Evaluation of punching shear strength of voided transfer slabs

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To satisfy the various space demands of occupants in high-rise buildings, such buildings are often constructed with different structural systems along the height of the building, which causes vertical irregularity in the structural system. In buildings with a vertically irregular structural system, transfer slabs are often used to transfer loads from the upper part to the lower part of the building. The transfer slab can perform more efficiently by placing voids in slab regions that do not resist a high level of slab loads. This study evaluated the punching shear strength of voided transfer slabs by conducting experimental tests on five transfer slab specimens. Based on the test results, methods were developed for accurately calculating the punching shear strength of voided transfer slabs.

Notation

- $a$: width (or diameter) of void
- $b$: closest distance between two voids (see Table 1 for details)
- $b_0$: perimeter of critical section
- $c_1$: dimension of square column section
- $d$: depth of slab
- $d_e$: diameter of circular section
- $d_c$: distance from column face to an assumed critical section
- $d_i$: distance from centre of column to critical section located $d/2$ from column face
- $d_v$: width of void overlapping the critical section
- $f'_c$: average compressive strength of concrete
- $f_y$: yield strength of reinforcement
- $h$: height of slab
- $h_v$: height of void overlapping the critical section
- $L$: distance between two supports in experimental set-up
- $l$: span of slab
- $l/d$: span-to-depth ratio of transfer slab
- $l_i$: length to be deduced from critical section located $d/2$ from column face
- $t$: cover thickness of voided area (see Table 1 for details)
- $V_c$: computed punching shear strength
- $V_{test}$: measured punching shear strength
- $V_{test-S}$: measured punching shear strength of reference specimen $S$
- $\alpha$: constant used to compute $V_c$ in slabs: 40 for interior columns; 30 for edge columns; 20 for corner columns
- $\beta$: ratio of long side to short side of column
- $\gamma$: ratio of reduced net area to area of original critical section
- $\Delta_{test}$: displacement at maximum load
- $\Delta_{test-S}$: displacement at maximum load of reference specimen $S$
- $\lambda$: modification factor for lightweight concrete

Introduction

Occupants of high-rise buildings have various demands on space usage. To satisfy these differing demands, high-rise buildings are often constructed with different structural systems along the height of the building, which causes vertical irregularity in the structural systems. In Korea, residential areas are located in the upper parts of the building while commercial and parking areas are often in the lower parts. For residential areas, bearing wall systems are commonly used, whereas moment frame systems are used in commercial and parking areas to provide open and flexible spaces. Figure 1 shows some examples of buildings with vertically irregular structural systems.

To transfer loads between the two different systems along the height of the building, transfer girders and transfer slabs can be used. A transfer slab distributes the load more efficiently than a one-way transfer girder because the transfer slab behaves in two-way action. The depth of a transfer slab is much shallower than that of a transfer girder, which leads to a decrease in building height. The concrete formwork for transfer slabs is also much simpler than that of transfer girders since the transfer slab has a flat surface. Furthermore, because the arrangement of bearing walls is commonly irregular in plan, it is very difficult to construct transfer girders below bearing walls.

The amount of concrete required to construct a transfer slab may, however, be greater than that for a transfer girder since the slab thickness is constant throughout the whole floor. The typical thickness of a transfer slab is 1000–3000 mm, which results in a span-to-depth ratio ($l/d$) of 2.5–5.0. The typical range of $l/d$ for
normal flat slabs is 20–30. For a floor area of 1000 m², the weight of the transfer slab is almost 30 000 kN.

In order to reduce the amount of concrete required for construction of a transfer slab, voids can be formed in the transfer slab where the internal shear force is not significant. For proper distribution of voids in a transfer slab, it is important to estimate the punching shear strength near a column. Punching shear failure of flat slabs occurs in a brittle manner without warning, causing catastrophic slab failure (Gardner et al., 2002). The consequences of failure of a transfer slab are more catastrophic than failure of normal individual flat slabs because failure of a transfer slab results in collapse of the whole structure (Cook, 2012). Furthermore, voided transfer slabs are more susceptible to punching shear failure than solid slabs.

