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# POST-EARTHQUAKE QUICK DAMAGE EVALUATION BASED ON CRACK ON THE CONCRETE FOUNDATION OF EXPOSED COLUMN BASE

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## *Abstract*

From lessons learned in the 2011 Tohoku earthquake, it becomes clear that the quick procurement of an emergent public shelter is very important in time of disaster. Structural engineers are required to estimate the seismic damage of structural components in buildings, and to judge whether these are able to be occupied or not. However, the visible damage can hardly be related with the damage to steel structural components, while crack width has been used as a clear damage index for reinforced concrete structures. It is very important to establish a visible damage index for quick damage estimation of steel structures. In the reconnaissance of the 2011 Tohoku earthquake, many cracks on the concrete foundation around exposed steel column base were observed. From the detailed investigations, it is pointed out that the crack width is strongly related with the seismic damage to the framing components covered by non-structural components.

In the present paper, cyclic loading tests focusing on crack patterns and its width of concrete foundation were conducted to confirm the relationship between structural performances and the visible damage indices. The test specimen is a single span full scaled frame subassembly composing of a beam, a column, a brace, and an exposed column base with concrete foundation.

All cracks on the concrete foundation are classified into the 2 major categories, that is, the cracks between concrete foundation and cover mortar, and those diagonally growing from anchor bolts in the compressive side to foundation beam. The cracks in the first category are a result of the column-base rotation together with the cover mortar. Therefore, on the assumption that the rotation center is located on the column flange in compression, the relationship between the crack width and column-base rotation is obtained. Meanwhile, because the residual crack width is roughly 90% of the maximum crack width after anchor bolts yielding, the maximum column base rotation can be estimated by measuring the residual crack width. The maximum story drift angle can in turn be estimated, since the column-base rotation constitutes most of the story drift ratio after the anchor bolts yield. The cracks in the second category can be attributed to the concrete edge failure due to shear forces on the column base. It was observed that the crack width is about half of the lateral deformation at the column base. Therefore, lateral deformation at the column base due to the concrete edge failure can be estimated by the width of the diagonal crack from anchor bolts in compression to foundation beam.

*Keywords: exposed column base, concrete foundation, damage evaluation, crack width, cyclic loading test*

## 1. Introduction

From lessons learned in the 2011 Tohoku earthquake, it becomes clear that the quick procurement of an emergent public shelter is very important in time of disaster. Structural engineers are required to estimate the seismic damage of structural components in buildings, and to judge whether these are able to be occupied or not. However, the visible damage can be hardly related with the damage to steel structural components, while crack width has been used as a clear damage index for reinforced concrete structures [1]. It is very important to establish a visible damage index for quick damage estimation of steel structures. In the reconnaissance of the 2011 Tohoku earthquake, many cracks on the concrete foundation around exposed steel column base were observed [2, 3]. Damage to concrete foundation of the exposed column base is shown in Fig.1. From the detailed investigations, it is pointed out that the crack width is strongly related with the seismic damage to the framing components covered by non-structural components.

In the present paper, cyclic loading tests focusing on crack patterns and its width of concrete foundation were conducted to confirm the relationship between structural performances and the visible damage indices.


Fig. 1 – Damage to concrete foundation of exposed column base in the 2011 Tohoku earthquake [2]

## 2. Experiments

### 2.1 Test setup

A test setup including overall of a test specimen is illustrated in Fig.2. The test specimen is a single span full scaled frame subassembly composing of a beam, a column, a brace, and an exposed column base with concrete foundation. The story height and beam span is 5.0m and 3.0m, respectively. The column base of the specimen is fixed on the strong floor, and a tip of the beam is connected to the hydraulic jack through pin jigs and the leaning columns. The yellow parts illustrated in Fig.2 were prepared at each specimen.

