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An Experimental Study on Dynamic Response of Deep Beams by Impact Loading Test

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Synopsis: The weights-dropping test on four different kinds of specimens was executed to obtain stress wave propagation characteristics. Steel bar as weight and synthetic resin mortar as specimen's material are used in the present experiment. Applied impact load on the specimen is measured from the strain of the dropping steel bar. Strain gauges were attached to some points of specimens, and stress responses were recorded. From these experimental results, the velocity of stress wave is compared with theoretical values. Furthermore, experimental dynamic response curves are compared with results of 2D FEM analyses.

Keywords: *stress wave propagation, theory of elastodynamics, deep beam, 2D FEM, synthetic resin mortar, steel bar*

1. Introduction

It is well known that the use of 2D elastodynamic theory gives accurate stress wave phenomenon of the deep beam than that of Bernoulli-Euler beam theory [1]. The theoretical solutions for isotropic materials consist of longitudinal wave, transverse wave and surface wave. It is very difficult to measure the accurate stress wave propagation by the impact test because of the problems in performance of dynamic strain measuring device. However, they are improving in performance and cost day by day. In this study, the dynamic strain-measuring device of 200 kHz performance (sampling time 5 μsec) is prepared for the dropping rod test. As the longitudinal stress wave velocity is proportional to square root of Young's modulus, synthetic resin mortar is adopted as material of specimens. Young's modulus of resin mortar is seemed to be about a half of the concrete's one.

2. Dropping Test

2.1 Apparatus

The test apparatus used is shown in **Fig. 1**. The apparatus consists of two parts. One is the part to prevent uplift of the specimen, and another is the part of guide for dropped steel rod which is 1500 mm long. Impact load is given by the steel rod dropping on the specimen, and then impact stress is estimated through the strain gauges, which is attached on the rod surface. To realize the hinged support condition at near both ends, the specimen are rested on the steel bar (ϕ40) and fixed by the vertical supporting bar (see **Fig. 1**). Only four channels of dynamic strain-measuring device were set up, and thus in order to obtain the dynamic strain data at more than four measuring points, the dropping tests under the same condition were executed repeatedly. After the transformation

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from analog data to digital data, the strain data are recorded in the data recorder. We used averaged data obtained by the several experiments, hereafter for consideration of test results.

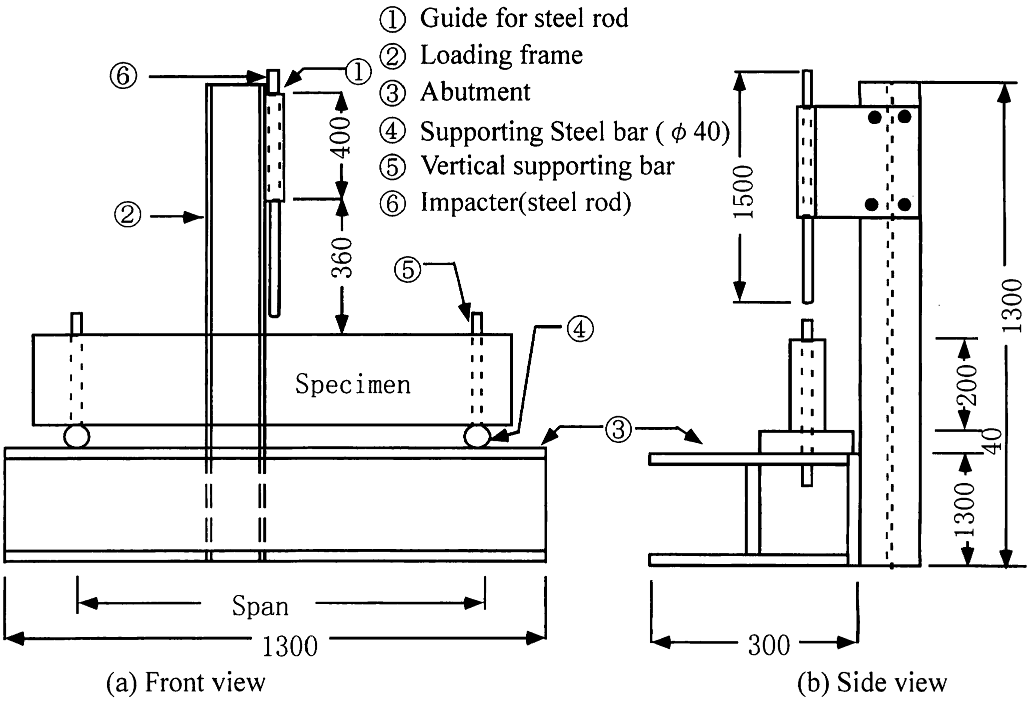

Fig. 1 Loading apparatus (unit: mm)