Numerous research studies have been conducted to evaluate the punching shear strength of solid flat slabs (Elstner and Hognestad, 1956; Han et al., 2006, 2012; Hawkins et al., 1974; Hueste and Wight, 1999; Islam and Park, 1976; Kang and Wallace, 2005; Kinnunen and Nylander, 1960; Pan and Moehle, 1992; Rodrigues, 2012; Sagaseta et al., 2011), but research on evaluating the punching shear strength of voided flat slabs has been limited (Aldejohann and Schnellenbach-Held, 2003; Schnellenbach-Held and Pfeffer, 2002). So far, research regarding the punching shear strength of voided transfer slabs with small $l/d$ has not been reported. Since accurate and systematic methods have not yet been developed for calculating the punching shear strength of voided transfer slabs, structural engineers can encounter difficulties when designing such slabs.

In order to fill this knowledge gap, experimental tests were conducted on four voided transfer slab specimens and one solid transfer slab considered as the reference specimen. Based on the test results, an accurate and simplified method for calculating the punching shear strength of voided transfer slabs was developed.

### Model building and test specimens

Figure 2 illustrates the floor plan and elevation of the ten-storey model building. The building was designed using the bearing wall system in the upper nine storeys and the moment frame system in the first storey. The thickness of the slab was assumed to be 1200 mm and the span length was 5500 mm, resulting in a span-to-depth ratio ($l/d$) of 4.6. Gravity loads on the slab transferred from the bearing walls were assumed to be a uniform load of 50 kN/m² on the transfer slab. The wall thickness was taken as 300 mm, with the wall arrangement as shown in Figure 2. The columns were of 800 mm square section; the column height was 3500 mm. Slab moments and shear forces due to gravity loads were obtained from finite-element analysis using the commercial software Midas/gen version 6.3.2 (Midas IT, 2004). Figure 3 shows the moment and shear diagrams used for slab design.

To construct the test specimens, this study considered interior transfer slabs in the model building as shown in Figure 2(a). Five one-third scale specimens were made. Four were voided transfer slab specimens (V1, V2, V3 and V4) and one was a solid transfer slab (S) used as the reference specimen. Specimen V1 had the smallest number of voids and V4 had the largest number of voids. The width and length of the slabs were both 800 mm and the slab thickness was 400 mm. Both ends of the slab were extended by a distance of 200 mm to provide a space for supports. Columns in the specimen were of square section with a dimension of 267 mm.

To make voids in the slab, circular column type Styrofoam of diameter 200 mm and height 250 mm was placed in the slab before casting the concrete. This study considered four different arrangements of slab voids, as shown in Figure 4. Table 1 gives detailed information on the specimens. As the specimens were made in order to evaluate the punching shear strength of transfer slabs, all had sufficient flexural reinforcement to avoid flexural failure prior to punching shear failure. The same amount of...
flexural reinforcement was placed in all the specimens. Rebars (D13) of diameter 13 mm and a specified yield strength of 400 MPa were used as flexural reinforcement.

In this study, the main test variables were the existence of voids in the transfer slabs, the arrangement of the voids and the location of the voids. Figure 4(a) shows the flexural reinforcement arrangement in the transfer slab specimens. Solid specimen S is shown in Figure 4(b). Specimens V1 and V2 (Figures 4(c) and 4(d)) had voids overlapping the critical section. The critical section specified in ACI 318-11 (ACI, 2011) is located at a distance of \( \frac{d}{2} \) from the column face (\( d \) being the effective slab depth), as shown in Figure 4. Specimens V1 and V2 had 8 and 12 voids respectively. Specimen V3 (Figure 3(e)) had voids outside the ACI critical section. Specimen V4 (Figure 3(f)) had two rows of voids. In the first row, 12 voids overlapped the ACI critical section. In the second row, 20 voids were placed at \( d (= 480 \text{ mm}) \) from the column face and did not overlap the ACI critical section.