### 2.2 Test specimens

Details of concrete foundation are illustrated in Fig.3. A feature point of the test specimen is to construct a concrete foundation following a real procedure. At first, the concrete foundation column with an extrusion of 238mm height was constructed with foundation beams. Anchor rods were installed in the foundation with reinforcement rods before casting the foundation. And then, a steel column base was set with a base mortar of 32mm thickness on the concrete foundation. Finally, a cover mortar to prevent corrosion of the anchor rods was cast as a finishing in same process as a real construction. As observation in Fig.1 (a) and (d), it is clear that a cover mortar affects the damage pattern on the concrete foundation.

A main test parameter is stress conditions at the column base to investigate its effects on crack patterns of the concrete foundation. The column base is subjected to large bending moment in specimens representing bare moment resisting frames with columns bent in the strong axis (M), to large shear force in specimens representing a braced frame with the column bent in the weak axis (S), and to both large shear force and moment in braced frame specimens where the brace is vertical offset from the column base (MS). Details of steel column base in the braced frames are illustrated in Fig.4. Here, beam was made of section (depth × flange width × web thickness × flange thickness) of 250×125×6×9, and column was made of section of 200×200×8×12. Steel grades JIS SS400 were chosen for the members.

In addition, a size of the concrete foundation is selected as the second parameter to investigate the effects of concrete volume on crack pattern. The compact foundation (C) is made dimensions of the normal foundation (N) in both directions 100mm smaller, and its size is expressed as number in brackets of Fig.3. And overall details are compiled in Table 1.

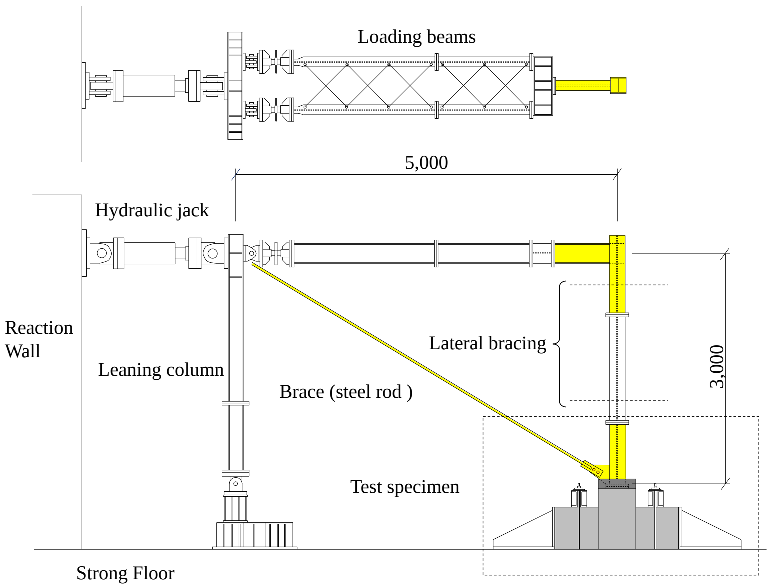
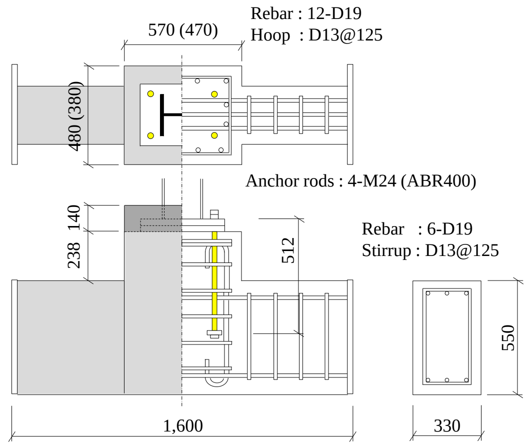
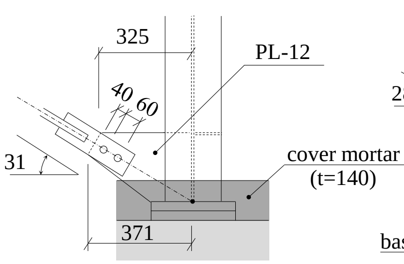


