and welded section are modelled by 8-node linear brick element with reduced integration. The bolt is modelled by 8-node linear brick element with reduced integration and 6-node linear triangular prism element. The number of the total elements of the analytical model is approximately 9,900. The welded section and the section near the bolt head are divided by fine meshes. The threaded portion of the bolt is modelled ignoring the screw shape and its diameter of the threaded portion is set to the effective diameter specified in JIS. The stress-strain relationship of the steel plate and the bolt used in the analysis are also shown in **Fig. 7** and **Fig. 8** respectively. The mechanical characteristics of the steel plate and the bolt including the shank and threaded portion are tabulated in **Table** 1. Von Mises yield criterion is used as the yield function.

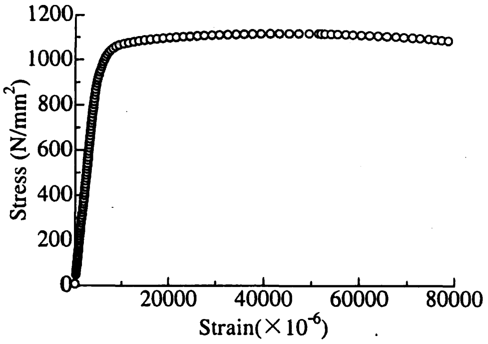


Fig. 7 Stress-strain relationship of bolt material

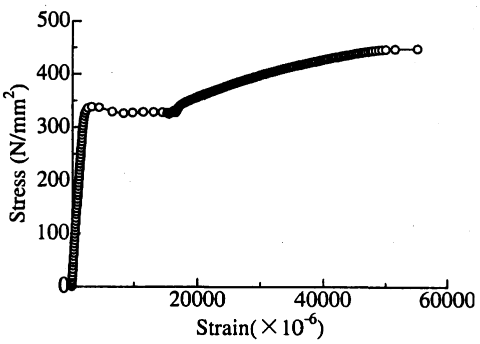


Fig. 8 Stress-strain relationship of steel plate

Table 1 Mechanical characteristics of steel plate and bolt

Material	Ultimate Tensile stress(N/mm^2)	Young`s modulus(N/mm2)	Yield stress(N/mm2)	Poisson ratio
SMY490	448	2.04×10^5	324	0.289
F10T	1115	2.08×10^5	1030	0.3

Table 2 Summary of the analytical models

Models	Web Thickness(mm)	Flange Thickness(mm)	Flange Length×Width(mm)	Bolt Diameter(mm)
T25-22	28	25	128×80	22
T25-20	28	25	128×80	20
T25-19	28	25	128×80	19
T28-19	28	28	128×80	19

In order to realize the contact/separation behavior of the joint, the contact surfaces are installed on the surfaces of the flange plates, the surface of the bolt, the washer, and the bolt hole. The friction coefficient of the respective contact areas is assumed to be 0.4.

Analytical cases are summarized in **Table 2**. As for the name of the analytical models, the first character T denotes the type of the joint, namely, split tee joint. The number following the character T means the thickness of the flange plate in mm. The last number indicates the diameter of the shank of the bolt in mm. For example, T25-19 means the split tee type joint with the thickness of the flange plate, 25mm and the bolt which shank is 19mm.

The number of the analytical models is 4 in this study with varying the thickness of the flange plate and the diameter of the shank of the bolt. In case that the thickness of the flange plate is 25mm, it is predicted by JSSC recommendation [3)] that the bolt failure and the flange plate failure will occur at almost same time.

3. Analytical Method

The analysis is carried out by 2 steps. At the first step, the bolt axial force is introduced as the initial stress. At the second step the tensile load is increased as the applied deformation at the top of the tee web.

The initial bolt axial force introduced into the bolt is 250kN for the diameter of the shank, 22mm and 20mm and 240kN for the diameter of the shank, 19mm, referring to Japanese Specifications for Highway Bridges (JSHB)[4)].

Fig.9 shows the applied tensile load *P* vs. separation displacement at the tee web δ_w curves obtained from the analysis and the experiment in order to verify the applicability of the F.E. model and analytical method used in the analysis.

It can be found that these curves obtained from the analysis for different failure mode cases are identical to those of the experiment with adequate accuracy.

Hence, the F.E model and analytical method can be applicable for parametric study on this type of joints.

