

Mechanical behaviour of bolted connection in bending evaluated with small-scale specimen

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Abstract. A tensile experiment is usually adopted to evaluate the mechanical behaviour of bolted connections, such as slip, yield, and ultimate behaviours or resistances. Tensile force is given by a universal test machine. A small-scale specimen of a bolted connection with a few bolts in a half side is used for the experiment. The small-scale experiment gives the mechanical behaviours easily. Tensile force applies to the specimen in the experiment; however, the bolted connection in an actual structure is exposed not only to tensile force but also to shear force or bending moment. In this study, a small-scale bolted connection for a specimen was developed to evaluate the bending behaviour of the bolted connection. The bolted connection was cranked at the centre. The crank is intended to generate the bending moment by the eccentricity of the applying tensile force and the force axis line. The mechanical behaviour of the bolted connection was investigated by finite element analysis. The bending moment is obtained theoretically as a product of the force and the eccentricity. However, the analysis reduced the applied bending moment by 75% from the theoretical value. The cause of the reduction was the support condition at the ends of the bolted connection. In a theoretical pinned supported case, the applied moment was not reduced; on the other hand, in a clamped supported case, which was assumed clamping by chucks in a universal test machine, the applied moment was reduced. From this finding, the behaviour of bolted connection in bending would be obtained in a small-scale experiment; however, the specimen is needed to design considering the support condition at the ends of the specimen.

1 Introduction

High-strength bolted frictional connection is a well-used connecting technique for steel structures and bridges. The mechanical behaviour of the bolted connection, such as slip or yield, is usually evaluated by tensile tests [1-3], although it is evaluated by compressed experiments in some procedures [4-6]. The tensile test gives safety side evaluation because applied tensile force makes the main and splice plates thinner and reduces bolt axial force and slip resistance. The tensile test or compressed experiment can be conducted with a small-scale specimen with one or two bolts in a shear plane. By the way, a bolted connection in an actual structure is applied not only tensile or compressed forces but also shear force or bending moment. Sakura et al. [7] conducted a girder bending experiment to evaluate the

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behaviour of bolted connections in bending. Hosoya et al. [8] performed a tensile experiment with bolted connection specimens to evaluate the behaviour in bending. Although a tensile force was applied to the specimen in the tensile experiment, the cranked part of the specimen in the middle generated a bending moment. The specimen had nine bolts in a half side. In these ways, bending behaviour can be evaluated; however, the specimen becomes larger and more expensive compared to that in the tensile test. In this study, a small-scale specimen of bolted connection for evaluation of mechanical behaviour in bending was designed and investigated by finite element analysis in some cases.

2 Bolted connection

Fig. 1 shows the shape of the designed bolted connection. The detailed dimensions of the connection are summarized in Table 1. The small-scale connection was designed as a specimen for a structural experiment, although the bolted connection in an actual structure is large. The connection assumed a row of the connection cut out from an actual connection. Three bolts were aligned on one side of the connection. The connection was cranked in the middle. The eccentricity of the applied axial forces is intended to generate a bending moment. The steel grades of plates and bolts were SM490Y [9] and F10T [10], assuming the connection was part of a steel highway bridge [11]. In previous statistical research [12], actual structural steel materials’ yield points and tensile strengths are 1.2187 and 1.1153 times higher than those defined in the specifications [9, 10], respectively. The actual slip coefficient was 1.1309 times higher than that defined in the specification [1]. The slip/yield resistance ratio is obtained by dividing the slip resistance by yield resistance. The ratio of 0.66 means that slip occurs before yield. That is similar to the standard slip test specimen [1].

Table 1. Dimensions of bolted connection.

	Parameters	Bolted connection
Bolts	Steel grade	F10T
	Bolt size	M16
	Proof strength (N/mm ²)	1096.8
	Tensile strength (N/mm ²)	1115.3
	Number of frictional planes	2
	Number of bolts in one side	3
	Design bolt preload (kN)	106
	Slip coefficient	0.57
Plates	Steel grade	SM490Y
	Yield point (N/mm ²)	432.6
	Tensile strength (N/mm ²)	546.5
	Width of plates (mm)	75
	Thickness of main plate (mm)	22
	Thickness of splice plate (mm)	12
	End distance (mm)	30
	Pitch of bolts (mm)	60
	Diameter of bolt holes (mm)	18
Design resistance	Slip resistance (kN)	363
	Yield resistance of main plate (kN)	542
	Slip/yield resistance ratio	0.66