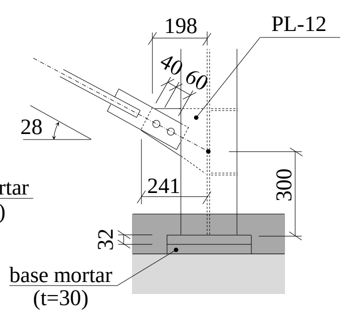

Fig. 2 – Experiment setup (unit :mm)




(a) the strong axis of column

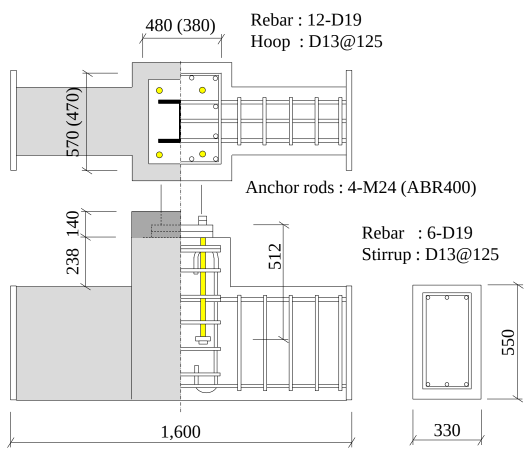



(a) normal brace connection




(b) offset brace connection

Fig. 4 – Detail of steel column base with brace (unit:mm)




(b) the weak axis of column

Fig. 3 – Detail of foundation(unit:mm)

Table 1 – List of the test specimen and its parameters

| Name | Axis of column | Framing type | Size of foundation |
|---|---|---|---|
| M_N | Strong | Moment Resisting | Normal |
| M_C | | | Compact |
| S_N | Weak | Braced Frame (Normal) | Normal |
| S_C | | | Compact |
| MS_N | | Braced Frame (Offset) | Normal |
| MS_C | | | Compact |

## 3. Test results and considerations

### 3.1 Overall behavior and crack patterns

Relationships between a lateral shear force and a story drift angle of the frame are plotted for all specimens in Fig.5. As observed in Fig.5, beam-column subassembly of all specimens exhibited a stable behavior during 1/33 radian story drift angle cycles. Meanwhile, a tension-only brace illustrated by a red line shows a typical slip behavior due to its buckling in compression at low levels of lateral load. The overall behaviors are hardly affected by the difference size of a concrete foundation.

Crack patterns in front of the concrete foundation of the specimen M_N and S_N are shown in Fig.6. Numbers in the figure express crack widths of the major cracks defined later and the crack widths were obtained by crack scale, a hand measuring. In the crack pattern of the specimen M_N which represents moment resisting frames, severe cracks were concentrated on a boundary line between the cover mortar and the concrete foundations. It indicates that the structural testing was able to reproduce damage situations in the reconnaissance of the 2011 Tohoku earthquake shown in Fig.1 (a) and (d). Because these cracks might be growing together with a column-base rotation, it is classified into a “bending crack” as shown in Fig.7.

On the other hand, in the crack pattern of the specimen S_N which represents a braced frame with a large shear force in the column base, a severe crack diagonally appeared from a top of the front anchor rods to edge of the concrete foundation. It also indicates that the structural testing was able to reproduce the shear damage shown in Fig.1 (b) and (c). The diagonal crack was caused by the large shear force and might lead an edge failure of an anchor rod [4]. Therefore, in this paper, these cracks are defined as a “shear crack” as shown in Fig.7.