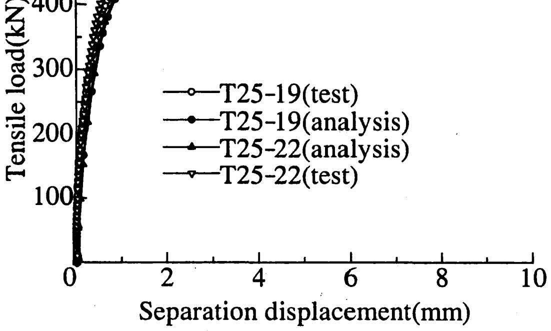


Fig. 9 Comparison of numerical and experimental results

4. Analytical Results and Discussion

4.1 Relationship between applied load and separation

The relationship between the applied tensile load P and the separation displacement δ_w at the tea web is shown in the Fig. 10. The vertical axis denotes the applied tensile load for the joint. The relationship between the applied tensile load P vs. the separation displacement at the bolt position δ_b is also depicted in Fig. 11. The measuring position of the separation displacement δ_w and δ_b are shown in Fig. 4. Analytical results for the 4 models are summarized in Table 3.

As for the case of T28-19 which the tee flange plate thickness is 28mm and the diameter of the shank is 19mm, it is found from the comparison among other cases that the decrease of the applied load after reaching the maximum load is smallest among cases. Especially, from the comparison of the normal high strength bolt with the high strength and high ductility bolt, it also can be understood that the decrease of the applied load after reaching the maximum load in the case with high strength and high ductility bolt is smaller than that of the case with normal shank.

Moreover, it is found that the smaller the diameter of the shank is, the lower the yield strength and maximum load become and the larger the separation displacement becomes. But, the difference of the cases of the diameter of the shank, 22mm and 20mm is not so large. The significant difference between the cases of 22mm and 19mm is observed after the load becomes peak. It is caused by the difference of the failure mode. That is, the former is broken at the threaded section of the bolt and the latter is broken at the shank. Plastic deformation in case of the smaller diameter of the shank with 19mm, T25-19, is approximately 1.5 times of the case, T25-22, with the normal shank bolt.

The load level when the separation between two flange plates at the bolt occurs depends on the diameter of the bolt shank, that is, the pre-installed bolt axial force. In fact, T28-19 begins to separate at the lowest load level among the cases. In addition, in cases of T25-22 and T25-20, the load levels when the separation starts are almost same.

Hence, it is concluded that adopting the high strength and high ductility bolt to the high strength bolted joint of short connection type is very effective to improve the deformability of the joint without decrease of the strength of such joints.

Table 3 Numerical results on limit loads and separation displacement

Analysis model	Flange yield load(kN)	Flange yield separation(mm)	Bolt yield load(kN)	Bolt yield separation(mm)	Maximum load(kN)	Maximum load separation(mm)
T25-19	420	1.11	415	0.99	472	5.04
T25-20	424	0.92	456	1.28	472	3.98
T25-22	436	0.87	460	1.00	480	3.25
T28-19	460	1.05	426	0.93	504	4.80

