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Masuhiro Beppu1,*, Tomonori Ohno1, Kazunori Ohkubo2, Bing Li3, Kazuyuki Satoh4

1Department of Civil and Environmental Engineering, National Defense Academy, Yokosuka, Japan
2Eastern Army Logistics Support Troop, Japan Ground Self Defense Force, Tokyo, Japan
3School of Civil and Environmental Engineering, Nanyang Technological University, Singapore
4Maeda Kosen Corporation, Tokyo, Japan

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ABSTRACT
The present work is intended to evaluate the effectiveness of fiber sheet reinforcement on explosive-resistant performance of concrete plates. Carbon fiber sheets or aramid fiber sheets have been employed to reinforce concrete plates. Explosion tests have been conducted to examine the effect of fiber sheet reinforcement on local damage and fragmentation of concrete plates. Test data are compared with the estimated values formulated by Morishita et al. and the characteristics of local damage are discussed. Local damage of concrete plates reinforced by carbon or aramid fiber sheets has been extremely reduced as compared with that of concrete plates without fiber sheet reinforcement. These fiber sheets also have prevented concrete plates from fragmentation.

Key words: contact explosion, fiber sheet reinforced concrete plates, explosive resistant performance.

1. INTRODUCTION
In recent years, explosive incidents caused by terrorist’s attack and accidental explosion in the chemical plants have increased in the world. It has been, then, recognized that the extreme dynamic loading in explosion should be taken into account in structural design for the need to protect both military and civilian facilities. To establish a design method which protects structures from the explosive load, a mechanism of the structural failure should be investigated. However, few studies on the failure behavior of concrete members and

*Corresponding author. Tel.: +81-468413811; fax: +81-468445913. E-mail address: beppu@nda.ac.jp
structures under blast loading have been conducted. When the explosive load is applied to concrete structures, global failure such as bending and shear and local damage, i.e. crater, spall and breach, will occur according to the intensity of the load.

Prediction methods and formulae on the penetration in concrete are described in TM5-855-1 [1] and TM5-1300 [2]. Fragmentation of RC slabs due to airblast loads was examined experimentally [3], and numerical simulations on fragmentation were attempted [4, 5]. For close-in explosion, explosion tests of concrete slabs were carried out by MacVay [6] to examine the effect of the mass of explosives, the stand-off distance and the thickness of the concrete plate. Recently, Morishita et al. [7, 8] conducted contact explosion tests for concrete slabs using Pentolite explosive. In a series of tests [7, 8, 9], influence of compressive strength of concrete and degree of reinforcement with reinforcing bars was examined. It was reported from the test that compressive strength of concrete and interval of reinforcing bars did not correlate with the intensity of the local damage of concrete slabs and fragmentation. The result points to a need for other measures to reduce the local damage of concrete plates. In the meantime, carbon and aramid fiber sheets have been widely used to reinforce and retrofit structural members under seismic or dynamic loading. These fiber sheets also can prevent projectiles formed by fragments of concrete due to deterioration, and are possibly effective in reducing the local damage of concrete plates subjected to the contact explosion.

The present work is intended to evaluate the effectiveness of fiber sheet reinforcement on explosive-resistant performance of concrete plates. Explosion tests were conducted to examine change of the failure mode and the effect of reinforcement with carbon or aramid fiber sheets.

2. EXPERIMENTAL SETUP
2.1. CONCRETE PLATES AND FIBER SHEETS
An outline of experimental setup is shown in Photo 1 and Fig. 1. A specimen is put on steel supports. The test specimens are made of concrete with compressive strength of 28.9 N/mm², and are square plates of 500 mm × 500 mm and 80 mm in thickness as shown in Fig. 2.

