Bending tests of the box form roof for underpass tunneling methods

Yota Togashi i), Tomoya Nakamura ii), Noriyuki Okano iii) and Kiwamu Tsuno iii)

i) Researcher, Structures Technology Division, Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji-shi, Tokyo 185-8540, Japan.
ii) Assistant senior researcher, Structures Technology Division, Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji-shi, Tokyo 185-8540, Japan.
iii) Senior researcher, Structures Technology Division, Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji-shi, Tokyo 185-8540, Japan.

ABSTRACT

Underpass tunnels are often constructed on the bottom of railway. For preventing a relaxation of natural ground by excavation, box form roofs are set around the area in which the underpass tunnel will be constructed. However, in some cases, box form roofs are gradually bended on bolted joints by both an earth pressure and railway load. It is needed for constructing underpass tunnels safely to manage the torque of bolts in the box form roof. Torque managements of bolts are a valuable important theme for various engineering fields. It is difficult to estimate an initial axial force of bolts, because the relationships between applied torque and initial axial force are changed and affected by both mechanical properties of materials between a bolts and the surface condition of bolts. In this study, in order to appropriate manage a torque of bolts in constructional materials bended by external forces, several bending tests for full-size box form roof used for underpass tunneling method are conducted. The results are demonstrated that as the torque of bolt is increased, both deflection and aperture are decreased. Furthermore, new evaluating method using FE analysis for this bending problem is developed.

Keywords: bolted joint, bending test, earth pressure, underpass tunnel, FEM

1 INTRODUCTION

For constructing underpass tunnel in shallow earth coverings, in order to decrease a relaxation of either embankments or natural grounds, the box form roofs are often inserted as shown in Fig. 1(a). However, in some cases, the box form roof is gradually bended on joints by both earth pressure and railway load as shown in Fig. 1(b) because the stiffnesses of joints are relatively smaller than the rigid part of the roof. For constructing an underpass tunnels more safely, it is needed to grasp the mechanical behaviors of the box form roof during bending.

On the other hand, it is an important theme for managing structures with bolted joints to estimate the axial force of torqued bolts (e.g. Jeong et al., 2007, Gaul and Lenz 1997). In order to decrease the deformation of joints, torque of bolts should be applied correctly considering the tensile strength of bolts. The torque of bolts is previously managed using the relationships between applied torque and an initial axial force in following empirical relation (1) called torque method (Bickford, 1995).

\[ T = KN_b d \]  

where \( T, N_b \) and \( d \) are applied torque, axial force and
diameter of bolts. $K$ is called coefficient of torque and constituted by coefficients of surface frictions of bolts. The torque method is used widely for the management of bolted joints. However $K$ is often scattered by the difference of surface conditions of a bolt. For determining $K$ correctly, for example, a method of determining $N_b$ by measuring ultra sonic wave velocity is developed by Sakai et al., 1977.

In this study, in order to clarify the mechanical properties of the box form roof with bolted joints, several bending tests are conducted. Furthermore, FE analysis with simple algorithm for bending test of the materials with bolted joints is developed. The results are well simulated for the relationships between the deformation during bending and axial force of bolts.

### 2 BENDING TEST

In order to grasp the deformation behavior of the box form roof with bolted joints, bending tests are conducted in 3 cases using full-size specimen.

The box form roof in this study is shown in Fig.2 and the specification is also shown as Table.1. To decrease friction forces acted on the joints of the roof, the joints are grinded as shown in Fig.2 (b). The specimen used for the bending test is prepared by connecting the roof with 4 bolts of chrome molybdenum. Four points bending tests are conducted by the testing apparatus as shown in Fig.3 (a) with measuring instruments as shown in Fig.3 (b). Deflection and aperture width at the bottom of specimen are measured by contact type displacement transducer and $\pi$ gauge respectively. Load $P$ is also measured on load cell in the jack. The loading pass is applied to approximately up to 0.2MN considering elastic deformation of both the box form roof and bolts as shown in Fig.4. In every load increment $\Delta P = 0.01MN$, holding $\Delta P = 0MN$ for 1 min, static measurements are conducted. To remove the effect of loading velocity to mechanical properties of specimens, 1 min measurement is conducted.

| Case No. | Torque $T$ (Nm) | Axial force of bolts $N_{b0}$ (MN) |
|----------|----------------|----------------------------------|
| 1        | 300            | 0.06                             |
| 2        | 700            | 0.14                             |
| 3        | 1200           | 0.24                             |

![Bending Test](image)

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**Table.1 Specifications of the box form roof**

| Height $H$ (m) | Width $W$ (m) | Length $L$ (m) | Number of bolt hole | Roughness |
|----------------|--------------|---------------|---------------------|-----------|
| 0.8            | 0.8          | 3.0           | 4 – 6               | $\leq 0.00041$ |
average load increment speed is sufficiently slow as $\Delta P / \text{min} = 0.006 \text{MN/min}$. 3 test cases are conducted as shown in Table.2 with changing torque $T$ applied to bolts as Fig.5. $T$ is converted to initial axial force $N_{b0}$ by equation (1).

