Three Dimensional Elasto-Plastic Impact Response Analysis of Large Scale RC Girder with Sand-Cushion

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1. INTRODUCTION

In order to ensure the safety of rock-sheds, nuclear power plants, fuel tanks and/or other protective structures against impact loads, many numerical and experimental researches have been carried out. A great deal of efforts have been made for the investigation on impact behavior and resistance of the structures when flying and/or falling bodies applied on the structures directly. Otherwise, it will be one of engineering approaches to attenuate the impact forces by using absorbing system. Rock-falls are one of the most prevailing natural hazards in the mountainous regions. Rock-sheds are used to protect the local infrastructures and lifelines against these potential rock impacts. Cushion materials are laid on the roof of rock-sheds to absorb the rockfall impact energy, which is one of the main input parameters in design of the rock-shed and, still now these structures have been designed based on an allowable stress design concept using simply estimated maximum impact force. However, in order to rationally design this type RC structures considering the performance up to ultimate state, impact resistant behavior and dynamic load-carrying for these should be investigated precisely. For these, not only experimental study but also numerical analyses one should be performed. From this point of view, here, in order to establish a rational numerical analysis method for real RC rock-sheds, non-linear finite element analysis was conducted based on the falling weight impact test results for prototype rectangular RC girder with partially mounted sand-cushion.

2. OVERVIEW OF LARGE-SCALE FALLING WEIGHT IMPACT TEST

2.1 Outline of testing model

RC girder, which is modeled for roof of real RC rock-sheds, is 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. The dimensions of the sand cushion used here are of 1.5 × 1.5 × 0.9 m at the centre of the girder. Figure 1 shows dimensions of the RC girder, distribution of stirrups, and measuring points for each response wave. In this figure, it is confirmed that 7 # D29 rebars are arranged as main rebar assuming 0.64 % of main rebar ratio corresponding to designing of real RC rock-sheds and 4 # D29 rebars are arranged as the upper axial rebar as a half of main rebar ratio. Thickness of concrete cover is assumed to be 150 mm as well as real rock-sheds. D13 stirrups are arranged with intervals of 250 mm which is less than a half of an effective height of the cross section. In this study, arranging interlayer stirrups and upgrading in shear load-carrying capacity, the RC girder was designed to be failed with flexural failure mode and axial rebars were welded to 12 mm steel-plate at the ends for saving of anchoring length of the rebars. The displacements of the girder were measured at mid-span (D1) and the five points (D2 ∼ D6) 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 accelerometers set at its bottom. Reaction force R was

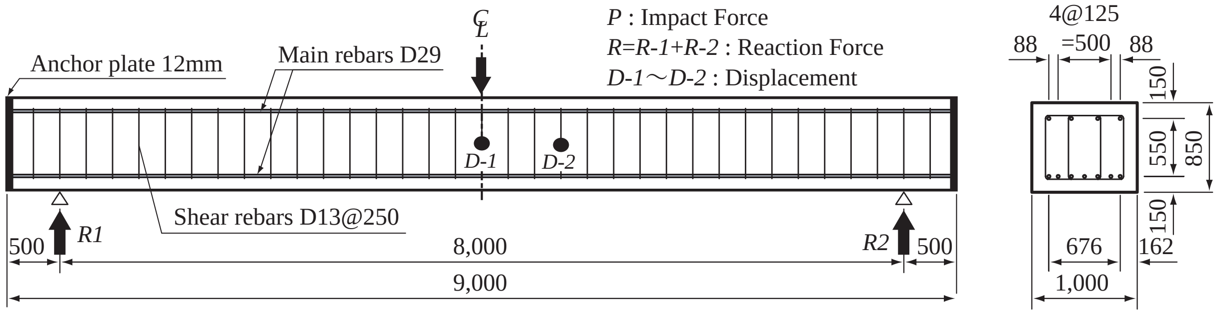

Figure- 1 Dimensions of RC girder and measuring items

Table- 1 Static design parameters of RC girder

Shear rebar ratio ρ_t	Static shear depth ratio a/d	Static shear capacity V_{usc} (kN)	Static bending capacity P_{usc} (kN)	Shear-bending capacity ratio α
0.0064	5.71	1794.0	619.8	2.894