Carbon and aramid fiber sheets are used for reinforcing some of the specimens. The lower surface of the concrete plate is covered with the fiber sheet using epoxy resin adhesive. The weave directions of fiber sheets are uni-directional or bi-directional as shown in Fig. 3.
Figure 1. Schematic diagram of experimental setup

Figure 2. Dimension of a concrete plate

Figure 3. Weave direction of fiber sheets
Table 1. Mechanical properties of each fiber sheet

<table>
<thead>
<tr>
<th>Type of sheet</th>
<th>Weave direction</th>
<th>Mass / unit area (g/m²)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>Uni-directional</td>
<td>3400</td>
<td>0.111</td>
<td>3400</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>Bi-directional</td>
<td>200</td>
<td>245</td>
<td>2500</td>
<td>0.0556/0.056</td>
</tr>
<tr>
<td>Aramid</td>
<td>Uni-directional</td>
<td>280</td>
<td>0.193</td>
<td>2060</td>
<td>0.193</td>
</tr>
<tr>
<td></td>
<td>Bi-directional</td>
<td>650</td>
<td>118</td>
<td></td>
<td>0.193/0.193</td>
</tr>
</tbody>
</table>

Table 2. Test cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of sheet</th>
<th>Direction</th>
<th>Number</th>
<th>Thickness (mm)</th>
<th>Tensile stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No reinforcement</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Uni-directional</td>
<td>Two</td>
<td>0.111/0.111</td>
<td>27.2</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>Bi-directional</td>
<td>One</td>
<td>0.0556/0.0556</td>
<td>13.6</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>7</td>
<td>Bi-directional</td>
<td>Two</td>
<td>0.111/0.111</td>
<td>27.2</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>Uni-directional</td>
<td>One</td>
<td>0.193</td>
<td>22.8</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>11</td>
<td>Uni-directional</td>
<td>Two</td>
<td>0.193/0.193</td>
<td>22.8</td>
<td>–</td>
</tr>
<tr>
<td>12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>13</td>
<td>Bi-directional</td>
<td>One</td>
<td>0.193/0.193</td>
<td>22.8</td>
<td>–</td>
</tr>
<tr>
<td>14</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Mechanical properties of carbon and aramid fiber sheets are summarized in Table 1. The mass per unit area of carbon fiber sheets of each direction is 200 g/m². For aramid fiber sheets, the masses per unit area of uni-directional and bi-directional sheets are 280 and 650 g/m² respectively. Young’s modulus of carbon fiber sheets is 245 GPa, and tensile strength of uni-directional and bi-directional sheets are 3,400 and 2,500 MPa respectively. Compared to mechanical properties of aramid fiber sheets, Young’s modulus and tensile stiffness of carbon fiber sheets is 2.1 times and 1.2 to 1.7 times larger than those of aramid fiber sheets, respectively. The thickness of aramid fiber sheet is 0.193 mm, which is 1.7 to 3.1 times larger than that of carbon fiber sheets. Experimental parameters are the number of sheet layers and weave direction as shown in Table 2. Based on the mechanical properties, tensile stiffness varies from 13.6 to 27.2 kN/mm.

2.2. C4 EXPLOSIVE

TNT and/or Pentolite explosives have been used widely in explosion tests for structural members. In this study, Composition C-4 (C4) explosive is used because it is very safe chemically and easier to cast. The mass of C4 was set so that a failure mode of no-reinforced
concrete plate would be “threshold breach”. For contact explosion, in order to predict occurrence of “breach”, the following formula has been proposed by Morishita et al. [7]. This empirical equation is applicable for the compressive strength of concrete between 17.2 and 84.8 MPa.

\[
T/W^{1/3} = 2.0
\]

(1)

where \( T \) is the thickness of a concrete plate (cm), \( W \) is the equivalent TNT mass (g), \( T/W^{1/3} \) is the scaled thickness of a concrete plate (cm/g\(^{1/3}\)).

Since the mass used in eqn (1) is the equivalent TNT mass, the mass of C4 must be converted into the equivalent TNT mass. The thermal energy [10, 11] of TNT is 4,521 kJ/kg and that of C4 explosive is 5,651 kJ/kg, thus the ratio of thermal energy between C4 and TNT explosive is 1.25. In this study, the mass of C4 is converted to the equivalent TNT mass using the above ratio.