2.2 Specimen and Measuring Points

Two types of specimen are prepared for the dropping test as shown in **Figs. 2** and **3**. The single-layer specimen shown in **Fig. 2** is made of only resin mortar. These models have three types of span whose lengths are 600, 800, and 1000mm. In the case of two-layered specimen shown in **Fig. 3**, the upper layer is made of steel and the lower resin mortar. The span is 600mm long. The measurement of strain is performed on the points of Nos. 1 - 8 for single-layer specimen, and on the middle points of both the resin mortar and steel layers for two-layered specimen. Strain gauges except Nos. 4, 7 and 8 are attached to measure the longitudinal stress wave. Strain gauges of Nos. 4, 7 and 8 are attached for measuring the dynamic strain due to bending vibration. Strain gauges of Nos. 5 and 6 are attached at an angle of 45-degrees to the centerline of the specimen to obtain the longitudinal stress wave.

Material constants for mortar and steel are shown in **Table 1**. The longitudinal stress wave velocity in plane stress state is given by

$$c = \sqrt{\frac{E}{(1-v^2)\rho}} \tag{1}$$

where E is Young's modulus, v is Poisson's ratio, and ρ is density. The longitudinal stress wave velocities for each material calculated by Eq. (1) are given in the right column of **Table 1**.

Table 1 Material constants by statical loading test

	Young's modulus E (Pa)	Poisson's ratio ν	Density ρ (g/cm^3)	Wave velocity(2D) (m/sec)
Resin mortar(Single-layer)	5.52×10^9	0.309	1.73	1878
Resin mortar(Two-layer)	5.49×10^9	0.363	1.60	1988
Steel	2.06×10^{11}	0.300	7.85	5370

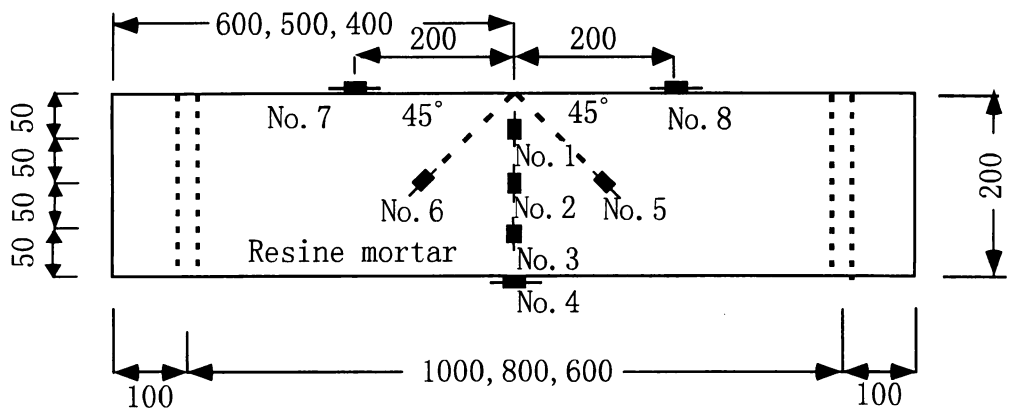

Fig. 2 Measuring points of single-layer specimen by strain gauge (unit: mm)

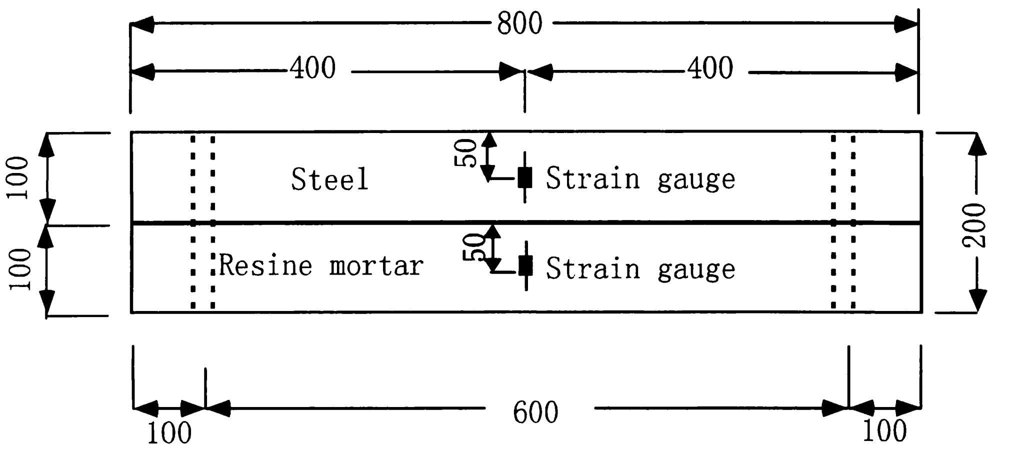

Fig. 3 Measuring points of two-layered specimen by strain gauges (unit: mm)

