A Prying Action Force and Contact Force Estimation Model for a T-Stub Connection with High-Strength Bolts

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Abstract

A T-stub connection with high-strength bolts under tensile force is affected by prying action force and the contact force, among others, between members. If a design equation that does not consider such prying action force and contact force between members is not proposed, the T-stub under tensile force is liable to be fractured under a strength lower than the estimated design strength. To prevent this, many studies have proposed contact force estimation equations between members as well as the prying action force of the T-stub connection with high-strength bolts. However, no design equations based on such research have been proposed in South Korea. Therefore, this study aims to propose an estimation model for more accurate prying action force and contact force, and to improve on previously proposed estimation models by implementing three-dimensional, nonlinear finite element analysis.

Keywords: prying action force; contact force; design strength; connection stiffness

1. Introduction

Bolted connections under tensile force are liable to be fractured under a strength lower than the estimated design strength due to the prying action force or contact force between members. Thus, there have been many studies on estimating such prying action force and contact force between members, which have proposed various estimation models.

Douty and McGuire (1965) estimate prying action force based on elastic analysis. In proposing an estimation model, they considered the material properties of high-strength bolts and connecting members as well as the geometric shape of connections. Similarly, Agerskov (1976) estimated prying action force based on elastic analysis. Agerskov’s estimation model considered the deformation of T-stub flanges connected with high-strength bolts and shear deformation, but did not consider non-linearity based on flange yielding. Struik and Back (1969) estimated the prying action force of connections that have generally geometric shapes based on the combination of high-strength bolts and T-stub flanges. Struik and Back’s estimation model, which is most widely used, however, offers a value larger than the prying action force acquired from the action test. Assuming that the central line of the axial bolt force moves by the contact force between members, Swanson (1999, 2002) proposed an estimation model, which improved the estimation model by Struik and Back. However, the application of the estimation model has become more complex. Jaspart and Maquoi (1995) observed the change in contact force between connection members according to bolt pretension, and showed that such a change affects the tensile stiffness of connections under tensile force. Faella et al. (1996, 1998) observed the change in contact force between connection members according to the change in the stiffness ratio (β) between the flexural stiffness of the connecting member flanges and the axial tensile stiffness of high-strength bolts, and estimated the change in the axial tensile stiffness of the connections.

This study aimed to improve the previous contact force estimation models between members and the prying action force. Toward this end, it performed the three-dimensional non-linear finite element analysis. The feasibility of the proposed estimation model was verified after a comparison and review of the analysis results of other researchers.

2. Three-Dimensional Non-linear Finite Element Analysis Modeling of Connections with High-Strength Bolts

The prying action force of the connection with high-strength bolts and the contact force between members were estimated by the three-dimensional non-linear finite element analysis. Generally, the contact effect of the members and the prying action is largest when the
The connection with high-strength bolts was modeled by ABAQUS (ver. 6.9.2). The T-stub that comprises the connection is a C3D8R (eight-node brick element with reduced integration) member element. In performing the three-dimensional non-linear finite element analysis, the effect of the contact and bearing between members as well as the pretension of the high-strength bolts were considered. The frictional coefficient between members was set to 0.5. This frictional coefficient was applied under the assumption that the faying surfaces between members are unpainted, blast-cleaned steel surfaces. The Korean Building Code (KBC2009) only provides the case of $\mu=0.5$. For high-strength bolts used in the T-stub analytical model, the horizontal movement was restrained by inserting the plate, which is 1.5 times thicker than the T-stub flange between the lower T-stub and the upper T-stub. As shown in Fig.3., the overall connection analysis model consists of a total of 40,716 elements and 55,376 nodes, and the analysis of each model lasted about 240 minutes. In modeling the connection with high-strength bolts, the applied ABAQUS options are as shown in Table 3.