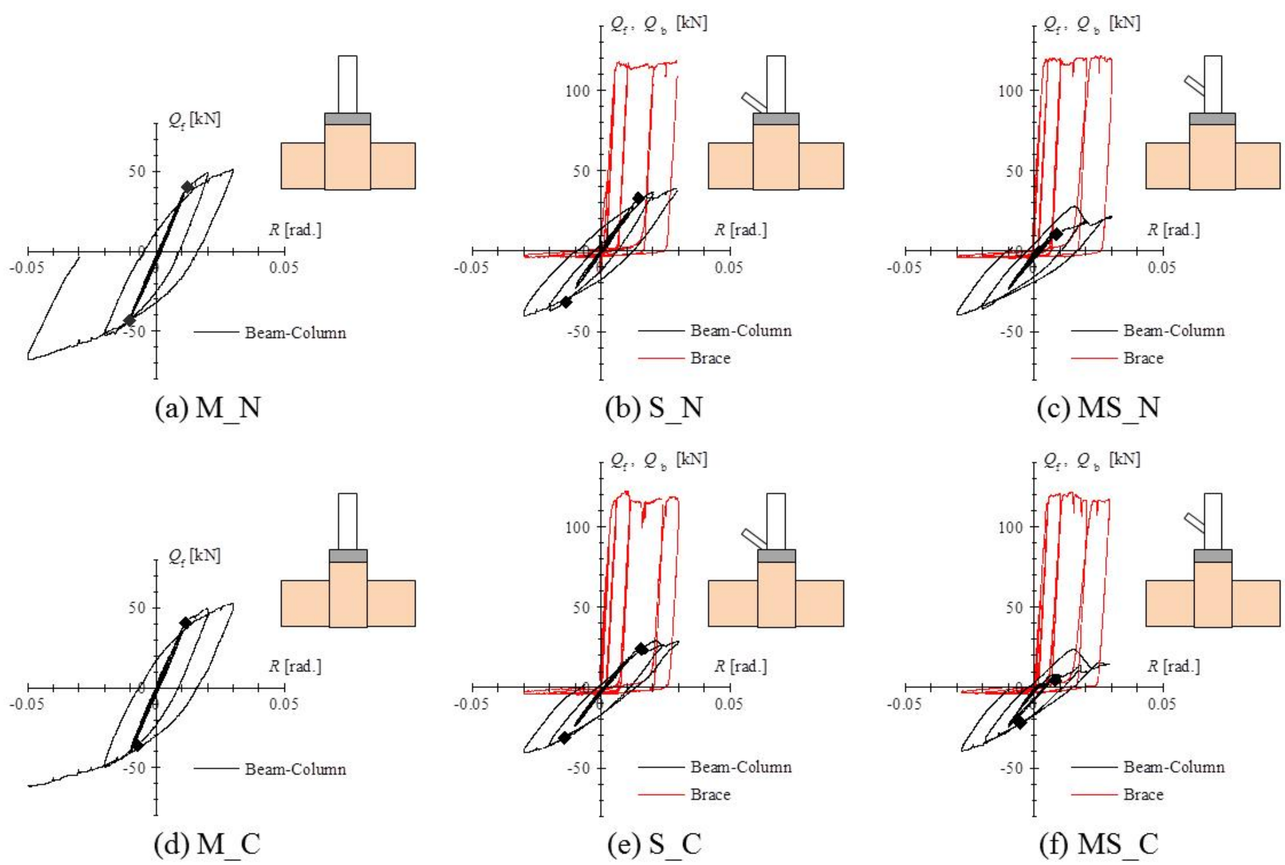
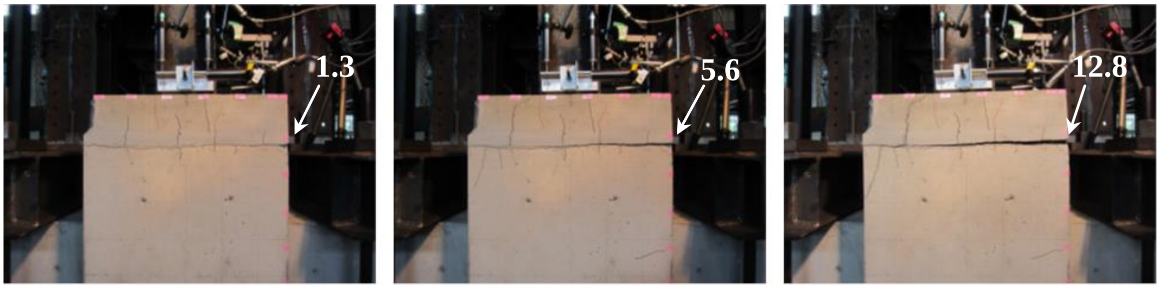
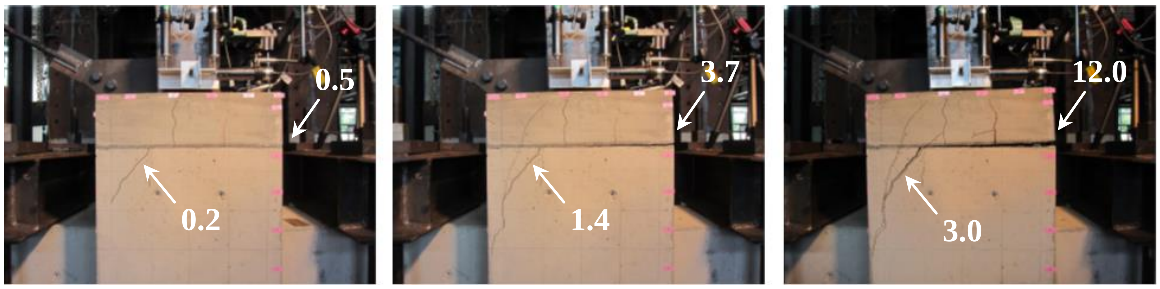



