Impact-resistant behavior of shear-failure-type RC beams under falling-weight impact loading

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Abstract

In this study, to investigate the impact-resistant behavior of shear-failure-type reinforced concrete (RC) beams, falling-weight impact tests were conducted by means of a single loading method. Nineteen simply supported rectangular RC beams were used for these experiments. All RC beams were of 200 mm wide, 400 mm deep, and 2,400 mm long in dimensions, in which shear rebar ratio and impact velocity were taken as variables. An impact load was applied on to the mid-span of each RC beam by dropping a steel-weight (hereinafter, striker) with a 400 kg mass. In these experiments, the impact force excited in the striker, the reaction force and the mid-span displacement were measured and recorded by wide-band analog data recorders. The results obtained from this study are as follows: 1) when the RC beam reaches the ultimate state with shear-failure mode, reaction force vs. mid-span displacement curve forms an isosceles triangle, irrespective of magnitude of shear rebar ratio; 2) at the time, maximum reaction force reaches an absolute value; 3) using the relationship between absolute maximum dynamic reaction force and static shear capacity, an impact-resistant design for shear-failure-type RC beams can be rationally performed using the static shear capacity.

1 Introduction

RC and prestressed concrete (PC) structures such as rock-sheds, check-dams, and nuclear power plants should be constructed with a margin of safety against impact loading. Recently, in order to establish a rational impact-resistant design procedure for these RC/PC structures, a number of fundamental studies for the impact-resistant behavior of RC/PC members (i.e. beam, slab, and column) have
been conducted experimentally and numerically [1-4]. As a result, the impact-resistant behavior of bending-failure-type RC/PC members has been cleared considerably. And, for this type of RC beam, a rational impact-resistant design procedure has been proposed and an applicability of the proposed design procedure has been confirmed within a range of 10 m/s impact velocity [5].

However, the impact-resistant behavior of shear-failure-type RC/PC members has not been investigated adequately. To more rationally design the RC/PC members subjected to impact loading, it is important to understand the impact-resistant behavior of not only bending-failure-type members but also shear-failure-type members. And also, it needs to establish an impact-resistant design procedure for shear-failure-type RC/PC members.

From this point of view, in this study, focusing on impact-resistant behavior of the shear-failure-type RC beam, falling-weight impact tests were carried out using nineteen RC beams with the shear rebar ratio and the impact velocity taken as variables.

2 Experimental overview

2.1 Dimensions and static design values of RC beams

Figure 1 shows an example of the dimensions of RC beam and rebar arrangement for RC beams used in this study. All RC beams were of 200 x 400 x 2,400 mm in dimensions. And D35 and D6 deformed rebars were used as the axial and shear reinforcement, respectively. Four axial rebars were used for all RC beams. On the other hand, regarding shear rebars, three types of arrangement were considered: 1) non-arrangement; 2) 150 mm interval arrangement; 3) 75 mm interval arrangement (see Fig.1). These types of RC beams were designated as S0, S2, and S4 beam, respectively. Referring to the shear rebar volume described above, each RC beam is designated using the volume, in which “S” stands for the beam with shear-failure type and one digit indicates the value of 1,000 times shear rebar ratio.

The static design values for these three types of RC beams are listed in Table 1. The static shear capacity $V_{usc}$ and the static bending capacity $P_{usc}$ were calculated using the Japanese Concrete Standard Specification [6], and static
Table 1. Static design values for three types of RC beams.

<table>
<thead>
<tr>
<th>Nominal name</th>
<th>Main rebar ratio $p_t$</th>
<th>Shear rebar ratio $p_s$</th>
<th>Static shear capacity $V_{usc}$ (kN)</th>
<th>Static bending capacity $P_{usc}$ (kN)</th>
<th>Capacity ratio $\alpha$ ($=V_{usc}/P_{usc}$)</th>
<th>Measured static shear capacity $V_{us}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>0.027</td>
<td>0.0</td>
<td>165</td>
<td>449</td>
<td>0.37</td>
<td>196</td>
</tr>
<tr>
<td>S2</td>
<td>0.002</td>
<td>0.027</td>
<td>254</td>
<td>409</td>
<td>0.57</td>
<td>409</td>
</tr>
<tr>
<td>S4</td>
<td>0.004</td>
<td>0.002</td>
<td>343</td>
<td>464</td>
<td>0.76</td>
<td>464</td>
</tr>
</tbody>
</table>

Table 2. Material properties of concrete.