Table 1. Geometric Variables of the T-Stub Analytical Model

| Analytical model | $b_1$ | $r$ | $t_r$ | $t_p$ | $g_0$ | $a$ | $b$ | $b_1$ | $p$ | $e$ | $l_1$ | $\alpha'$ |
|-----------------|-------|-----|-------|-------|-------|-----|-----|-------|-----|-----|-------|---------|
| G260-T15-B350   | 350   | 15  | 15    | 260   | 22    | 45  | 122.5| 100   | 100 | 50  | 400   | 7.58    |
| G310-T15-B400   | 400   | 15  | 15    | 310   | 22    | 45  | 147.5| 100   | 100 | 50  | 400   | 8.14    |
| G260-T19-B350   | 350   | 12  | 19    | 260   | 20    | 45  | 124  | 100   | 100 | 50  | 400   | 4.59    |
| G310-T19-B400   | 400   | 12  | 19    | 310   | 20    | 45  | 149  | 100   | 100 | 50  | 400   | 4.96    |
| G260-T21-B350   | 350   | 13  | 21    | 260   | 22    | 45  | 123.5| 100   | 100 | 50  | 400   | 3.67    |
| G310-T21-B400   | 400   | 13  | 21    | 310   | 22    | 45  | 148.5| 100   | 100 | 50  | 400   | 3.98    |
| G110-T28-B200   | 200   | 18  | 28    | 110   | 22    | 45  | 46   | 100   | 100 | 50  | 400   | 0.58    |
| G140-T28-B230   | 230   | 18  | 28    | 140   | 22    | 45  | 61   | 100   | 100 | 50  | 400   | 0.98    |
| G110-T35-B200   | 200   | 20  | 35    | 110   | 22    | 45  | 45   | 100   | 100 | 50  | 400   | 0.08    |
| G140-T35-B230   | 230   | 20  | 35    | 140   | 22    | 45  | 60   | 100   | 100 | 50  | 400   | 0.37    |

Table 2. Material Properties of the T-Stub Specimen

| $F_y$ (N/mm²) | $F_u$ (N/mm²) | $\varepsilon_y$ | $\varepsilon_u$ | $E$ (N/mm²) | $E_u$ (N/mm²) |
|--------------|--------------|---------------|---------------|-------------|-------------|
| 347.33       | 518.78       | 0.001612      | 0.094512      | 215,446.40  | 1,814.04    |
assumed that, as in Fig.5., the contact

Constraint

Finite

Tie

Table 3. ABAQUS Options for Finite Element Analysis

| Contact surface       | Command | Option                    |
|-----------------------|---------|--------------------------|
| Washer contact surface| Constraints | Tie                      |
| T-stub – T-stub       | Contact | Finite sliding            |
|                       |         | Allow separation          |
|                       |         | after contact             |
| T-stub – High-strength bolt | Contact | Finite sliding            |
|                       |         | Allow separation          |
|                       |         | after contact             |
| Nut - High-strength bolt | Contact | Small sliding              |
|                       |         | Adjust only               |
|                       |         | to remove                 |
|                       |         | over closure              |

3. Estimation of the Praying Action Force on the Connection with High-Strength Bolts and the Contact Force between Members

In the case of axial tensile force on the connection with high-strength bolts, as shown in Fig.4., Struijk and Back proposed the ratio $Q/T$, as in Eq. (7), where $Q$ is the prying action force, and $T$ is the axial tensile force. In using Eq. (7), if $\alpha'$ is larger than 1.0, that is, the connection is fractured by the plastic deformation after the flexural yielding of the flange due to the prying action force, $\alpha'$ is set to 1.0. On the other hand, if $\alpha'$ is between 0 and 1, that is, the connection is fractured by partial yielding of the flange followed by bolt failure, $\alpha'$ is set to the value directly obtained from Eq. (1).

Also, it is assumed that the prying action force is applied to the end of the flange. However, as pointed out by Kulak et al. (2001), Eq. (7) results in excessive prying action force.

$$\left( \frac{Q}{T} \right)_{\text{head & back}} = \frac{\delta a' b' (1 + \delta a') a'}{(1 + \delta a') a'}$$  \hspace{1cm} (7)

Kulak et al. proposed the axial tensile force on the high-strength bolts of the connection under tensile force, as in the following Eq. (8). The coefficient 1.6 in Eq. (8) includes the effect of prying action force.

$$k_s = 1.6 \frac{E_a}{t_s}$$  \hspace{1cm} (8)

where

$$L_s = L_{p, t} + L_{p, a} + 2L_{b} + \frac{L_{a} + L_{b}}{2}$$  \hspace{1cm} (9)

Faella et al. assumed that, as in Fig.5., the contact force between the high-strength bolt head and the connection flange at an angle of 45° would occur due to the pretension of the high-strength bolt. Also, they proposed $K_s / K_w$, the ratio of the high-strength bolt stiffness to the connection flange stiffness under such contact force, as in Eq. (10), which offers similar values to those of the equations proposed by Agerskov and Bursi (1990). In the application of Eq. (10), $K_s$ can be obtained through the application of deformability characteristics by decompression. The value, $A(z)$, used in Eq. (11) signifies the area of the T-stub flange compressed by the axial force of high-strength bolts.

