Testing and modeling of dowel action for a post-installed anchor subjected to combined shear force and tensile force

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A R T I C L E   I N F O

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A B S T R A C T

In seismically active regions, the resistance of buildings against earthquakes must be improved. Post-installed anchors are generally used to connect retrofitting members to existing concrete members of a structure. However, research on the mechanical behavior of post-installed anchors subjected to combined shear and tensile stress is insufficient. Therefore, in this study, loading tests were conducted on anchor bolts by applying cyclic shear loading and constant tensile forces. Additionally, a mechanical model was constructed to evaluate the experimental results. In this model, the shear force was equal to the sum of the bending resistant force at the plastic hinge, the supporting stress of the concrete, and the shear component of the tensile stress of the anchor bolt. The results demonstrate that, with increasing tensile force, the shear force decreases and the joint separation increases. In addition, the proposed model was shown to reasonably replicate the shear load and slip relationship determined from experimentation results.

1. Introduction

In seismically active regions, seismic retrofits are often used to improve the resistance of buildings against earthquakes. Commonly, retrofitting is achieved by connecting strengthening members to existing members of a structure by using post-installed anchors. During an earthquake, these anchors distribute the shear stress by dowel action and catenary action in the reinforced concrete structures [1], therefore post-installed anchors are very vital elements.

Although the retrofitting members are typically internally connected within an existing structure, the method of externally connecting them is gaining popularity. Fig. 1 shows an image of an external seismic retrofit. The main advantage of an externally connected seismic retrofit, as opposed to its internally connected counterpart, is that the construction will not obstruct the internal functions of the building. At the joints of such structures, a tensile force is caused by bending moments acting between the existing and expanding frames. Therefore, the joints of the structures with externally connected retrofits are subjected to both shear and tensile forces. However, it is thought that the vertical loading slightly affects the shear strengths of the post-installed anchors, but this paper focuses on the shear behaviors as an early step in the investigation of the anchors.

Distribution of the shear stress of reinforced bars in concrete occurs by dowel action. Since Friberg’s study on dowel action in the 1930s [2], many researchers have studied this topic [1,3–12], with most studies primarily focusing on the linear elastic models of one-sided dowel action. Recently, a nonlinear dowel model was proposed by Sorensen [1], and a dowel model was implemented in finite element analysis by He [11]. Although Soltani and Maekawa proposed the model under coupled cyclic shear and pull out tension for a reinforcing bar, in this model, catenary action was not taken into account [12].

As previously mentioned, because externally connected post-installed anchors are subjected to a combined shear/tensile force, it is important to understand the mechanical behavior of post-installed anchors. However, despite its significance, only a few studies have focused on the mechanical behavior of post-installed anchors. Shirai conducted an experimental study on post-installed anchors subjected to transverse diagonal loading [13]. However, the tensile and shear forces were considered, the findings of that study do not adequately describe the mechanical behavior.

The author previously conducted several fundamental tests related to the dowel action of post-installed anchors subjected to pure shear force, and tried to construct a fundamental model [14]. Building on the previous study, in the current study, shear loading tests were conducted on post-installed anchors subjected to constant tensile force as based on the optimized design of dowel action in the external connection of the anchors. Moreover, a mechanical model was proposed in this study to estimate the relationship between shear load and slip under a combined force. In this model, the both dowel action and catenary action were taken into account.
2. Experimental program

Fig. 2 shows the mechanism of shear-stress transfer in a post-installed anchor subjected to combined force. In this section, the experimental program is described.

2.1. Test parameters

Table 1 shows the individual characteristics of 13 specimens tested in this paper. The experimental parameters include a diameter $\phi$, a concrete compressive strength $f_c$, and tensile stress on the anchor $f_N$. The diameters of the deformed bars used as anchor bolts are 13 mm, 16 mm, and 19 mm. $f_c$ is set as 10, 20, and 30 N/mm², as is common in older buildings, and $f_N$ is set as approximately 0, 0.33 $f_y$, and 0.66 $f_y$ N/mm², where $f_y$ is the yield strength of the anchor bolt. Because of a lack of specimens, those with an $f_c$ of 10 and 30 N/mm² were only tested at $f_N = 0$ and 0.56 $f_y$ N/mm². Subsequently, the tensile stress ratio $\eta = f_N / f_y$ is used as the index instead of $f_N$.

