DYNAMIC RESPONSE OF EMBEDDED STRUCTURES
AFOSR-86-0058

FINAL REPORT

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A shock impulse environment simulated by low velocity impact (free-drop impact system) was developed to generate a well characterized dynamic loading on the free surface. Low velocity impact of a circular plate resting on sand provided the vehicle by which the dynamic loading on the free surface was characterized. An analysis based on linear elastodynamics was derived for transient waves on a thin plate resting on an elastic half-space (sand). The results provide an understanding of plate vibration (foundation vibration), of the interaction between the plate and the sand, and of the propagation of the load into the sand.

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Abstract

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The dynamic behavior of a typical elastic buried structure was studied by using plexiglas; where as micro reinforced-concrete was used to study the behavior of a buried reinforced concrete structure. Loading relief at the center of the roof of the buried structures was observed. Furthermore, the stiffer structure was observed to experience less soil arching. When a linear-elastic dynamic analysis by the finite element method was conducted, the numerical results were found to have good correlation with the experimental observation of the peak displacement on the buried roof. However, the behavior after the peak response can not be simulated using the current linear elastic formulation.

INTRODUCTION

Small-scale model tests were used to simulate some of the major aspects of the full-scale field observations. The model testing of dynamic soil-structure interaction provided a useful and relatively inexpensive method of understanding basic aspects related to the complex coupling between soil and structure. It was recognized that the data from field tests were difficult to analyze because the loading conditions on the free surface were difficult to measure. Through small-scale model testing, the generation of an impulse loading on the free surface can be well controlled and the propagation of this impulse loading through the soil and then its action on the buried structure can be traced.

The experiments and analysis for this research are conducted in two phases. During the first phase, the loading set-up was developed and the measured free field responses were verified with an analytical (wave propagation) model. These results are summarized in a paper "Low Velocity Impact of an Elastic Plate Resting on Sand" which has been accepted for publication in the Journal of Applied Mechanics (attached in the AFOSR-86-0058 Annual Report, February, 1988). The analysis and experiments with the buried structures constitute the second phase. Part of the second phase research is summarized in a paper "Dynamic Response of Shallow Buried Cylindrical Structure". The overall idea of the work performed in this research can be summarized by answering two questions: What are the major tasks accomplished so far and what are the current limitations. First, the major tasks accomplished are:

(1) development and characterization of the dynamic loading

(2) development of well-defined boundary conditions

(3) modeling material properties of sand by wave speed measurement

(4) measurement and analysis of the free field response

(5) measurement and analysis of elastic buried structure (made of plexiglas)

(6) measurement and analysis of reinforced concrete buried structure (made of miniature reinforcement and micro-concrete).

Second, the current limitations are:

(1) linear-elastic simplification for the analysis is unable to consider the following features:

(i) zero tensile capacity of sand

(ii) nonlinear behavior of reinforced concrete structure

(2) stress-strain relationship of sand was only modelled in an average sense; the nonhomogeneity in sand due to different stress magnitude, induced by the dynamic loading propagating through the sand, (a local phenomenon) was not considered.

(3) an interfacial element was not used to include separation and sliding in the analysis.

(4) a direct comparison of the failure behavior of the model RC structure to prototype RC structure could not be made.

SUMMARY OF PAST RESEARCH

The research of the first phase describes the measurement and analysis of plate and soil response under low velocity impact (Fig.1). A free-drop impact system was developed to generate the dynamic loading on the plate free surface. The radial strain of the target plate, the longitudinal wave speed and the acceleration of the sand were measured. The measured wave speed data were then used to evaluate the elastic constants of the sand. Based on the Hertzian contact law, momentum balance and measured contact duration, the impact loading function was assumed as a Hanning function for the following analysis.

A time domain analysis based on linear elastodynamics was developed for transient waves on a thin plate resting on an elastic half space. The contact stresses and the normal displacements of the plate were taken as unknown functions. The contact between the plate and the half space was assumed frictionless. The experimental results of the radial strain at the bottom of the target plate and the acceleration of the sand beneath the center of the target plate were compared with the analytical solution. The arrival time, the duration and the magnitude show good correlation between the analysis and experiment. The overall results appear good and provide an understanding of the transmission of impact load through the plate, the interaction between the plate and the sand, and the propagation of the load into the sand.

STATUS OF CURRENT RESEARCH

The status of the current research is as follows.

(a) experiment

In order to study wave propagation phenomena consistent with field test observation, a test of an approximately 1/40 scale model cylinder structure (15.24cm x 15.24cm) with 0.635cm thickness and embedded under about 7.6cm thickness of sand was conducted (Fig.2). A low velocity impact system was used to generate the dynamic loading on the free surface. The particular test of a circular aluminum (6061-T51) plate with 30.48cm in diameter and 1.27cm in thickness impacted at its center by a 7.62cm diameter steel (E52100) ball was considered.