Table- 2 Material properties of concrete, rebar and sand

<table>
<tr><th>Type</th><th>Density
ρ (ton/m^3)</th><th>Elastic coefficient
E (GPa)</th><th>Poisson Ratio
ν</th><th>Yielding strength
f'_c (MPa)</th></tr>
<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 rowspan="2">7.85</td><td rowspan="2">206</td><td rowspan="5">0.3</td><td>390</td></tr>
<tr><td>Rebar D29</td><td>400</td></tr>
<tr><td>Heavy weight</td><td>7.25</td><td rowspan="3">206</td><td rowspan="4">-</td></tr>
<tr><td>Support device</td><td rowspan="2">7.85</td></tr>
<tr><td>Anchor Plate</td></tr>
<tr><td>Sand Layer</td><td>1.6</td><td>10</td><td>0.06</td></tr>
</table>

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 Japanese Concrete Standards. From this table, it is confirmed that the RC girder designed here will fail with flexural failure mode under static loading. The static material properties of concrete and rebars during experiment are listed in Table 2.

2.2 Experimental method

In the experiment, a 5,000 kg heavy weight was lifted up to the prescribed height of 10 m by using the track crane, and then dropped freely to the sand cushion set at the mid-span of girder with a desorption device. A heavy weight is made from steel outer shell with 1 m in diameter, 97 cm in height, and spherical bottom with 80 cm in radius. Its mass is adjusted filling concrete and steel balls. Moreover, the accelerometers were set up in a heavy weight, and the acceleration of a heavy weight can be measured. 90 cm thick sand cushion was set on the top of RC girder. RC girder is set on the supporting gigues with load-cells for measuring reaction force, in which supporting gigues are made so as to freely rotate but not move toward each other. The ends of beam are prevented from jumping up at a heavy weight impacted using protecting girders. In this experiment, impact force wave (P), reaction force wave (R), and displacement waves at 6 points along the girder were measured. Those analog signals are amplified and converted to digital ones. The digital data were continuously recorded with 0.1 ms time intervals by using digital data recorders. After that, impact force wave was numerically filtered by means of rectangular moving average method having a 0.5 ms time-window. After experiment, pictures for views of crack patterns occurred around impacted point and on the side-surface of RC girder, and a view of exfoliation and spalling of concrete cover were took. These cracks were also sketched.

3. ANALYTICAL OVERVIEW

3.1 FE models

One quarter of RC girder was three-dimensionally modeled for numerical analysis with respect to the two symmetrical axis. The boundary conditions (symmetry condition) were applied to the symmetry plane. The boundary condition was applied also under sand absorbing material lying on the top of RC girder. Figure 2 shows a mesh geometry of the girder with sand as absorbing material, which is finally used for numerical analysis with optimum design accuracy investigated here. A geometrical configurations of the heavy weight and sand cushion material were modeled as the real ones. Supporting gigues including load-cells and gigue for protecting the girder from jumping up were also precisely modeled corresponding to the real ones. In this model, axial rebar and stirrup were modeled using beam element having equivalent axial stiffness, cross sectional area and mass with those of real ones. The others were modeled using eight-node and/or six-node solid elements. Total number of nodal points and elements for one-fourth model are shown in Fig. 2 are 84,804 and 76,215, respectively. Number of integration points for solid and beam elements are one and four, respectively. In order to take into account of contact interface between sand and a head of heavy weight elements and between adjoining concrete and supporting gigue elements, contact surface elements for those are defined, in which contact force can be estimated by applying penalty methods for those elements but friction between two contact elements were neglected. A head of heavy weight was set so as to contact the impacting point of the upper surface of sand cushion set at the mid span of RC girder and pre-

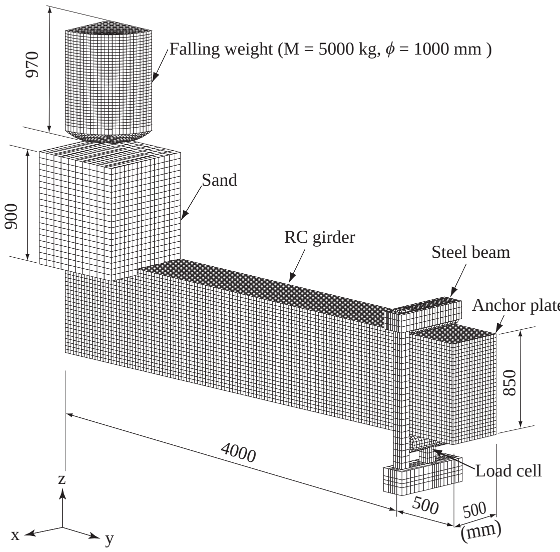

Figure- 2 FE Numerical analysis model

determined impact velocity was applied to all nodal points of the weight model.