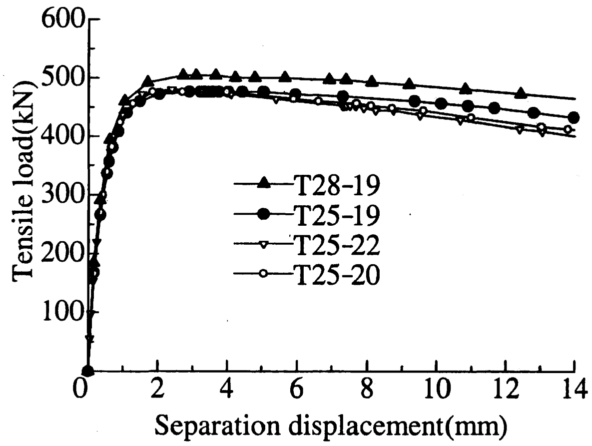


Fig. 10 Tensile load P vs. separation δ_w

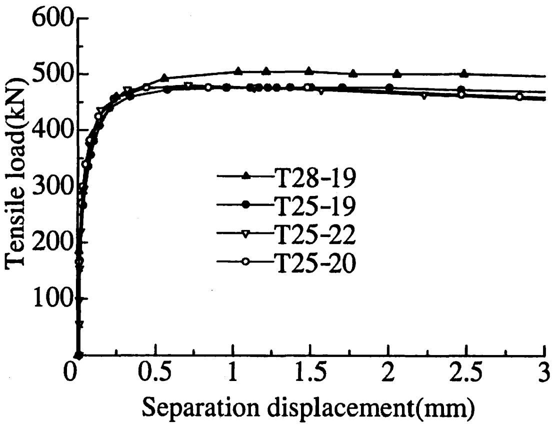
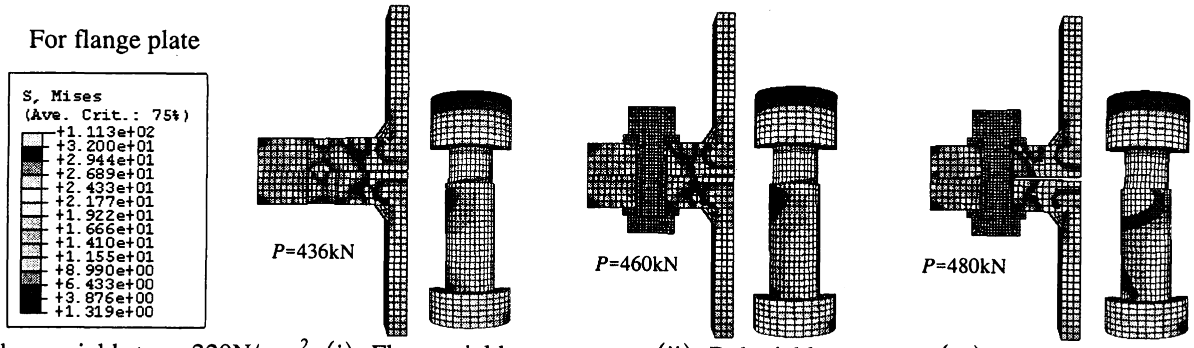


Fig. 11 Tensile load P vs. separation δ_b

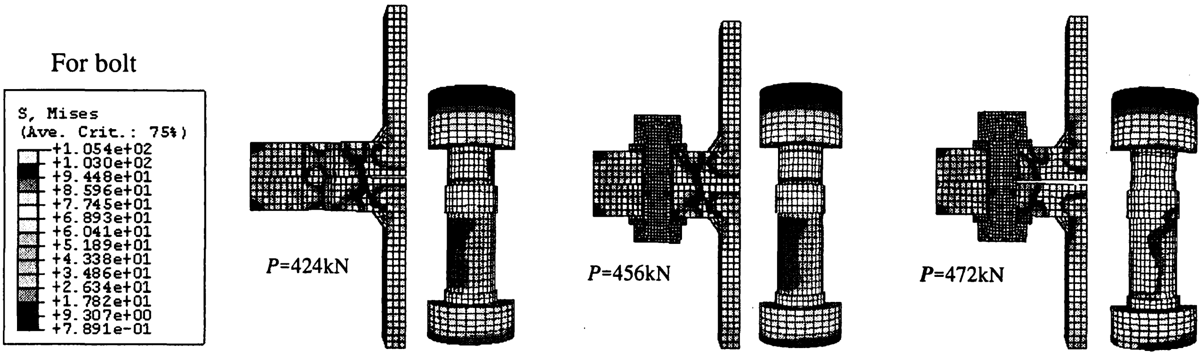
4.2 Failure modes

The progress of the yielding area and the deformation of all the cases are shown in Fig. 12 for the states of yielding of the flange plate, bolt yielding and maximum load of the joint. In this figure, the contour plots of von Mises stress are depicted. Flange yield means that the full plastic state of a certain cross section of the flange plate. Bolt yield means the state of the yielding of the bolt shank/threaded section, namely, the stress of the cross section reaches 1,030 N/mm^2. In addition, the maximum load denotes the maximum strength of the joint.