Fig. 5 – Overall behavior of the test frame




(a) M_N (+1/100, +1/50, +1/33rad)




(b) S_N (+1/100, +1/50, +1/33rad)

Fig. 6 –Crack pattern on the concrete foundation and its width

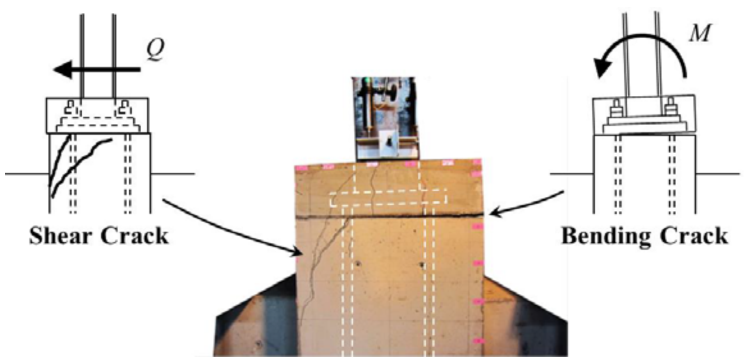



Fig. 7 – The major severe cracks on the concrete foundation around the steel column base

In crack patterns of the specimen MS_N which represented a stress condition with large shear forces and bending moments in the column base showed the same trend of both the specimen M_N and S_N. In addition, the small size of a concrete foundation resulted in wider cracks on the concrete foundation at the same loading cycles.

### 3.2 Bending cracks and damage evaluation based on its width

All cracks on the concrete foundation are classified into the 2 major categories, that is, the cracks between the cover mortar and the concrete foundation, and those diagonally growing from the front anchor rods to the edge of a foundation. From the reconnaissance of the 2011 Tohoku earthquake [2], the bending cracks might be a result of the column-base rotation together with the cover mortar. Therefore, under the assumption that a rotation center of the column base is located at the column flange in compressive side as shown in Fig.8 (a), relationship between the crack width and the column-base rotation is obtained as the below equation.