3.2 Modeling of materials

The stress and strain relations of concrete and rebar are shown in Fig. 3. The outline of the material physical properties model such as concretes, rebar and sand cushion are shown in Table 2. For the compression region, assuming that concrete is yielded at 1,500 μ strain, perfect elasto-plastic bilinear model was used. In this study, finally, yielding of concrete has been judged based on the Drucker-Prager's yield criterion. For the tension region, linear model was applied, but it is assumed that the stress cannot be transferred when a tensile pressure acted in the element reaches the breaking point. Here, the pressure is evaluated as an average of three normal stresses acted in each element and the tensile strength of concrete is assumed to be one-tenth of compressive strength similarly to the case of the numerical analysis for small-scale RC beams conducted by authors. 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. Yield of rebar and stirrup was judged following von Mises yield criterion. Heavy weight, supporting gigues 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 Material Characteristics of Sand

In Fig. 3(c), the constitutive model of sand cushion is shown. To rationally analyze in stress behavior of sand when a heavy weight collides, second order parabolic stress-strain relation for sand cushion was applied in which the constitutive relation is described in the following expression.

$$\sigma_{sand} = 50\varepsilon_{sand}^2 \qquad (1)$$

Here, σ (MPa) is stress and ε_{sand} is the volumetric strain. It was set in this research based on experimental and analytical results where 5,000 kg heavy weight falls by 10 m. Moreover, the modulus of initial Elasticity, the density and Poisson ratio were assumed to be E =10 GPa, ρ_{sand}=1,600 kg/m^3 and ν_{sand} = 0.06, respectively.

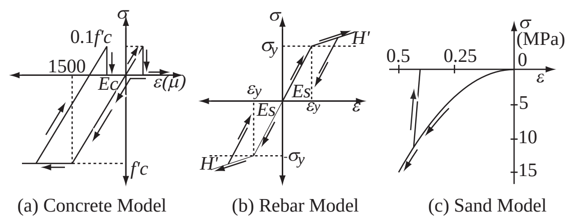

Figure- 3 Stress-strain relation of constitutive model

4. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESUTLS

Figure 4 shows the comparisons of the impact response waves of the girder obtained using FE analysis method with the experimental results when sand cushion is used as absorbing material. In the numerical analysis model two types of mesh size were tried. It is found that mesh with dense distribution gives similar displacement waveform than that from course mesh. From Figs. 4(a) and 4(b), it is observed that time increment of the first dominant wave for each response obtained using numerical analysis is smaller than that obtained using experimental one. However, in numerical analysis, the time increment of the wave cannot be increased up to that of the experimental results and the maximum amplitude is also a little smaller than experimental one. From the comparisons of second dominant wave shown in Fig. 4(b), it is observed that: in case of numerical analysis, impact force wave has been excited during 50 ms with smaller magnitude after first dominant wave being excited. This wave configuration is greatly different from that of experimental results. The wave configuration is some different from that of experimental results. From Fig. 4(c), it is seen that reaction force waves for one supporting point obtained using numerical analysis and experimental results are almost the same to each other. From Fig. 4(d) of enlarged wave configuration of the reaction force in the beginning of impact, configurations of the first dominant wave obtained from numerical analysis are almost the same to that from experimental results. The maximum amplitude for those wave configurations is smaller to that of experimental results and the time increment of the wave at the beginning of impact is also smaller than that of the experimental results. From the

