Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles
Part 3: Full-Scale Tests

Kiyoshi Muto, Tadashi Sugano, Harjui Tsubota,
Nobuhide Nagamatsu, Norihide Koshika, Masaaki Okano,
Kiyotaka Suzuki, Satoshi Ohrui
Muto Institute of Structural Mechanics, Inc., Tokyo, Japan
Walter A. von Riesemann, D. C. Bickel, R. L. Parrish, R. D. M. Tachau
Sandia National Laboratories, Albuquerque, NM USA

1 INTRODUCTION

In the final tests of the experimental program for evaluating the local damage caused by a deformable missile, six high-speed full-scale impact tests were conducted to determine the physical damage to and the dynamic response of reinforced concrete panels when they are subjected to the impact of a full-scale aircraft engine traveling at a velocity of 215 m/s. This impact velocity corresponds to the highest level of the velocities that were used in the scale tests [1,2], because extrapolation to lower velocity damage is more precise than extrapolation to higher velocity.

The test results will be used to

1) Confirm the local damage caused by real engines
2) Validate empirical formulas for local damage (e.g., penetration, scabbing, perforation) of reinforced concrete panels against an aircraft engine impact
3) Evaluate the effect of a thin steel liner on the impact resistance of reinforced concrete panels
4) Examine the validity of the design of a simple model to simulate the characteristics of the engine
5) Evaluate the scaling laws used in the small- and intermediate-scale impact tests

2 TEST PARAMETERS

2.1 Test Panels

The test panels for the six impact tests were 7 m square as shown in Fig. 1. The panel thicknesses were 90, 115, 135 and 160 cm. The basic steel reinforcement ratio of the test panels was 0.4% each way, each face; there was no shear reinforcement. One panel had a 2.3 mm thick corrugated steel liner fastened to the rear face with shear studs. The measured actual concrete strength had a mean value of 23.5 MPa (240 kgf/cm^2), the same as the design strength.

These panel thicknesses and reinforcement ratios were determined in consideration of the reinforcements and thicknesses expected to prevent scabbing and perforation as defined by the results from the small- and intermediate-scale tests [1,2]. The panels were attached at the four corners to the load cells mounted to the backup structure (Photo. 1).

2.2 Missiles

Two types of missiles were used in the full-scale tests. Obsolete GE J79 turbojet engines without the afterburner installed (Fig. 2) were used in Tests No.1, 2, 3, 4 and 6. A simple model of the engine (Fig. 2) was used in Test No.5. The weight of the engine was less than the actual engine; the weight of the missile was increased by the addition of a telemetry package and a ballast plate to closely approximate the weight of the actual engine. The weight breakdown is listed in Table 1. The simple model was a direct scale-up of the models used in the small- and intermediate-scale tests.

2.3 Test Method

The tests were conducted at the Sandia National Laboratories Rocket Sled Track Facility in Albuquerque, New Mexico, U.S.A. The missile to be tested was supported above the track by a carriage mount and sled structure (Fig. 3). The missile and carriage was propelled down the track by a pusher sled containing one Nike rocket motor and two Zuni rocket motors. Immediately following the burnout of the rocket motors, the missiles separated from the pusher sled as it encountered the water in the trough between the track rails, engaging the water brake. The missiles coasted along the remaining length of the track, and then traveled in free flight for a few meters and impacted the test panel. The carriage mounts remained attached to the missiles until impact. They were designed to break loose from the missile at impact so that they would not have an appreciable effect on the amount of damage inflicted on the test panels.

2.4 Measurements

Strain gages and kinematic sensors consisting of accelerometers, velocity gages, and displacement gages were used to monitor the response of the panels. The reaction forces were measured by the load cells at the four corners of the panels. Three accelerometers were mounted to the missiles in five of the tests to measure the deceleration of the missile during the impact sequence.