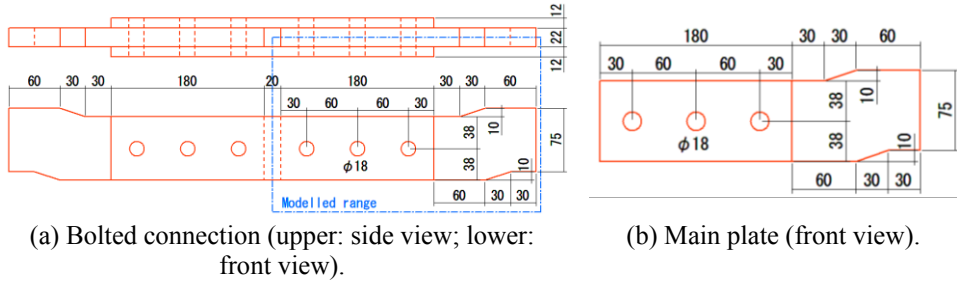


Fig. 1. Shape of bolted connection (unit: mm).

3 Study cases

Study cases are summarized in Table 2. MP case includes only the cranked main plate without bolt holes. The case investigated the basic bending behaviour of the cranked main plate. Considering the experimental loading by a universal testing machine, the tensile force was given by uniformed displacement at the end of the main plate. MP case, which is part of the designed bolted connection, has the main plate with three bolt holes. The case investigated the influence of stress concentration caused by the bolt holes. BC case includes the designed bolted connection with cranked main plates. The case investigated the bending behaviour assuming an experiment. Although the bolted connection in BCp case has the same dimensions as that in BC case, the support condition at the end of the main plate is different. The condition of BCp case is pinned supported, which allows rotating at the supported end of the main plate. The comparison between BC and BCp cases was intended to investigate the influence of the support conditions.

Table 2. Study cases.

Case Name	Subject	End support condition
MP	Main plate without bolt holes	Clamped
MPh	Main plate with bolt holes	Clamped
BC	Bolted connection	Clamped
BCp	Bolted connection	Pin supported

4 Numerical models

Nonlinear finite element analysis was conducted by Abaqus standard 6.13. The material, geometry, and boundary nonlinearity were considered. Fig. 2 shows the outline of the numerical models. Each component which is the main and splice plate, bolt, and washer, was meshed with linear reduced integration solid elements. The element measured approximately 2 mm. Fig. 3 shows stress-strain models. Young's modulus of SM490Y and F10T was 200 000 N/mm². The Poisson's ratio was 0.3. The slope in stress-strain models from the yield point to the tensile strength was 0.01 times Young's modulus [13]. The slope after the tensile strength was zero.

As shown in Fig. 2, in MP and MPh cases, half of the main plate in the thickness direction was modelled considering symmetry. The left side of the main plate was fixed, and uniformed imposed displacement was given at the other side of the main plate to give tensile force.

In BC and BCp cases, one-fourth of the parts were modelled considering symmetry in two directions. Symmetry boundary conditions according to the direction were given on the symmetry surfaces. The bolt preload of each bolt was installed at first. The preload was given by force increment. After the preload installation, a tensile force was given. The left side of the splice plate was fixed. In BC case, the uniformed imposed displacement was given to

apply tensile force as the same to MP and MPh cases. On the other hand, in BCp case, a force was given by imposed displacement at the centre of the main plate in width. The Young's modulus near the end of the main plate was elevated 10^{10} times Young's modulus to avoid local deformation of the element due to the application of concentrated imposed displacement.

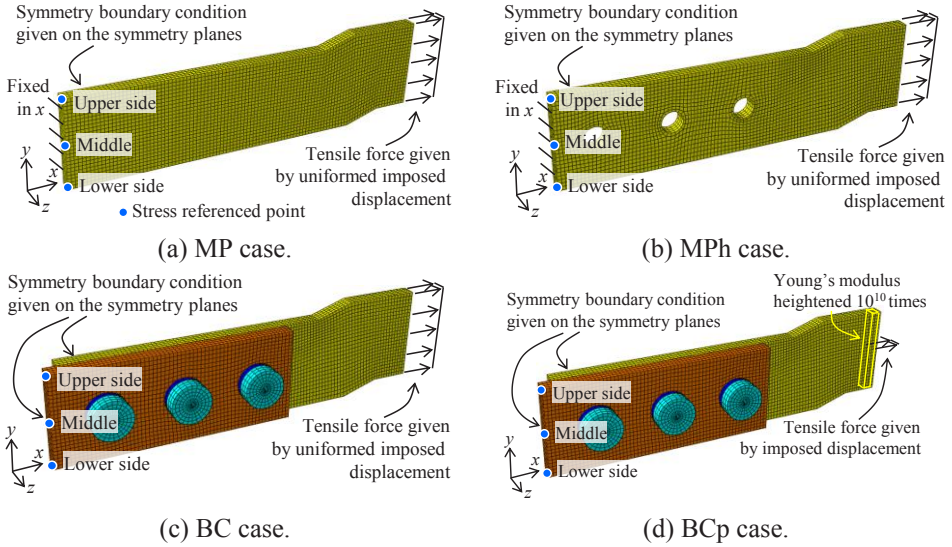


Fig. 2. Outline of numerical models.

