Development of Shear-key Consisted of Steel Disk and Anchor Bolt for Seismic Retrofitting

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SUMMARY:
Seismic retrofitting is so important to ensure the safety of seismic vulnerable buildings. In order to achieve the effect of the seismic retrofitting, it is essential to connect the strengthening members to existing structures rigidly. Therefore the new shear-key consisted of steel disk and anchor bolt was developed. In this paper, some shear loading tests were conducted to investigate the structural characteristic of proposed shear-key. As the result, it was found that this shear-key has high shear strength and high shear stiffness. Furthermore, the estimation formula of the shear strength was proposed and test results were estimated by the proposed formula reasonably.

Keywords: Seismic retrofitting, Post-installed anchor, Shear-key, Bearing stress

1. INTRODUCTION

Earthquake disaster prevention is so important in Japan in where huge earthquakes often occur. Seismic retrofitting is one of methods for reduction of earthquake risk. During earthquake, shear force is transferred form existing structures to the strengthening members through joint elements, for example post-installed anchors, shear-keys and so on. To achieve the effect of the seismic retrofitting, it is essential to connect seismic retrofitting members to existing structures rigidly. Generally, post-installed anchors are used as joint elements. In such a structures, shear stress is transferred by the dowel action of post-installed anchors. For using post-installed anchor, it is needed to be embedded deeply. But, being steel frames into the existing columns or beams, post-installed anchors may not be able to be used. In addition, shear load come to the maximum strength in large slip deformation which is more than 5mm in previous studies. In other words, it is difficult to connect rigidly by post-installed anchor in some conditions.

Thus, a joint element which has high shear strength and high stiffness despite short embedded length had been demanded. In this paper, the new shear-key consisted of steel disk and anchor bolt was developed. This shear-key is called “Disk shear-key”. To investigate the characteristics of Disk shear-key, the shear loading tests was conducted. Furthermore, the strength formula of Disk shear-key is essential to be used for structural design. Hence, the strength formula which could estimate the test results was constructed. In this paper, the results of the shear tests and details of the proposed strength formula are reported.

2. OUTLINE OF SHEAR-KEY

Fig. 1. shows details of Disk shear-key and the application method for indirect joints. Disk shear-key is consisted of the steel disk, the anchor bolt, the high nut and the connecting bolt. The diameter of the steel disk is 90mm and the height is 42mm. The steel disk has a circular limb of which height is 19mm. The circular limb is embedded in existing concrete and resist bearing stress from the existing concrete. The anchor bolt is used due to resisting rotational moment by the bond stress of cements. The connecting bolt is attached to the anchor bolt through the high nut. During earthquake, shear force is transferred by truss mechanism formed between the connecting bolt and the stud bolt.

3. OUTLINE OF SHEAR LOADING TEST

3.1 Test parameters

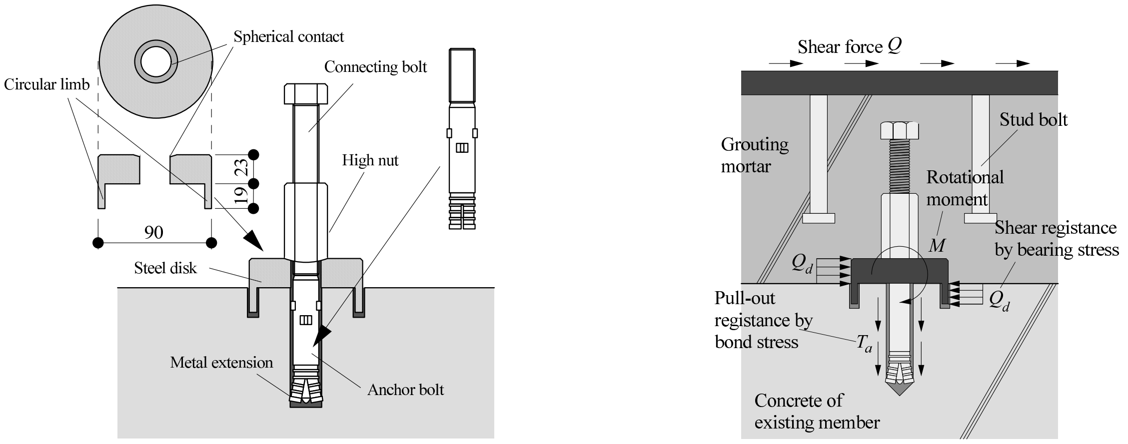
Table 1. shows the details of the specimens for the shear loading tests. It is considered that shear strength of Disk shear-key is influenced by the concrete strength, the bearing area and the embedded length of anchor bolt. Therefore, the embedded length is set to 4.5*da*(*da* is the diameter of anchor bolt), 7*da*, and 9*da*. The concrete design strength is set to 15, 21 and 36 N/mm^2. The specimen width was set to 250, 350, 450 and 600mm. The diameter of anchor bolt of all specimens are 20mm. The name of specimens are consisted of the numerical values indicated the concrete strength, the width and the embedded length. Specimen M30-60-4.5-s is only scale-down size.