Figure 5(a) shows the stress–strain curve for concrete obtained from material tests. The average compressive strength was 33 MPa, which was obtained from strength tests using three 100 × 200 mm cylindrical specimens at the time of testing. The maximum aggregate size for the concrete was 19 mm and the slump of the concrete was 100–150 mm. The stress–strain curve of the D13 reinforcement is shown in Figure 5(b). The specified yield strength was 400 MPa, but the actual yield and tensile strengths were determined to be 523 MPa and 604 MPa respectively.

Test set-up and instrumentation
Figure 6(a) shows the test set-up. For convenient application of a concentrated load to cause punching shear failure, a specimen was placed upside down and vertical loading was applied in the downward direction to the top of the column using a hydraulic jack with a capacity of 3000 kN. A load cell was mounted on the hydraulic jack at the top of the column. A simple support condition was maintained by placing rollers along the support line as shown in Figure 6. In order to measure vertical displacements of the specimen, seven linear variable displacement transducers (LVDTs) were installed at the positions shown in Figure 6(b).

Test results
Crack patterns
Figure 7 shows the cracks on the bottom surface of the transfer slab specimens observed after completing the tests. All specimens experienced punching shear failure. Most of the cracks in the voided transfer slab specimens were distributed within a narrow band at a distance slightly greater than \( d \) from the column face (Figure 7(b)–7(f)). The solid specimen showed more cracks over a wider area, as shown in Figure 7(a).

Comparing the crack patterns of specimens V1 and V2 with voids overlapping the ACI critical section at \( \frac{d}{2} \) from the column face (Figures 7(b) and 7(c)), the number of cracks increased with a decrease in the number of voids. In specimen V3, with voids located at \( d \) from the column face and not overlapping the ACI critical section (Figure 7(d)), cracks were observed at a greater
distance from the column face compared with the other voided specimens. In specimen V4 with two rows of voids (Figure 7(e)), sparse cracks were distributed more widely than the other voided specimens.

**Punching shear strength and displacement at maximum load**

Figure 8 shows the force–displacement curves using the force and displacement values taken from the load cell and the LVDT at the column centre (Figure 6(b)). Table 2 summarises the punching shear strengths ($V_{\text{test}}$) and displacements at maximum load ($\tilde{\delta}_{\text{test}}$) of the specimens measured at failure.

The punching shear strength of the voided transfer slab specimens was as low as 50–70% of that of the reference specimen S ($V_{\text{test-S}}$). Specimen V4, which had the largest number of voids, had the least punching shear strength (= 51% of $V_{\text{test-S}}$). It was found that the punching shear strength did not vary with a constant rate according to an increase in the number of voids.

The net area of the ACI critical section at $d/2$ from the column face was calculated by deducting the area of voids overlapping the critical section from the original critical section. The ratio of the reduced net area to the area of the original critical section is represented by $\gamma$. As shown in Table 2, the punching shear strength of the voided transfer slabs did not vary consistently according to $\gamma$, indicating that the punching shear strength estimated by only considering the ACI critical section located at $d/2$ from the column face may not guarantee an accurate punching shear strength of voided transfer slabs.

