

NUMERICAL ANALYSIS OF FALLING WEIGHT IMPACTING RC GIRDERS COVERED WITH PARTIALLY SUPPORTED SAND CUSHION

敷砂を設置した大型 RC 梁の重錘落下衝撃解析

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In order to establish a proper finite element model of prototype RC girder with sand element for impact response analysis, dynamic response analysis of RC girders with sand cushion subjected to impact force due to weight falling from the height of $H = 2.5, 5, 7.5$ and 10 m was performed to improve the state of the art of protective design for real scale rock-sheds by using LS-DYNA code. An applicability of proposed model was discussed comparing with experimental results (e.g. impact force, reaction force and displacement waves). From this study, dynamic characteristics of impact response can be better simulated by using the proposed model. As a result, when the sand cushion was set up, the impact force, reaction force, mid span displacement waves, distribution of reaction force-displacement loops, and crack patterns obtained from the numerical analysis are in good agreement with those from the experimental results.

Key Words: *prototype RC girder, impact resistant design, LS-DYNA, sand cushion, impact response.*

1. Introduction

In engineering practice, there are many situations in which structures undergoes impact or dynamic loading, such as during an explosion, impact of ice load on pile structures, accidental falling loads, tsunamis and tornadoes generated projectiles etc. The characteristics of impact load are different from those of static and seismic loads¹⁾. Structural response depends not only on impact energy, but also on the stiffness of the structure, the contact stiffness, and the mechanical properties of materials directly²⁾. Rock falls are one of the most prevailing natural hazards in the mountainous regions. Cushion materials are laid on the roof of rock-sheds to absorb the rock fall 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 force³⁾. However, in order to rationally design this type RC structures considering the performance up to ultimate state, impact resistant behavior and dynamic load carrying capacity for those

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, nonlinear finite element analysis was conducted based on the falling weight impact test results for full-scale rectangular RC girders with partially mounted sand-cushion. Impact response analysis must be able to handle short-duration impact dynamics with complicated experimental techniques. LS-DYNA code is used for a three-dimensional finite element analysis⁴⁾.