The results of bending tests are demonstrated as shown in Fig.6. As applied torque become larger, deflection $\delta$ and aperture $W_a$ are decreased. In the case of $T=300 \text{Nm}$, $\delta = 2.0 \text{mm}$ and $W_a = 0.6 \text{mm}$ are obtained on $P = 0.2 \text{MN}$. Comparison between the case of $T=300 \text{Nm}$ and that of $T=1200 \text{Nm}$ shows that as initial torque of bolts become 900Nm increased, $\delta$ and $W_a$ become 25% and 30% smaller respectively. Overall tendency of these results shows non-linear behaviors. An overall mechanical modeling considering the behavior of bolted joints is discussed in the next chapter.

3 MODELING OF DEFORMATION BEHAVIOR OF THE BOX FORM ROOF WITH BOLTED JOINTS DURING BENDING

For bending tests of a box form roof with bolted joints, non-linear mechanical behaviors are obtained by several bending tests as shown in chapter 2. For four points bending tests, bending moment and shear force distributions are known as Fig.7. In addition, the deformations during bending are expressed as shown in Fig.8. Comparison between continuum structures (a) and the box form roof with bolted joints (b) are also expressed as axial symmetric area. For continuum structures, only deflection is occurred during bending, and the neutral axis is coaxial with the center line of the structures. On the other hand, for the box form roof with bolted joints, both deflection and aperture are occurred during bending, and the neutral axis may be took upper position from the center line of the roof.

![Diagram](image-url)
Furthermore, the deformations of bolted joints are classified two types as Fig.9 (a). Assuming axial force of the bolt $N_b$ is plus to tensile direction. In case (i), initial axial force $N_{b0} >$ axial force increment $\Delta N_b$ by load $P$, the joint around the bolt is connected. On the other hand, in the case (ii), $\Delta N_b > N_{b0}$, the joint is not connected. Expressly, the relation the traction force on bolt perpendicular to joints $\Delta f_b$ with both axial force of bolts $\Delta N_b$ and shear force acted on bolts $Q_b$ are modeled as shown in Fig.9 (b). $f_b$ is acted to vertical direction against the surface of the joint deformed by the load for bending. Assuming the deflection angle of bolts is much fewer than that of the roof, $f_b$ is resolved to $N_b$ and $Q_b$.

For these deformatonal behaviors as shown in both Fig.8 and Fig.9, the relationships between load $P$, deflection $\delta$, aperture width $W_s$ and axial force $N_b$ are modeled by Fig.10. Even though applied loading levels are only elastic, $P-\delta$ relationship becomes non-linear (bi-linear) because the modes of deformation are changed by loading levels. In order to obtain axial force of bolt $N_b$ during loading considering the deformation behavior discussed in this chapter, simple algorithm of numerical simulation using FE analysis is explained in next chapter.

4 NUMERICAL SIMULATIONS

To obtain axial force of bolts during bending, simple numerical algorithm is developed in this study. Fig.11 shows the plane strain axial symmetric area (Wu and Kurokawa, 2002, Tsuji et al., 1997) for explaining deformation behaviors of box form roof with the bolted joint. For modeling of the area Fig.9 (i), FE area is modeled by Fig.11 (a), while for that of Fig.9 (ii), the area is modeled by Fig.11 (b) and to obtain axial force on the bolt, spring element is set at the position of the bolts. For modeling the traction force on bolt perpendicular to joints $f_b$, both axial force of bolts $N_b$ and shear force acted on bolts $Q_b$ as shown in Fig.9 is described by equation (2).

\[ N_b = k_b u_b \]
\[ Q_b = k_s v_b = \frac{1}{3} k_a v_b \]

where $(u_b, v_b)$ are displacements of the bolt, $k_b$ and $k_s$ are spring modulus for vertical and shear direction. In this study, $k_s = (1/3)k_a$ is assumed. In this study, the effect by the bolts at the top of the roof is assumed quite low, so spring element is set only bottom position of bolts. For loading, vertical displacement $v$ is acted on the top of symmetry axis, and to output load $P$ that displacement point is fixed to external area.