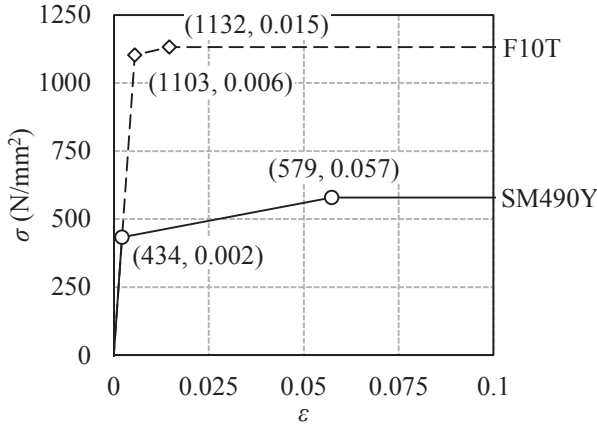


Fig. 3. Stress-strain models.

5 Results

Fig. 4 shows the distribution of the normal stress (σ_x) at the tensile force reached 100 kN. In MP case, the stress at the symmetry side, which was the left side of the figure, differed from the point in the width direction due to the application of the bending moment. The change of stress in width was the same as the bending stress distribution. In MPh case, which added bolt holes, stress at the upper and lower sides was higher than that in MP case. The higher stress bands were extended diagonally from the bolt hole to the side surfaces. The stress elevation was caused by stress concentration around bolt holes. On the contrary, the stress in the middle was lower than that in MP case.

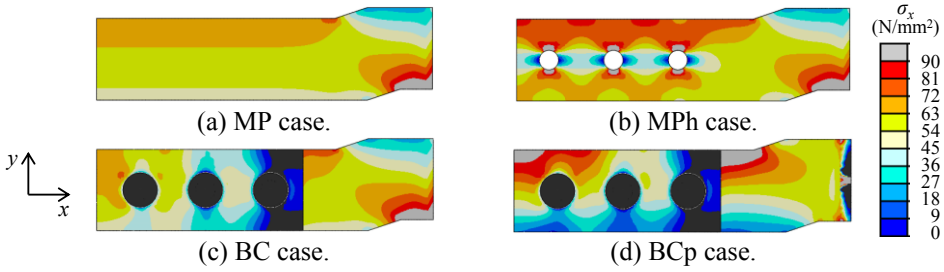


Fig. 4. Distribution of normal stress σ_x at tensile force = 100 kN.

On the other hand, in BC and BCp cases, the stress distribution at the symmetry side was similar to that in MP case without bolt holes, although BC and BCp cases have bolt holes. Tightened bolts transmitted stress over bolt holes by friction and reduced the effect of the stress concentration on the main and splice plate.

Fig. 5 shows stress and tensile force curves. The figure compares the stresses obtained from the finite element analysis and design stresses from theoretical calculations. The stress referenced points, which are middle, upper side, and lower side points, are shown in Fig. 2. The stresses on the main plate were measured in MP and MPh cases. The stresses on the splice plate were measured in BC and BCp cases.

The designed tensile stress (σ_T) was simply obtained by dividing the applied tensile force (P) by the cross-sectional area of the main plate or splice plate (A):

$$\sigma_T = \frac{P}{A}. \quad (1)$$

Applied bending moment (M) was obtained from the tensile force (P) and the eccentricity of force axial (e). The bending stress (σ_B) is calculated as

$$\sigma_B = \frac{M}{I} y = \frac{Pe}{I} y, \quad (2)$$

where I is a moment of inertia of area, and y is the normal distance from the neutral axis to the referenced point. The design stress was calculated as the superposition of tensile stress and bending stress. Hence, the stresses in the upper side (σ_U), middle (σ_M), and lower side (σ_L) is obtained as

