Blast Resistance of Double-Layered Reinforced Concrete Slabs Composed of Precast Thin Plates

Makoto Yamaguchi¹, Kiyoshi Murakami², Koji Takeda³ and Yoshiyuki Mitsui⁴

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Abstract

When designing blast-resistant reinforced concrete (RC) structures, reducing spall damage due to reflected tensile stress waves is a major problem. Furthermore, for rapid construction of the blast-resistant structures against sudden terrorist bomb attacks, it is necessary to build it with precast concrete walls and reduce the weight of the precast elements by reducing their size for ease of transportation and construction.

In this study, to propose an idea for rapid construction and better blast resistance of blast-resistant RC structures, double-layered RC slabs composed of precast thin plates, 50 mm thick, were fabricated and utilized for contact detonation tests. The tests were conducted under a condition that the amount of explosives and the dimensions of specimen were constant respectively, and two types of concrete, normal concrete and polyethylene fiber reinforced concrete (PEFRC), were employed as the slab materials. Our results showed that creating an air cavity between the two layers of PEFRC slab was effective in reducing spall damage, while the air space had no advantage in normal RC, under a condition that the thickness of the air space was fixed at 15 mm. Furthermore, the above difference between PEFRC and normal RC slabs was discussed, based on the numerical result on the fracture process of the air-sandwiched normal RC slab.

1. Introduction

When designing important structures such as industrial plants and public facilities, it is necessary to ensure their safety against accidental explosions and terrorist bomb attacks, which happen rarely but can cause serious damage.

It is well known that the behaviors of structures under blast loadings are more complicated than those under static loadings. In particular, the fracture modes of reinforced concrete (RC) slabs subjected to blast loadings are characterized by spalling, due to the tensile stress wave being reflected from the back side of the slab. To protect human lives inside a structure under such conditions, it is necessary to prevent the launch of concrete fragments that accompany spalling. Therefore, reducing spall damage is the most important problem faced by designers of blast-resistant RC structures.

The position of the explosives with relation to the RC structures is classified into three locations: 1) a position close to the structure (standoff detonation), 2) a position on the surface of the structure (contact detonation), and 3) a position inside the structure. Among these, contact detonation is regarded as a standard for the other two cases. Until now, a number of experimental and numerical studies have been conducted regarding the evaluation of damage to normal RC slabs subjected to contact detonation (Hader 1985; McVay 1988; Kraus et al. 1994; Nash et al. 1995; Morishita et al. 2000, 2004; Tanaka et al. 2003; Katayama et al. 2007). Furthermore, the following techniques have been proposed for improving the blast resistance of RC slabs: one is strengthening with fiber reinforced polymer (FRP) composites (Muszynski et al. 2003; Buchan et al. 2007; Razaqpur et al. 2007; Silva et al. 2007) or steel plates (Lan et al. 2005) on the back surface of the RC slab; the other technique is employing a fiber reinforced concrete as a slab material (Sun et al. 1999; Banthia et al. 2004; Lan et al. 2005; Ngo et al. 2007; Zhou et al. 2008; Coughlin et al. 2010). The authors also conducted the contact detonation tests on polyethylene fiber reinforced concrete (PEFRC) slabs and showed that the PEFRC was more effective in reducing spall damage due to contact detonation as compared with normal concrete (Yamaguchi et al. 2008a, 2011).

For rapid construction of the blast-resistant RC structures against sudden terrorist bomb attacks, it is necessary to build it with precast concrete walls and reduce the weight of the precast elements by reducing their thickness for ease of transportation and construction. However, it is easily predicted that there will be a decrease in the blast resistance of single RC slabs due to reducing their thickness. Shirai et al. (1997) and Kishi (1999) proposed the multi-layered systems, in which an air cavity or an elastic shock absorber is inserted between two thin RC layers, and showed their good impact resistance to projectile or weight falling impacts, but the blast resistance of these systems to contact detonation has not yet been
clarified. In this study, to propose an idea for rapid construction and better blast resistance of blast-resistant RC structures, double-layered RC slabs composed of precast thin plates, 50 mm thick, were manufactured and used for the contact detonation tests. The tests were conducted under a condition that the amount of explosives and the dimensions of specimen were constant respectively, and two types of concrete, normal concrete and PEFRC, were employed as the slab materials. The investigation items of this experiment were as follows: 1) influence of internally laid polyethylene fiber mesh reinforcement on the blast resistance, 2) influence of presence of air space between two layers on the blast resistance, 3) influence of shock absorber inserted into the air space on the blast resistance, and 4) influence of thickness of air space and shock absorber on the blast resistance. Furthermore, a numerical simulation with the ANSYS AUTODYN code (Birnbaum et al. 1987; Katayama et al. 2007) was conducted to reveal the fracture process of the double-layered normal RC slab with an air cavity to help understanding of the difference between PEFRC and normal RC slabs.

2. Experiment

2.1 Experimental method

2.1.1 Materials and mix proportions

Table 1 shows the materials used in this experiment. As a normal concrete, ready-mixed concrete with a nominal strength of 30 MPa and a specified slump of 18 cm was employed. For making the PEFRC, binding polyethylene short fiber, 30 mm in length, was used. In order to compensate for decrease in slump of fresh PEFRC due to the surface area effects of mixed fibers, ground granulated blast furnace slag and superplasticizer were used. High-early strength Portland cement was also used, in view of the intended application of PEFRC to precast concrete walls. As shock absorbers, chloroprene rubber (HCR), chloroprene sponge (SCR), and expanded poly-styrol (EPS) were used, based on their good shock absorbing capacity against projectile or weight falling impacts (Shirai et al. 1997; Kishi 1999).