Comparing $\tilde{\delta}_{\text{test}}$ of the specimens at punching shear failure, solid specimen S had the largest value of $\tilde{\delta}_{\text{test}}$. Among the voided slab specimens, specimen V1 had the largest $\Delta_{\text{test}}$ (88% of that of specimen S) and specimen V4 had the smallest value of $\Delta_{\text{test}}$ (54% of $\Delta_{\text{test-S}}$): specimens V1 and V4 respectively had the least and greatest numbers of voids. Voided specimens V2 and V3 showed $\Delta_{\text{test}}$ values of 72% and 81% of that of the solid specimen respectively.
Figure 4. Transfer slab specimens: (a) arrangement of flexural reinforcement; (b) specimen S; (c) specimen V1; (d) specimen V2; (e) specimen V3; (f) specimen V4 (dimensions in mm)
Prediction of punching shear strength of voided transfer slabs

According to section 11.11.2.1 of ACI 318-11 (ACI, 2011), the punching shear strength ($V_c$) of two-way slabs without shear reinforcement is determined as the smallest of the values obtained from Equations 1–3:

1. $V_c = 0.33\lambda (f'_c)^{1/2}b_0d$

2. $V_c = 0.17\left(1 + \frac{2}{\beta}\right)\lambda (f'_c)^{1/2}b_0d$

3. $V_c = 0.083\left(\frac{\lambda d}{b_0} + 2\right)\lambda (f'_c)^{1/2}b_0d$

in which $f'_c$ is the mean compressive strength of concrete (note that $f'_c$ is defined as the specified compressive strength in ACI 318-11), $b_0$ is the perimeter of the ACI critical section (assumed to be at $d/2$ from the column face), $\beta$ is the ratio of the long side to the short side of the column, $\alpha_i$ is 40, 30 and 20 for interior, exterior and corner columns respectively and $\lambda$ is a modification factor for lightweight concrete. Since normal-weight concrete was used in this study, $\lambda$ is unity. For the transfer slab specimens tested in this study, Equation 1 produced the smallest punching shear strength. Equations 1–3 do not account for the effect of flexural reinforcement. Although it has been reported that slab flexural reinforcement strongly affects the punching shear strength and the failure mechanism (Han et al., 2012; Sagaseta et al., 2011), this study only considered the equations specified in ACI 318-11.

For slabs with discontinuities, two possible methods can be used.
for determining the critical section according to ACI 318-11 (ACI, 2011). First, when openings are located in a two-way slab, the perimeter of the critical section should be reduced according to section 11.6.1 of ACI 318-11. The second method is to determine the critical section governing the punching shear strength of the slab with a discontinuity in slab section. For example, in two-way slabs with drop panels, two critical sections should be considered, located at $d/2$ from the column face and from the drop panel face (Wight and MacGregor, 2009).

However, a method for calculating the punching shear strength of voided transfer slabs has not yet been proposed. Schnellenbach-Held and Pfeffer (2002) reported that the punching shear strength of voided flat slabs may be calculated using the method used for solid flat slabs if voids are not located within the critical section. This observation was made solely based on normal flat plates, and may not be valid for transfer slabs with very low span-to-depth ratios. In this study, the punching shear strength of transfer slabs was calculated using the area of the critical section determined by three different methods – based on rectangular and circular critical sections and considering void sections as slab openings – as described in the following sections.

Punching shear strength based on a rectangular critical section

First, it was assumed that the critical section is located at a distance $d/2$ from the column surface, as shown in Figure 4. In this method, only voids overlapping the critical section were deducted from the critical section. As mentioned earlier, of Equations 1–3, Equation 1 produced the smallest value of $V_c$. To consider a reduced critical section due to voids in the slab, Equation 1 was modified as

$$V_c = 0.33\left(\frac{f_{c}}{2}\frac{b_0}{C_0}\sum d_i h_i\right)^{1/2}$$

where $d_i$ and $h_i$ are the width and height of voids overlapping the critical section (Figure 9(a)).

Table 3 summarises errors in the punching shear strength ($V_c$) predicted by Equation 4 with respect to the actual punching shear strengths ($V_{test}$) obtained from the tests. The punching shear strength predicted by Equation 4 matches the actual punching shear strengths within less than 50% error apart from specimen V3. Equation 4 overestimated the punching shear strength of V3 by 70%. Specimen V3 had voids completely outside the ACI critical section at $d/2$ from the column surface (Figure 4(e)).