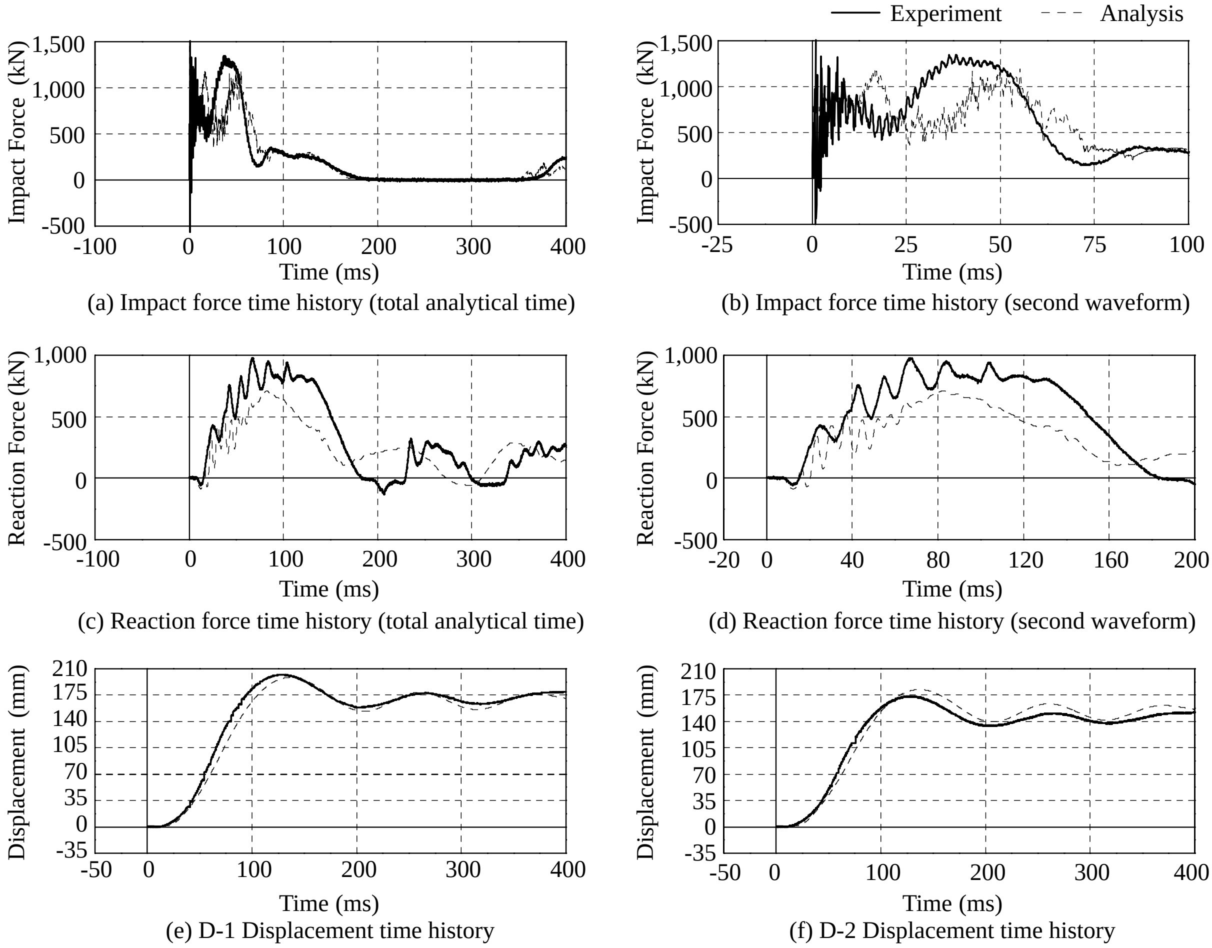

Figure- 4 Comparison between experimental and analysis results

Figs. 4(e) and 4(f) for displacement waves at the points D-1/2, it is confirmed that numerical response wave during the impact load surcharging to the RC girder is similar to that of the experimental results. From Fig. 4(f), it is observed that numerically estimated period for free vibration is almost the same with that of experimental results and is about 100 ms. In order to fit the displacement wave, a damping factor of $h = 0.1$ % was used which gives similar results to experimental one. However if damping factor $h = 0.5$ % is used, the displacement is estimated as about 180 mm. Residual displacement obtained from numerical analysis is almost the same to the experimental result is about 196 mm.

5. CONCLUSIONS

In order to establish a proper FE model of RC girder with prototype sand element for impact response analysis, dynamic response analysis of RC girder with sand cushion subjected to falling weight impact force was performed by using LS-DYNA code. An applicability of proposed model was discussed comparing with prototype experimental results. The results obtained with this study are as follows;

1) The response characteristics obtained using proposed numerical analysis have comparatively similar tendency for impact force, reaction force and displacement wave form to those of experimental results.
2) The tendency of analytical maximum response generation time for impact force is delayed a little as compared with the experimental results.
3) The numerical analysis result for impact force has a tendency to be smaller than the experimental results.
4) The displacement wave from numerical analysis corresponds to the experimental results well.

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