The mix proportions of the PEFRC are shown in Table 2. In previous studies (Yamaguchi et al. 2008a, 2011), the authors showed that the flexural toughness, which represents energy absorption capacity of fiber reinforced concretes, was an important mechanical characteristic for

<table>
<thead>
<tr>
<th>Normal concrete</th>
<th>Ready-mixed concrete Nominal strength: 30 MPa, Specified slump: 18 cm, Maximum size of coarse aggregate: 20 mm Measured slump: 13.5 cm (in series 1) and 11.5 cm (in series 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEFRC</td>
<td>Cement High-early strength Portland cement Fine aggregate River sand Surface-dried density: 2.63 g/cm³, Water absorption: 2.69%, Maximum size: 2.5 mm, Fineness modulus: 2.58 Coarse aggregate Crushed stone Surface-dried density: 2.95 g/cm³, Water absorption: 1.27%, Maximum size: 15 mm, Percentage of absolute volume: 56.3% Admixture Blast furnace slag Density: 2.89 g/cm³, Specific surface area: 6140 cm²/g Supreplasticizer (polycarboxylic acid type) Short fiber Polyethylene fiber Density: 0.97 g/cm³, Size: 68 μm (diameter) × 30 mm (length), Tensile strength: 1870 MPa, Tensile elastic modulus: 43 GPa, Fracture strain (elongation): 5%</td>
</tr>
<tr>
<td>Reinforcing steel bar</td>
<td>Polished steel bar (Ø5) 0.2% proof stress: 650 MPa, Tensile strength: 733 MPa, Fracture strain (nominal value): 12.8%</td>
</tr>
<tr>
<td>Continuous fiber</td>
<td>Polyelethylene fiber mesh sheet Unit weight: 44 g/m² (fiber: 27 g/m²²), Thickness: 0.27 mm, Pitch: 10 mm, Strength: 1.36–1.37 kN/5cm</td>
</tr>
<tr>
<td>Shock absorber</td>
<td>Chloroprene rubber (HCR) Density: 1.40 g/cm³, JIS hardness (A): 63.3 Chloroprene sponge (SCR) Density: 0.25 g/cm³, JIS hardness (A): 18.9 Expanded poly-styrol (EPS) Density: 0.028 g/cm³, Flexural strength: 0.34 MPa</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Polymer cement mortar (in series 1) and Epoxy resin (in series 2)</td>
</tr>
</tbody>
</table>

Table 2 Mix proportions of PEFRC.

<table>
<thead>
<tr>
<th>Series</th>
<th>Vf [%]</th>
<th>W/B [%]</th>
<th>Sg/B [%]</th>
<th>s/a [%]</th>
<th>Unit weight [kg/m³]</th>
<th>Sp/B [%]</th>
<th>Slump [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>Sg</td>
<td>W</td>
</tr>
<tr>
<td>1</td>
<td>4.0</td>
<td>33</td>
<td>50</td>
<td>65</td>
<td>488</td>
<td>488</td>
<td>325</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
<td>33</td>
<td>50</td>
<td>65</td>
<td>488</td>
<td>488</td>
<td>325</td>
</tr>
</tbody>
</table>

evaluating the blast resistance of single PEFRC slab. If the flexural toughness of the PEFRC in the upper layer of the double-layered slab is large enough, the damage to the lower layer is expected to be reduced by sacrificial ‘breaching’. Therefore, the mix proportion of the PEFRC was determined based on the energy absorption of the upper layer. Thus, the mix proportion of the PEFRC was determined based on the energy absorption of the upper layer. Therefore, the mix proportion for which the flexural toughness was at its peak and the slump was over 10 cm (Yamaguchi et al. 2008b).

For mixing the PEFRC, a forced double axis mixer (55L) was used: first, the cement, blast furnace slag, and aggregates were dry mixed for 15 seconds; secondly, the water and superplasticizer were added and mixed for 90 seconds; finally, the polyethylene short fibers were added and mixed for 3 minutes.

2.1.2 Mechanical characteristics of PEFRC

Table 3 shows the material test methods. Three specimens were prepared for each test, which were cured in wet conditions for 14 days (for PEFRC) and 28 days (for normal concrete), and then cured in air until testing. The flexural toughness coefficient \( \sigma_b \) (JCI 1984; JSCE 2004; Tanaka et al. 2003) was calculated using the following equation:

\[
\sigma_b = \frac{3 \cdot l}{2bd^2} \frac{T_b}{\delta_b - \delta_0}
\]

where \( T_b \): an area under the load – displacement curve until the displacement reached 2.0 mm [N·mm], \( \delta_b \): displacement of 2.0 mm, \( l \): span length [mm] and \( b, d \): width and depth of the prism specimen [mm].