In addition, in order to explain the deformation behavior of joint shown in Fig.8 (b), the boundary condition of the joint $\Gamma_j$ is considered in equation (3).

\[ \begin{align*}
\text{START} \\
i = \text{node at middle of joint} \\
\text{Solving FE equation: } Ku = f \\
\text{END} \\
i = \text{node at top of roof ?} \\
\text{YES} \\
\sigma_c > 0 \text{ MPa on Node } i ? \\
\text{YES} \\
\text{Removing x axis confinement of Node } i \\
\text{NO} \\
\text{END} \\
i = i + 1 \\
\end{align*} \]

\[ \begin{align*}
\text{START} \\
i = \text{node at middle of joint} \\
\text{Solving FE equation: } Ku = f \\
\text{END} \\
i = \text{node at top of roof ?} \\
\text{YES} \\
\sigma_c > 0 \text{ MPa on Node } i ? \\
\text{YES} \\
\text{Removing x axis confinement of Node } i \\
\text{NO} \\
\text{END} \\
i = i + 1 \\
\end{align*} \]

Fig.12 Algorithm of FE analysis for materials with bolted joint
Before loading

After loading

Step1

Step2

Step3

Step4

Step5

Step6

Table.3 Comparison between 3D and plane strain condition for FE analysis

| Conditions  | Bending stiffness (MPa・m^4) | E (MPa) | \( v \) | Load (MN) |
|------------|-----------------------------|---------|---------|-----------|
| 3D         | EI 200000                   | 0.3     | P       |
| Plane strain | EI 37100               | 0.3     | PW      |

\[
\begin{align*}
\sigma_x & = 0 \quad \text{if} \quad \sigma_x < 0 \text{MPa} \quad \text{on} \quad \Gamma_j \\
\sigma_z & = 0 \quad \text{if} \quad \sigma_z > 0 \text{MPa}
\end{align*}
\]

where \( u \) and \( \sigma_x \) are horizontal displacement and stress, \( \sigma_z \) get plus values to tensile direction. From equation (3), the weak form of equilibrium is described as equation (4) assuming virtual displacement \( \delta \mathbf{u} = 0 \) on Dirichlet boundary \( \Gamma_j \) (Souza et al., 2008).

\[
\int_{\Omega} \left( \text{div} \, \delta \mathbf{u} : \mathbf{\sigma} - \rho g \delta \mathbf{u} \right) d\Omega + \int_{\Gamma_j} \mathbf{t} \cdot \delta \mathbf{u} d\Gamma = 0
\]

where \( \mathbf{\sigma}, \rho g \) and \( \mathbf{t} \) are Cauchy stress, body force vector and traction vector. Equation (4) is discretized to finite element by Galerkin method. For \( \Gamma_j \), simple numerical algorithm using finite element equation \( \mathbf{Ku} = \mathbf{f} \) made from equation (4) developed as shown in Fig.12. Firstly, FE analysis is conducted with \( u = 0 \) on \( \Gamma_j \) by isotropic elastic body. Secondly, assuming tensile strength on joints \( \sigma_z = 0 \text{MPa} \) (Goodman, 1987), if \( \sigma_z > 0 \text{MPa} \) in \( \Gamma_j \), node confinements for \( x \) direction are sequentially released from the bottom on \( \Gamma_j \), \( \sigma_z \) at node is calculated as average values of Gauss points in the vicinity of node as both Fig.12 (b) and (c). Finally, the flow is ended by reaching the compressive stress area as Fig.7 (c). Modeling the material parameters of 3D box form roof to plane strain condition is conducted as Table.3. The bending stiffness and load \( P \) is adjust to plane strain condition. Fig.13 shows one of the results of repeated calculation algorithm. As calculation steps go to convergence, the deformation properties as shown in Fig.8 (b) are well simulated. Fig.14 shows the relationships \( P/\delta \) with \( k_n \) for FE model as shown in

\[
P/\delta = 0.06 + 9.44 \times 10^{-3} k_n
\]

Fig.13 \( \sigma_z \) distribution by repeated algorithm (i.e. case (ii))

Fig.14 The relationships between \( P/\delta \) and \( k_n \)

Fig.15 The example of simulating axial force of bolt during bending
Fig. 11 (b). One of the results of numerical simulation are demonstrated as shown in Fig. 15. Deformation behaviors of both deflection $\delta$ and aperture width $W_a$ are appropriately simulated. Furthermore, axial forces of bolts during loading, which have not ever been obtained correctly, can be obtained by proposed FE algorithm. Using this method, it may be possible to manage the torque of bolts appropriately for engineering components with bolted joints.

5 CONCLUSIONS

For safely construction of underpass tunnel with shallow earth coverings, the box form roofs are often inserted in either natural grounds or railway embankments before conducting excavation. Relaxation of grounds are decreased by these support methods, but in some cases, the box form roofs are gradually bended by both earth pressure and railway load. In order to construct underpass tunnels more safely, the deformation behaviors of the box form roof with bolted joint should be studied based on actual phenomena. On the other hand, torque management for structures with bolted joints is important topic in various engineering fields. It is strongly needed to investigate axial force of bolts during external forces acting on the structures.

In this study, several bending tests of the box form roof with bolted joints are conducted, assuming the roof deformed on joints by earth pressure. Furthermore, deformation behaviors of materials with bolted joints are modeled and FE analysis with simple algorithm for explaining its mechanical properties during bending is proposed. The results demonstrated following two main conclusions: as the torque of bolts is increased, both deflections and aperture width are decreased; from proposed FE algorithm, the axial force of bolts is appropriately obtained during bending.

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