One buried structure (Fig.3) was made of Clear Cast Acrylic (Ain Plastic Co.) with Young's modulus and Poisson's ratio equal to 3103 MPa units and 0.35 respectively. The response of this structure can be assumed elastic. Thus, analysis can be simplified and some useful phenomenon can be characterized.

Micro-concrete and miniature reinforcement developed by Townsend, et al.(1985) were used to construct a model RC circular roof. This RC roof was clamped on a plexiglas hollow-cylinder base to become a RC composite buried structure (Fig.4). The micro-concrete has properties similar to regular concrete but contains a finer aggregate. It is believed that the interface behavior between the concrete and the soil can be preserved with microconcrete (Shin, 1987). The miniature reinforcement, 28-gauge black-annealed wire manufactured by Anchor Wire Co. was used. Two wire meshs were constructed with 0.5" (12.7mm) square opening for each RC roof. As shown in Figure 5, the RC roof with 5/16" (7.9mm) in thickness and 6" (152.4mm) in diameter was reinforced with the wire mesh on both upper and bottom surface (tension and compression) and the concrete cover was about 1/32" (0.8mm) on both side.

The formwork was made of plexiglass with two aluminum sheets attached on the top and bottom in order to provide the thickness of the concrete cover and to hold the wire mesh in the designed position (Figure 5). The concrete was cast into the formwork on a mechanical vibrating table. 2"-cube concrete specimens were constructed from the same batch, and the strength properties of the model concrete were obtained from the uniaxial compressive test of the cube.

(b) analysis

The study of dynamic soil-structure interaction by the Finite Element Method (FEM) has progressed rapidly since 1970's. In general, the considerations in using the finite element method are the types of element, the constitutive modeling description, the finite geometries, the boundary conditions, and the applied loadings.

The FH test results have been analyzed by several researchers. However, the general problems and uncertainties in the FEM application are:

(1) the applied loading on the free surface was adopted by the pressure gages measurements. However, out of six gages, only two or three sets of records were available and were averaged to get the applied loading which was then assumed uniformly distributed along the free surface. As a result of the reflection from the buried roof the uniform pressure assumption is, in general, not likely to be true.

(2) The dynamic behavior of sand is not well understood. Typically, the constitutive relationship of sand depends on loading rate, loading magnitude, and loading history (Kiger, 1980). Highly nonlinear, nonhomogeneous stress-strain behavior would have occurred during the field test.

(3) The boundary conditions of the free surface before and after the explosion were very different.

With the above understanding, as a first order approximation, the current numerical study tends to reveal the physical meaning of dynamic soil-structure interaction. Linear-elastic model for both soil and structures were assumed in the current approach, and the dynamic linear-elastic finite element code, SAP4, was applied. Two-dimensional axisymmetric elements and a direct time integration method were used. This analysis can properly simulate the physical phenomena of the soil-structure system, and provide an understanding of the loading wave propagating on the buried structure and the corresponding structural response. This program also forms the basis for the proposed nonlinear analysis.

(c) results

(i) plexiglas buried structure (elastic structure)

The experimental results in comparison with the FEM calculations are shown in Figure 6. In Figure 6(a), the displacement at the center of the roof of the buried structure is plotted. In Figure 6(b), the radial strain at r=1.91cm from the center of the ceiling is plotted and the pressure at the center of the roof is shown in Figure 6(c). The calculated response has good agreement in some of its quantities with the measured response of those three different measurements. In all three plots, there was good agreement between the calculated and the measured arrival time. The peak displacement at the roof center (Fig.6(a)) and the corresponding radial strain (Fig.6(b)) can be predicted by the current linearly elastic analysis with about 75 percent accuracy for both the peak amplitude and the peak arrival. However, the response subsequent to the peak showed poor agreement. The FEM calculation predicted a lower amplitude because of the influence of the tension in the assumed "linear-elastic sand" (after the loading peak, the loading reflected from the bottom of the roof as tension), and the interface between soil and structure was assumed continuous and perfect bonded.

The loading measurement (Fig.6(c)) at the roof center was averaged by the surface area of the load cell and compared with the calculated normal stress of the element right above the center of the roof. Again, there was a poor agreement because of the deflecting roof, separation of the interface and the arching phenomenon which induced a release of the stress field between the sand particles above the center of the structural-roof (resulting in a lower measured loading duration). It is also noted that due to geometric nonlinearity on the interface as well as the local behavior of stress-strain law of sand, the calculated amplitude is less than the measured amplitude. Therefore, to improve the prediction to accommodate the behavior after the peak of the loading (unloading process) and to reveal the interfacial stress behavior, the nonlinearity due to zero tensile capacity of sand as well as the separation of the interfaces (including the interface between sand element if possible) should be considered.