The material test results are shown in Table 4. The values of the flexural toughness coefficient of the PEFRC were 9.52 MPa (in series 1) and 8.69 MPa (in series 2); the values of total damage depth (the sum of crater and spall depths) in single, 100-mm thick PEFRC slab by the 200 g explosive charge were estimated to be 55 mm (in series 1) and 59 mm (in series 2), based on previous studies (Yamaguchi et al. 2008a, 2011). As for normal concrete, Morishita et al. (2004) have clarified that the influence of concrete strength on the blast resistance of normal RC slab is negligible. Based on their method for estimating damage to normal RC slab, the failure mode of single, 100-mm thick normal RC slab by the 200 g explosive charge was estimated to be ‘breaching’.

2.1.3 Specimen configuration

Table 4 and Fig. 1 show a list of thirteen kinds of specimens and how to manufacture the specimens for the contact detonation tests, respectively. The single plate, composed of a double-layered slab, was of the same size, 600 mm long, 600 mm wide, and 50 mm thick. These dimensions were the same as those in previous studies dealing with the blast resistance of single slab (Morishita et al. 2000, 2004; Tanaka et al. 2003; Yamaguchi et al. 2008a, 2011). The curing age of the specimens for the contact detonation tests was the same as that in the material tests.

<table>
<thead>
<tr>
<th>Specimen configuration</th>
<th>Number</th>
<th>Measurement item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive test</td>
<td>3</td>
<td>Compressive stress – strain curve</td>
</tr>
<tr>
<td>Splitting tensile test</td>
<td>3</td>
<td>Maximum load</td>
</tr>
<tr>
<td>Flexural test</td>
<td>3</td>
<td>Load – displacement curve (three-point bending)</td>
</tr>
</tbody>
</table>

Note; the flexural test was not conducted for normal concrete, because the flexural toughness of normal concrete is negligible due to its brittle post-peak behavior.

Table 4 Thirteen types of specimens for contact detonation tests and material test results.

<table>
<thead>
<tr>
<th>Series</th>
<th>Specimen</th>
<th>Type of concrete</th>
<th>Middle layer</th>
<th>Composition</th>
<th>( f_c ) [MPa]</th>
<th>( E ) [GPa]</th>
<th>( f_t ) [MPa]</th>
<th>( f_b ) [MPa]</th>
<th>( \sigma_b ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PE-Mesh</td>
<td>PEFRC</td>
<td>Mesh reinforcement</td>
<td>A</td>
<td>70.6</td>
<td>23.2</td>
<td>7.28</td>
<td>10.2</td>
<td>9.52</td>
</tr>
<tr>
<td></td>
<td>NC-Mesh</td>
<td>Normal concrete</td>
<td>Mesh reinforcement</td>
<td>A</td>
<td>41.5</td>
<td>32.1</td>
<td>3.33</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>PE-AIR-15</td>
<td>PEFRC</td>
<td>AIR</td>
<td>15 mm B</td>
<td>70.6</td>
<td>23.2</td>
<td>7.28</td>
<td>10.2</td>
<td>9.52</td>
</tr>
<tr>
<td></td>
<td>NC-AIR-15</td>
<td>Normal concrete</td>
<td>AIR</td>
<td>15 mm B</td>
<td>41.5</td>
<td>32.1</td>
<td>3.33</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>PE-HCR-15</td>
<td>PEFRC</td>
<td>HCR</td>
<td>15 mm C</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>NC-HCR-15</td>
<td>Normal concrete</td>
<td>HCR</td>
<td>15 mm C</td>
<td>35.8</td>
<td>29.3</td>
<td>2.78</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>PE-SCR-15</td>
<td>PEFRC</td>
<td>SCR</td>
<td>15 mm C</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>NC-SCR-15</td>
<td>Normal concrete</td>
<td>SCR</td>
<td>15 mm C</td>
<td>35.8</td>
<td>29.3</td>
<td>2.78</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>PE-EPS-15</td>
<td>PEFRC</td>
<td>EPS</td>
<td>15 mm C</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>NC-EPS-15</td>
<td>Normal concrete</td>
<td>EPS</td>
<td>15 mm C</td>
<td>35.8</td>
<td>29.3</td>
<td>2.78</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>PE-AIR-5</td>
<td>PEFRC</td>
<td>AIR</td>
<td>5 mm B</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>PE-AIR-30</td>
<td>PEFRC</td>
<td>AIR</td>
<td>30 mm B</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>PE-HCR-5</td>
<td>PEFRC</td>
<td>HCR</td>
<td>5 mm D</td>
<td>59.4</td>
<td>24.3</td>
<td>7.94</td>
<td>9.37</td>
<td>8.69</td>
</tr>
</tbody>
</table>

Notes; \( f_c \): compressive strength, \( E \): Young’s modulus, \( f_t \): splitting tensile strength, \( f_b \): flexural strength, \( \sigma_b \): flexural toughness coefficient. The symbols of ‘Composition’ correspond to those in Fig. 1.
The double-layered slabs used in this experiment were classified into three types:

1) Slabs strengthened with polyethylene fiber mesh sheets in the bond surface of two layers. Double polyethylene fiber mesh sheets were bonded diagonally with respect to each other between the bond surfaces of two layers by polymer cement mortar.

2) Slabs with an air space inserted between two layers. We used three different thicknesses of the air space in the air-sandwiched PEFRC slab: 5, 15, and 30 mm. The materials used for making the air space varied between the two experiment series, however, their influence on the size of the crater and spall is considered negligible because the sizes of the crater and spall are ruled by the propagation of the stress waves.

3) Slabs with various shock absorbers inserted into the air space. The thickness of the shock absorber HCR inserted into the middle of the double-layered PEFRC slab varied between 5 and 15 mm.