$$K_s = 4.10 + 3.25 \frac{t_s}{a_0}$$  \hspace{1cm} (10)

where

$$K_s = \frac{1}{2} \int_0^{\infty} \frac{1}{E(z)} dz$$  \hspace{1cm} (11)

4. Three-Dimensional Nonlinear Finite Element Analysis Result on the Connection with High-Strength Bolts

If a connection with $\alpha' > 1.0$, linked with the high-strength bolts, is under the axial tensile force, the
A connection is fractured by plastic deformation after the flexural yielding of the flange. Whereas a connection is fractured by partial yielding of the flange followed by bolt failure if the connection with $0 < \alpha' < 1.0$. Shown in Fig. 6. is the stress distribution on the connection when the applied load reaches the reference load, which, as defined by Richard et al. (1988), is the value at which the slope of the region that shows the strain hardening symptom of the connection meeting the y-axis and the load axis. As shown in Fig. 6. (a), the flexural yielding occurs by the concentrated stress in the area, which is at a certain distance from the T-stub fillet and the area at which the end of the interior of the high-strength bolt head and the T-stub flange meet when $3.67 < \alpha' < 8.14$. On the other hand, as shown in Fig. 6. (b), the flexural yielding only occurs by the concentrated stress in the area at which the end of the interior of the high-strength bolt head and the T-stub flange meet when $0.08 < \alpha' < 0.98$. Such concentrated stress shows the plastic hinge line in a beam pattern, as predicted by Faella et al. as well as Ballio and Mazzolani (1994), and results in a fracture.

Shown in Fig. 7. is the applied load-bolt force relationship curves of the T-stub connection, resulting from the three-dimensional non-linear finite element analysis result, which shows very similar behavioral characteristics to those of the same curve from Struik and Back's test. In other words, with the increase in the applied load, the axial bolt force of the high-strength bolt also gradually increases, and after the reference load, such an increase of the axial bolt force accelerates, resulting in the failure of the high-strength bolt. Such a rapid increase of the axial bolt force of the axial bolt force on the high-strength bolt is believed to be due to the prying action effect.

According to the three-dimensional non-linear finite element analysis result, the average increase rate of the axial bolt force on the high-strength bolt due to the prying action effect is $228.2\%$ when $3.67 < \alpha' < 8.14$, as shown in Table 4., resulting in $3.282$ of the axial bolt force ratio of the high-strength bolt to the applied load. This ratio is much larger than that referred to by Eq. (8). That is, the prying action effect is excessive since each connection with $3.67 < \alpha' < 8.14$ has much thinner flange thickness and larger bolt gauge distance than the connection with $\alpha' = 1.0$. On the other hand, the average increase rate of the axial bolt force on the high-strength bolt due to the prying action effect is $11.4\%$ when $0.08 < \alpha' < 0.98$, as shown in Table 5. Therefore, the following Eq. (12) was proposed by applying a revised parameter to Eq. (7), which offered excessive $Q/T$, based on the three-dimensional finite element analysis result.
element analysis result. In addition, if the equilibrium equation \( B = T + Q \) among \( T \), the applied load, \( B \), the axial force of high-strength bolts, and \( Q \), the prying action force, is applied, the correlation between the applied load and the axial force of high-strength bolts is summarized in Eq. \((14)\). As shown in Eq. \((13)\), the above-mentioned value of 3.282 is the sum of 2.282, the average increase in the ratio of the prying action force, as summarized in Table 4., and 1.0. As shown in the following Eq. \((14)\), the tensile stiffness of high-strength bolts is summarized from the correlation between the constitutive equation on the high-strength bolts and the axial force of high-strength bolts. That is, the tensile stiffness of a couple of high-strength bolts is affected by the prying action force, as shown in Eq. \((14)\), and it is reflected in the value, 1.6, the coefficient mentioned in Eq. \((8)\). In implementing Eq. \((15)\) and Eq. \((16)\), \( a'_n \) and \( b'_n \) are defined as the distance from the central line of the axial force of the high-strength bolt to the end of the flange and the distance from the central line of the axial force of the high-strength bolt to the stem, respectively. As the load acting on T-stub increases, the stress that occurs in the shank of high-strength bolts moves from the centroid point of the shank of high-strength bolts to the right, as shown in Fig.8., showing non-uniform distribution. In this case, the axial force of high-strength bolts is assumed to be acting on the centroid point of non-uniform stress distribution. The centroid point of non-uniform stress distribution obtained from the stress distribution that occurred in the shank of high-strength bolts of each analytical model was the point that moved as much as an average of 0.3\( d_b \) from the central axis of high-strength bolts.