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 1.0×0.850 m

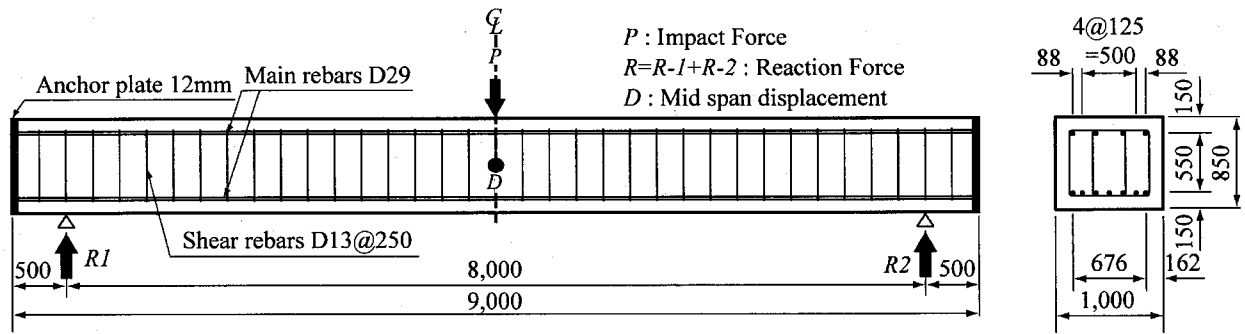


Fig. 1 Dimensions of RC girder and measuring items

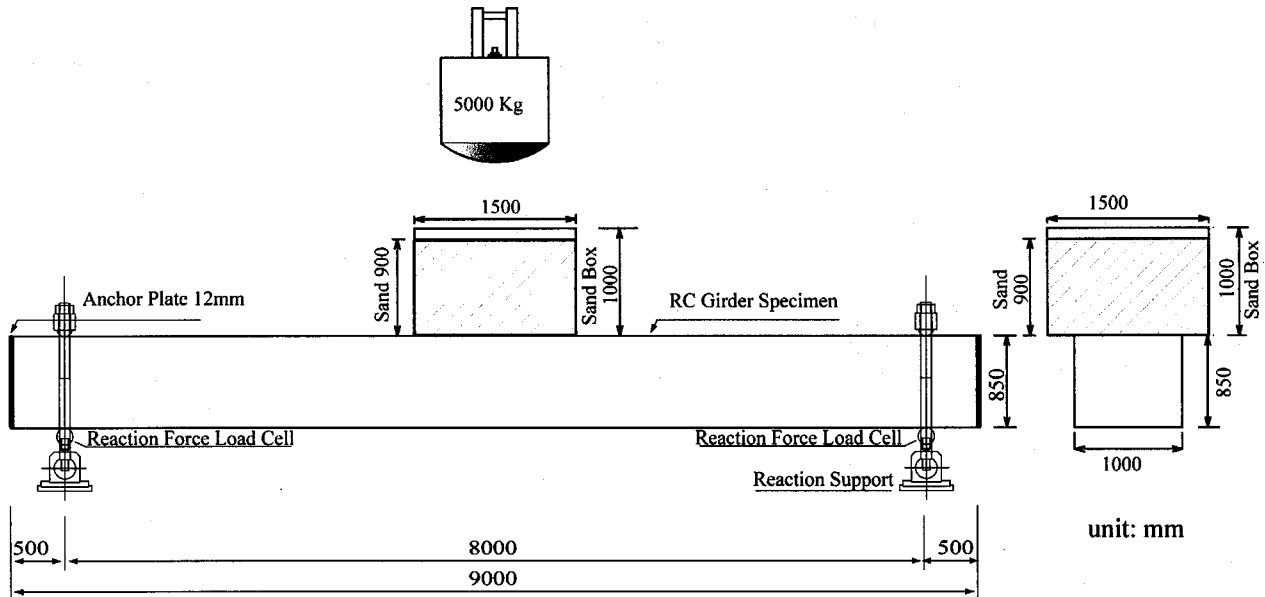


Fig. 2 Experimental setup

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	619.8	2.894

Table 2 Material properties of concrete and rebar

Type	Density ρ (ton/m ³)	Elastic coefficient E (GPa)	Poisson's Ratio ν	Yielding strength (MPa)
Concrete	2.343	25.4	0.177	31.2
Rebar D13	7.85	206	0.3	390
Rebar D29				400

and clear span is 8 m long. As the impact force is distributed at the mid span of the RC girder, therefore the sand cushion was set on the center of girder with the dimensions of 1.5 x 1.5 x 0.9 m. Figure 1 shows dimensions of the RC girder, arrangement of rebars, and measuring points for each response wave. In this figure, it is confirmed that 7#D29 rebars are arranged

which is for 0.64% of main rebar ratio corresponding to designing of real RC rock shed and 4#D29 rebars are arranged as the upper axial rebar in which the rebar volume corresponds to a half of main rebar ratio. Axial rebars were welded to 12 mm steel-plate at the ends for saving of anchoring length of the rebars. Thickness of concrete cover is assumed to be 150 mm as well as

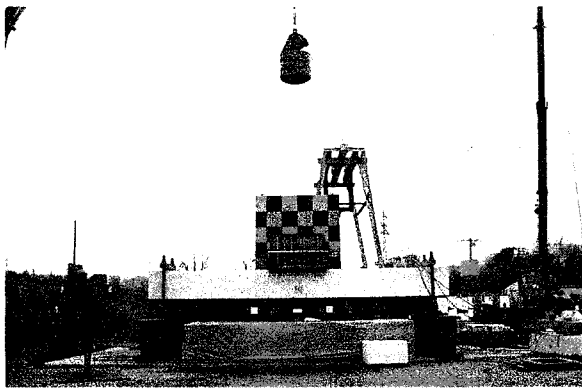


Photo 1 Pictorial view of the experimental setup with falling height of 5 m

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. 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 structure⁵⁾. 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 2.⁸⁾

2.2 Experimental method

In the experiment, 5,000 kg heavy weight was lifted up to the prescribed height of 2.5, 5, 7.5, and 10 m by using the track crane, and then dropped freely to the mid-span of girders due to 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 and its mass is adjusted by filling concrete and steel balls.