2.1.4 Test set-up

Figure 2 shows the test set-up for the contact detonation. The specimen was supported by two wooden jigs with an inside span of 510 mm, in accordance with previous studies (Morishita et al. 2000, 2004; Tanaka et al. 2003). The explosives (penthrite: 65%, paraffin: 35%, density: 1.30 g/cm³) were installed in the center of the upper surface of the specimen and blasted using an electric detonator. For direct comparison of double-layered and single slabs, both the shape and the amount of explosives were set to the same as those in previous studies dealing with the blast resistance of single slab (Yamaguchi et al. 2008a, 2011): the explosives were cylindrical shaped, with a diameter equal to the height, and the amount of explosives was fixed at 200 g.

2.1.5 Measuring the size of the external damage

After the contact detonation tests, the fracture behaviors of the specimens were observed in detail. Before measuring the size of the external damage, the concrete fragments were removed by hand. Measurement items are shown in Fig. 3. The diameters of the crater, spall, and...
breach were defined as the average value of four measurements along the straight lines 1-4, shown in Fig. 3, because the crater, spall and breach might not be symmetrical. The depth of the damage in the double-layered slabs was evaluated by measuring the maximum damage depth of both layers, since the border between the crater and the spall was not clear in most of the double-layered slabs as will be seen later.

2.2 Results and discussion
2.2.1 Fracture behaviors of the specimens
Table 5 shows the fracture behaviors of the specimens after the contact detonation tests.

In specimen PE-Mesh, a delamination of the bond surface between the PEFRC layers was observed. On the back surface of the lower layer, a small bulge and spall occurred, but the launch of the PEFRC fragments was prevented. Multiple fine cracks propagated in a radial pattern from the spall, and a straight macro-crack parallel to the wooden jigs was also observed on the back side of the lower layer.

In specimen NC-Mesh, no breach occurred in the bond layer because of the polyethylene fiber mesh reinforcement, but the bond layer was largely twisted under the detonation point and breach occurred in both of the normal RC layers. On the back side of the lower layer, a very large spall occurred and macro-cracks propagated in a radial pattern from the spall. Furthermore, cracks penetrating from the top to the bottom were observed in both of the normal RC layers.

In specimen PE-AIR-15, no breach occurred in the upper layer, because the PEFRC fragments at the back surface of the upper layer were prevented from being launched by contact with the upper surface of the lower layer. On the back surface of the lower layer, cross-shaped cracking similar to static flexural cracking was observed without the spall which is typical of contact detonation. Furthermore, fine internal cracks parallel to the back surface were observed in the lower layer.

In specimen NC-AIR-15, which had the same structure as specimen PE-AIR-15, a large breach occurred in both of the normal RC layers. The local failure, which occurred in the lower layer, was in the shape of a truncated cone, which is characteristic of punching shear failure. The cracks in this specimen were larger than those in specimen NC-Mesh, and cracking parallel to the sides of the slab was also observed.

As for specimens PE-HCR-15, PE-SCR-15 and PE-EPS-15, a PEFRC bulge created in the back surface of the upper layer compressed the shock absorber below it in all of the three specimens; however, the damage to the shock absorbers was different according to their hardness: shock absorbers SCR and EPS (with low hardness) were completely squashed under the detonation point, and the PEFRC bulge made contact with the upper surface of the lower layer; shock absorber HCR (with high hardness) prevented the PEFRC bulge from contacting the upper surface of the lower layer. Cross-shaped cracking was detected on the back surface of the lower layer in all of the three specimens, but there was no great difference in them among the three specimens.

The fracture behaviors of specimens NC-HCR-15, NC-SCR-15 and NC-EPS-15 were similar to that of specimen NC-AIR-15 in spite of the variety of shock absorbers, except for the spall diameter in specimen NC-HCR-15, which was slightly larger than those in the others. In specimen NC-EPS-15, the EPS shock absorber was completely squashed under the detonation point.

In specimen PE-AIR-5, a PEFRC bulge which formed in the back surface of the upper layer was in contact with the upper surface of the lower layer. This was also observed in specimen PE-AIR-15. However, the local failure in the upper layer of specimen PE-AIR-5 was smaller than that in specimen PE-AIR-15, and the cracking on the back surface of the lower layer in the former became larger than that in the latter. In specimen PE-AIR-30, on the other hand, a breach occurred in the upper layer because of the launch of the PEFRC fragments created in the back surface of the upper layer, and very fine radial cracks were observed on the back surface of the lower layer.

In specimen PE-HCR-5, large cross-shaped cracks were observed, and a small bulge and spall occurred on the back surface of the lower layer. Furthermore, the internal cracks in the lower layer propagated more extensively than those in specimen PE-HCR-15.

2.2.2 Evaluating the size of the external damage
Table 6 shows the size of the external damage measured.

(1) Influence of internally layered polyethylene fiber mesh reinforcement on external damage
Figure 4 shows the influence of the internally laid polyethylene fiber mesh reinforcement on the external damage. In Figs. 4 and 5, the damage depth of the single slab (Yamaguchi et al. 2008a, 2011) is expressed by the crater depth \(D_c\) and spall depth \(S_s\).

For normal RC, the damage in the mid-reinforced slab is almost as large as that in the single, 100-mm thick slab,
Table 5 Fracture behaviors of specimens.