<table>
<thead>
<tr>
<th>Age (day)</th>
<th>Compressive strength $f'_c$ (MPa)</th>
<th>Elastic modulus $E_c$ (GPa)</th>
<th>Poisson’s ratio $\nu_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>42.2</td>
<td>25.7</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 3. Material properties of axial and shear rebars.

<table>
<thead>
<tr>
<th>Nominal name</th>
<th>Grade</th>
<th>Yield stress $\alpha_f$ (MPa)</th>
<th>Elastic modulus $E_s$ (GPa)</th>
<th>Poisson’s ratio $\nu_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D35</td>
<td>SD345</td>
<td>373</td>
<td>206</td>
<td>0.3</td>
</tr>
<tr>
<td>D6</td>
<td>SD295A</td>
<td>373</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Test cases.

<table>
<thead>
<tr>
<th>Nominal name</th>
<th>Impact velocity of striker $V$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>0.9, 3.6, 4.0, 4.5,</td>
</tr>
<tr>
<td>S2</td>
<td>0.9, 3.6, 4.5, 5.4, 6.3, 7.2, 8.1</td>
</tr>
<tr>
<td>S4</td>
<td>0.9, 3.6, 4.5, 6.3, 7.2, 8.1, 9.0, 9.9</td>
</tr>
</tbody>
</table>

Shear-bending capacity ratio $\alpha$ is obtained by dividing $V_{usc}$ by $P_{usc}$. According to the specification, all three types of RC beams will be collapsed in a shear-failure mode under static loading because their $\alpha$'s are less than 1.0. At the commencement of the experiments, the material properties of the concrete and rebar are listed in Tables 2 and 3.

2.2 Test case and test procedure

The test cases considered here are listed in Table 4. More than four specimens were prepared for each type RC beam. One specimen for each was tested at 0.9 m/s impact velocity to investigate the elastic behavior of the RC beam. Here, the impact velocity was defined as the velocity of striker at which it was just impacted onto the RC beam. The remained specimens were tested at impact velocities of $V \geq 3.6$ m/s to investigate the impact-resistant behavior of RC beams from the elasto-plastic region to the ultimate state.

Each specimen was simply supported and was fixed on its top and bottom surface at a point 200 mm inside the ends as shown in Photo 1. An impact load was singly applied onto the mid-span of RC beam by dropping a 400 kg striker.
The striking face is of spherical surface with a radius of 1,407 mm. From the previous test results by Kishi et al. [7], it was confirmed that the effects of a radius of the striking face on the dynamic response and the failure mode of RC beams are relatively small.

In these experiments, the impact force excited in the striker, the reaction force, and the mid-span displacement (hereinafter, displacement) were measured and recorded using wide-band analog data recorders. After testing, crack patterns developed on the side-surface of RC beams were sketched.

3 Experimental results and discussions

3.1 Crack patterns

Figure 2 shows an example of the crack patterns on the side-surface of three types of RC beams. Here, impact-resistant characteristics for each RC beam are investigated focusing on the crack patterns in case of $V = 3.6$ m/s impact velocity.

From these figures, it can be seen that severe diagonal cracks and/or arch-shaped cracks occur from the loading point to the support points in each type RC beam. And also, other diagonal cracks with inclination of about 45 degrees occur in the central area of all RC beams. Observing the crack pattern for each RC beam in detail, in case of S0 beam, arch-shaped cracks are developed. It means that concrete and main rebars resist against an impact shear force. And horizontal cracks are developed from the edges of the arch-shaped cracks toward the support points along the axial rebars and the cover concrete in
these regions of both sides is split. It is seemed that these are due to a dowel action of main rebars. Also the area around the loading point is intended to be under compression failure.

On the other hand, in cases of S2 and S4 beams, diagonal cracks become predominant and crack spacing becomes small corresponding to the magnitude of shear rebar ratio. This is because initially concrete and main rebar jointly resist against the impact shear force, but after developing diagonal cracks, mainly shear rebars resist effectively.

### 3.2 Time histories of impact force $P$, reaction force $R$, and mid-span displacement $\delta$

Figure 3 shows the time histories of impact force $P$, reaction force $R$, and the mid-span displacement $\delta$ for each type RC beam. Here, the results for the cases of all impact velocities except the cases of $V = 4.0, 9.0, \text{ and } 9.9 \text{ m/s}$ are shown. The reaction force $P$ is evaluated by summing up the values obtained from both support points.