3.2 Specimen dimension

Fig. 2. shows the specimen dimension. The Specimen is full scale except specimen M30-60.4.5-s. All specimens are rectangular, 400mm in height, 1300mm in length. The specimen widths are 250, 350, 450 and 600mm based on the test parameter. Two Disk shear-keys are placed in one specimen. Each Disk shear-key is subjected to shear toward the outside.

3.3 Loading and measurement

Fig. 3(a). shows the setup of the shear loading test. Fig. 3(b). shows details of the loading plate. The steel frame with a hydraulic jack is tightened to the specimen by prestressing bar. Disk shear-key is subjected to shear load through the loading plate shown in Fig.3(b). By inserting a PTFE sheet between the specimen and the loading plate, friction force between them are reduced. The measurement values by load cell



(a) Component of Disk shear-key (b) Indirect joint of using disk shear-key

Figure 1. Details of Disk shear-key and application method for indirect joint

Table 1. Details of specimens of shear loading tests

Specimen	Width (mm)	σ_B (N/mm^2)	E_c (kN/mm^2)	L_e (mm)
M15-45-4.5	450	17.0	19.4	90
M21-25-4.5	250	23.4	23.6	90
M21-35-4.5	350	23.4	23.6	90
M21-45-4.5	450	23.4	23.6	90
M21-60-4.5	600	23.4	23.6	90
M36-25-4.5	250	37.8	26.8	90
M36-45-4.5	450	37.8	26.8	90
M15-45-7	450	17.0	19.4	140
M21-25-7	250	23.4	23.6	140
M21-45-7	450	23.4	23.6	140
M21-60-7	600	23.4	23.6	140
M21-25-9	250	23.4	23.6	180
M36-25-9	250	37.8	26.8	180
M36-45-9	450	37.8	26.8	180
M30-60-4.5-s	600	33.0	28.3	45

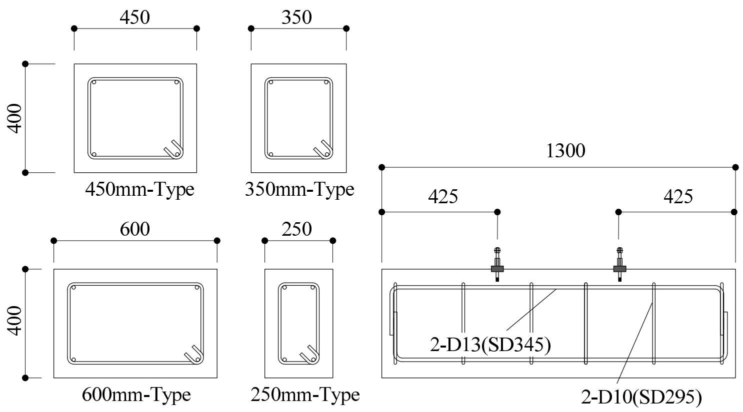
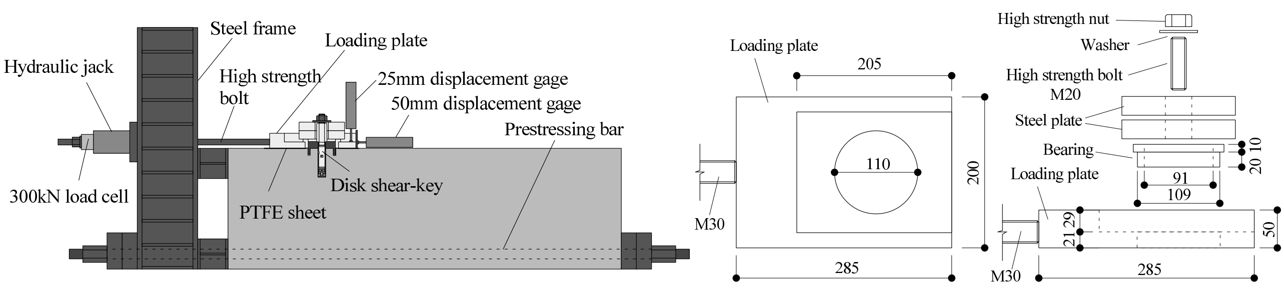