<table>
<thead>
<tr>
<th>Detonation side</th>
<th>PE-Mesh</th>
<th>NC-Mesh</th>
<th>PE-AIR-15</th>
<th>NC-AIR-15</th>
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<td><img src="image25" alt="Image" /></td>
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</table>

Note: each specimen had been supported at both the left and right sides.
and the total damage depth (the sum of damage depths in both layers for the double-layered slabs) reached 100 mm in both specimens. In PEFRC, on the other hand, the total damage depth in the mid-reinforced slab was slightly smaller than that in the single slab. This may be because the flexural toughness coefficient of the PEFRC used in the former was slightly larger than that in the latter or because a delamination of the bond surface had occurred in the former.

More investigations are needed to develop a stronger means of joining the layers, however, it may be difficult to improve the blast resistance of both the PEFRC and the normal RC slabs using layered polyethylene fiber mesh reinforcement because the propagation of the stress wave into the lower layer cannot be prevented by this method.

(2) Influence of the presence of air space between two layers on the external damage

**Figure 5** shows the influence of the presence of air space between the two layers on the external damage.

In the PEFRC, the spall damage in the lower layer was remarkably reduced by inserting an air space, because the propagation of the stress wave into the lower layer was prevented by the air cavity. For the normal RC, however, the size of the external damage in the air-sandwiched slab was as large as that in the single, 100-mm thick slab, and the total damage depth reached 100 mm in both specimens.

From these results, it was shown that the effect of an air space inserted between two layers depended on the kind of concrete used: making an air space 15 mm thick in the middle of the double-layered PEFRC slab was effective in reducing spall damage, however the air space had no advantage in the normal RC. The fracture mechanism of the air-sandwiched slab subjected to contact detonation will be analytically investigated in the next chapter.

### Table 6 Size of external damage measured.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>T [mm]</th>
<th>C [mm]</th>
<th>S [mm]</th>
<th>Du [mm]</th>
<th>Dl [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE-Mesh</td>
<td>100</td>
<td>127</td>
<td>54</td>
<td>35</td>
<td>19</td>
</tr>
<tr>
<td>NC-Mesh</td>
<td>100</td>
<td>164</td>
<td>378</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>PE-AIR-15</td>
<td>100</td>
<td>131</td>
<td>0</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>NC-AIR-15</td>
<td>100</td>
<td>180</td>
<td>306</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>PE-HCR-15</td>
<td>100</td>
<td>134</td>
<td>0</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>NC-HCR-15</td>
<td>100</td>
<td>192</td>
<td>408</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>PE-SCR-15</td>
<td>100</td>
<td>138</td>
<td>0</td>
<td>43</td>
<td>0</td>
</tr>
<tr>
<td>NC-SCR-15</td>
<td>100</td>
<td>195</td>
<td>329</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>PE-AIR-30</td>
<td>100</td>
<td>139</td>
<td>0</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>PE-SCR-15</td>
<td>100</td>
<td>141</td>
<td>47</td>
<td>40</td>
<td>19</td>
</tr>
</tbody>
</table>

Note: T: total slab thickness (except for thickness of air space or shock absorber).

**Fig. 4** Influence of internally laid polyethylene fiber mesh reinforcement on external damage.

**Fig. 5** Influence of presence of 15-mm thick air space between two layers on external damage.

(3) Influence of shock absorber inserted into the air space on the external damage

**Figure 6** shows the influence of a shock absorber inserted into the 15-mm thick air space on the external damage. In this figure, experimental data on the double-layered slab with a 15-mm thick air space are also shown for comparison.

In all of the four PEFRC specimens, the total damage depth was determined by the damage depth of the upper layer, because the local failure in the lower layer was prevented completely. The total damage depth of the specimens with EPS and AIR reached nearly 50 mm, which was the thickness of the upper layer, and the
damage to the specimen with HCR was the smallest of the four specimens. This may be because the PEFRC bulge formed on the back surface of the upper layer tends to be more easily buried in the least resistant shock absorber below it.

In the normal RC, the values of spall diameter in the specimens with shock absorbers were larger than that in the specimen with the air space; that tendency was most noticeable in the specimen with HCR. However, the total damage depth reached 100 mm in all of the four specimens.

From these results, in both double-layered PEFRC and normal RC slabs, we conclude that the addition of a shock absorber in the air space shows no advantage in reducing spall damage.

(4) Influence of thickness of air space and shock absorber on the external damage

Figure 7 shows the influence of the thickness of the air space and the HCR shock absorber on the external damage of the double-layered PEFRC slab.

For the air-sandwiched PEFRC slab, the damage depth of the upper layer tended to increase as the air gap became thicker, because the launch of the PEFRC fragments occurred in the back surface of the upper layer. On the other hand, the cracking on the back surface of the lower layer became smaller with a thicker air gap, as shown in Table 5. Therefore, increasing the thickness of the air space may be effective in improving the blast resistance of the air-sandwiched PEFRC slab, because the upper layer behaves as an effective sacrificial element.

The damage depth of the upper layer of the double-layered PEFRC slab with the HCR shock absorber stayed almost constant in spite of the change in the thickness of the HCR shock absorber, because the launch of the PEFRC fragments in the back surface of the upper layer was hindered by the shock absorber HCR below. In the lower layer, a small spall occurred with the 5-mm thick shock absorber, while the 15-mm one prevented the spall. Therefore, the blast resistance of the double-layered PEFRC slab may be raised by increasing the thickness of the shock absorber. However, the shock absorber has no advantage over the air space in reducing spall damage, as stated above.