Focusing on the impact force wave $P$, in case of $V = 0.9 \text{ m/s}$, it can be seen that each wave is composed of two sinusoidal waves with a vibration period of almost 2.5 ms, irrespective of beam type, and the shapes of their waves are similar among three types RC beams. Similarly, in cases of $V \geq 3.6 \text{ m/s}$, each wave is composed of two waves: one is a half sinusoidal wave excited in the beginning of impact and another is a wave with relatively long duration. However, the shapes of the waves are different between S0 beam and the other beams. Namely, the second peak of S0 beam is smaller than those of S2 and S4 beams. This means that: 1) in case of S0 beam, the shear stiffness is decreased...
Figure 3: Time histories of impact force $P$, reaction force $R$, and mid-span displacement $\delta$.

rapidly due to severe arch-shaped cracks being developed and opened (Fig. 2a),
because any shear rebars are not arranged; 2) on the other hand, in cases of S2
and S4 beams, the shear stiffness is not decreased suddenly because shear rebars
resist against the impact force after severe diagonal cracks being generated (Figs.
2b and 2c).

Moreover, in comparison of the impact force wave $P$ between S2 and S4
beams, it can be confirmed that these waves behave similarly to each other,
irrespective of the magnitude of impact velocity. This tendency can be also seen
in the reaction force wave $R$ and the displacement wave $\delta$. This implies that
almost the same level of shear stiffness may be kept during impact load being
surcharged and the shear rebars may not be yielded remarkably, irrespective of
the magnitude of the shear rebar volume.

For the reaction force wave $R$, in case of $V = 0.9$ m/s, the shapes of the
waves are in good agreement among three beams. However, in cases of $V = 3.6$
m/s and 4.5 m/s, their shapes are different between S0 beam and the other beams.
This is the similar result to that of impact force wave $P$. Considering the
difference of their shapes at $V = 3.6$ m/s and 4.5 m/s, the reaction force wave $R$
for S0 beam is composed of the first half sinusoidal wave at the beginning of
impact and the second wave with long duration (8-10 ms) and the amplitude less than one-third that of the first wave. In contrast, those of S2 and S4 beams are composed of two sinusoidal waves with the period of about 4 ms and a half sinusoidal wave with long duration (8-10ms) and the amplitude of twice that of the former waves. In addition, focusing on the waves in cases of $V \geq 5.4 \text{ m/s}$, the duration and the amplitude of the waves for S2 and S4 beams become longer and larger than those in cases of $V \leq 4.5 \text{ m/s}$. However, the former shapes are almost similar to the latter ones.

For the displacement wave $\delta$, in case of $V = 0.9 \text{ m/s}$, it can be observed that each RC beam behaves elastically, because the residual deflection is not appeared. And the waves are sinusoidal and are similar among three types of RC beams. Moreover, no high-frequency components are included in these waves. The period and amplitude of the waves for each RC beam increase gradually with an increment of impact velocity. In cases of $V = 3.6 \text{ m/s}$ and $4.5 \text{ m/s}$, however, the shapes of their waves are different between S0 beam and the other beams. That is, the period and amplitude of the waves for S0 beam are longer and larger than those of S2 and S4 beams. As mentioned above, this implies that the shear stiffness of S0 beam is suddenly reduced due to severe arch-shaped cracks being developed.

### 3.3 Hysteretic loops of reaction force vs. mid-span displacement

Figure 4 shows hysteretic loops of reaction force vs. mid-span displacement $R-\delta$ for S0, S2 and S4 beams. From these figures, it can be seen that the absorbed energy estimated integrating the looped area increases with an increment of impact velocity for all type of RC beams.

Focusing on the results in case of $V = 0.9 \text{ m/s}$, it can be seen that the reaction force of each RC beam increases monotonically with an increment of displacement. After reaching the maximum value, the force decreases to zero. The displacement is also restored to near zero. This implies that the RC beam behaves elastically at this time. Moreover, it can be also observed that the shapes of their $R-\delta$ curves are similar among three types RC beams.