Figure2. Specimen dimension



(a) Loading apparatus

(b) Loading plate

Figure 3. Setup of shear loading test

attached to the hydraulic jack are regarded as the shear load Q. The slip between the specimens and the loading plate is measured at two points. Average of these slip is regarded as the shear displacement δ. In addition, the vertical displacement of the loading plate is measured for reference.

4. TEST RESULTS

4.1 Failure mode

The example of the failure mode is shown in Photo 1. In the most specimens, it was observed that concrete was crushing on the side of the steel disk. Thus, the maximum shear strength is considered to be dependent on the bearing failure of concrete on the steel disk side. In addition, it was afraid that Disk shear-key failed in ply out in the case of short embedded length: $L_e = 4.5\ da$. But, such a failure mode was not observed, the ductile behavior was confirmed.

4.2 Relations of shear load and displacement

It was pointed that an allowable slip deformation was 2mm for PCa structures(Nakano and Matsuzaki 2001). Therefore, this suggestion is considered to be applied to seismic retrofitting structures. Thus, Q_{2mm} is defined as the maximum strength which is obtained up to 2mm. This is the one of the important evaluation index for knowing the characteristics of joint elements. Table 2. shows test results. Q_{2mm} are range from

Table 2. Test results

Specimen	Q_{max} (kN)	δ_{max} (mm)	Q_{2mm} (kN)	Q_{2mm}/Q_{max}
M15-45-4.5	102.64	2.06	102.43	0.998
M21-25-4.5	107.52	1.11	107.52	1.000
M21-35-4.5	144.91	2.41	140.04	0.966
M21-45-4.5	142.88	2.05	142.68	0.999
M21-60-4.5	143.69	2.72	137.80	0.959
M36-25-4.5	132.11	1.59	132.11	1.000
M36-45-4.5	175.20	2.15	173.78	0.992
M15-45-7	122.76	3.37	106.91	0.871
M21-25-7	156.00	3.04	148.57	0.952
M21-45-7	154.87	2.32	139.43	0.900
M21-60-7	167.07	2.81	154.87	0.927
M21-25-9	167.07	2.59	163.82	0.981
M36-25-9	185.77	2.55	181.00	0.974
M36-45-9	189.22	1.97	189.00	0.999
M30-60-4.5-s	49.05	3.96	48.26	0.984

(a) Specimen M21-35-4.5

(b) Specimen M21-35-7

Photo 1. Example of failure mode

100kN to 190kN except specimen M30-60-4.5-s. The shear strength of a normal cemented anchor is about 50kN where da=16mm,σ_y=295N/mm^2. Therefore, the strength of Disk shear-key is two to four times of normal cemented anchor. In the most specimens, more than 90% of maximum strength Q_{max} are obtained up to δ = 2mm. As these results, it is considered that Disk shear-key has high shear stiffness.

Subsequently, load - displacement(Q- δ) relations is shown in Fig. 4. Results of specimens of L_e=4.5da are shown in Fig. 4(a). and (b). In the most specimens in Fig. 4(a). and (b)., the peak points are observed when δ is around 2mm and the shear load are moderately-sftening in the post peak behavior except specimen M21-25-4.5. In this specimen, both of the width and the embedded length are the shortest of all specimens. Due to these conditions, it is considered that the slightly brittle behavior was observed in specimen M21-25-4.5.