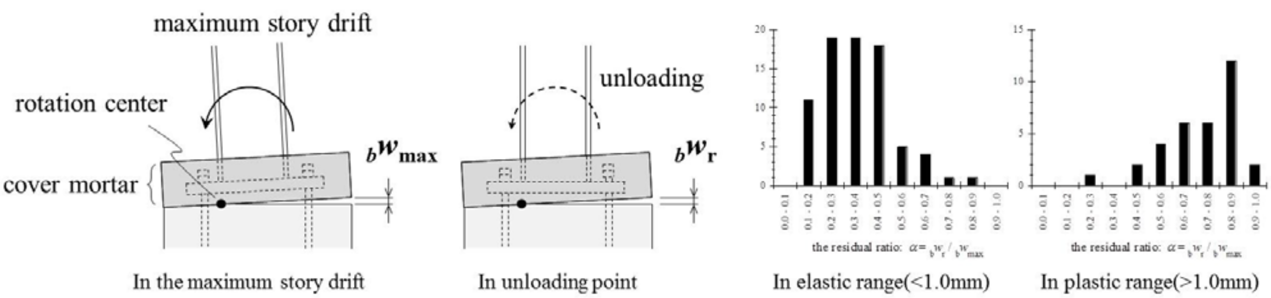
$$ {}_{\mathrm{b}}w = \left| {}_{\mathrm{cb}}\theta \cdot \left( d_{\mathrm{c}} + \frac{D}{2} \right) \right| \tag{1} $$

Here, $d_c$ is the distance from the column center to the compression edge, and $D$ is length square of the concrete foundation column. Relationships between the maximum width of the bending cracks and column-base rotation are plotted for all specimens in Fig.9. The white mark expresses the residual width. The solid lines calculated by equation (1) show good agreement with the experimental results of the crack width and it indicates that the column-base rotation caused the bending cracks on the boundary line around the cover mortar.

On the other hand, in the post-earthquake inspection, it is important to evaluate damage to the whole structures by using the residual width of the bending cracks. A histogram of the residual ratio $\alpha$ of the bending cracks, which is defined as a ratio of the residual width in the unloading point to the maximum width, is shown in Fig.8 (b). As observed in the histogram, the residual ratio is roughly 90% with the anchor rods yielding, although the ratio is less than 50% with that in elastic range. The yielding anchor rods cannot be shrunk by the bending moment as shown in Fig.8 (a), and it is the reason why the high residual ratio is obtained after yielding.

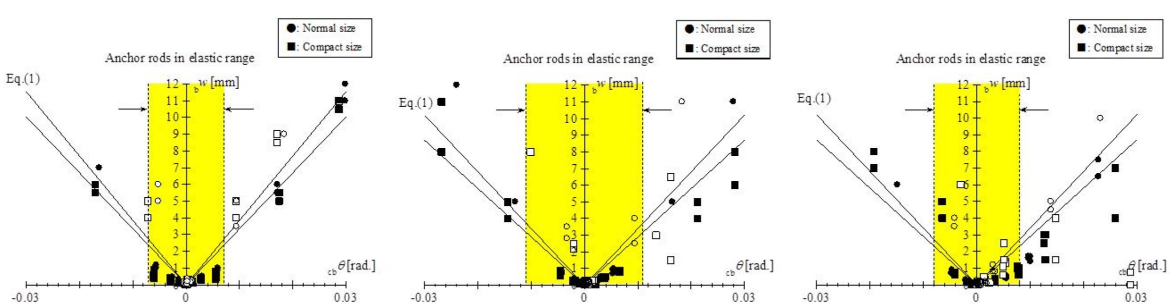
And then, whole structure in the mechanism state, the column-base rotation is considered equal to the story drift. Therefore, the residual width ${}_{\mathrm{b}}w_{\mathrm{r}}$ of the bending crack, which might be obtained in the post-earthquake inspection, is able to be related with the maximum story drift $R_{\max}$ experienced in the earthquake as shown in the below equation.