RC girder was set on the supporting girdes with load cells for measuring reaction force, which are made so as to freely rotate, but not to move toward each other. The ends of RC girder are fixed in the upward direction using steel rods and 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 wave (D) at mid span of the girder were measured. Impact force wave was estimated using a deceleration of heavy weight, which is measured by using accelerometers set at the top-surface of the weight. The experimental setup is shown in Fig. 2.

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 a 200 mm maximum stroke and 915 Hz measuring frequency. Those measured waves will be described later accompanying with the analytical results. After experiment, pictures for views of the cracks occurred around impacted area and on the side surface of RC girder, and a view of peeling and spalling of concrete cover were taken. Those cracks were also sketched and the crack patterns will be discussed latter comparing with the analytical ones. Photo 1 shows pictorial view of falling-weight impact test for RC girder partially mounted with sand cushion. Photo 2 (a) and 2 (b) show supporting gigue including load cells and gigue for preventing RC girder from jumping up, respectively.

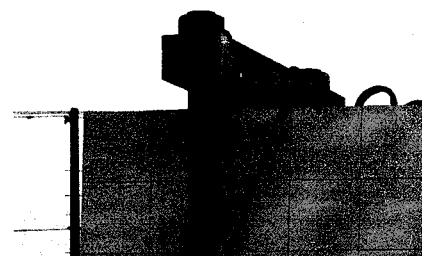
3. Analytical Overview

3.1 Finite Element model

One quarter of RC girder was three dimensionally modeled for numerical analysis with respect to the two symmetrical axes. Four side-surfaces of sand cushion were confined laterally. Figure 3(a) shows mesh geometry of the girder with sand as absorbing material. A geometrical configuration of the heavy weight and sand cushion were precisely modeled following the real ones.



(a) Supporting gigue with load cell



(b) Support gigue to prevent jumping

Photo 2 Pictorial view of supporting gigue

Supporting girdes including load-cells and the 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. The mesh geometries for axial rebar and stirrup arrangement are shown in Fig. 3(b). Number of integration points for solid and beam elements are one and four, respectively⁷⁾.

Total number of nodal points and elements for one-fourth model are of 43,838 and 38,167, 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 was not considered. By applying the penalty method, each slave node is checked for penetration through the master surface. If the slave node does not penetrate, nothing is done. If it does penetrate, an interface force is applied between the slave node and its contact point. The magnitude of this restoring force is proportional to the penetration distance into the solid and acts in the direction normal to the surface of the solid.

A head of heavy weight was set so as to contact the impacting point of the upper surface of sand cushion mounted at the mid span of RC girder and predetermined impact velocity was applied to all nodal points of the heavy weight model.

3.2 Modeling of materials

Figure 4 shows the stress and strain relations for each material: concrete; rebar; and sand. Neither strain rate effect of concrete and rebar nor softening phenomena