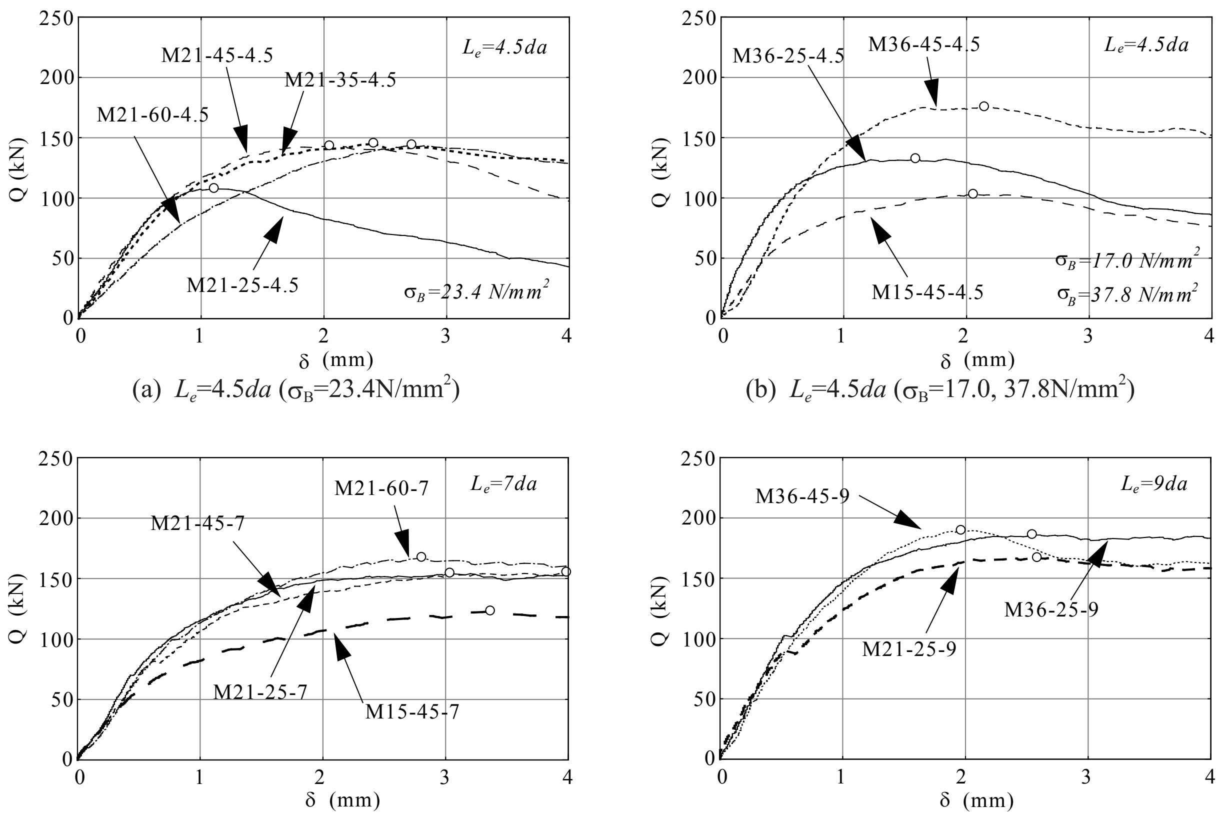
Results of specimens where L_e=7.0da and specimens where L_e=9.0da are shown in Fig. 4(c). and (d). respectively. The peak points in these figures are observed when δ is around 2mm as well as Fig 4(a). and (b). In all specimens, shear load are moderately-sftening in the post peak behavior. Being length L_e embedded more than 7.0da, the shear load is not decreased exponentially in the post peak behavior in spite of both of the width and the embedded length.

4.3 Relations of shear strength Q_{2mm} and test parameters

Eqn. 5.1. was proposed as the shear strength of stud bolt (Fisher et al. 1971).

$$Q_S = 0.5 \cdot A_S \cdot \sqrt{E_C \cdot \sigma_B} \tag{4.1}$$

According to Eqn. 5.1., the shear strengths are dependent on $\sqrt{E_C \cdot \sigma_B}$. Therefore, it is possible that the shear strength of Disk shear-key is also dependent on $\sqrt{E_C \cdot \sigma_B}$. Fig. 5 (a) shows relations of Q_{2mm} and