$$\sigma_U = \frac{P}{A} + \frac{M w}{I} \frac{1}{2}, \quad (3)$$

$$\sigma_M = \frac{P}{A}, \quad (4)$$

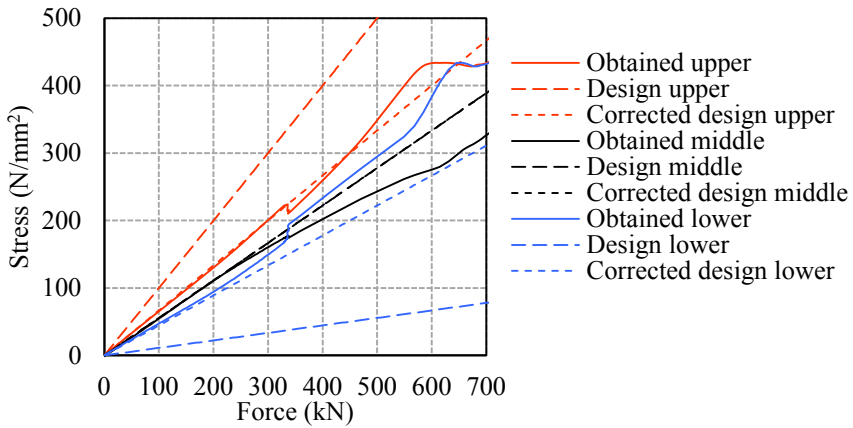
and

$$\sigma_L = \frac{P}{A} - \frac{M w}{I} \frac{1}{2}, \quad (5)$$

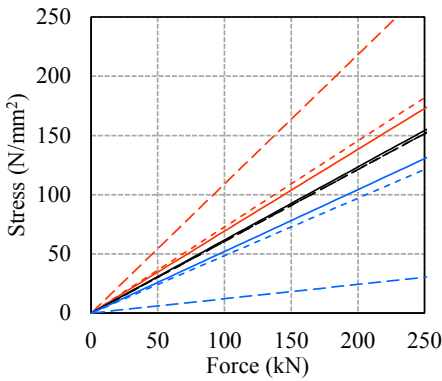
where w is the width of the main or splice plates.

As shown in Fig. 5 (a), at the force reached around 335 kN, a non-contiguous step in obtained curves occurred due to the slip of the bolted connection. The stress and force relationship was kept linearly until around 250 kN.

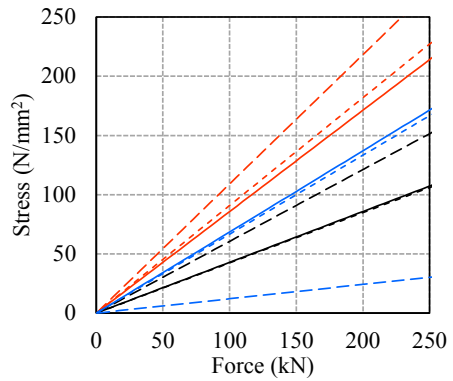
In MP case, as shown in Fig. 5 (b), the obtained stress at the middle point was similar to design stress. On the other hand, the obtained stresses at the upper and lower side points were close to the stress at the middle point, whereas the design stresses at the upper and lower side points were spread from the stress at the middle point. By multiplying the design bending stress by 0.25, the obtained stresses at the upper and lower side points were similar to the corrected design stress. This tendency means that the effect of bending was reduced by 75% due to some reasons. In MPH case, as shown in Fig. 5 (c), obtained stress at each point was different from design stress. The obtained stress at the middle point was similar to the design stress corrected by multiplying it by 0.7. Obtained stresses at the upper and lower side points were similar to the corrected design stress. Corrected design stress at the upper and lower side points after multiplying the tensile stress by 1.3 and bending stress by 0.25 was similar to obtained stress, respectively.



(a) BC case.



(b) MP case.



(c) MPH case.

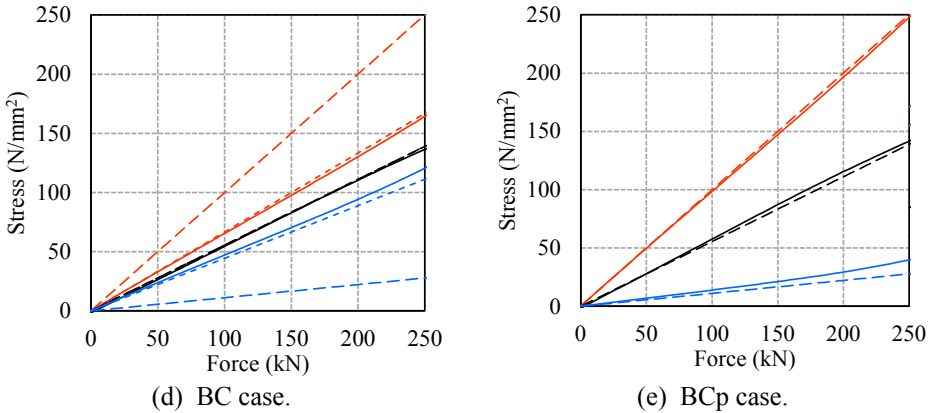


Fig. 5. Stress and tensile force relationship.