$$ R_{\max} \approx {}_{\mathrm{cb}}\theta_{\max} = \frac{{}_{\mathrm{b}}w_{\mathrm{r}}}{\alpha \cdot \left( d_{\mathrm{c}} + \frac{D}{2} \right)} \tag{2} $$




(a) mechanism of the residual cracks (b) the residual ratio of the bending cracks

Fig. 8 – Mechanisms of the residual bending cracks and the residual ratio of bending cracks




(a) M_N&C (b) S_N&C (c) MS_N&C

Fig. 9 – Relationships between the maximum and residual width of the bending cracks and column-base rotation

### 3.3 Shear cracks and damage evaluation based on its width

The crack in the second category, the shear crack, can be attributed the concrete edge failure due to large shear forces on the column base in a braced frame. Relationships between the maximum crack width ${}_{s}w$ of the shear crack and a column-base slippage ${}_{bp}\delta_{h}$ is plotted in Fig.10. It was observed that the crack width ${}_{s}w$ is about half of the column-base slippage ${}_{bp}\delta_{h}$, as shown in the below equation.

$$ {}_{bp}\delta_{h} = 2.0 \cdot {}_{s}w \tag{3} $$

In addition, the diagonal crack cannot be closed by the inversed shear force, because the shear force on the concrete foundation is transferred from the front anchor rods. In other words, the residual width of the shear crack is equal to the maximum width of that. Therefore, the damage to anchor rods due to the concrete edge failure can be estimated by measuring the width of the diagonal crack from anchor bolts in compression to foundation beam.

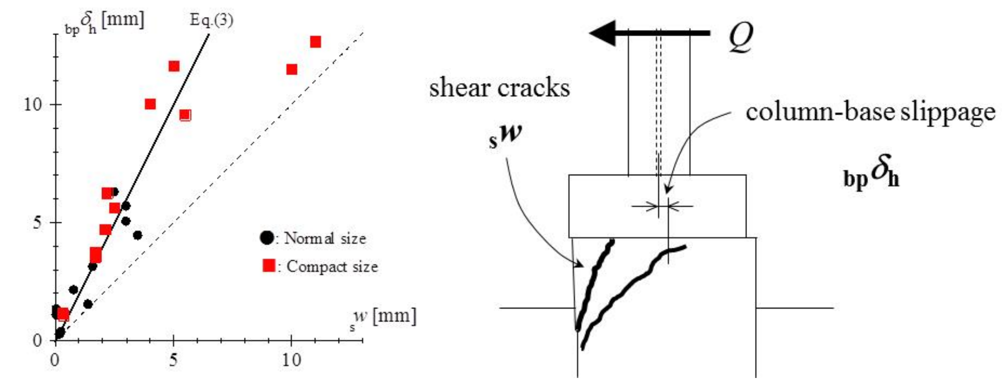



Fig. 10 – Relationships between the maximum width of the shear cracks and column-base slippage

## 4. Conclusions

From lessons in the 2011 Tohoku earthquake and the 2016 Kumamoto earthquake, it becomes clear that the quick procurement of emergent public shelters is required in time of disaster. Especially in steel gymnasium used for emergent public shelters, it is very important to establish a visible damage index for quick damage estimation of steel structures. In the reconnaissance of the 2011 Tohoku earthquake, many cracks on a concrete foundation around the exposed steel column base were observed and were related with damage to the whole structure.

In the present paper, cyclic loading tests focusing on crack patterns and its width of a concrete foundation were conducted to confirm the relationship between structural performances and the visible damage indices. The major findings obtained from the test are summarized as follows: (1) the maximum story drift angle experienced in earthquake can be estimated by measuring the residual crack width between the cover mortar and the concrete foundation; (2) the slippage due to the concrete edge failure can be estimated by measuring the residual crack width growing diagonally from a top of the front anchor rods to edge of the concrete foundation.

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