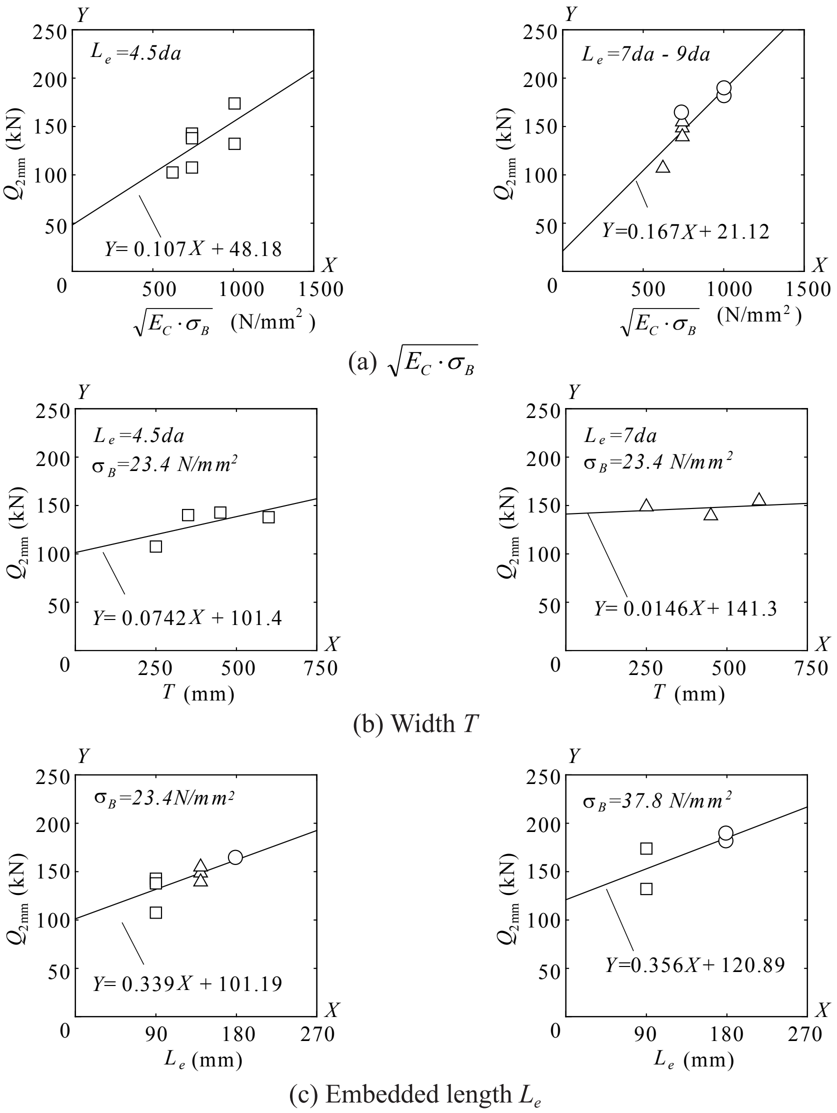
(a) L_e=4.5da (σ_B=23.4N/mm^2)

(b) L_e=4.5da (σ_B=17.0, 37.8N/mm^2)

(c) L_e=7.0da

(d) L_e=9.0da

Figure 4. Load - displacement(Q - δ) relations



(a) $\sqrt{E_C \cdot \sigma_B}$

(b) Width T

(c) Embedded length L_e

Figure 5. Relations of shear strength Q_{2mm} and test parameters

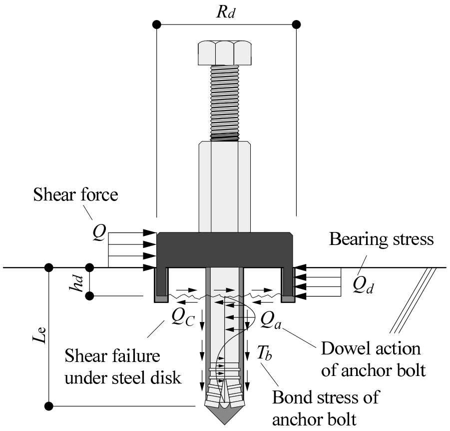
$\sqrt{E_C \cdot \sigma_B}$. It is obvious that the shear strength is dependent on this function. The regression coefficient in the case of L_e=9.0*da* and 7.0*da* are greater than the case of L_e=4.5*da*. Because the action of pull out of the anchor bolt was smaller by being embedded deeply, it was considered that the effect of $\sqrt{E_C \cdot \sigma_B}$ appeared clearly.

The relations of Q_{2mm} and the width is shown in Fig.5(b). This figure illustrates that Q_{2mm} was influenced on the width in the case of L_e=4.5*da*. But, Q_{2mm} of the specimens of which the embedded length were 7.0*da* are not influenced as much as the specimens of L_e=4.5*da*. Moreover, the relations of Q_{2mm} and embedded length are shown in Fig.5(c). Q_{2mm} were affected by the embedded length. That is why Q_{2mm} are influenced of the concrete strength, the specimen width and the embedded length, though these parameters are seemed to be in the complicated interrelationships.