\[
\left( \frac{Q}{T} \right)_{\text{avg}} = R \left( \frac{\delta a'}{(1 + \delta a') a'_n} \right), \quad (12)
\]

\[
\left( \frac{B}{T} \right)_{\text{avg}} = 1 + R \left( \frac{\delta a'}{(1 + \delta a') a'_n} \right) = 1 + \left( \frac{Q}{T} \right)_{\text{avg}}, \quad (13)
\]

where

\[
R = 2.05 \text{ if } \alpha' > 1.0
\]

\[
R = 0.42 \text{ if } 0 < \alpha' < 1.0
\]

\[
k_b = \frac{2}{1 + R \left( \frac{\delta a'}{(1 + \delta a') a'_n} \right)} \left( \frac{E_d A_b}{L_s} \right) = \frac{2}{1 + \left( \frac{Q}{T} \right)_{\text{avg}}} \left( \frac{E_d A_b}{L_s} \right), \quad (14)
\]

where

\[
\alpha'_n = a + 0.3d_b, \quad (15)
\]

\[
b'_n = b - 0.3d_b, \quad (16)
\]

### Table 4. Prying Action Effect Coefficient from the T-Stub Connection Analysis Result when \(3.67 < \alpha' < 8.14\)

| Analytical model       | Average increase ratio of the axial load on high strength bolt (%) |
|------------------------|---------------------------------------------------------------|
| G260-T15-B350          | 233.2                                                         |
| G310-T15-B400          | 314.6                                                         |
| G260-T19-B350          | 197.6                                                         |
| G310-T19-B400          | 247.5                                                         |
| G260-T21-B350          | 160.6                                                         |
| G310-T21-B400          | 215.4                                                         |
| Average increase ratio | 228.2                                                         |

### Table 5. Prying Action Effect Coefficient from the T-Stub Connection Analysis Result when \(0.08 < \alpha' < 0.98\)

| Analytical model       | Average increase ratio of the axial load on high strength bolt (%) |
|------------------------|---------------------------------------------------------------|
| G110-T28-B200          | 11.8                                                          |
| G140-T28-B230          | 27.5                                                          |
| G110-T35-B200          | 1.4                                                           |
| G140-T35-B230          | 4.9                                                           |
| Average increase ratio | 11.4                                                          |
The ratio of the contact force between members to the stiffness of the connection flange and the high-strength bolt is affected by such stress distribution. According to Fig. 9., the contact force between the head of the high-strength bolt and the connection flange occurs at 9°.

As described in Table 6. and Table 7., the contact force is exerted at a stress distribution angle, which results from the finite element analysis result, and is smaller than that proposed by Faella et al. Based on such a stress distribution angle, the stiffness ratio of the connection flange to the high-strength bolt can be expressed as Eq. (17).

$$K_{v \text{pretension}} = 3.893 + 0.642 \frac{\alpha_p}{d_h}$$

(17)

Table 6. Stress Distribution Angle Resulting from the T-Stub Connection Analysis Result when 3.67 < $\alpha'$ < 8.14

| Analytical model | Angle (°) |
|------------------|-----------|
| G260-T15-B350    | 10        |
| G260-T15-B350    | 10        |
| G260-T19-B350    | 7         |
| G310-T19-B400    | 10        |
| G260-T21-B350    | 8         |
| G310-T21-B400    | 9         |
| Average angle    | 9         |

Table 7. Stress Distribution Angle Resulting from the T-Stub Connection Analysis Result when 0.08 < $\alpha'$ < 0.98

| Analytical model | Angle (°) |
|------------------|-----------|
| G110-T28-B200    | 1         |
| G140-T28-B230    | 1         |
| G110-T35-B200    | 1         |
| G140-T35-B230    | 2         |
| Average angle    | 1         |

The feasibility of the application of Eq. (12), the proposed estimation of the prying action effect, was assessed by comparing and reviewing the result from that of the T-stub analysis, in Fig. 10., which was conducted by Hantouche (2011). In the development of Hantouche's model, a normalizing factor $\beta^*$ was used to relate the primary prying strength model to the primary prying finite element model. That is, in order to estimate the prying action effect, the normalizing factor $\beta^*$ should be obtained by performing a finite element analysis for each connection. The test performed the three-dimensional non-linear finite element analysis again by applying the identical geometric shape, material properties, boundary conditions, and loading conditions to the T-stub finite element analysis model by Hantouche, shown in Fig. 10.(a) and 10.(b). The stress distribution of the T-stub model, resulting from the re-performed finite element analysis, is shown in Fig. 11. As shown in Fig. 12., the prying action effect of the high-strength bolt, resulting from the re-analysis of the T-stub by Yang, offers a very similar prying action effect to that of the high-strength bolt by Hantouche. Although Yang's analysis model showed a slightly larger Q/T value than Hantouche's analysis model for the W24x76 analysis model, the Q/T from Yang's analysis model offered a value close to that of Hantouche's analysis model. Therefore, it is determined that using Yang's analysis model is feasible. In addition, it is much easier to estimate the prying action effect of a connection since Yang's analysis model does not need to use the normalizing factor $\beta^*$. The normalizing factor $\beta^*$ can only be obtained by performing a complex finite element analysis.