The influence of different values of the Poisson's ratio, , was also studied by assuming the longitudinal wave velocity to be equal to the measured wave velocity (263 m/sec). For =0.25 and =0.4, the calculated elastic constants would have about 50% difference. However, by inspecting the calculated response before the peak (Fig.6), it was found that the dynamic response of the buried structure was not influenced significantly by the material properties of the adjacent soil. This can be understood by knowing that the stiffness of the structure is much larger then the surrounding soil and that there are large differences of the mechanical impedance between the structure and the soil.

(ii) Reinforced concrete buried structure

(1) load, strain, and acceleration measurements

The experimental results of the test with the reinforced concrete buried structure are described. In Figure 7, the load measurements of the second (dotted line), third (small-dashed line) and forth (large-dashed line) hits in comparison with the first hit (solid line) are plotted. It can be seen that although the response of the second, third, and fourth hits were stable and similar, the first hit had more oscillations caused by cracking of the concrete. This phenomenon was also seen in the the radial strain measurements on the roof of the structure.

The time history of the acceleration measurement on the center roof during the first hit is plotted in Figure 8(a). Again, high-mode oscillation is observed. The time expansion of the history between 0.6 msec and 1 msec is displayed in Figure 8(b). The results of the second, third, and fourth hits behaved similarly, but the first hit acted differently between 0.7 msec to 1 msec. In Figure 8(c), the velocity histories of these four hits obtained by integration of the acceleration measurements are displayed. The velocity histories of the second, third, and fourth hits show about the same peak velocity of 2.3 m/sec. However, the peak velocity of the first hit was only 1.5 m/sec. This lower value is suspected as another sign of cracking. The displacement histories shown in Figure 8(d) were obtained by integrating the velocity histories. The constant values of displacements for time up to 4 msec were not dependable since very little offset of the acceleration signals would result in great error of displacement after double integration. However, the displacements before the peak were fairly reliable, and the response of second, third and fourth hits were very close, having a peak displacement of about 0.7 mm.

(2) failure mode

Flexural failure was observed after completion of ten hits. The picture of the damaged RC roof is shown in Figure 9(b). The load cell became unbonded because of cracking which was radially formed. This cracking might be due to insufficient clamp boundary of the roof. The picture of the bottom roof (ceiling) is shown in Figure 9(a). The accelerometer was still bonded at the center ceiling. However, large cracks next to the accelerometer can be seen.

(3) comparison between the reinforced concrete roof and plexiglass roof

The dynamic behavior of the buried roof with different rigidity (plexiglas and RC) were compared to obtain better understanding of the arching phenomenon. A test with plexiglas roof mounted on the plexiglas base was conducted. The thickness of the circular plexiglas roof was 1/4 inch. The comparison of the load measurements on the center of the roof between the RC roof and the plexiglas roof is shown in Figure 10. Response of the first hit (solid line) and second hit (dotted line) of the RC roof are plotted as well as the response of the plexiglass roof (which behaved elastically) is also plotted as a dashed line. It can be seen that the RC roof which has higher stiffness experienced a longer duration and higher loading magnitude than the plexiglass roof. It was concluded that with the same surrounding soil, the stiffer buried structure experienced less soil arching.

(4) comparison between experimental and numerical results

The experimental data are compared with the FEM results in Figure 11. In Figure 11(a), the displacements at the center of the roof of the buried structure are plotted, and the pressure at the center of the roof is shown in Figure 11(b). The calculated displacement has reasonable agreement with the measured displacements up to about 0.7 msec. It was noted that the calculated values represent the displacement of an uncracked concrete roof. Therefore, a calculated response lower than the measured displacements was expected; however, the response after 0.7 msec showed poor agreement between the experiments and FEM results. Because this is due to the linear-elastic assumption of treating sand as a continuum, due to separation at the interface, and due to the nonlinear behavior of the model reinforced concrete structure after cracking. The continuation research includes improved measurement and analytical techniques to overcome some of the difficulties mentioned here.