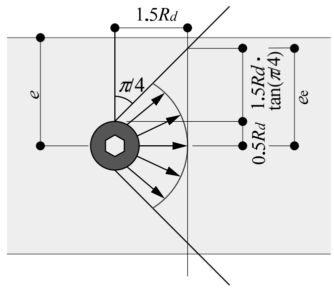
5. PROPOSE OF SHEAR STRENGTH FORMULA OF DISK SHEAR-KEY

5.1 Shear stress transfer mechanism

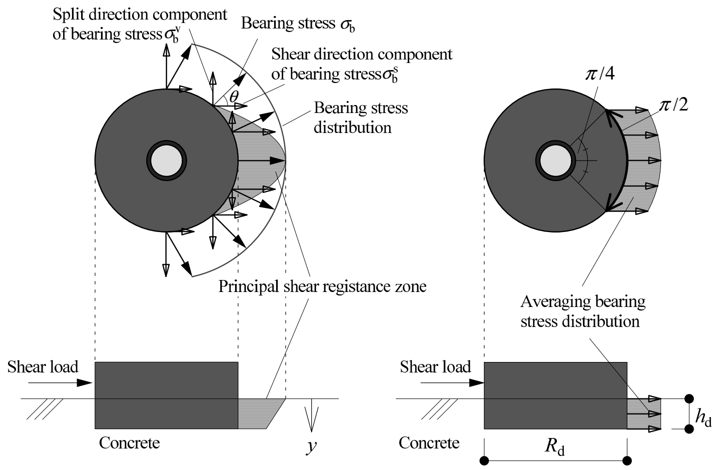
Shear strength Q of Disik shear-key is affected by the bearing stress on the side of the steel disk, shear failure of the bottom of the steel disk and dowel action of the anchor bolt. Fig. 6(a). shows the concept of these



(a) Mechanism



(c) Effect of end side



(b) Bearing stress

Figure 6. Shear stress transfer mechanism of Disk shear-key

strength. This hypothesis is modelled as follows:

$$Q = Q_d + Q_a + Q_C \tag{5.1}$$

where, Q_d equals the shear strength by bearing failure, Q_a equals the shear strength of dowel action of anchor bolt and Q_C equals the shear strength by shear failure of the bottom of the steel disk. As mentioned in the introduction, the maximum shear strength of anchor bolts were observed in large slip deformation which was more than 5mm according to the previous studies. But, the peak strengths of Disk shear-key were obtained when the shear displacement δ was around 2mm. Therefore, Q is seemed to be not affected too much by Q_a. In addition, the shear failure of the bottom of the steel disk is considered to be brittle behavior. But, because the behavior of Disk shear-key was not brittle, the effect of Q_C was seemed to be small. Thus, Q is considered to be the most affected by only Q_d .

5.2 Basic formula

Based on Fisher's formula and test results, the basic shear strength formula was proposed as Eqn. 5.2.

$$Q_d = \alpha \cdot K_1 \cdot K_2 \cdot A_B \sqrt{E_C \cdot \sigma_B} \tag{5.2}$$

where, α equals the empirical coefficient, K_1 equals the corrective coefficient for the end side, K_2 equals the corrective coefficient for the embedded length, and A_B equals the bearing area.

5.3 Coefficients

It is seemed that the bearing stress distributed radially as shown in Fig. 6(b) left. from the failure mode of the specimens after the shear loading tests. The shear strength is considered to be the sum of the shear component of the bearing stress. Therefore, Q_d is represented as follows:

$$Q_d = \iint_R \sigma_b \cdot \cos\theta \cdot d\theta dy = \iint_R \sigma_b^s \cdot d\theta dy \tag{5.3}$$

where, σ_b equals the bearing stress and σ_b^{s} equals the shear component of σ_b. But, this equation is too difficult for constructing the shear strength formula. In this paper, the bearing stress field is averaged as shown in Fig. 6(b) right. Therefore, assuming that bearing stress are acting in the range from - $1/4\pi$ to $+1/4\pi$ radian on the side of the steel disk, the bearing area A_B is represented as Eqn. 5.4

$$A_B = \frac{\pi \cdot R_d \cdot h_d}{4} \tag{5.4}$$

To evaluate the effect of the width, the coefficient K_1 is represented as follows:

$$K_1 = \begin{cases} e/e_e & (e < e_e) \\ 1 & (e_e \le e) \end{cases} \tag{5.5}$$