$$K_{t} = K_{d} + \left( K_{p} \right)_{\text{pretension}}$$

(10)

$$m_{Yang} \begin{cases} a_1 = m_{Yang} a_1 \\ b_1 = b_1 \end{cases}$$

(12)

$$m_{Yang} \begin{cases} a_2 = a_2 \\ b_2 = b_2 \end{cases}$$

(13)

$$m_{Yang} \begin{cases} a_3 = a_3 \\ b_3 = b_3 \end{cases}$$

(16)

$$m_{Yang} \begin{cases} a_4 = a_4 \\ b_4 = b_4 \end{cases}$$

(17)
5. Conclusion

This study aimed to offer an improved analysis model that could estimate the prying action force of the T-stub connection with high-strength bolts under tensile force, as well as the contact force between members. The study resulted in the following conclusions:

1) Based on the three-dimensional non-linear finite element analysis, the ratio of the axial force on the high-strength bolt to the applied load by the prying action effect is 3.282 when $3.67 < \alpha' < 8.14$. Hence, it is recommended that the coefficient referred to by Eq. (8) is set to 0.609 for a connection with $3.67 < \alpha' < 8.14$.

2) The three-dimensional non-linear finite element analysis result showed that the contact force is delivered at a maximum angle of 9º, the angle of the stress distribution between the head of the high-

Table 8. Comparison of the Analysis Result by Hantouche and the Analysis Model (With Continuity Plates)

| Analytical model | $t_c/t_{tf}$ | $\left( \frac{Q}{T} \right)_{Yang}$ (%) | $\left( \frac{Q}{T} \right)_{Hantouche}$ (%) | Differences (%) |
|------------------|--------------|----------------------------------------|-------------------------------------------|-----------------|
| W24x76           | 0.67         | 36.65                                  | 11.87                                     | 24.78           |
| W30x108          | 0.6          | 30.28                                  | 31.32                                     | 1.04            |
| W36x150          | 0.72         | 23.69                                  | 22.09                                     | 1.60            |

Table 9. Comparison of the Analysis Result by Hantouche and the Analysis Model (Without Continuity Plates)

| Analytical model | $t_c/t_{tf}$ | $\left( \frac{Q}{T} \right)_{Yang}$ (%) | $\left( \frac{Q}{T} \right)_{Hantouche}$ (%) | Differences (%) |
|------------------|--------------|----------------------------------------|-------------------------------------------|-----------------|
| W24x76           | 0.67         | 36.65                                  | 19.85                                     | 16.80           |
| W30x108          | 0.6          | 30.28                                  | 40.70                                     | 10.42           |
| W36x150          | 0.72         | 23.69                                  | 39.63                                     | 15.94           |
strength bolt and the connection flange, which is smaller than the angle proposed by Faella et al.

3) As shown in Table 8. and Table 9., in estimating Q/T of the T-stub, Yang's analysis model offered a closer value to the actual test than Hantouche's analysis model did. Therefore, it is determined that estimating Q/T of the T-stub by using Yang's analysis model is valid.

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List of Nomenclatures

| Symbol | Description |
|--------|-------------|
| d₁  | Diameter of the bolt |
| d²  | Diameter of the bolt hole |
| kₜ | Axial tensile stiffness of the bolt |
| r  | Radius of the fillet of the T-stub |
| B₀  | Bolt pretension force used in the T-stub |
| B  | Bolt force developed by the applied load |
| E  | Young's modulus of steel |
| Eₛ | Secant modulus of steel |
| Fᵧ  | Yield strength of steel |
| Fᵤ  | Ultimate strength of steel |
| Q  | Prying action force of the T-stub |
| T  | Load applied to the T-stub |
| T₀  | Reference load of the T-stub |
| a  | Value that either maximizes the bolt's available tensile strength for a given thickness or minimizes the thickness required for a given bolt's available tensile strength |
| εᵧ  | Yield strain of steel |
| εᵤ  | Ultimate strain of steel |

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