3. Numerical simulation

Based on the above test results, it is important to clarify the fracture mechanism of the double-layered slab with an air space. In this chapter, a numerical simulation was conducted to reveal the fracture process of the air-sandwiched normal RC slab to help understanding of the difference between normal RC and PEFRC slabs. For the numerical simulation, a multiple solver type hydrocode, ANSYS AUTODYN, was used (Birnbaum et al. 1987; Katayama et al. 2007).

3.1 Analytical method

3.1.1 Analytical system

A two-dimensional axisymmetric model was used in the numerical simulation, as shown in Figure 8. In problems where the explosives behave as a gas after the detonation, the Eulerian solver that is suitable for modeling the fluidity of the explosive products should be properly adapted to the explosive parameters. However, in this problem, the element with few bulks (steel bars) and the explosive products may interact after the breaching of the RC slab. Since the thickness of the steel element is smaller than the mesh size of the Eulerian element modeling the explosive products, the Lagrangian-Eulerian interactive solver cannot give an accurate
solution in this case. Therefore, in this calculation, the concrete and the explosives were modeled by the Lagrangian element, and shell elements were applied to the steel bars and the aluminum plate, in accordance with the previous study of Katayama et al. (2007). The polymer cement mortar of the bonding layer was ignored.

Although the target RC slab was square in the experiment, it was assumed to be a circular plate which was inscribed to the actual RC slab. The reinforcement was also modeled by a thin circular plate with an equivalent mass. The bending moment was ignored for the shell element modeling of the reinforcement, i.e., it was assumed to be a membrane. The wooden jig which supported the RC slab was assumed to be stiff and was modeled by the boundary condition.

3.1.2 Material models
(1) Explosives
We applied the Jones-Wilkins-Lee (JWL) equation of state to the explosives (Lee et al. 1968) and used a programmed ‘on-time burning’ model, assuming ideal stationary detonation. The equation of state (EOS) is defined as follows:

\[ p = A \left( 1 - \frac{\eta \rho}{\rho_\text{ref}} \right) \exp \left( -\frac{R_1}{\eta} \right) + B \left( 1 - \frac{\eta \rho}{\rho_\text{ref}} \right) \exp \left( -\frac{R_2}{\eta} \right) + \omega \eta \rho_\text{ref} e \]

(2)

where \( p \): pressure, \( \eta \): internal energy, and \( A, B, R_1, R_2, \) and \( \omega \) are the material parameters of the explosives. The detonation properties and the JWL parameters for many explosives have been compiled by Dobratz et al. (1985). However, since the explosives used in this experiment were not ordinary ones, we calculated their properties and parameters by the revised Kihara-Hikita EOS (Tanaka 2003). The material parameters for the explosives used are shown in Table 7. The constitutive model of the explosives was ignored and assumed to be hydrodynamic.

(2) Concrete
Koshika et al. (1992) analytically clarified that -6.0 MPa was suitable for the spall strength (negative threshold hydrostatic pressure when spall occurs) of concrete subjected to steel projectile impact (impact velocity: 400 m/s). However, in case of the contact detonation (detonation velocity: 6278 m/s), the absolute value of spall strength was expected to be larger than -6.0 MPa, because of the strain rate effect on concrete strength. Therefore, in this calculation, the spall strength of the concrete was assumed to be -7.0 MPa. In the previous report of the Japan Nuclear Energy Safety Organization, it was confirmed that the numerical result with the concrete spall strength of -7.0 MPa showed a good agree-

![Fig. 8 Two-dimensional axisymmetric model used in numerical simulation.](image-url)

Table 7 Material parameters for explosives.

<table>
<thead>
<tr>
<th>Equation of state</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference density ((\rho_\text{ref})) [g/cm³]</td>
<td>1.3189</td>
</tr>
<tr>
<td>JWL parameter ((A)) [GPa]</td>
<td>578.4123</td>
</tr>
<tr>
<td>JWL parameter ((B)) [GPa]</td>
<td>10.1342</td>
</tr>
<tr>
<td>JWL parameter ((R_1)) [-]</td>
<td>5.711761</td>
</tr>
<tr>
<td>JWL parameter ((R_2)) [-]</td>
<td>1.425701</td>
</tr>
<tr>
<td>JWL parameter ((\omega)) [-]</td>
<td>0.279831</td>
</tr>
<tr>
<td>Detonation velocity ((V_{det})) [m/s]</td>
<td>6278</td>
</tr>
<tr>
<td>Internal energy per unit volume ((E_i)) [GJ/m³]</td>
<td>5.8409</td>
</tr>
<tr>
<td>C-J pressure ((P_{C-J})) [GPa]</td>
<td>12.774</td>
</tr>
<tr>
<td>Constitutive law</td>
<td>(Hydro)</td>
</tr>
<tr>
<td>Erosion strain (Geometrical strain) [%]</td>
<td>500</td>
</tr>
</tbody>
</table>

Note: ‘Erosion’ is a technique wherein Lagrangian elements are transformed into free mass points not connected to the original element (Katayama 2007).
ment with the experimental result on normal RC slab subjected to contact detonation. The EOS adapted to the concrete was the linear equation in which pressure \( p \) is proportional to density \( \rho \):

\[
p = K\mu, \quad \mu = \rho / \rho_{ref} - 1
\]

where \( K \): bulk modulus, \( \mu \): compressibility, \( \rho \): density, and \( \rho_{ref} \): reference density.