3 TEST RESULTS AND CONSIDERATIONS

3.1 Panel Damage

Panel No.1 (90 cm thickness) was severely damaged. A hole was knocked out of the panel and the concrete from the top to the bottom of the rear face was also broken to the depth of the rear rebar. For the No.2 panel (115 cm thickness), the concrete was broken off the back face to the depth of the rebar over approximately 4.5 m height by 3 m width. For No.3 panel (135 cm thickness), a little concrete was spalled off the rear face, but it was cracked extensively. In addition to the cracks extending outward, there was a nearly circular crack; this crack was indicative of shear cone cracking. For No.4 panel (160 cm thickness), an extensive number of radial and shear cone cracks were seen on the rear face and a crater depth on the front face was about 7 cm. The damage to panel No.5 was similar to No.4 but the crater depth was about 21 cm. No.6 panel was as of the same design as panel No.2 except for the addition of a 2.3 mm thick corrugated steel liner. The apparent damage to panel No.6 was less and the liner prevented concrete scabbing.

A summary of the damage for each panel is shown in Table 2 and Fig. 4. Judging from the damages, perforation will occur if the thickness is less than 90 cm, while the scabbing thickness is more than 135 cm.

Following the method used in the scale model tests, the perforation and scabbing thickness derived by multiplying the reduction factors to the typical empirical formulas for rigid missiles are compared with the test results of the deformable missiles in Fig. 5. In the figure, the conditions for the evaluation of the thickness by the empirical formulas were as follows: concrete strength is 23.5 MPa (240 kgf/cm^2), the missile diameter is 76 cm and the mass is 1500 kg.

3.2 **Missile Damage**

In the tests, the engine impacted normal to the test panel and was crushed from the front as shown in Photo. 3. On Test No.1, the engine was crushed to a length of 65 cm and on Tests No.2, 3, 4 and 6, the engine was completely destroyed. Pieces of the engine rebounded off the panel. The simple model crushed to the middle bulkhead on Test No.5. However, the 20 mm thick outer shell of the aft section was not crushed, but broken into large pieces.

3.3 **Measured Responses**

Fig. 6(a) shows the total reaction forces measured with the load cells and 6(b) shows the difference in the peak reactions, caused by the changes in the panel thickness, the two types of missiles, and the addition of a steel liner. In the engine tests, the sum of the load cell forces increased and the duration time shortened with an increase in panel thickness. The peak value of the reaction of Test No.5, where the simple model was used, was in relatively good agreement with that of the engine on Test No.4. Note the effect of the steel liner on the No.6 panel. The addition of the liner to the 115 cm thick panel made the rigidity equivalent to the No.4 (160 cm thick) panel.

The acceleration records from the on-board accelerometers and still photographs printed from high speed films were used to obtain the decrease in missile velocity versus time, Fig. 7(a). The velocity reduction on four tests, with the engine as the missile, was of approximately the same magnitude during the impact. Based on this curve and a mass distribution, an impact force-time function was evaluated, Fig. 7(b).

A large number of kinematic measurements of test panel motion were acquired. The data obtained from the velocity gages were fairly good. Fig. 8 shows the time histories of displacement at the center of the No.3, 4, and 5 panels. Based on the time-integrated velocities, Fig. 9 shows the deflection mode along the diagonal line of the No.3 and No.5 panels at 5 msec increments during the impact. For Test No.3, the vibration mode of lower frequency was dominant and after 10 msec only the inner portion of the shear cone deflected noticeably. On the other hand, on Test No.5, a higher frequency vibration mode, which generated the pronounced deflection at the center part of the panel, was excited continuously during the impact.

Likewise, a large amount of strain data was acquired. Fig. 10 compares the difference in time histories of vertical rebar strain of the rear face at the center of the panel, caused by changes in the panel thickness and the addition of a steel liner. On the thinner No.2 panel, the rebar strain rapidly increased at 6 msec after the impact when the peak force were acted, while on Test No.3 and 6 the strain increased after 12 msec, this corresponds to the second peak of the impact force. In Test No.4, which had no scabbing, the strain was small throughout. The effect of the liner is shown again where the strain from Test No.6 compared favorably with that from Test No.4.