The specimens were named according to their specifications; the number that follows the first letter D indicates the diameter $\phi$, followed by the parameter values for $\eta$ and $f_c$.

Table 2 outlines the material properties of the concrete and the mortar, and Table 3 shows those of the anchor bolts.

$\phi$: Diameter of anchor-bolt, $\eta$: Tensile force ratio, $f_c$: Designed concrete compressive strength.

2.2. Test specimens

Fig. 3 shows details of the specimens. Table 2 outlines the material properties of the concrete and the mortar, and Table 3 shows those of the anchor bolts.

The specimens used to model the existing members are 440 mm × 400 mm × 250 mm reinforced concrete blocks, and those used to model the supporting members are...
350 mm × 170 mm × 160 mm grouting mortar blocks with reinforcing bars of φ = 10 mm. Post-installed anchors were adhered to the concrete blocks, and the grouting mortar blocks were constructed around them. Normal-weight concrete was used to cast the specimens.

The joining surfaces between the concrete and grouting mortar were greased in order to minimize the effects of friction. To connect the post-installed anchors, a rotary hammer was used for drilling, and injectable epoxy adhesives were applied for anchoring.

2.3. Loading and measurement method

Fig. 4 shows the loading setup, and the measurement method is illustrated in Fig. 5. The test specimens were subjected to a cyclic shear force and a constant tensile force from the loading equipment shown in Fig. 4. The two hydraulic jacks and one center-hall jack were used to apply shear loading and tensile loading, respectively, and the test specimens were fixed to the reaction beam and loading beam. The loading beam was attached to the loading frame by using a pantograph, thereby enabling horizontal displacement during shear loading.

Note that the slip δ and the separation ω are the average values of the relative horizontal displacement and the vertical displacement, respectively. In addition, the loading cycle is illustrated in Fig. 6.

3. Experimental results

3.1. Relationship between tensile force ratio and shear force ratio

Ordinarily, when the combined stresses of steel are calculated, the von Mises stress is often applied. Moreover, this stress is only applied under the condition of simple shear and normal stress. However, because the stress field of the tests performed in this study was significantly more complex, a strength formula, such as that given as Eq. (1), that is generally applied to structural designs subjected to combined force was used.

\[
\frac{T}{T_0} + \frac{Q}{Q_0} = 1
\]

where \( T_0 \) and \( Q_0 \) are the specific tensile strength and shear strength of an anchor bolt, respectively, and \( T \) and \( Q \) are the tensile force and shear force, respectively, that are allowed under a combined stress. \( \alpha \) is an experimental coefficient that generally takes a value between 1 and 2.

\[
T_0 = a_t \times f_y
\]

where \( a_t \) is the cross-sectional area of an anchor bolt.

A shear strength formula for an anchor bolt can be used to determine \( Q_0 \). However, these formulas can considerably differ from test results. Therefore, the shear force \( Q \) obtained from testing with \( r_N = 0 \) is used instead of \( Q_0 \) to solve Eq. (1). Using this value, the results of the specimens with \( r_N = 0 \) can be directly compared to those of the specimens under tensile stress.

Fig. 7 shows the relationship between \( T/T_0 \) and \( Q/Q_0 \) that was obtained by way of loading testing for \( \delta = 0.25, 0.75, 1.0, 2.0, 3.0, \) and 4.0 mm. The test results revealed \( \alpha \) ranged from 0.75 to 1.5. Specifically, a smaller slip, i.e., \( \delta = 0.25-0.75 \), yielded an \( \alpha \) value ranging from 0.5 to 1.0, whereas, a slip larger than \( \delta = 1.0 \) yielded an \( \alpha \) range of 1.0–1.5.