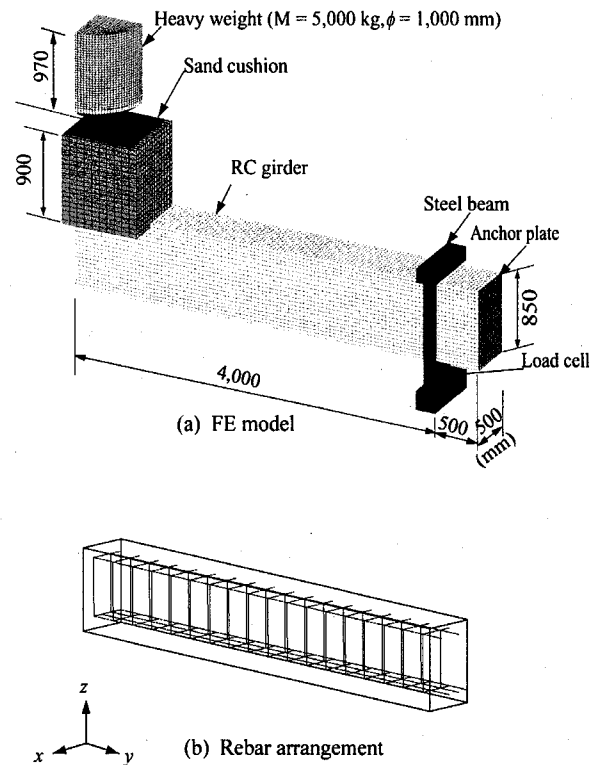


Fig. 3 Finite element mesh scheme for RC girder of concrete were considered for this elasto-plastic impact response analysis method for the RC girder. But viscous damping factor of $h = 0.2\%$ was considered which is proportional to mass of RC girder. The constitutive law for each material characteristic is briefly described below:

(1) Concrete

Stress-strain relationships of concrete were assumed by using a bilinear model in compression side and a cut-off model in tension side as shown in Figure 4(a). It is assumed that 1) yield stress is equal to compressive stress f'_c ; 2) concrete yields at 0.0015 strains; 3) the tensile stress is perfectly released when an applied pressure reaches tensile strength of concrete;