Substituting the thickness of plates of 8 cm into eqn (1), the mass of C4 was set to be 46 g for all test cases. Shape of the C4 explosive is a cylinder in which the ratio between the height and diameter is 1.0 as shown in Fig. 4. A detonator is inserted on the top of the C4 explosive.

### 2.3. DEFINITION AND MEASUREMENT OF THE LOCAL DAMAGE

Based on observation of local damage in cross sections, failure modes of concrete plates were classified into “crater”, “spall”, “breach”, “diagonal crack” and “interface damage”, as shown in Fig. 5. The definition and difference between “spall” and “diagonal crack” are as follows: “Spall” is fragmentation where fragments are detached from a concrete plate completely. “Diagonal crack” shows apparent crack, which comes from the inside of the concrete plate to the lower surface diagonally. “Interface damage” is fracture between a concrete plate and a fiber sheet. After the tests, the diameter and depth of “crater”, the depth and width of “diagonal crack”, the depth of spall and the width of “interface damage” are measured as shown in Fig. 6.
3. RESULTS AND DISCUSSION
3.1. FAILURE MODES OF CONCRETE PLATES
Failure modes of no-reinforced concrete plates (no fiber sheet) observed in our tests are shown in Fig. 7. In the figures, supports are set at right and left sides of the concrete plate as depicted in the figure of case 1. In the following figures, configuration of supports is the same. It can
be seen in Fig. 7 that failure modes of case 1 and 2 are “crater and spall” and “breach”, respectively. That is, these failures agree with the prediction by Morishita’s formula.

Shown in Fig. 8 is the local damage of concrete plates with carbon fiber sheet reinforcement. Circular solid lines on lower surfaces show damage areas confirmed by change of sound when a percussion-hammer rolls on the lower surface. For “Uni-directional two carbon sheets” (case 3 and 4), both of the failure modes are “crater, diagonal crack and interface damage”, where the degree of spall is less than that of “no-reinforced concrete plates” significantly. For “Bi-directional one carbon fiber sheet” (case 5 and 6), failure modes show “crater, spall, diagonal crack and interface damage” and “crater, diagonal crack and interface damage”. It follows from these data that this failure mode is probably “threshold spall”. The difference between “Uni-directional two carbon sheets” and “Bi-directional one carbon fiber sheet” seems to be caused by the difference of the thickness of each sheet because the thickness of “Bi-directional sheet” is half of that of “Uni-directional sheet” as shown in Table 2. To predict “threshold spall”, Morishita et al. [7] have proposed the following formula based on test data.

\[
T/W^{1/3} = 3.6
\]

\[ \text{(2)} \]

Thickness of “threshold spall” for a no-reinforced concrete plate can be calculated to be 12.9 cm by eqn (2), whereas, thickness of the fiber sheet reinforced concrete plate showed “threshold spall” is 8 cm. This result indicates that the effect of reinforcement with “Bi-directional one sheet” is equivalent to concrete thickness of about 5 cm. Next, for “Bi-directional two carbon sheets” (case 7 and 8), both of the failure modes are “crater, diagonal crack and interface damage”, where spall does not occur at all. These findings above clearly indicates that fragmentation is prevented completely and spall can be reduced by “Uni-directional two carbon sheets” and “Bi-directional two carbon sheets”.

Local damage of concrete plates with aramid fiber sheet reinforcement is shown in Fig. 9. It can be seen in Fig. 9 that both of failure modes are “crater, spall, diagonal crack and

<table>
<thead>
<tr>
<th>Case</th>
<th>Upper face</th>
<th>Lower face</th>
<th>Cross section</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Upper face image" /></td>
<td><img src="image2" alt="Lower face image" /></td>
<td><img src="image3" alt="Cross section image" /></td>
<td>Crater spall</td>
</tr>
<tr>
<td>2</td>
<td><img src="image1" alt="Image 1" /></td>
<td><img src="image2" alt="Image 2" /></td>
<td><img src="image3" alt="Image 3" /></td>
<td>Breach</td>
</tr>
</tbody>
</table>