RESEARCH CURRENTLY IN PROGRESS

In order to have a useful interpretation of the prototype's behavior from the model response, microconcrete specimens are being tested. Using microconcrete, reinforced with deformed annealed wires, we can observe and record in the laboratory, the model's behavior. So, in order to verify the accuracy of simulation (of the buried reinforced concrete model), round slabs are being tested. The slabs are 5/16" in thickness, reinforced with a (deformed) wire mesh of #20 (0.0348" dia.) and #28 (0.0162" dia.) @0.5 inch (in each direction). Using the aparatus described in the continuation proposal, these slabs are being subjected to uniform load, applied in different rates, under constant rate of mid-point deflection (which controls the application of load through the MTS).

Results of these experiments will enable us to verify the quality of using these microconcrete slabs as the model buried structure's roof. Also, by testing microconcrete beams, other parameters, such as the bond between the microconcrete and the microreinforcement of the model, will be examined.

Once the behavior of these structural elements is examined and learned, they can be efficiently used in the model buried structure (as suggested in the continuation proposal).

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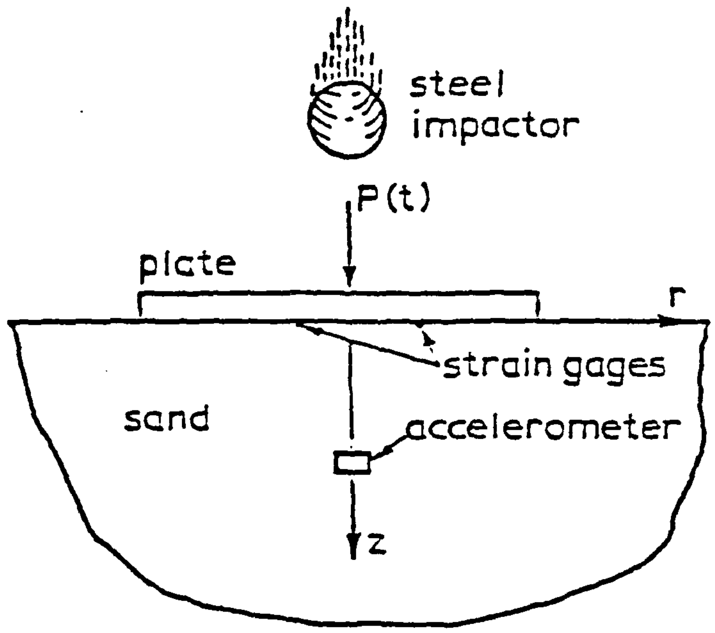