3. Results and Discussion

3.1 Results of Test

Figures 4 - 6 show the stress histories of single-layer specimens with 600mm, 800mm and 1000mm spans, respectively. Top figures in **Figs. 4 – 6** show the stress of steel rod, which means the applied dynamic load on the specimen. In these figures, recorded time t_{exp} is calibrated by Δt that is the time duration of transmission on longitudinal wave from the tip of steel rod to the attached strain gauge of 100mm away from the tip. Then, the actual loading time t is given by

$$t = t_{exp} - \Delta t \tag{2}$$

The middle figures in **Figs. 4 – 6** present the strain histories at the points of Nos. 1 – 3, 5 and 6. The bottom figures in **Figs. 4 – 6** show the strain histories due to the beam vibration.

Figure 7 presents the dynamic response of two-layered specimen. The top figure shows the stress history of the tip of steel rod. It is appear that applied impact load on the specimen is different from the case of single-layer specimen in spite of the same test condition. The middle and bottom figures in **Fig. 7** show the strain histories at the middle point of steel and mortar layers, respectively. Although the characteristic of stress wave propagation is considered in these figures, high frequency vibration phenomenon which appeared in theoretical treatment [2,3] is not seen apparently except the initial response of steel layer.

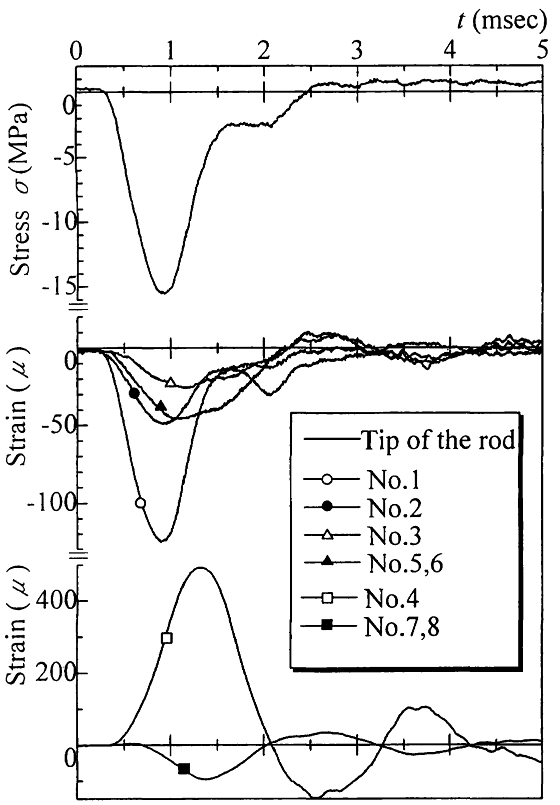

Fig. 4 Response of rod and beam with length 600mm

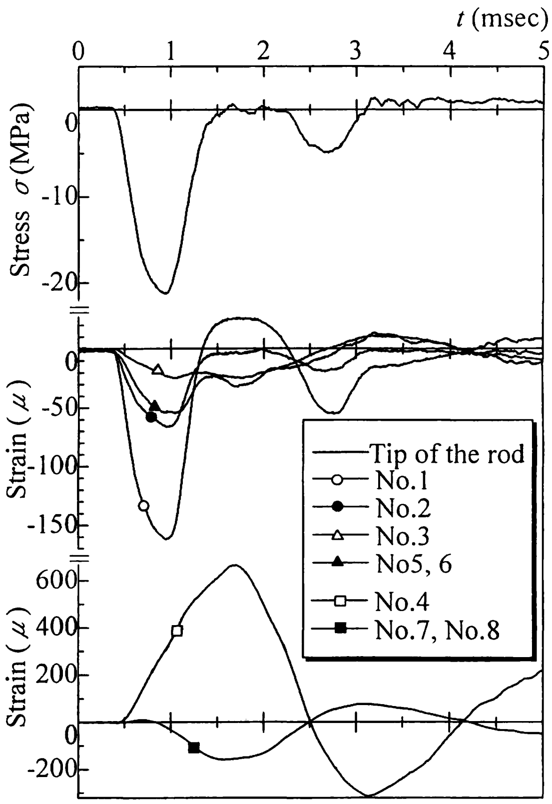

Fig. 5 Response of rod and beam with length 800mm

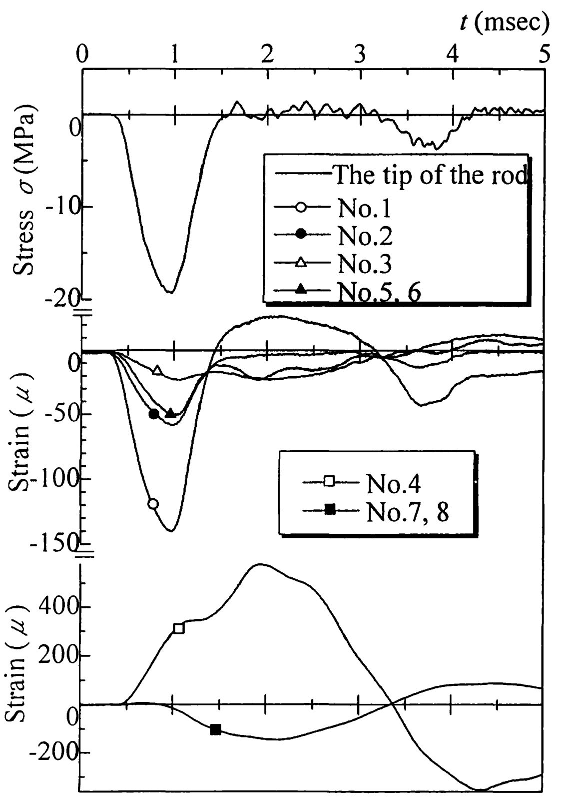

Fig. 6 Response of rod and beam with length 1000mm

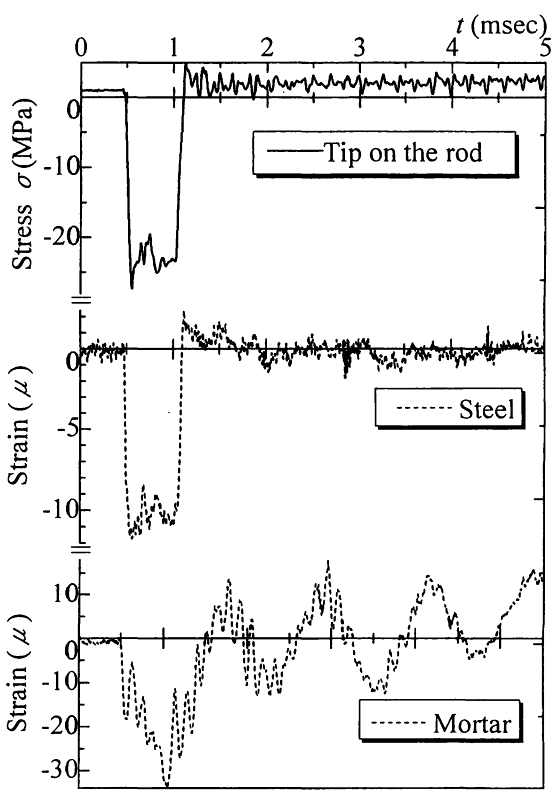

Fig. 7 Stress response of two-layered specimen

3.2 Wave Velocity and Beam Vibration Period

The average time duration of stress wave propagation from the points No. 1 to No. 2, which is estimated by **Figs. 4 - 6**, is given in **Table 2**. The arriving time of stress wave is used for the purpose of estimating the time duration. However, it is difficult to estimate the arriving time of stress wave at the points of Nos. 3, 5 and 6 because of damping phenomenon, and thus the arriving time of stress wave at No. 2 is used for the case of single-layer specimen as time duration. The right column of **Table 2** shows Young's modulus, which are calculated by Eq. (1) using these measured wave velocities. Comparing these Young's modulus with those obtained by static test in **Table 1**, these dynamical Young's modulus show 2 to 3 times as much [4].