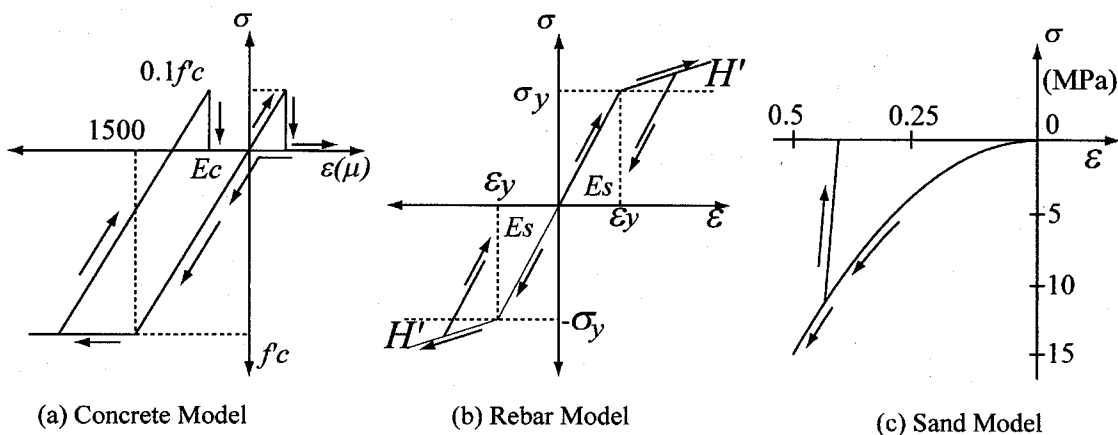


Fig. 4 Stress-strain relation of material constitutive models

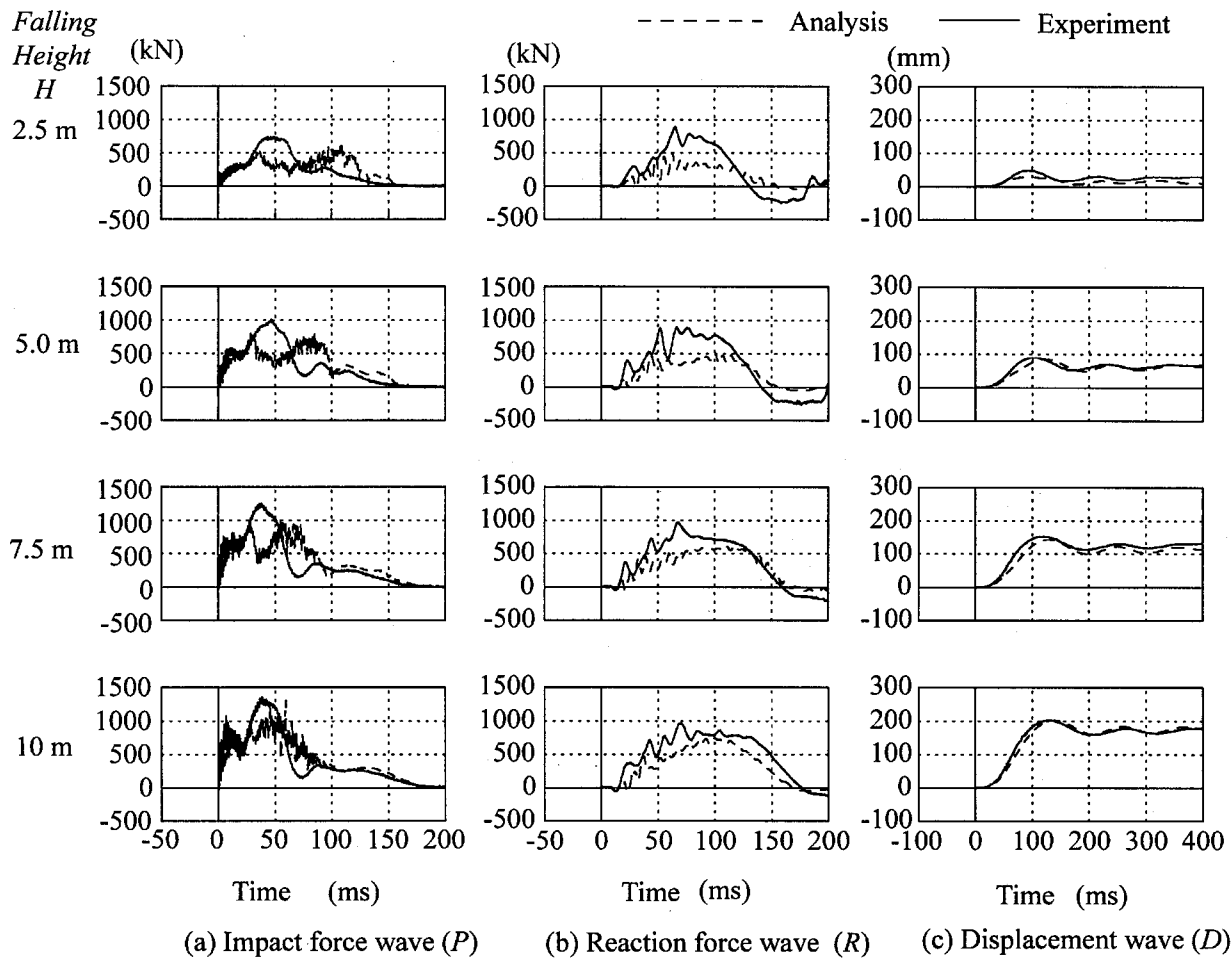


Fig. 5 Time histories of impact force wave (*P*), reaction force wave (*R*), and mid-span displacement wave (*D*)

4) The tensile strength is set to be $1/10^{\text{th}}$ of the compressive strength; and 5) von Mises criterion was applied to the yielding of concrete.

(2) Rebar

For main rebars and stirrups, an elasto plastic model following isotropic hardening rule was applied as shown in Figure 3(b). Here, the plastic hardening modulus H' was assumed to be 1% of elastic modulus E_s (E_s : Young's modulus). The yielding condition was judged based on von Mises criterion.

(3) Sand cushion

Figure 4(c) shows the constitutive model for sand cushion, which is fully elastic. To rationally analyze in stress behavior of sand cushion when a heavy weight collides, second order parabolic stress-strain relation for sand cushion³⁾ was applied in which the constitutive relation for stress strain load curve is described in the following expression.

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

Here, σ_{sand} is stress and ε_{sand} is the volumetric strain

of sand element. Here, referring to reference³⁾, material properties of sand for impact response analysis were assumed as; Young's modulus $E_{sand} = 10$ GPa; Poisson's ratio; $\nu_{sand} = 0.06$ and density $\rho_{sand} = 1,600$ kg/m³.

(4) Falling weight, support device, and anchor plate

The other elements (steel weight, supporting apparatus and anchor plate) were modeled as elastic body based on experimental observations. Young's modulus, Poisson's ratio and density were assumed as $E_{steel} = 206$ GPa, $\nu_{steel} = 0.3$, and $\rho_{steel} = 7.85 \times 10^3$ kg/m³, respectively.