Figure 7. Failure modes of no-reinforced concrete plates
interface damage” for “Uni-directional one aramid fiber sheet” (case 9 and 10). Failure modes for “Uni-directional two aramid fiber sheets” (case 11 and 12) are “crater, diagonal crack and interface damage”. For “Bi-directional one aramid fiber sheet”, both of failure modes are “crater, diagonal crack and interface damage”. The intensity of damage in this case is similar to that of “Uni-directional two aramid fiber sheets”.

### 3.2. RELATIONSHIP BETWEEN DEPTH AND DIAMETER FOR CRATER AND SPALL

The depth versus diameter of crater is plotted as shown in Fig. 10. In the figure, a solid line shows the relationship between crater depth and diameter, and dashed lines show predicted crater depth and diameter for the plate thickness and the mass of C4 explosive used in the

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>Upper face</th>
<th>Lower face</th>
<th>Cross section</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Uni-dir. two sheets</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td>Crater Diagonal crack Interface damage</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td>Crater Diagonal crack Interface damage</td>
</tr>
<tr>
<td>5</td>
<td>Bi-dir. one sheet</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td>Crater Spall Diagonal crack Interface damage</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td>Crater Diagonal crack Interface damage</td>
</tr>
<tr>
<td>7</td>
<td>Bi-dir. two sheets</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td>Crater Diagonal crack Interface damage</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
<td>Crater Diagonal crack Interface damage</td>
</tr>
</tbody>
</table>

Figure 8. Failure modes of carbon fiber reinforced concrete plates
test. The formulas were proposed by Morishita et al. [7] based on their test data and expressed as follows:

\[
\frac{C_d}{T} = -0.047 \frac{T}{W_{1/3}} + 0.43 \quad (3a)
\]

\[
\frac{C_d}{T} = 0.20 \frac{C}{T} \quad (3b)
\]

where \( C_d \) is the depth of crater, \( C \) is the diameter of crater.
It can be seen from this figure that the diameter varies from 130 to 160 mm, and the depth varies from 20 to 28 mm. Comparing the test data with the results of eqn (3), it is found that the diameter and depth of crater can be estimated comparatively well regardless of type and the number of fiber sheet. The depth versus diameter of spall is plotted as shown in Fig. 11. In the figure, solid lines show the relationship between the
depth of spall $S_d$ and diameter $S$, the equation for which has been also developed by Morishita et al. [7] as follows:

\[
\frac{S_d}{T} = 0.15 \frac{S}{T} \quad \text{(For no breach, } \frac{S}{T} < 2.9) \tag{4a}
\]

\[
\frac{S_d}{T} = -0.017 \frac{S}{T} + 0.71 \quad \text{(For breach, } \frac{S}{T} \geq 2.9) \tag{4b}
\]

where $S_d$ is the depth of spall, $S$ is the diameter of spall.

Morishita reported that the relationship between the depth and diameter of spall was not continuous as shown in eqn (4) and Fig. 11 according to their test data. For “no-reinforced concrete plates”, since the failure mode is “threshold breach”, the depth of spall is close to the result of “breach”. In contrast, for fiber reinforced concrete plates, the depth of spall is closer to that of “no breach”. The result indicates that damage of concrete is reduced by reinforcing with fiber sheets. For “Bi-directional one carbon fiber sheet”, the depth and diameter are reduced by 21% and 10% compared with that of no-reinforced concrete plates, respectively. For “Uni-directional one aramid fiber sheet”, the depth and diameter are reduced by 31% and 11%, respectively. However, the diameter of diagonal crack and interface damage were larger than those for no-reinforced concrete plates. The larger damage area was probably caused due to deformation after the local damage was formed.