Table 2 Duration of wave propagation from point No.1 to No.2 and wave velocity

Type	Span (mm)	Duration Average (μsec)	Distance (mm)	Wave velocity (m/sec)	Young's modulus (Pa)
Single-layer	600	17.0	50	2941	1.35×10^{10}
Single-layer	800	16.7	50	2994	1.40×10^{10}
Single-layer	1000	15.0	50	3333	1.74×10^{10}
Two-layer	600	15.7	50	3185	1.41×10^{10}

The experimental natural period of single-layer specimens and theoretical one based on Bernoulli-Euler beam theory are given in **Table 3**. The former values are the estimated from the **Figs. 4 – 6**, and the latter is the fundamental period based on Bernoulli-Euler beam theory. Although the boundary condition of specimen in the present experiment gives almost both-end hinged condition, the natural period in experiment is nearer to the theoretical period of beam with both-end fixed than both-end hinged. These results show that the assumed experimental boundary condition is not both-end hinged perfectly.

Table 3 Results of natural period at the points of Nos. 4, 7 and 8

results of vibration period		Natural period based on beam theory	
Span(Single-layer) (mm)	Both-end hinge (μsec)	Both-end fixed (μsec)	Both-end hinge (μsec)
600	2500	1355	7052
800	3700	2410	12540
1000	4800	3764	19630

3.3 2D FEM Analysis

Figures 8 and **9** show the results of 2D FEM (12×42 elements) analysis for single-layer and two-layered specimens with 600mm-span length. Young's modulus and damping factor used in 2D FEM analyses are given in **Table 4**. The damping factor of resin mortal is assumed to be higher value than steel's one, say 2 times. Applied stress-time relations to the FEM model are shown in the top figures of **Figs. 4** and **7**. The analytical response curves at points of Nos.1 and 2 shown in **Fig. 8** coincide well with experimental results in period and magnitude of amplitude.

Table 4 Young's modulus and damping factor for 2D FEM analysis

Type (Span ; 600mm)	Young's modulus (Pa)	Damping factor (%)
Resin mortar(Single-layer)	1.33×10^{10}	12
Resin mortar(Two-layer)	1.41×10^{10}	12
Steel	2.06×10^{11}	6

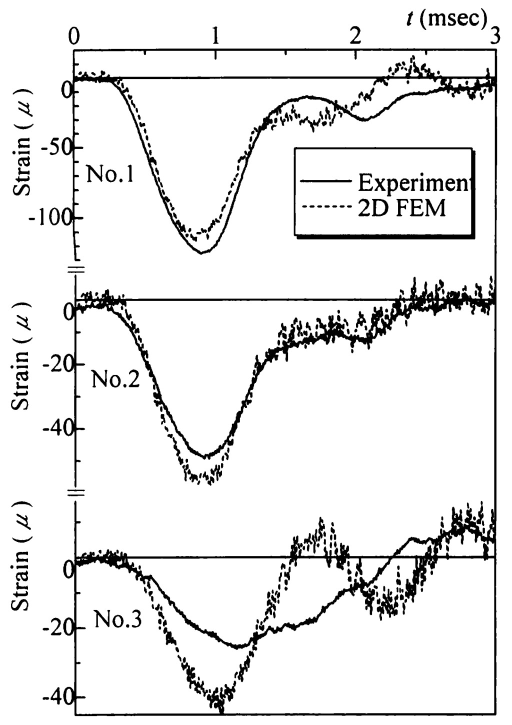

Fig.8 Comparison of experiment and 2D FEM for beam width 600 mm

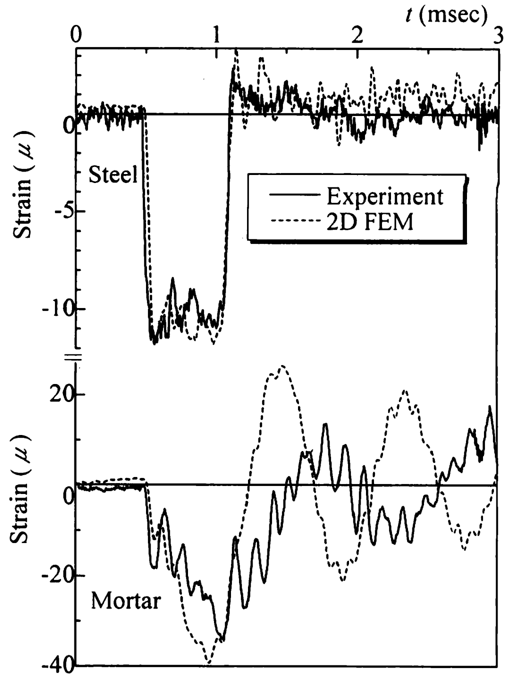

Fig.9 Comparison of experiment and 2D FEM analysis for two-layered beam

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