4. Analytical and Experimental Results

4.1 Impact force, reaction force, and displacement

Figure 5 shows comparisons between the analytical and experimental results for impact force (*P*), reaction force (*R*) and mid-span displacement (*D*). Here the applicability of a proposed FE analysis method was investigated focusing on four specimens of RC girder with falling heights of $H = 2.5, 5, 7.5$ and 10 m. Fig. 5(a) shows the comparisons of the impact response

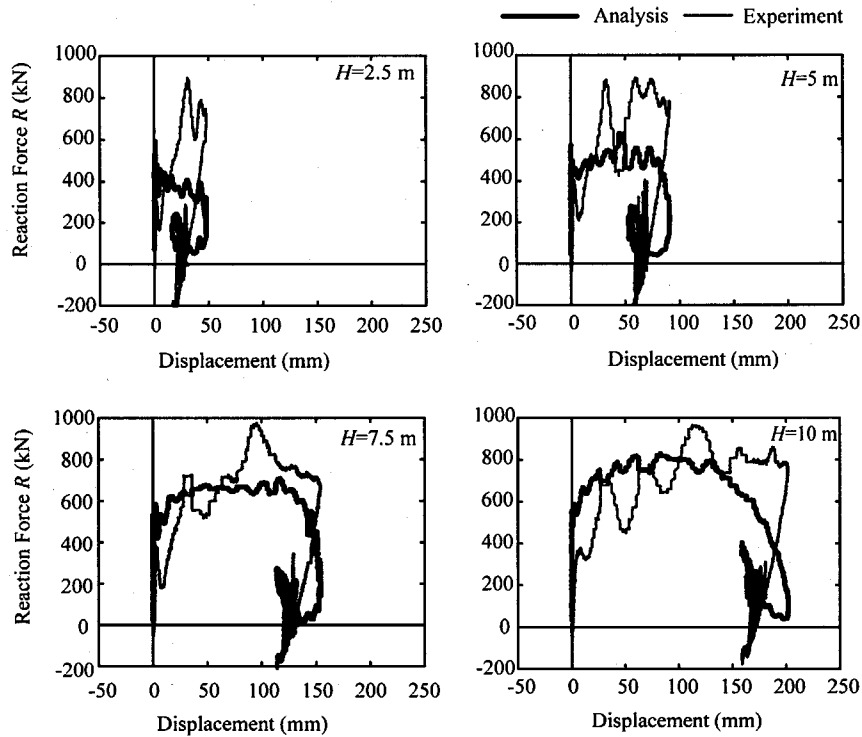


Fig. 6 Comparison between Reaction force and Displacement

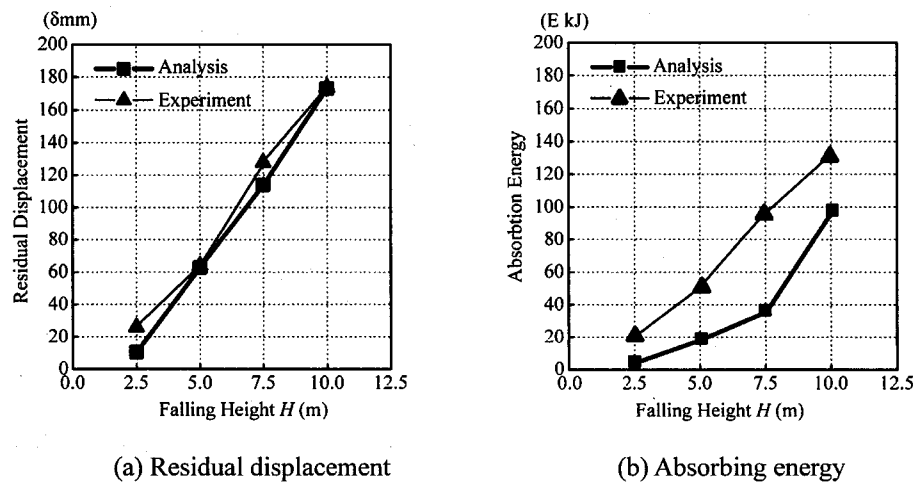


Fig. 7 Comparisons of residual displacements, and absorption energy with falling height

waves of the girder obtained using FE analysis method with the experimental results. For each response wave, characteristics of wave and an applicability of proposed numerical analysis method by comparing with experimental results will be discussed below.