Since voids not overlapping the ACI critical section cannot be considered in this method, the predicted punching shear strength of voided specimen V3 was the same as that of solid specimen S.

Punching shear strength based on a circular critical section

Figure 7 shows that crack patterns obtained were neither perfectly rectangular nor perfectly circular. ACI 318-11 (ACI, 2011) adopts a rectangular critical section and this work thus attempted to use a circular critical section to calculate the punching shear strength. Accordingly, the square column in the transfer slab specimen was
Figure 7. Crack patterns on transfer slab specimens at failure: (a) specimen S; (b) specimen V1; (c) specimen V2; (d) specimen V3; (e) specimen V4; (f) section view
substituted with an equivalent circular column having the same cross-sectional area. The diameter of the circular column section \( (d_c) \) was calculated from

\[
d_c = 2c_1(1/\pi)^{1/2}
\]

where \( c_1 \) is the dimension of the square column section.

Again, the critical section was assumed to be located at a distance \( d/2 \) from the column face, as shown in Figure 9(b). To calculate the area of the critical section, the area of voids overlapping the critical section was excluded. The punching shear strength was then calculated using

\[
V_c = 0.33(f_c)^{1/2} \left( 2\pi d_1 d - \sum 2\pi d_i \frac{\theta}{360} h_v \right)
\]

where \( d_i \) is the distance from the centre of the column to the perimeter of the critical section and \( \theta \) is the angle (in degrees) measured at the centre of the column between the two points along the perimeter of the void overlapping the critical section as shown in Figure 9(b).

Table 3 summarises the punching shear strength predicted using Equation 6. With an assumed circular critical section located at \( d/2 \) from the face of the equivalent circular column, Equation 6 predicted the punching shear strength of solid specimen S with

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**Table 2. Punching shear strength \( V_{test} \) and drift capacity \( \Delta_{test} \) at failure**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( V_{test} )</th>
<th>( V_{test}/V_{test-S} )</th>
<th>( \Delta_{test} )</th>
<th>( \Delta_{test}/\Delta_{test-S} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>100</td>
<td>100</td>
<td>7.2</td>
<td>100</td>
</tr>
<tr>
<td>V1</td>
<td>69</td>
<td>70</td>
<td>6.3</td>
<td>88</td>
</tr>
<tr>
<td>V2</td>
<td>51</td>
<td>58</td>
<td>5.2</td>
<td>72</td>
</tr>
<tr>
<td>V3</td>
<td>100</td>
<td>60</td>
<td>5.8</td>
<td>81</td>
</tr>
<tr>
<td>V4</td>
<td>51</td>
<td>51</td>
<td>3.9</td>
<td>54</td>
</tr>
</tbody>
</table>

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**Figure 8. Force–displacement curves**

**Figure 9. Assumed critical sections in voided transfer slabs:**
(a) rectangular critical section; (b) circular critical section; (c) considering void sections as slab openings
good accuracy (2% overestimation). For the voided specimens, Equation 6 underestimated the punching shear strengths of V1, V2 and V4 by 12%, 16% and 5% respectively, and overestimated the punching shear strength of specimen V3 by 70%. Methods considering only voids overlapping the critical section may thus not guarantee an accurate prediction of the punching shear strength of voided transfer slabs. This observation is somewhat different from that for normal flat slabs (Schnellenbach-Held and Pfeffer, 2002).

Prediction of punching shear strength considering void sections as slab openings

To estimate the punching shear strength of voided transfer slabs, this study also considered voids in transfer slabs as slab openings. According to ACI 318-11 (ACI, 2011), when openings are located at a distance less than ten times the slab thickness from a column, the effect of openings should be considered in the calculation of punching shear strength.