The EOS adapted to the steel was the linear equation in which pressure \( p \) is proportional to density \( \rho \):

\[
p = G\nu, \quad \nu = \rho / \rho_{ref} - 1
\]

where \( \nu \): assumed to be 0.2.

As the constitutive law for concrete, the Drucker-Prager criterion was adopted (Chen 1982). This model assumes that the yield stress (\( Y \)) is proportional to the pressure (\( p \)), as shown in Fig. 9. In this calculation, it was assumed that \( Y \) did not exceed the maximum value (\( Y_{max} \)). The Drucker-Prager equation is expressed by Eq. (6) using the slope (\( a \)) and vertical intercept (\( b \)) of the straight line:

\[
Y = \min(Y_{max}, aP + b)
\]

The static tensile strength (\( f_t \)) was calculated using Eq. (7) with a static compressive strength (\( f_c \)) (JSCE 1996):

\[
f_t = 0.23 \times f_c^{3/3}
\]

The strain rate (\( \dot{\varepsilon} \)) was assumed to be in the order of \( 10^9 \) (unit: 1/s), and the dynamic compressive strength (\( f_c^d \)) and dynamic tensile strength (\( f_t^d \)) proposed by Yamauchi et al. (1989a, 1989b) were introduced into the Drucker-Prager equation as follows:

\[
\begin{align*}
\frac{f_c^d}{f_c} &= 1.021 - 0.05076 \cdot \log \dot{\varepsilon} + 0.02583 \cdot (\log \dot{\varepsilon})^2, \\
\frac{f_t^d}{f_t} &= 0.8267 + 0.02987 \cdot \log \dot{\varepsilon} + 0.04379 \cdot (\log \dot{\varepsilon})^2
\end{align*}
\]

where the unit of \( \dot{\varepsilon} \) in Eqs. (8) and (9) was 1/\( \mu \).s.

The relationship between the cohesion (\( c \)) and friction angle (\( \phi \)) is defined as follows:

\[
\begin{align*}
f_c^d &= 2c\cos\phi/(1 - \sin\phi) \\
f_t^d &= 2c\cos\phi/(1 + \sin\phi)
\end{align*}
\]

The following equations are derived using the relationship of \( n = f_c^d / f_t^d \):

\[
c = \sqrt{n} f_t^d / 2
\]

\[
\cos\phi = 2n/(n + 1)
\]

\[
\sin\phi = n - 1/(n + 1)
\]

The failure surface in the Drucker-Prager model is defined as the following expression using coefficients \( \alpha \) and \( \kappa \):

\[
\alpha I_1 + \sqrt{J_2} - \kappa = 0
\]

where \( I_1 \) and \( \sqrt{J_2} \) are the first and second invariants of stress, respectively. By adapting a condition that the failure surface of the Drucker-Prager model is inserted into Mohr-Coulomb’s law, the following expressions are derived:

\[
\alpha = \frac{2\sin\phi}{\sqrt{3(3 - \sin\phi)}}
\]

\[
\kappa = \frac{6\cos\phi}{\sqrt{3(3 - \sin\phi)}}
\]

From Eqs. (13), the slope (\( a \)) and vertical intercept (\( b \)) in the Drucker-Prager model are:

\[
a = 3\sqrt{3}\alpha, \quad b = \sqrt{3}\kappa
\]

Equation (14) can be rewritten using \( n \) and \( f_c^d \):

\[
a = \frac{3(n - 1)}{n + 2}, \quad b = \frac{3}{n + 2} f_c^d
\]

The slope (\( a \)) and vertical intercept (\( b \)) were calculated by substituting \( f_c^d \), \( f_t^d \) and \( n \) in Eq. (15). The material parameters used for the concrete are shown in Table 8.

(3) Steel

In cases where steel is subjected to a strong shock force, an EOS which depends on density and internal energy should be properly adapted. In this calculation, however, the linear EOS was adapted to the steel, because the steel
reinforcements were modeled by shell elements in which the status of both the density and the internal energy was not taken into account. $E = 205.9$ GPa and $v = 0.3$ were assumed, and the bulk modulus and shear modulus were calculated by the same method as adapted to concrete.

The Johnson-Cook constitutive model was applied to the steel (Johnson and Cook 1983). In this model, the yield stress ($Y$) is estimated by the function of equivalent plastic strain ($\varepsilon_p$), dimensionless equivalent plastic strain rate ($\dot{\varepsilon}_p / \dot{\varepsilon}_0$, $\dot{\varepsilon}_0 = 1.0 (1/s)$) and homologous temperature ($T^*$):

$$Y = (A + B \dot{\varepsilon}_p^my)(1 + C\ln\dot{\varepsilon}_p)(1 - T^*/Tm)$$  \hspace{1cm} (16)

where $A$, $B$, $n$, $C$, $m$ are the material parameters, and $T^*$ is defined by:

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$$  \hspace{1cm} (17)

where $T_{room}$ is the room temperature, and $T_{melt}$ is the melting temperature.