Figures 5(a) show the time histories of impact force waves with total duration time of 200 ms. From those figures, it is observed that; 1) duration time of impact force wave was roughly about 180 ms; 2) the experimental wave was mainly composed of a three damped sinusoidal waves with gradually elapsed period; 3) the wave during about 50 ms from the beginning of impact may be excited due to interacting between heavy weight and compacted sand, and the

wave after that may be occurred due to heavy weight impacting against the RC girder through compacted sand; and 4) during about 25 ms at beginning of impact, high frequency waves were also excited. However, those waves may be come out from vibration characteristics of accelerometer and/or stress wave transmitted in the weight, because the high frequency wave components were hardly excited in the heavy weight due to colliding against sand which was of extremely loose and soft comparing with the weight.

Comparing with the analytical and experimental waves, it is confirmed that 1) duration time of a whole wave and wave configuration after about 75 ms from the beginning is in good correspondence with the

experimental results; 2) period and phase of waves around the beginning of impact are a little different from experimental results; but 3) the maximum response value may be almost same to each other.

From Figures 5(b), for reaction force wave, it was observed from experimental results that: 1) the loading time due to heavy weight was about 200 ms and 2) the maximum reaction force was about 894 kN in case of $H = 2.5$ m and increases with increment in falling height and about 965 kN in case of $H = 10$ m. 3) after unloading, the RC girder freely vibrates with damping having a period of 100~110 ms in case of $H = 2.5$ m and increase with increment in falling height. Comparing with the analytical and experimental results, it was seen that the wave configurations from both results are almost same to each other, even though maximum amplitude from experimental results was a little bigger than that from analytical ones.

From the Figures 5(c) for displacement wave (D) at mid span, it was confirmed that numerical response waves during the impact load surcharging to the RC girder are similar to those of the experimental results. The numerically estimated period for free vibration was almost the same with that of experimental results and was about 100 ms.

4.2 Hysteretic loops of reaction force (R) and mid span displacement (D)

Figure 6 shows comparison of hysteretic loops of reaction force (R) and displacement (D) relationship between analytical and experimental results. Comparing between analytical and experimental results, the distribution of R - D hysteretic loops estimated using numerical analysis were similar to those of experimental results irrespective of the falling heights. The level of damage for low falling height was small as confirmed from the time histories of reaction force wave and displacement wave as shown in Fig. 5 for falling height $H = 2.5$ m having smaller areas under curve with no spalling of concrete at the bottom surface of the girder. Moreover, it was understood that the area of the hysteretic loops increases with increasing of the maximum displacement and the residual displacement due to increase in the falling height. It was also seen that the shape of hysteretic loop is a parallelogram type. From these observations, it was seen that the ultimate strength of flexural failure type RC girder may be rationally estimated by using the R - D hysteretic loops. From those discussions, it was confirmed that the hysteretic loops of R and D can be approximately estimated by using the proposed FE method.

4.3 Residual displacement and absorption energy amount

The relation between the residual displacement and the falling heights is shown in Figure 7(a). From this figure, it was understood that the residual displacement increases proportionally with increment in falling heights. The comparison of both results from experimental and analytical was in good agreement. Moreover, the residual displacement obtained for falling height of $H = 10$ m was about 174 mm which is similar to the experimental results.

However, if it was assumed that the RC girder reaches to ultimate state when residual displacement is 2% of the span length such as being estimated in cases of small RC girder⁶⁾. The RC girder subjected to impact force due to falling weight from $H = 10$ m height may be reached ultimate state because of the residual displacement being more than 2% of the span length (174 mm).