ACI 318-11 specifies that for slabs without shear studs, the part of the perimeter of the critical section that is enclosed by straight lines projecting from the centroid of the column and tangential to the boundaries of the openings should be considered ineffective (Figure 9(c)). Here, since the voids did not pass throughout the slab thickness (Figure 9(a)), the concrete area above and below the void was not excluded from the critical section. Considering voids as slab openings, the punching shear strength was calculated using

\[
V_c = 0.33(f'_c)^{1/2}(b_{yd} - \sum l_i h_i)
\]

in which \(l_i\) is the length to be deducted from the critical section located at a distance \(d/2\) from the column face (Figure 9(c)). Table 3 shows that Equation 7 underestimated the punching shear strengths of voided transfer slab specimens V1, V2, V3 and V4 by 14%, 33%, 34% and 24%, respectively.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(V_{\text{test}}): kN</th>
<th>Rectangular critical section (Equation 4)</th>
<th>Circular critical section (Equation 6)</th>
<th>Slab openings (Equation 7)</th>
<th>Accurate method</th>
<th>Simplified method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(V_c): kN</td>
<td>(V_c/V_{\text{test}})</td>
<td>(V_c): kN</td>
<td>(V_c/V_{\text{test}})</td>
<td>(V_c): kN</td>
<td>(V_c/V_{\text{test}})</td>
</tr>
<tr>
<td>V1</td>
<td>1297</td>
<td>0.78</td>
<td>1144</td>
<td>0.88</td>
<td>1304</td>
<td>1.01</td>
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<tr>
<td>V2</td>
<td>1071</td>
<td>0.44</td>
<td>895</td>
<td>0.84</td>
<td>930</td>
<td>0.87</td>
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<tr>
<td>V3</td>
<td>1111</td>
<td>1.70</td>
<td>1883</td>
<td>1.02</td>
<td>1249</td>
<td>1.13</td>
</tr>
<tr>
<td>V4</td>
<td>944</td>
<td>0.50</td>
<td>895</td>
<td>0.95</td>
<td>929</td>
<td>0.99</td>
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</tbody>
</table>

Table 3. Summary of actual and predicted punching shear strengths

Prediction of punching shear strength with a modified critical section

The punching shear strength of voided transfer slabs was calculated using three different methods. As shown in Table 3, none of the methods predicted the punching shear strength accurately for all specimens. They were particularly erroneous for predicting the punching shear strength of specimen V3, which had voids outside the ACI critical section at \(d/2\) from the column face (Figure 4(e)). As shown in Figure 7(d), cracks in specimen V3 formed at a distance greater than in the other voided transfer slab specimens. This indicates that the location of the critical section could vary according to the location of voids.

An accurate method for calculating the punching shear strength of voided transfer slabs was developed based on the experimental results. An iterative procedure was adopted for determining the critical section that produced the smallest punching shear strength. In this method, the punching shear strength of the slab is first calculated at the ACI critical section at \(d/2\) from the column face. The area of voids overlapping the critical section is then removed from the critical section and the punching shear strength calculated using the reduced critical section. The critical section is then relocated to a distance greater than \(d/2\) from the column face and the punching shear strength is recalculated with the changed critical section using Equation 4. This process is repeated until detection of the critical section producing the smallest of the calculated punching shear strengths. Figure 10 shows the punching shear strength \(V_c\) calculated at different locations of critical sections normalised by the actual strength \(V_{\text{test}}\).

As shown Figure 10(a), the punching shear strength of specimen V3 increases with an increase in \(d_e\) until void sections were encountered, \(d_e\) being the distance from the column face to the assumed critical section. (Recall that the voids in specimen V3 were located outside the initial ACI critical section (at \(d/2\) from the column face), with no overlap of the critical section.) Then,
the punching shear strength decreased with an increase in $d_e$ (from location ‘2’ to the minimum shear strength (MSS)) prior to reaching the MSS indicated by a cross in Figure 10(a)). Beyond the MSS, the strength increased again with a further increase in $d_e$. The punching shear strength, which was the smallest of the values in Figure 10(a), matched the actual strength of specimen V3 (13% overestimation) obtained from the experiment, whereas Equations 4 and 6 overestimated the punching shear strength of V3 by 70%. Unexpectedly, it was observed that the punching shear strength measured with the critical section at the centre of the voids (location ‘3’ in Figure 10(a)) was almost the same as that obtained with the critical section using the iterative procedure.