The material parameters used for the steel are shown in Table 9. Among the parameters of the Johnson-Cook model, $A$ was determined by the measurement of 0.2% proof stress, and the other parameters were determined based on the values of 1006 carbon steels standardized by the American Iron and Steel Institute. However, the thermal term is neglected for the shell solvers, because no volume change, consequently no temperature changes of the elements are calculated in the solvers.

As the fracture strain in the calculation, not the nominal value (12.8%) but the true value (12.6%) was adopted. The tensile strength calculated by the Johnson-Cook equation with these parameters was 778.1 MPa, which was close to the measured value of 733 MPa.

(4) Aluminum

For aluminum, the Mie-Grüneisen form of the shock Hugoniot EOS (McQueen et al. 1970) and the Johnson-Cook constitutive model (Johnson and Cook 1983) were applied. The material parameters were determined by the value for 2024Al (Johnson and Cook 1983), however, the details were left out because it is not a principal object of this calculation.

### 3.2 Results and discussion

Figure 10 shows the comparison of the damage of the air-sandwiched normal RC slab between the experiment and the calculation at 0.5 ms.

The numerical result seems to evaluate the spall diameter in the lower layer a little larger than the experiment, but the overall results of the damage to the RC slab in the calculation show a fairly good agreement with the experiment. It should be noted that all of the red-colored parts of concrete in Fig. 10 (a) are not necessarily crushed, because the concrete is expected to retain its strength in the direction of no cracking.

The distribution of equivalent plastic strain is also shown in Fig. 10 (b). Parts with over 1.5% of strain exist within the concrete, however they are distributed within...
a limited area. Therefore, the damage to both layers may be ruled by the spall failure mode rather than the compressive failure mode.

**Figure 11** shows the temporal changes in the material status (0.02–0.20 ms). In the figure, the concrete fragments launched from the back side of the upper layer due to the spall failure act as an impact load on the upper surface of the lower layer, and then cause spall failure accompanied by breaching to the lower layer. Therefore, it was clarified that the damage in the lower layer was not due to the detonative loading directly but to the impact of the concrete fragments from the back surface of the upper layer.

**Table 10** shows the analogical fracture process of the double-layered PEFRC slab with a 15-mm thick air gap (specimen PE-AIR-15), as well as the fracture process of specimen NC-AIR-15 based on the numerical result. In the upper layer of the PEFRC slab, the PEFRC near the back surface is not broken into pieces by the tensile stress wave, because of the bridging effects of polyethylene short fibers. Simultaneously, the PEFRC fragments bulged from the back surface of the upper layer may be decelerated by the polyethylene short fibers bridging at the spall face of the upper layer. Therefore, the fragments, which are thrust from the back surface of the upper layer of the normal RC slab, are prevented from being launched by their contact with the upper surface of the lower layer in the PEFRC slab. Moreover, in the lower layer of the PEFRC slab, very fine internal cracks parallel to the back surface are observed, which are expected to form the spall face in the normal RC slab, but the cracks

![Fig. 11 Temporal change in material status.](image)
opening is prevented by the polyethylene short fibers bridging at the spall cracking face, and cross-shaped cracking similar to static flexural cracking is observed on the back surface.

Based on the above discussion, the better blast resistance of the air-sandwiched PEFRC slab may be explained qualitatively, considering the interaction between the following two factors: 1) the decline in impact force of the upper layer fragments on the lower layer, by means of the deceleration of the fragments, and 2) the change in failure mode of the lower layer from ‘local failure’ to ‘flexural failure’ (Zhang et al. 2007). Both factors are due to the bridging effects of the polyethylene short fibers.

4. Conclusions

In this study, to propose an idea for rapid construction and better blast resistance of blast-resistant RC structures, the contact detonation tests were conducted on double-layered RC slabs composed of precast thin plates, 50 mm thick, made of either normal concrete or PEFRC. Furthermore, a numerical simulation was conducted to reveal the fracture process of the double-layered normal RC slab with an air cavity to help understanding of the difference between PEFRC and normal RC slabs. As a result, the following conclusions were reached:

(1) It is difficult to improve the blast resistance of double-layered PEFRC and normal RC slabs by internal polyethylene fiber mesh reinforcement sheets.

(2) Creating an air cavity in the middle of the double-layered PEFRC slab is an effective way of reducing the spall damage, while the air space has no advantage in the normal RC, under a condition that the thickness of the air space is fixed at 15 mm. Furthermore, the damage in the lower layer of the air-sandwiched PEFRC slab tends to diminish as the thickness of the air gap increases.

(3) In both the double-layered PEFRC and normal RC slabs, shock absorbers (chloroprene rubber, chloroprene sponge, and expanded poly-styrol) inserted into the air space had no advantage in reducing spall damage.

(4) On the analogy of the numerical result on the air-sandwiched normal RC slab, the better blast resistance of the air-sandwiched PEFRC slab may be explained qualitatively, by the high toughness of both layers due to the bridging effects of the polyethylene short fibers.

We are assuming the double-layered slabs with an air cavity to be applied to a sandwich wall system, in which the structural frames are inserted between two thin PEFRC plates, composing important structures such as industrial plants and public facilities. However, the conclusions of this study cannot directly be applied in the practice of building constructions, because the blast resistance of the double-layered slab may be influenced by other factors such as dimensions of slab, amount of explosives, mix proportion of fiber reinforced concrete, and way of attaching the panels to the frames. Further, more investigations are needed to clarify the fracture mechanism of the double-layered PEFRC slabs subjected to contact detonation.

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