3.4 **Concrete Scabbing**

On Tests No.1, 2 and 3, scabbing of concrete from the back surface occurred. Fig. 11 shows that a reduction of panel thickness caused the scabbing of heavier concrete debris, for a given test, the heavier pieces spalled at a lower velocity.

4 CONCLUSIONS

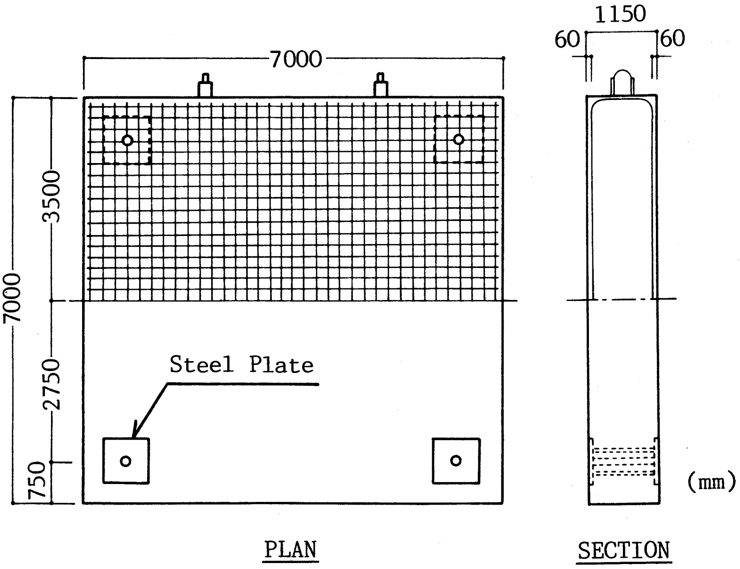
Six high-speed full-scale impact tests were conducted to determine the physical damage to reinforced concrete panels when they are subjected to the impact of a full-scale aircraft engine.

The test results showed that the actual damages are a little smaller than expected and the results also confirmed the reduction of the local damage due to the deformability of the engine. The results were used for validation of scaling laws and correlation with results obtained from small- and intermediate-scale impact tests.

REFERENCES

[1] Muto, K. et al (1989). Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles, Part 1: Outline of Test Program and Small-Scale Tests. Proc. 10th SMiRT.

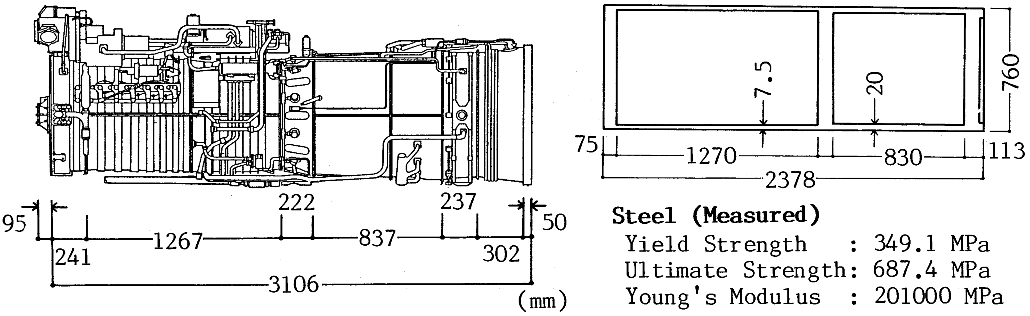
[2] Esashi, Y. et al (1989). Experimental Studies on local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles, Part 2: Intermediate-Scale Tests. Proc. 10th SMiRT.