Specimens V1 and V2 had voids overlapping the ACI critical section at $d/2$ from the column face. The critical section producing the smallest punching shear strength was located between the initial ACI critical section and the centre of the voids (locations 1–2 in Figure 10(b)). The punching shear strengths calculated with the ACI critical sections at $d/2$ and at the centre of the voids were very close to the MSS (marked with crosses in Figure 10(b)). The proposed method using the iterative procedure predicted the punching shear strengths of specimens V1 and V2 with good accuracy – an overestimation of 1% for V1 and 13% underestimation for V2. When the critical section was assumed to be at the centre of the voids instead of the location determined from the iterative procedure, the punching shear strengths of V1 and V2 were almost same as those obtained from the method using the iterative procedure. As shown in Figure 10(b), the punching shear strengths of specimens V1 and V2 could be also calculated using the ACI critical section at $d/2$ from the column face with relatively good accuracy.

Unlike the other voided specimens, V4 had two rows of voids (Figure 4(f)). As shown in Figure 10(b), the punching shear strength calculated from the method using the iterative procedure matched the actual strength, with negligible error. The critical section producing the smallest punching shear strength was located between the centres of the first row of voids (1–2 in Figure 10(b)). Similarly to the punching shear strengths of specimens V1 and V2, the punching shear strength of V4 could also be calculated with good accuracy using critical sections located at the centre of the voids in the first row and at $d/2$ from the column face of two rows of voids.

**Summary of proposed methods for calculating punching shear strength of voided transfer slabs**

The punching shear strength of voided transfer slabs can be calculated using the proposed accurate method using the iterative procedure or the simplified method avoiding the iterative procedure.

In the accurate method, the critical section that produces the smallest punching shear strength is determined from an iterative procedure. In the simplified method, critical sections are assumed to be located at either $d/2$ from the column face or at the centre of the voids. If there is more than one row of voids, the centre of the voids in each row should be considered as the possible location of the critical section. Then, punching shear strengths are calculated for all possible critical sections ($d/2$ and the centre of each row of voids). Among the calculated values, the smallest gives the punching shear strength to be determined. Figure 11 illustrates the assumed critical sections for the simplified method.

**Conclusions**

Accurate and simplified methods for calculating the punching shear strength of voided transfer slabs have been proposed. To evaluate the punching shear strength of voided transfer slabs,
experimental tests were conducted using five specimens. The following conclusions can be drawn from this study.

- The punching shear strengths of voided transfer slabs were lower than that of the solid slab. The punching shear strengths of voided transfer slabs varied according to the arrangement and location of voids.
- Punching shear strength was poorly predicted by the method only considering the ACI critical section located at $d/2$ from the column face, particularly for transfer slab specimen V3 with voids located outside and not overlapping the ACI critical section at $d/2$ from the column face. The error in the calculated punching shear strength obtained from this method was as high as 70%.
- An accurate method was developed that determined the critical section producing the smallest shear strength using an iterative procedure. This method accurately predicted the punching shear strength of all the specimens. The largest error, for specimen V3, was only 13%.
- A simplified method that does not require an iterative procedure to determine the critical section was also proposed. In this method, critical sections were assumed to be located at either $d/2$ or the centre of each row of voids. The punching shear strengths were calculated with assumed critical sections and the smallest value was taken to be the punching shear strength to be determined. The errors associated with this method were almost the same as that of the accurate method using the iterative procedure.

**Acknowledgement**

The authors would like to acknowledge financial support provided by the National Research Foundation of Korea (2012R1A2A2A 06045129).

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