Absorbing energy was evaluated based on the area enclosed by integrating the time history of the reaction force and displacement waves and the R - D loop showed in Figure 6. The relationships between absorbing energy and falling heights shown in Fig. 7(b), it can be seen that the absorption energy from experimental results increases almost linearly up to the maximum value with an increment in the falling height. It was understood that the absorption energy was almost proportional to the falling height as well as in case of residual displacement for the amount of the absorption energy. However it was seen that the absorption energy from numerical analysis was underestimated the experimental one. It was almost 0.73 times the amount of absorption energy in case of falling height $H = 10$ m to the amount of absorption energy obtained from the experimental results.

4.4 Crack patterns on side-surface of RC girders

The crack pattern here will be predicted based on the principle that concrete stress is converted to zero when the pressure applied to an element reaches a tension cut-off value following the constitutive law of concrete assumed before.

The crack patterns obtained from experiments were sketched in black solid lines as shown in Figure 8 for four different falling heights $H = 2.5, 5, 7.5$ and 10 m. It is seen that the damage occurred in the RC girder will increase with increasing of falling heights. Figure shows the contours of the maximum principal stress range from -0.001 to 0.001 MPa with white color on the side-surface under the maximum displacement. Then the white colored elements can be considered as being

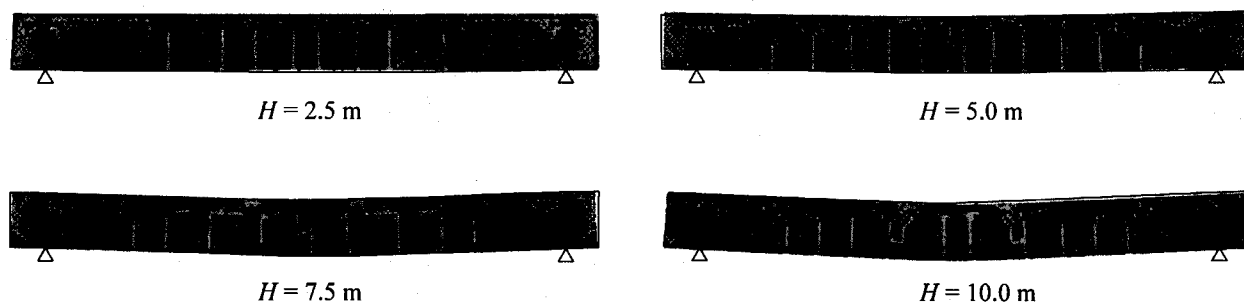


Fig. 8 Analytical crack patterns on front side of RC girders (white, 0.001MPa, dark/black > 0.001 MPa)

cracked region. Figure shows that a series of white elements developed from the upper to the lower edge of the beam. Then, it is seen that the distribution of white colored elements are almost similar with the crack patterns from experimental results. It is confirmed that the crack patterns observed experimentally can be predicted by the proposed FE analysis method.

5. Conclusions

In order to establish a proper FE model of RC girders with prototype sand cushion for impact response analysis, dynamic response analysis of RC girders with sand cushion subjected to impact force due to weight falling from the height of $H = 2.5, 5, 7.5$, and 10 m was conducted. An applicability of proposed numerical analysis method was discussed comparing with prototype experimental results. The results obtained with this study are as follows:

- (1) The response characteristics obtained by using proposed numerical analysis method have comparatively similar tendency to impact force wave, reaction force wave and displacement wave forms to those of experimental results;
- (2) The numerical analysis results for impact force wave and reaction force wave have a tendency to be smaller than those from experimental ones;
- (3) The displacement wave from numerical analysis results are in good agreement with the experimental results;
- (4) Crack patterns of concrete on side surface can be roughly predicted by the distribution of the elements with zero value of the maximum principal stress;
- (5) Area of loops under reaction force displacement curves was showing the underestimation of numerical analysis results. The configuration of the hysteretic loops at failure of RC girders can be approximated by a parallelogram; and
- (6) Comparison of relationship between falling heights and residual displacements are in good

correspondence, but the results obtained from numerical analysis are underestimated in the case of absorption energy.

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