In case of $V = 3.6 \text{ m/s}$, the shapes of $R-\delta$ curves between S0 beam and the other beams are different from each other. Namely, the $R-\delta$ curve for S0 beam shows that after reaching the maximum reaction force, the displacement increases gradually even while the reaction force decreases, and finally some displacement has been remained. And the shapes of the curves resemble a triangle. On the contrary, the $R-\delta$ curves for S2 and S4 beams show that after reaching the maximum reaction force, the force decreases temporarily. After that, it increases to near the maximum value again and decreases to zero with a similar stiffness to the initial one. Finally, the displacement is restored to the almost initial point. The former implies that the RC beams without shear rebars resists the impact force at the beginning of impact, but the dynamic shear capacity is decreased gradually with an increment of displacement due to severe arch-shaped cracks being developed and opened. Whereas, the latter suggests that in case of RC beams with shear rebars, the dynamic shear capacity is not
decreased remarkably because the shear rebars resist against the impact force after cracking. The shear rebars may still be healthy by this level of input impact energy because of displacement being restored to the initial point.

Moreover, increasing the impact velocity, in case of S0 beam, a secondary loop appears clearly after the triangular loop is formed. This implies that only the main rebars resist the impact force after severe arch-shaped cracks occur. On the other hand, in cases of S2 and S4 beams, with an increment of impact velocity, the residual deflection increases and the shape of the initial loop at the beginning of impact approaches an isosceles triangle. And also, the area of a sequential secondary loop increases gradually. In addition, in cases that the hysteretic loop forms into isosceles triangle at the beginning of impact, the values of the maximum reaction force are almost the same irrespective of the magnitude of impact velocity. This suggests that even when the shear rebars are arranged, reaction force vs. mid-span displacement ($R$-$\delta$) curve of RC beam reaching the ultimate state with shear-failure mode forms an isosceles triangle in the beginning of impact, and the maximum reaction force at the time indicates an absolute value similarly to those in case of RC beams without shear rebar.

Comparing the $R$-$\delta$ curves between S2 and S4 beams, although the residual displacement of S2 beam is slightly bigger than that of S4 beam, the shapes of their $R$-$\delta$ curves are similar between them, irrespective of the magnitude of the impact velocity.

### 3.4 Relationship between maximum reaction force and impact velocity

The relationships between maximum reaction force $R_{ud}$ and impact velocity $V$ are shown in Fig. 5. Symbols of circles, triangles, and squares mean the results for S0, S2, and S4 beams, respectively. The black mark for each type RC beam indicates the value that the RC beam reaches the ultimate state with shear-failure mode.
Figure 5: Relationship of maximum reaction force vs. impact velocity.

From this figure, it can be seen that the reaction force increases almost linearly up to the absolute maximum value with an increment of the impact velocity, irrespective of beam type. After that, the value of the reaction force does not increase with an increment of impact velocity mentioned above.

Comparing the values of the maximum reaction force among three types of RC beams, it can be observed that their values are in good agreement among them at \( V = 0.9 \) m/s. At \( V = 3.6 \) m/s impact velocity in which severe diagonal cracks occur in each RC beam, the value for S0 beam is slightly smaller than those for S2 and S4 beams. Pointing to the distributions of the reaction force for S2 and S4 beams, these are almost the same to each other in the region less than \( V = 7.2 \) m/s impact velocity. This implies that almost the same maximum reaction force is developed from elastic region to the ultimate state.

3.5 Dynamic response ratio of reaction force to static shear capacity

The dynamic response ratios \( R_{ud} / V_{us} \) for three types of RC beams are plotted in Fig.6, in which \( R_{ud} \) indicates the absolute maximum dynamic reaction force and \( V_{us} \), the static shear capacity (see Table1).

From this figure, it is seen that the values of \( R_{ud} / V_{us} \) for all RC beams are
distributed within the range from 2.7 through 3.1 and are almost similar among them. This implies that when the shear-bending capacity ratio $\alpha$ is less than unity, the impact-resistant design for shear-failure-type RC beams can be rationally performed by using static shear capacity.

4 Conclusions

In this study, to investigate the impact-resistant behavior of shear-failure-type RC beams, falling-weight impact tests were conducted by means of a single loading method with a 400 kg steel weight. Here, the shear rebar ratio and the impact velocity are taken as variables. The results obtained from this study are as follows:

1) When the RC beam reaches the ultimate state with shear-failure mode, reaction force vs. mid-span displacement loop forms into an isosceles triangle, irrespective of magnitude of shear rebar ratio;
2) The maximum reaction force at the time reaches an absolute value;
3) Using the relationship between absolute maximum dynamic reaction force and static shear capacity, an impact-resistant design for shear-failure-type RC beams can be rationally performed using the static shear capacity.

References