3.2. Relationship between separation and slip

Fig. 8 shows the relationship between separation \( \omega \) and slip \( \delta \). It is evident that \( \omega \) increased with increasing tensile force. As an example, in the case of \( r_N = 0 \), \( \omega \) remained at a value of less than 1 mm, even for \( \delta = 6 \) mm. However, for \( r_N = 0.33 \) and \( r_N = 0.56-0.66 \), \( \omega \) was observed to exceed 1 mm before the slip \( \delta \) reached a value of 2 mm. Furthermore, because the average separation \( \omega \) of the second step was larger than that of the first step, it is essential that the number of loading cycles be considered. Additionally, the remaining separations of specimens with \( r_N = 0.33 \) and \( r_N = 0.56-0.66 \) were found to be larger than those with
\( n_f = 0 \). The resulting separation tendency of specimens with \( \phi = 16 \text{ mm} \) and \( 19 \text{ mm} \) was found to be similar to that of a specimen with \( \phi = 13 \text{ mm} \). It should also be noted that the amount of separation was also comparable to the diameter of the anchor bolts, and that the influence of the concrete compressive strength on the amount of separation was small.

### 4. Proposed model

To realize the aim of this study, which was to construct a mechanical model of an adhesive post-installed anchor subjected to a combined force, a mechanical model that considers the following two failure modes of post-installed anchors is proposed: (i) the yielding of the anchor bolt and (ii) the supporting failure of concrete. This chapter describes the proposed model in detail.

#### 4.1. Equilibrium of shear force

Fig. 9 illustrates how dowel action was modeled for a post-installed anchor. When the displacement is small, it is possible to apply the elastic beam theory to a post-installed anchor. However, because elastic beam theory cannot be extended to the case in which the anchor bolt or concrete is within its plastic range, the model shown in Fig. 9 has been proposed to better describe the behavior in a nonlinear zone.

To construct the proposed model, the plastic behavior of the anchor bolt at the bending point (the hinge) was initially calculated. Because it was assumed that the anchor bolt deforms in a linear manner about the plastic hinge, the supporting stress must act on the concrete. Additionally, the modeled anchor bolt tended to elongate between the concrete surface and plastic hinge, thereby making the anchor bolt subject to tensile stress with a significant shear component. As was mentioned above, when \( r_s = 0 \), the shear force \( q_s \) equates to the sum of (i) the bending moment of the plastic hinge \( q_s \), (ii) the supporting stress of the concrete \( q_c \), and (iii) the shear component of the tensile stress of the anchor bolt \( q_{e_1} \) by catenary action.

\[
q_s = q_c + q_b + q_{e_1}
\]  

In addition, the shear force when the anchor bolt is subjected to tensile force is expressed as is described in the following equation, which is derived from Eq. (1):

\[
q = \frac{1}{2} \left( 1 - \left( \frac{T}{T_a} \right)^2 \right) q_s
\]

Here, \( a \) is set to 1 from the test results.

#### 4.2. Depth of plastic hinge

As was mentioned in the Section 4.1, the depth of plastic hinge \( L_a \) is needed to calculate, because \( L_a \) influences the three components of the shear force. According to the elastic beam theory, the depth of the largest moment \( L_M \) can be calculated as follows:

\[
L_M = \frac{4}{3} \frac{1}{E_x} \frac{L}{k \times \phi}
\]

where \( k \) is the supporting stiffness of the concrete and \( L_c \) is the second section moment of the anchor bolt.

However, when concrete is in its plastic range, \( k \) is relatively small. This means that, within this range, the small \( k \) causes \( L_M \) to be relatively larger. Therefore, the following equation, which takes three-halves of \( L_M \), is implemented as \( L_a \) in the proposed model.

\[
L_a = \frac{3}{8} \frac{1}{E_x} \frac{L}{k \times \phi}
\]

Then, \( k \) is obtained by solving the equation below, which was derived in a previous study [12].

\[
k = 150 \frac{f_c}{\phi}
\]

where \( f_c \) is the compressive strength applied on the concrete (N/mm²).