Rebar (Measured)

Type : Deformed Bar
Diameter: 32.3 mm
35.8 mm
Yield Strength: 488.7 MPa
466.5 MPa
Ultimate Strength: 744.4 MPa
732.9 MPa
Young's Modulus : 206000 MPa

Fig. 1 Dimensions and Rebar Layout of Test Panel (t=115cm)



Steel (Measured)
Yield Strength : 349.1 MPa
Ultimate Strength: 687.4 MPa
Young's Modulus : 201000 MPa

GE-J79 Engine

Simple Model (Test No.5)

Fig. 2 Missiles for Impact Tests

Table 1 Weight Breakdown (kg)

Missile	Test Number					
	No.1	No.2	No.3	No.4	No.5	No.6
Engine(Excluding Accessories)	1252	1252	1252	1252	1420	1252
Accessories	166	166	166	166	(Simple Model)	166
Extra Weight Telemetry Package	346	316	363	349	43	349
Total Weight	1764	1734	1781	1767	1463	1767

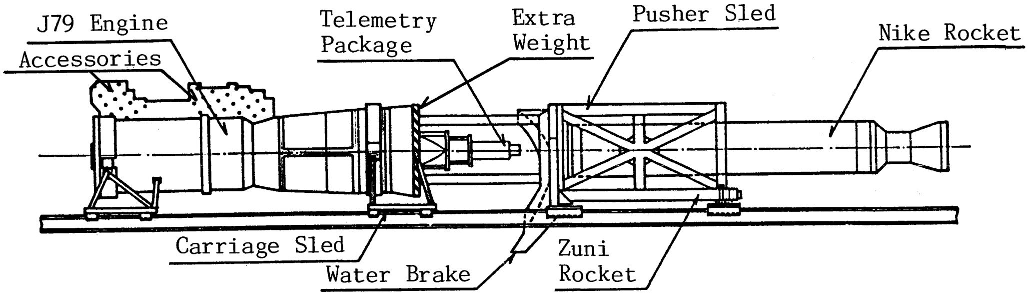


Fig. 3 Rocket Sled System

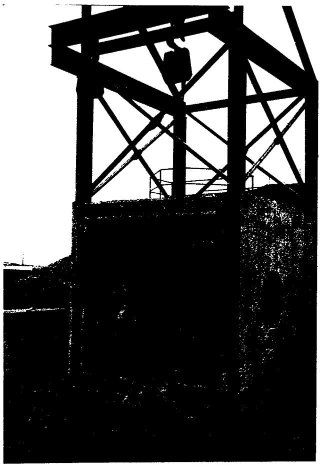


Photo. 1 Support Structure

Photo. 2 Crushed Engine after Test

Table 2 Summary of Test Results

Missile	Test Panel				
	Panel Thickness(cm)				Type
	90	115	135	160	
Engine	-●- No.1	⊘ No.2	-⊘- No.3	○ No.4	R/C Panel
Simple Model				○ No.5	R/C Panel
Engine		○ No.6			R/C Panel with Liner

