1. INTRODUCTION

The continuous expansion of urban zones in mountain regions needs to establish the systems for protecting infrastructures from natural hazards such as snow avalanches, falling rocks, and landslides. In numerical analysis for estimating dynamic response behavior and/or sectional forces of the RC structures by means of FE method, mesh size may act very important role if cracking or tearing or penetration occurs. However, considering the relationship between mesh size and material properties, rational response analysis method for precisely analyzing prototype RC structures under impact loading has not been established yet.1)

This work constitutes an effort directed towards the development of an objectivity algorithm for tensile failure of concrete elements based on the smeared cracking formulation. The algorithm has been implemented into LS-DYNA for hexahedron solid elements and correctly accounts for crack directionality effects.2) Thus enabling the control of energy dissipation will be associated with each failure mode regardless of mesh refinement.

The advantage of the proposed technique is that mesh size sensitivity on failure is removed leading to results, which converge to a unique solution, as the mesh is refined. The proposed algorithm has been validated by a full-scale prototype test using different cases of mesh refinement.

Here, in order to establish a modification method for material properties of concrete so as to rationally analyze using coarse mesh, an equivalent fracture energy concept for concrete element is proposed and the applicability was conducted comparing numerical analysis results and experimental results.

2. EXPERIMENTAL OVERVIEW

2.1 Dimensions and static design of RC girder

In this study, a RC girder, which is for designing roof of real RC rock-sheds, was taken for falling-weight impact test of prototype RC structures. The girder is of rectangular cross section and the dimensions are of 1 m × 0.850 m and clear span is 8 m long, which is similar to the width of real RC rock-sheds. Figure 1 shows dimensions of the RC girder, distribution of rebar, and measuring points for each response wave. In this figure, it is confirmed that 7 # D32 rebars are arranged as main rebar assuming 0.64 % of main rebar ratio corresponding to designing of real RC rock-sheds and 4 # D32 rebars are arranged as the upper axial rebar to be about a half of main rebar ratio. Thickness of concrete cover is assumed to be 150 mm as well as real rock-sheds. D16 stirrups are arranged with intervals of 250 mm, which is less than a half of an effective height of the girder. In this study, arranging interlayer stirrups and upgrading in shear load-carrying capacity, the RC girder was designed to be collapsed with flexural failure mode. Axial rebars were welded to 12 mm steel-plates at the ends to save the anchoring length of the rebars.

The displacements of the girder were measured at mid-span $D - 1$ and $D - 2$ with the intervals of 750 mm from the mid-span. Impact force $P$ was estimated using deceleration of the heavy weight, which is measured using accelerometer set at its top surface. Reaction force $R(= R_1 + R_2)$ was also measured using load-cells installed in the supporting gigues. The detailed static design parameters of the RC girder are listed in Table 1. Static flexural and shear load-carrying capacities $P_{usc}$ and $V_{usc}$ were calculated based on Standard Specifications for Concrete Structures in Japan (JSCE, 2002)3).

From this table, it is confirmed that the RC girder designed here will collapse with flexural failure mode under static loading because shear-bending capacity ratio $\alpha$ is larger than unity. The static material properties of concrete and rebars during experiment are listed in Tables 1.

2.2 Experimental method

In the experiment, a 2,000 kg heavy weight was lifted up to the prescribed height of 10 m by using the track crane, and then dropped freely to the mid-span of girder with a deceleration device.
A heavy weight is made from steel outer shell with 1 m in the diameter, 97 cm in height, and spherical bottom with 80 cm in radius and its mass is adjusted filling concrete and steel balls. RC girder was set on the supporting giguers, which are made so as to freely rotate but not to move toward each other.

The ends of RC girders were fixed in the upward direction using steel rods and cross-section beams to prevent from jumping up at the time of impacted by a heavy weight. In this experiment, impact force wave (P), reaction force wave (R), and displacement waves (D) at six point along the girder were measured. Impact force wave was estimated using a deceleration of heavy weight which is measured using accelerometers set at the top-surface of weight. The accelerometer is of strain gauge type and its capacity and frequency range for measuring are 1,000 times gravity and DC through 7 kHz, respectively. Each load-cell for measuring reaction force are of 1,500 kN capacity and more than 1 kHz measuring frequency. For measuring displacements, laser-type variable displacement transducers (LVDTs) were used which are of 200 mm maximum stroke and 915 Hz measuring frequency. Analog signals from those sensors were amplified and converted to digital ones.

### Table-1 Static design parameters of RC girder

<table>
<thead>
<tr>
<th>Shear rebar ratio ( \rho_l )</th>
<th>Static shear depth ratio ( \alpha d )</th>
<th>Static shear capacity ( V_{acc} ) (kN)</th>
<th>Static bending capacity ( P_{acc} ) (kN)</th>
<th>Shear-bending capacity ratio ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0064</td>
<td>5.71</td>
<td>1794.0</td>
<td>619.8</td>
<td>2.894</td>
</tr>
</tbody>
</table>

### Table-2 Material properties of concrete and rebar

<table>
<thead>
<tr>
<th>Type</th>
<th>Density ( \rho ) (ton/m³)</th>
<th>Elastic coefficient ( E ) (GPa)</th>
<th>Poisson Ratio ( \nu )</th>
<th>Yielding strength ( f'_c ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>2.343</td>
<td>25.4</td>
<td>0.177</td>
<td>31.2</td>
</tr>
<tr>
<td>Rebar D13</td>
<td>7.85</td>
<td>206</td>
<td>0.3</td>
<td>300</td>
</tr>
<tr>
<td>Rebar D29</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
</tr>
</tbody>
</table>