#### 4.3. Supporting stress of concrete

The concrete strain around an anchor bolt is influenced by the deformation of the anchor bolt. Assuming that the anchor bolt linearly deforms about the plastic hinge, the displacement \( \delta(x) \) is described as follows.

\[
\delta(x) = \frac{\delta(0)}{L_a} x \quad \text{for} \quad 0 \leq x \leq L_a
\]

\[
\delta(x) = 0 \quad \text{for} \quad L_a < x
\]

where \( x \) is the depth from the joint surface.

Although concrete strain is considered to be the highest near the anchor bolt, and thus decreasing with increased distance from the anchor bolt, it is difficult to provide evidence of this phenomenon. In this study, the concrete strain is described as the average strain.

\[
\epsilon_a(x) = \frac{\delta(x)}{L_a}
\]
where $L_{eb}$ is the effective length used to calculate the concrete strain; $L_{eb}$ was set as $5\phi$.

The supporting force of the concrete $q_b$ was calculated by multiplying the circumference of the semicircle of the anchor bolt by the integral of the supporting stress from $x = 0$ to $x = L_h$.

$$q_b = \frac{\pi \phi}{2} \int_0^{L_h} f_b(x) \, dx$$

(11)

4.4. Tensile stress of anchor bolt

When the anchor bolt deforms about the plastic hinge, it is stretched between the hinge point and the concrete surface by catenary action. The increase in length $\Delta L_{th}$ is expressed as follows:

$$\Delta L_{th} = \sqrt{\delta_h^2 + L_h^2} - L_h$$

(12)

$$\Delta \sigma_{th} = \Delta L_{th}/L_h$$

(13)

As is given in Eq. (13), $\Delta L_{th}$ is used to determine the increasing...
Here, $\delta_y$, that is the displacement when $q_L = q_L$, is set to 0.75 mm.

(2) Supporting Stress of Concrete

Since the supporting stress is related to the local compressive stress in the concrete, the previous constitutive laws of compressive stresses can be applied to the supporting stress up to the level of the maximum stress [17].

$$f_s = \frac{E_{0b} \varepsilon_0}{1 + \left( \frac{E_{0c}}{E_{bc}} - 2 \right) \left( \frac{\varepsilon_0}{E_{0c}} \right) + \left( \frac{\varepsilon_0}{E_{bc}} \right)^2}$$

(17)

Additionally, the maximum supporting stress exceeds the maximum compressive stress $f_s$. Fisher et al. proposed the design shear strength formula for stud bolts on the basis of the root of the supporting stress $f_{bc}$ by using the fourth root of $f_s$:

$$f_{bc} = \frac{20}{3} \sqrt[4]{f_s}$$

(18)

After the maximum stress, the stress is slowly reducing because the concrete subjected to supporting stress is restrained. In this model, stress softening is considered, with an experimentally determined modulus that is 1% of the Young’s modulus.

Fig. 10(c) shows the behavior during unloading and reloading. An unloading curve is expressed as a parabolic function through Point Z [19] in Fig. 10(c). $\varepsilon_Z$ is the strain at Point Z, which is obtained by subtracting 0.5% of $\varepsilon_{bc}$ from $\varepsilon_Q$.

The reloading curve is expressed as a linear function through Points R and C. $\varepsilon_R$ is the strain at Point R, and $f_C$ is the stress at Point C. These strain [19] and stress values can be respectively determined as follows:

$$\varepsilon_R = \left[ 0.143 \left( \frac{\varepsilon_C}{\varepsilon_{bc}} \right)^2 + 0.127 \left( \frac{\varepsilon_C}{\varepsilon_{bc}} \right) \right] \varepsilon_{bc}$$

(19)

$$\varepsilon_C = \left[ \frac{\varepsilon_Q}{\varepsilon_{bc}} - 2.828 \right] \varepsilon_{bc}, \text{ for } \varepsilon_C \geq 4 \times |\varepsilon_0|$$

(20)

$$f_C = \frac{5 f_s}{6}$$

(21)

$\varepsilon_{bc}$ is the strain at the peak point. Eq. (21) is applied to this model to simply reproduce the reloading path obtained in previous test results under cyclic compressive loading [20].