Velocity= 215 m/s

Legend

-●-: Just Perforation
⊘ : Scabbing
-⊘-: Just Scabbing
○ : Penetration

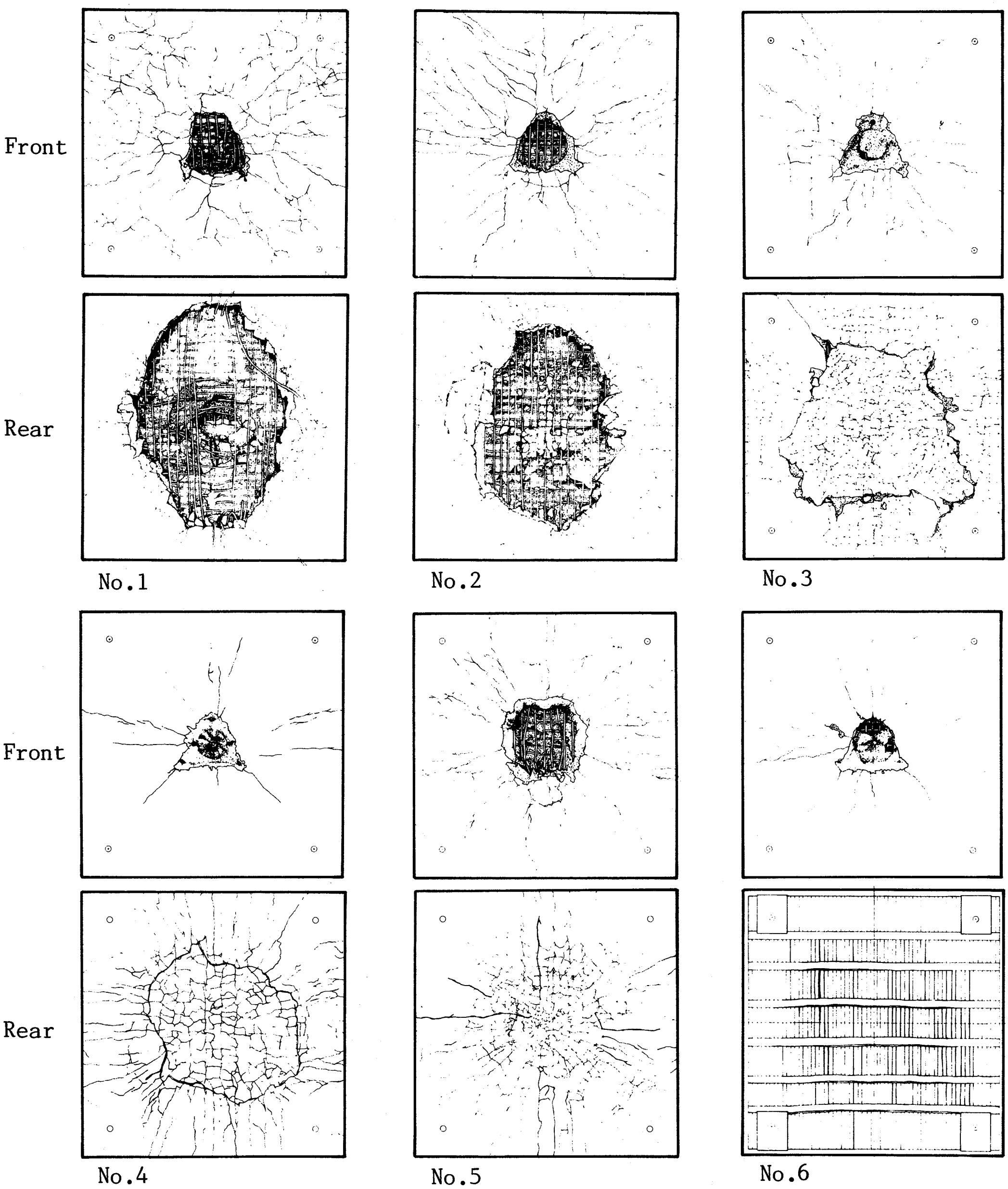


Fig. 4 Test Panel Damage

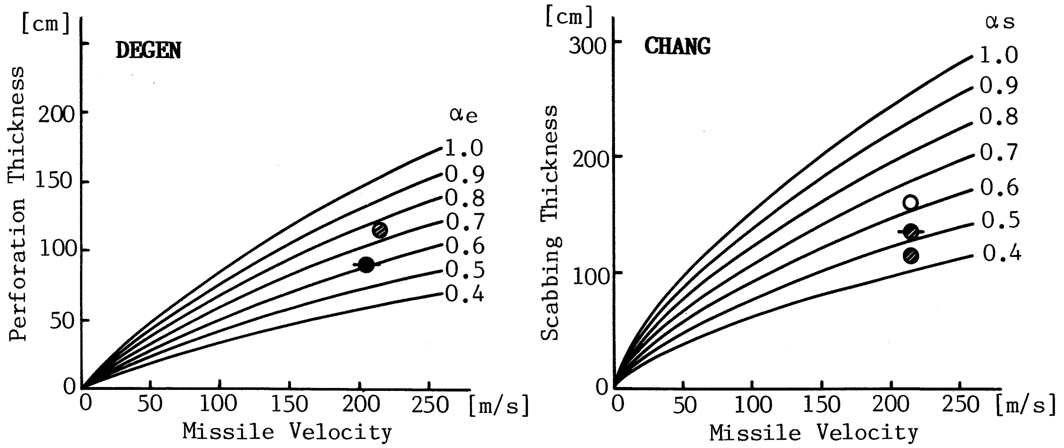