3.3. DIAGONAL CRACK

In Fig. 12, the height versus width of “diagonal crack” is plotted, where the relationship calculated by eqn (4) is also drawn. It is found from this figure that the height of “diagonal crack” tends to be higher than that of “spall” though diagonal crack appears as slight damage before occurrence of “spall”. This result probably indicates that fiber sheet reinforcement

![Figure 12. Height and width of diagonal crack](image-url)
will reduce spalling significantly, but the inner crack, which will be caused by stress wave, will be developed due to local deformation and oscillation of the concrete plate. Notice that the tensile stiffness has been used to describe punching shear capacity of slabs. Figure 13 shows the relationship between the height of diagonal crack and the tensile stiffness of fiber sheets. The relationship indicated that the height of diagonal crack decreases with increasing tensile stiffness of fiber sheets in the test range. The result gives us a clue to the effect of fiber sheet reinforcement, that is, the punching shear capacity of a concrete plate might increase with increasing tensile stiffness. The punching shear capacity of concrete plates can be calculated using the following equation as given in the standard specifications for concrete structures [12] published by Japan Society of Civil Engineers.

\[
V_{pcd} = \beta_d \cdot \beta_p \cdot \beta_f \cdot f'_{pcd} \cdot u_p \cdot d / \gamma
\]  

(5)

where \( f'_{pcd} = 0.20 \sqrt{f_c}, u_p = u_0 + 2\pi \cdot d / 2, \beta_d = 1000/d, \beta_p = \sqrt{100p}, p = (p_x + p_y) / 2, \beta_f = 1 + 1/(1 + 0.25u_0/d), f_c \) is the compressive strength of concrete (N/mm²), \( u_0 \) is the perimeter of loading area (mm), \( u_p \) is the perimeter of assumed cross section (mm), \( d \) is the effective thickness of plate (mm), \( p_x \) and \( p_y \) are the ratios of rebar in x and y directions.

Then, converting the tensile stiffness of fiber sheets into the ratio of rebar, the parameter \( \beta_p \) is modified as follows [13]:

\[
\beta'_p = \sqrt[100](p + n_f A_f / (bd))
\]  

(6)

where \( n_f = E_f / E_s \) is the ratio of Young’s modulus between fiber sheet and steel, \( E_f \) is Young’s modulus of fiber sheet, \( E_s \) is Young’s modulus of rebar, \( A_f \) is the cross section area of fiber sheet, \( b \) is the width of a concrete plate.
Because perimeter of loading area could not be measured in this test, loading area is assumed to be the same as cratering area. Based on eqns (5–6), punching shear capacity of concrete plate is obtained as shown in Table 3. Punching shear capacity of the fiber reinforced concrete plate increases by 15 to 27% compared with that of no-reinforced concrete plate of which punching shear capacity is 40.3 kN. This fact indicates that the increase of punching shear capacity probably correlates with enhancement of the explosive resistant performance of concrete plates.

4. CONCLUSION
In the present work, effectiveness of carbon or aramid fiber sheet reinforcement on explosive-resistant performance of concrete plates has been investigated. The degree of local damage of concrete plates subjected to contact explosion has been estimated adequately by Morishita’s formulae, converting the mass of C4 into equivalent TNT mass. For either fiber sheets, fragmentation has been prevented completely. In the case of carbon fiber sheet reinforcement, spall was not totally prevented, but the intensity of local damage has been decreased. For aramid fiber sheet reinforcement, spall has been prevented completely. As the tensile stiffness of fiber sheets increases, the height of diagonal crack has decreased. This result indicates that the increase of tensile stiffness of fiber sheets probably correlates with enhancement of the explosive resistance of concrete plates.

REFERENCES

<table>
<thead>
<tr>
<th>Type of sheet</th>
<th>Thickness (mm)</th>
<th>Punching shear capacity (kN)</th>
<th>Ratio to no-reinforced concrete plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.111</td>
<td>51.3</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>0.0556</td>
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<tr>
<td>Aramid</td>
<td>0.193</td>
<td>49.9</td>
<td>1.23</td>
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</table>