3.2 Modeling of materials

The stress and strain relations of concrete and rebar are shown in Fig. 5. The outline of the material physical properties model such as concretes, rebar are shown in Table 2. For the compression region, assuming that concrete is yielded at 1,500 MPa compression, perfect elasto-plastic bilinear model was used. For the tension region, tensile strength of concrete is assumed to be one-tenth of compressive strength for the standard case of MS35-\( G_f \) but for other cases equivalent fracture energy concept was applied. Yielding of concrete has been judged based on the Drucker-Prager’s yield criterion. Stress-strain relationship for main rebar and stirrup was defined using a bilinear isotropic hardening model. Plastic hardening coefficient \( H' \) was assumed to be 1% of Young’s modulus \( E_s \). Yield of rebar and stirrup was judged following von Mises yield criterion. Heavy weight, supporting giguers and anchor plates for axial rebars set at the both ends of RC girder were assumed to be elastic body because of no plastic deformation for those being found.

3.3 Equivalent fracture energy concept

In this paper, the element was assumed to be failed in the whole area of element because of applying smeared crack model, when negative pressure surcharged to the element reaches a tension.
sile strength.

Assuming one flexural crack occurs in a element irrespective of magnitude of element size, the element must be set so as to be failed at the time when a strain energy stored in the element reaches fracture energy which is the same among all concrete element size irrespective of magnitude of element size.

Based on this equivalent fracture energy concept, each concrete element can retain the equivalent fracture energy due to setting a fictitious tensile strength corresponding to volume of element. In Fig. 5(a), assuming fracture energy of standard concrete element and volume of the element as $G_f$ and $V_0$, respectively, the volume of the standard element is as follows:

$$V_0 = x_0 y_0 z_0$$

By putting the values of Eq. (2) and Eq. (3), the fracture energy $G_f$ of Eq. (1) can be obtained as,

$$G_f = \frac{f^2_{t0}}{2E_c x_0 y_0 z_0}$$

(4)

Here, setting the fictitious tensile strength and element size in $y$ direction of $i$-element as $f_{ti}$ and $y_i$ and applying an equivalent fracture energy concept between standard element and $i$-element, following relationship can be obtained as;

$$\frac{f^2_{t0}}{2E_c x_0 y_0 z_0} = \frac{f^2_{ti}}{2E_c x_0 y_i z_0}$$

(5)

Fictitious tensile strength of $i$-element $f_{ti}$ can be obtained as follows;

$$f_{ti} = f_{t0} \sqrt{\frac{y_0}{y_i}}$$

(6)

Therefore, taking the fictitious tensile strength $f_{ti}$ obtained from Eq. (6) for $i$-element with $y_i$ as the size in $y$-direction, the crack occurred in the $i$-element can be rationally estimated similar to $f_{t0}$ of the standard element with fracture energy $G_f$. The fictitious tensile strength for each element size in $y$-direction used in this study is listed in Table 3.

<table>
<thead>
<tr>
<th>Element size in span direction (mm)</th>
<th>Fictitious tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>1.18</td>
</tr>
<tr>
<td>83</td>
<td>2.04</td>
</tr>
<tr>
<td>50</td>
<td>2.64</td>
</tr>
<tr>
<td>35</td>
<td>3.12</td>
</tr>
</tbody>
</table>

Table 3 Tensile strength for different analytical cases
4. COMPARISON OF RESULTS

The applicability of the proposed method is examined for the set of each element length for different cases considering $G_f$ in this section and comparing with experimental results. An analytical result concerning all cases with different element length considering $G_f$ is compared with the experimental results as shown in Fig. 4.

The maximum value of impact force wave is smaller than the experimental results regardless of the mesh size of the element length as previously observed. The maximum impact force indicates that the value in case of MS250-$G_f$ is the nearest to the experimental results. It is understood that the response characteristics is similar regardless of the size of the element length as well as the case of impact force and for the reaction force waveform. From Fig. 4(b), it is confirmed that the reaction force wave at the one supporting point tends to be high amplitude in case of one-division was almost similar to experimental one.

It is understood that the amplitude of $D - 1/2$, the both cycle and the residual displacement are in the state of a free vibration after the maximum displacement regardless of the size of the element length by comparing the experimental results and the analytical one. By comparing the experimental results, among four cases the most underestimating case is MS83-$G_f$ though the level of the error margin is not large when seeing in detail.

By converting the tensile strength as the case of MS35-$G_f$ is shown, and it can be confirmed to an analytical result of MS250-$G_f$ when the element length is the largest then the analytical accuracy is good enough even if the element division is coarse. Even if the span direction element length is different from a standard element, it means that the mesh size up to seven times the standard element length having the same accuracy as the case to use a standard element by using the fracture energy concept.

5. CONCLUSIONS

In order to establish a modification method for material properties of concrete so as to rationally analyze using coarse mesh, an equivalent fracture energy concept for concrete element is proposed and the applicability was conducted comparing numerical analysis results and experimental results. From this study, it is confirmed that even though coarse mesh was used for RC girder, similar results with those obtained using fine mesh can be assured and are in good agreement with the experimental ones.

REFERENCE