Fig. 5 Reduction Factors Evaluated from Empirical Formulas

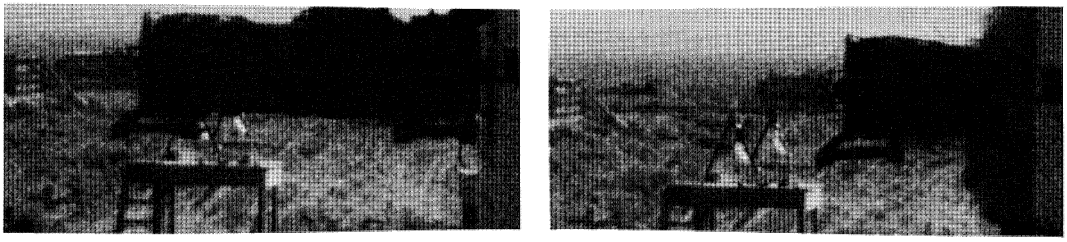
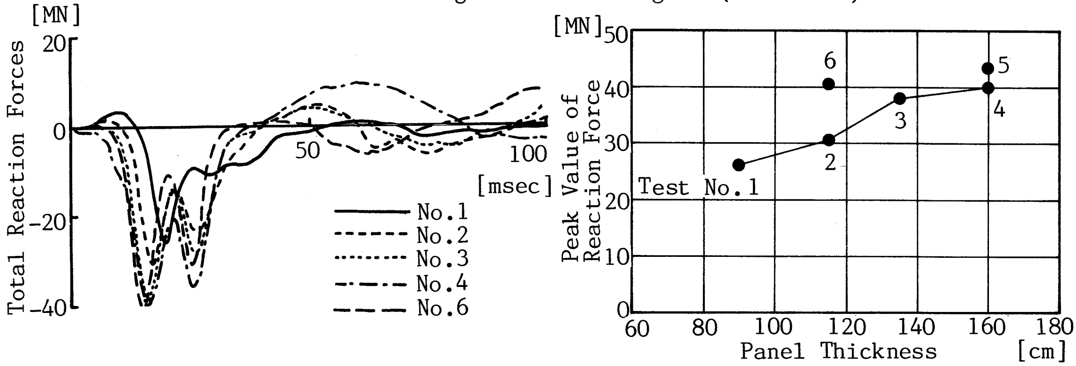


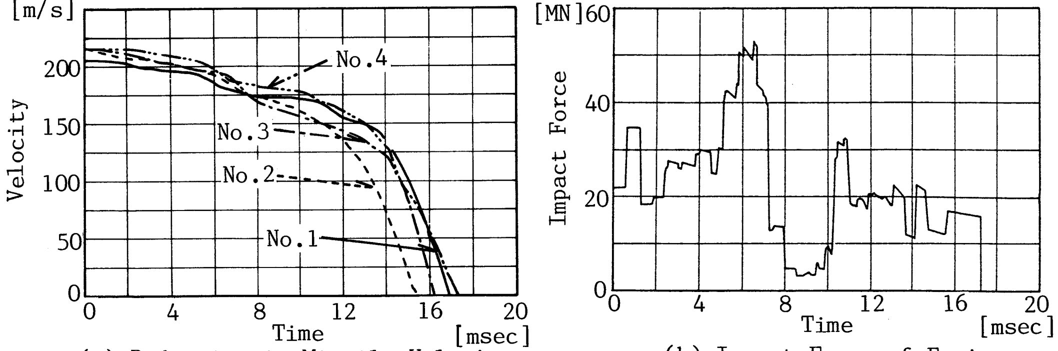
Photo. 3 Crushing Process of Engine (Test No.2)