(3) Tensile Stress of Anchor bolt by catenary action

The resulting behavior of a bilinear anchor bolt model under a tensile stress is shown in Fig. 10(d). Additionally, the behavior of $L_{br}$ subjected to cyclic loading is illustrated in Fig. 10(e). During unloading, the strain of the anchor bolt was reduced until $f_{br} = 0$. Furthermore, after the slip was reversed, the strain was found to increase again as described by Eqs. (12) and (13).

5. Adaptability of proposed model to experimental results

Fig. 11(a)–(m) shows the comparison of the results of shear load—slip relations ($Q - \delta$ curves) obtained through experimentation and analysis.

Under the condition of actual loading, the anchor-bolt deformation occurs on the grouting mortal side. This fact must be considered. In this study, the anchor-bolt deformation was modeled as deformation of a rigid body, because the grouting mortal stress at the joint is considerably higher than that of the concrete on the exiting side.

According to Fig. 11, a larger anchor-bolt diameter results in a larger shear force $Q$. Additionally, increasing the tensile stress ratio $\tau_T$ causes the shear force $Q$ to decrease.

The results of specimens D13-T000-20 (Fig. 11(a)) and D16-T000-
20 (Fig. 11(f)) demonstrate that the proposed model estimates a maximum force that is slightly less than that obtained during testing. However, beyond $\delta = 1$ mm, the behaviors are predicted reasonably well. In contrast to these two specimens, the analytical stiffness of the model was found to be higher than that observed in the test results for D19-T000-20. Nevertheless, the test behavior observed beyond $\delta = 1$ mm for D19-T000-20 was appropriately evaluated by the model.

The test results of the specimens subjected to a tensile force, as illustrated in Fig. 11(b, c, e, g, h, j, l, and m) were also observed. For the specimens with $r_S = 0.33$, the test and analytical results were found to be in agreement. However, the analytical results are moderately lower than the corresponding test results for the specimens with $r_S = 0.66$. This tendency is especially apparent for D19-T066-20, as it is clearly depicted in the positive loading shown in Fig. 11(m). In this model, the phenomenon that the shear force is reduced in response to increasing tensile force is described in Eq. (4). However, although this model is useful and simple, it is not stringent. The accuracy of the model can be improved by increasing the amount of strain applied to the anchor bolt and decreasing the supporting stress of concrete under a combined force.

As was mentioned above, because the proposed model can accurately evaluate the overall mechanical behavior of post-installed anchors during unloading and reloading, it is expected to be useful in various fields of engineering, such as in the field of seismic design and analysis.

6. Conclusions

Shear loading tests were conducted in this study on concrete specimens subjected to cyclic shear force and constant tensile force. Additionally, a mechanical model was proposed for a post-installed anchor used in seismic retrofitting. In this model, the shear force is equal to the sum of the bending resistant force $q_s$, the supporting stress of concrete $q_r$, and the shear component of the tensile stress $q_T$. The findings of this study are summarized as follows:

(1) With increasing tensile force, the shear force decreases and the joint separation increases.
(2) Setting $\alpha = 0.75–1.5$ (Eq. (1)) yielded an estimation of the relationship between $T/T_a$ and $Q/Q_a$ that is in agreement with the testing results.
(3) By setting $\alpha = 1$ in Eq. (4), the proposed model can predict test results reasonably well.
(4) This model proposed the respective mechanical behaviors of $q_s$, $q_r$, and $q_T$ under cyclic loading. Moreover, the proposed model reasonably estimates the cyclic behavior of post-installed anchors.
(5) The proposed model is useful for evaluating the shear force–slip relations of post-installed anchors subjected to a combined force.

Future work will focus on improving the model by considering the stress–slip behavior of bond adhesives, and the separation of joints. In addition, it is thought that the reinforcement ratio and the vertical loading in a structure affect the dowel action. The author will also
investigate these effects in future research.

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**Appendix A. Supplementary material**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.engstruct.2019.05.086.

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