As shown in Fig. 5 (d), the trend in BC case was similar to that in MP case. The obtained stress at the middle point was similar to the design stress. By multiplying the design bending stress at the upper and lower side points by 0.25, the corrected design bending stress was similar to the obtained stress. As shown in Fig. 5 (e), the obtained stress in BCp case was similar to the design stress without any correction.

The differences between the obtained stress and the design stress or corrected design stress were summarized in Table 3. These values were obtained when the force reached 213 kN by dividing the slip resistance of 363 kN by the safety factor of 1.7. Although the difference between the obtained and design stress was large in the upper and lower side points except BCp case, the difference between the obtained and corrected design stress was small, which is less than 10% or 10 N/mm². Although the maximum percentage of the difference between the obtained and design stress in BCp case was large as 35%, the difference was less than 10 N/mm². As a result, the obtained stress in BCp case was similar to the design stress.

Table 3. Difference between obtained stress and design stress.

Case	Stress referenced point	Obtained stress	Design stress	Difference percentage	Difference	Corrected design stress	Difference percentage	Difference
		(N/mm ²)	(N/mm ²)		(N/mm ²)	(N/mm ²)		(N/mm ²)
MP	Upper side	149	234	-37%	-86	156	-5%	-8
	Middle	133	130	2%	2	130	2%	2
	Lower side	112	26	330%	86	104	8%	8
MPh	Upper side	185	235	-21%	-51	196	-6%	-11
	Middle	92	131	-29%	-38	91	1%	1
	Lower side	148	26	466%	122	144	3%	4
BC	Upper side	138	212	-35%	-74	141	-2%	-3
	Middle	117	118	-1%	-1	118	-1%	-1
	Lower side	100	24	326%	77	94	6%	6
BCp	Upper side	211	214	-2%	-3	-	-	-
	Middle	123	119	3%	4	-	-	-
	Lower side	32	24	35%	8	-	-	-

6 Discussion

In BC and BCp cases, as shown in Fig. 5 (d) and (e), the stress at the middle, upper and lower side points were different. The fact shows that a bending moment was applied to the designed bolted connection because the cranked part in the middle of the bolted connection generated the bending moment due to the eccentricity of the force axis, although the tensile force was only applied to the connection. The behaviour of bolted connection in bending would be obtained in the small-scale experiment.

The obtained stress in BCp case is similar to the design stress, as shown in Table 3. On the other hand, the obtained stress in BC case was different from the design stress at the upper and lower side points, although the obtained stress at the middle point was similar to that of the design stress. This means that the applied bending moment was reduced. The difference between BC and BCp cases was the support condition at the end of the main plate. The applied bending moment was different according to the support condition at the end, although the applied bending moment can be calculated theoretically by multiplying tensile force and eccentricity. 75% of the bending moment was reduced in BC case. The reduction of the bending moment might be different according to the dimensions of the connection.

The assumptive support condition in design calculation is pinned support because obtained stress equals designed stress in BCp case. However, in an experiment with a universal testing machine, the ends of the specimen were gripped by chucks. The support condition in the situation seems to be similar to clamped as BC case. Hence, the specimen for the experiment to evaluate bending behaviour is needed to design considering the support condition at the ends of the specimen.

7 Conclusions

In this study, a small-scale specimen of bolted connection to obtain bending behaviour was designed and investigated by finite element analysis. Obtained results and conclusions are as follows:

- (1) Although only tensile force was given to the designed bolted connection, a bending moment was applied to the connection because the cranked part in the middle of the connection generated the bending moment due to the eccentricity of the force axis. The behaviour of bolted connection in bending would be obtained in the small-scale experiment.
- (2) The applied bending moment was different according to the support condition at the end of the bolted connection, although the applied bending moment can be calculated theoretically by multiplying tensile force and eccentricity. 75% of the bending moment was reduced in BC case. The reduction of the bending moment might be different according to the dimensions of the connection.
- (3) Hence, the specimen of bolted connection for the experiment to evaluate bending behaviour is needed to design considering the support condition at the ends of the specimen.

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