(a) Time Histories of Total Reaction Forces

(b) Comparison of Maximum Reaction Forces

Fig. 6 Total Reaction Forces



(a) Reduction in Missile Velocity

(b) Impact Force of Engine

Fig. 7 Evaluation of Impact Force

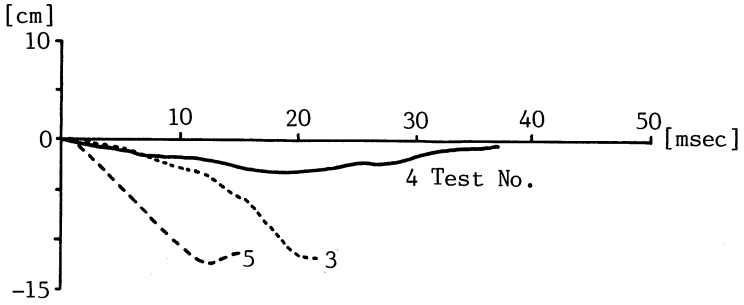


Fig. 8 Panel Displacement Time Histories at the Center

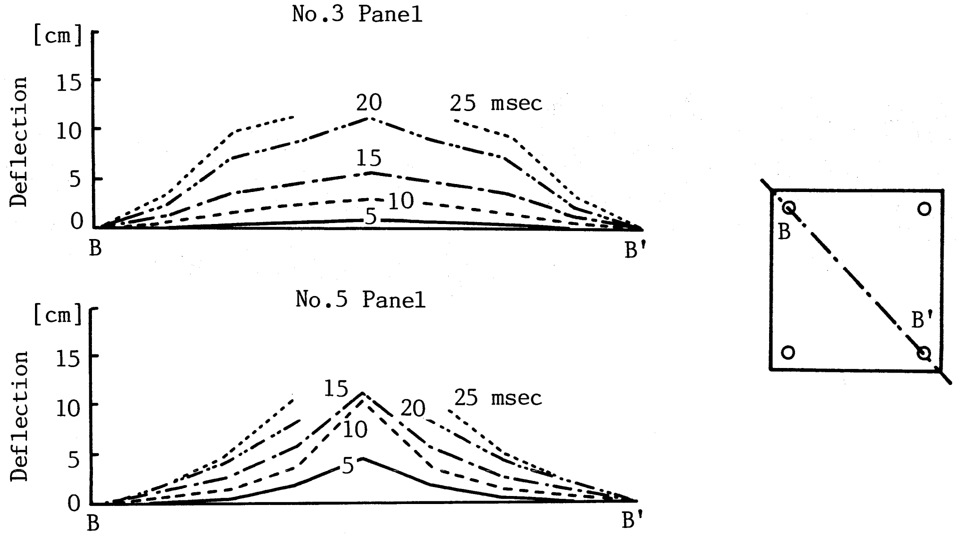
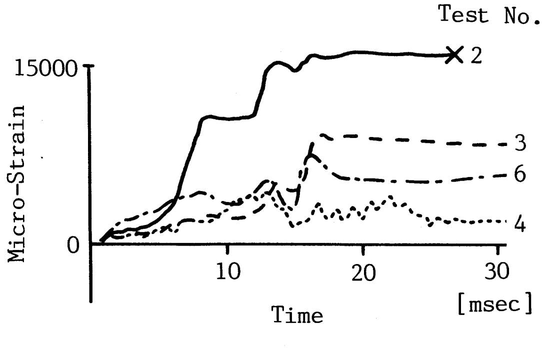


Fig. 9 Deflection Mode along the Diagonal Line



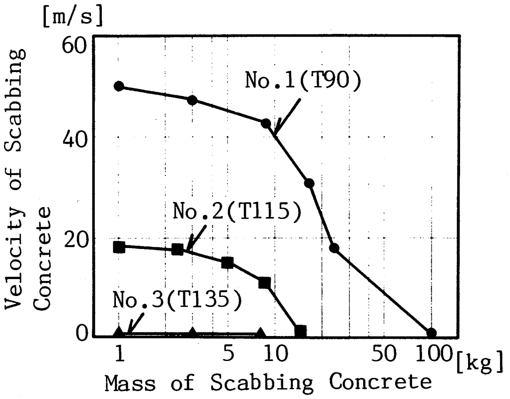


Fig. 10 Strain Time Histories, Rear Vertical Rebar at the Center

Fig. 11 Relation between Mass and Velocity of Scabbing Concrete