$$e_e = 0.5R_d + 1.5R_d \cdot \tan\frac{\pi}{4} = 2R_d \tag{5.6}$$

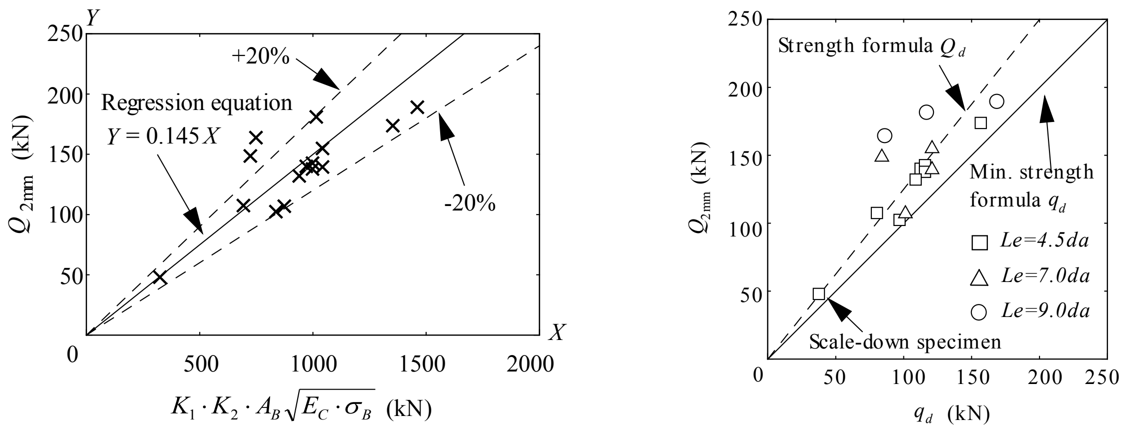
where, e equals the end side of Disk shear-key and e_e equals the effective end side. These are shown in Fig.6(c).

To consider the effect of the embedded length of anchor bolt, the coefficient K_2 is represented as follows:

$$K_2 = \begin{cases} 1.0 + 0.08 \times \left(\dfrac{L_e}{4.5da} - 1 \right) & (4.5da \le L_e < 9da) \\ 1.08 & (9da \le L_e) \end{cases} \tag{5.7}$$

5.4 Comparison of calculation and test results

Fig. 7(a). shows relations of Q_{2mm} and $K_1 \cdot K_2 \cdot A_B \sqrt{E_C \cdot \sigma_B}$. The angles of regression lines of each point



(a) Empirical coefficient α (b) Comparison Q_{2mm} and q_d

Figure 7. Conformance of proposed strength formla to test results

means the empirical coefficient α for Eqn. 5.2. Because the regression coefficient is 0.145 as the results of regression analysis, the strength formula Q_d is as follows:

$$Q_d = 0.145 \cdot K_1 \cdot K_2 \cdot A_B \sqrt{E_C \cdot \sigma_B} \quad (5.8)$$

To estimate the minimum strength of Q_{2mm}, Q_d is 0.8 times as Eqn. 5.9.

$$q_d = 0.8 \cdot Q_d = 0.116 \cdot K_1 \cdot K_2 \cdot A_B \sqrt{E_C \cdot \sigma_B} \quad (5.9)$$

Fig. 7(b). illustrates the comparison Q_{2mm} and the calculation results of these formula. According to this figure, the calculation results of Eqn. 5.8. are in good estimation for all specimens and the minimum strengths of Q_{2mm} for the shear loading tests are evaluated by q_d of Eqn. 5.9.

6. CONCLUSIONS

In this study, Disk shear-key for being used in joints of seismic retrofitting structures was developed. To investigate the characteristic of Disk shear-key, the shear test was conducted and the strength formula was constructed. The findings obtained in this paper are as follows:

1) The maximum strength obtained up to δ = 2mm are more than 90 % of the maximum strength. Then, shear load was moderately-softening.
2) The shear strength Q_{2mm} were affected of $\sqrt{E_C \cdot \sigma_B}$, the width and the embedded length. Moreover, these three parameters affected mutually.
3) The shear strength Q_{2mm} of the disk shear-key were two to four times as the shear strength of usual post-installed anchors.
4) Test results were able to be predicted by the proposal strength formula Q_d reasonably.
5) The minimum test results were able to be estimated by the proposal strength formula q_d.

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