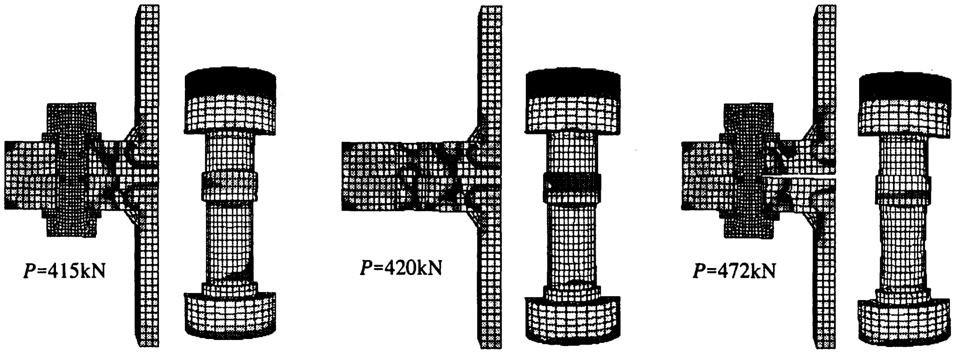
Flange yield stress 320N/mm^2 (i) Flange yield (ii) Bolt yield (iii) Maximum load

(a) Analytical model T25-22



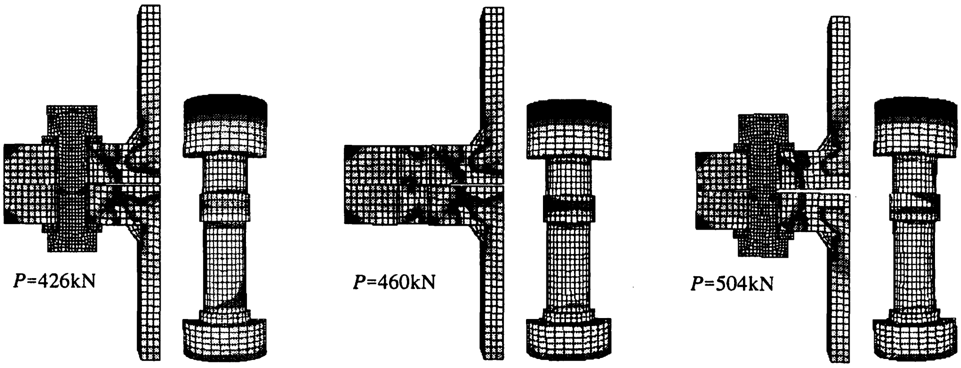
Bolt yield stress 1,030N/ mm^2 i) Flange yield ii) Bolt yield iii) Maximum load

(b) Analytical model T25-20



i) Bolt yield ii) Flange yield iii) Maximum load

(c) Analytical model T25-19



i) Bolt yield ii) Flange yield iii) Maximum load

(d) Analytical model T28-19

Fig. 12 Stress contours and deformations of the joints at representative load levels (magnification ratio: 1.0)

In both cases T25-22 and T25-20, flange adjacent of the connection of the tee web and tee flange plate yields at first, afterwards the threaded portion of the bolt yields. On the other hand, in case of T25-19 and T28-19, yielding occurs at the portion of the shank, and then, the flange plate yields in the vicinity of the connection of the tee web and tee flange plate. In all cases, the yielding portion of the flange plate is in the vicinity of the connection of the tee flange plate and the tee web plate. Yielding of the portion near the bolt hole cannot be observed.

It is also confirmed that yielding occurs at the bolt shank for the case that the high strength and high ductility bolt is adopted. Namely, it shows the effectiveness of using the high strength and high ductility bolt from the view point of plastic deformation of the joint.

From the judgment of the progress of yielding at the maximum strength, the case of T25-19 is the most effective case, because the area of yielding of this case is spread most widely.

5. Conclusions

The high strength bolted tensile joints of short connection type using the high strength and high ductility bolts are dealt with in this study. And the effectiveness of using this type of bolt is discussed based on the F.E analysis considering geometrical and boundary non-linearity. Obtained concluding remarks are as followings:

(1) From the comparison of the experimental results with the analysis results, the F.E model and analytical method can be applicable to the analysis of this type of the joint.

(2) By using the high strength and high ductility bolt for the high strength bolted tensile joint of short connection type, the deformability can be improved more than 1.5 times of that with the normal high strength bolt by keeping the strength due to the plastic deformation of the bolt shank.

(3) Yielding of the flange plate occurs in the vicinity of the connected portion of the tee flange plate and the tee web plate. Yielding of the portion near the bolt hole cannot be observed.

(4) In order to investigate the effectiveness of this type of the joint, structural analyses for the overall structure considering the behavior of this type of joint should be conducted in the future.

References

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