Figure 1 Low Velocity Impact of an Elastic Plate Resting on Sand

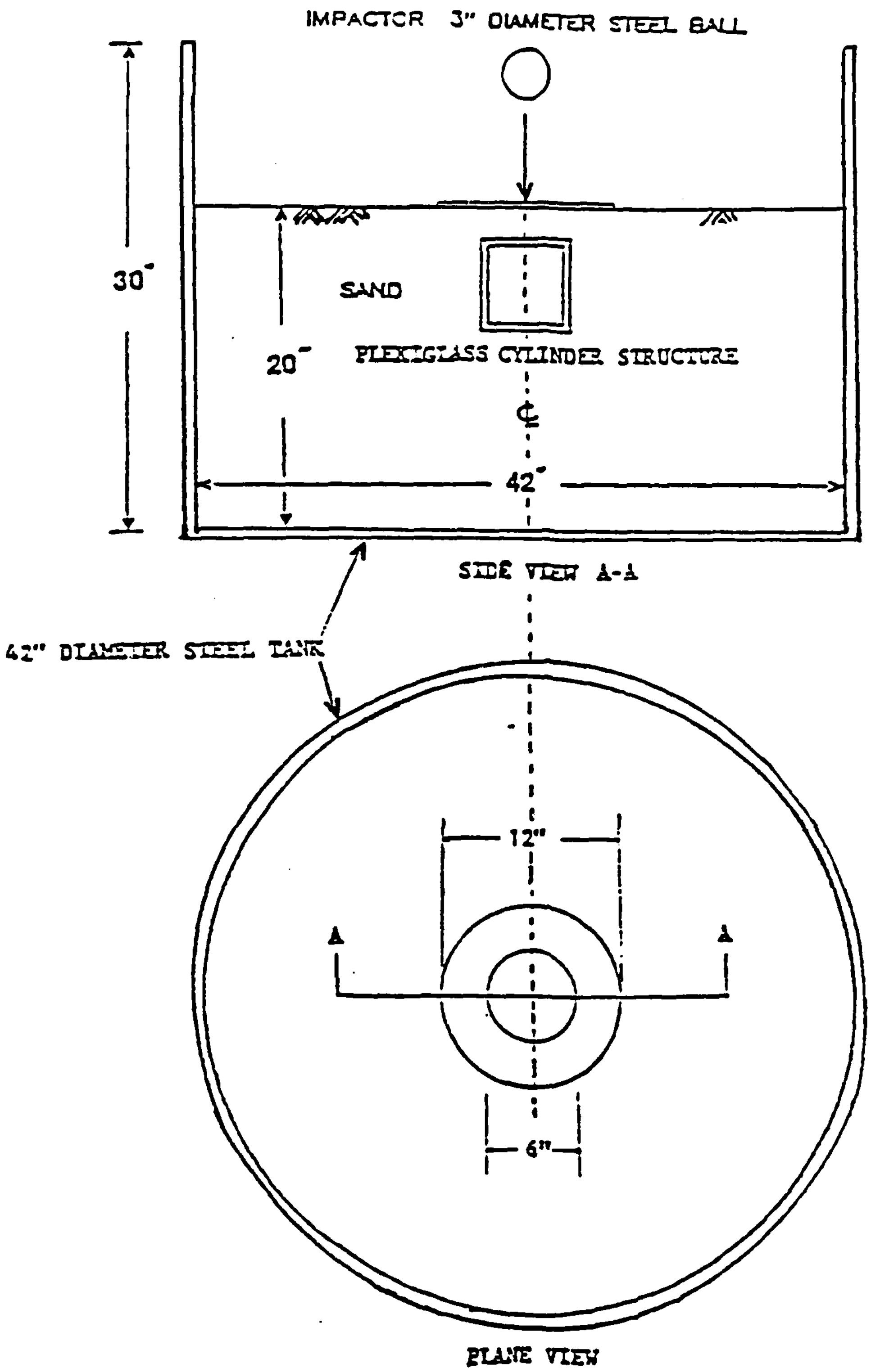


Figure 2 Test Layout (1" = 25.4 mm)

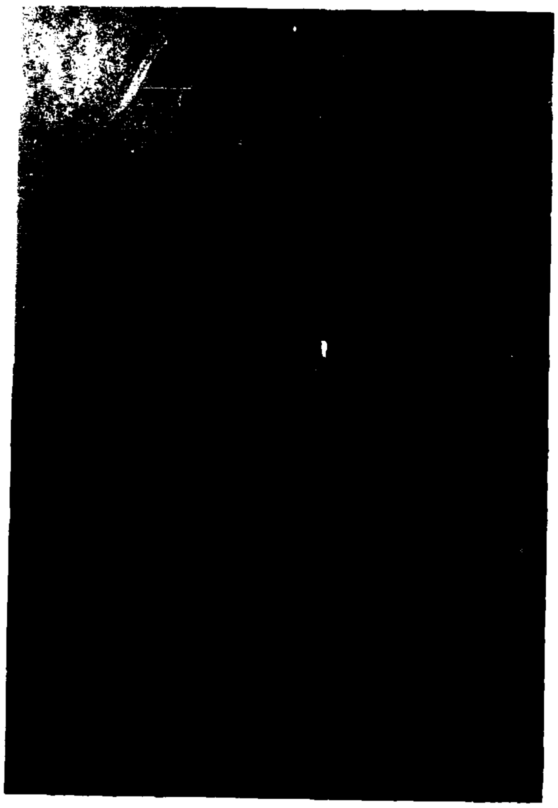
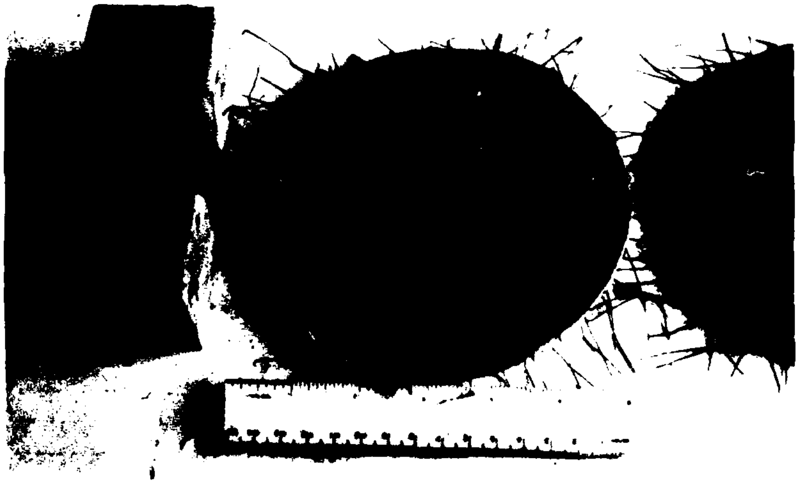


Figure 3 Picture of Elastic Buried Structure

Figure 4 Picture of RC Roof on Plastic Base



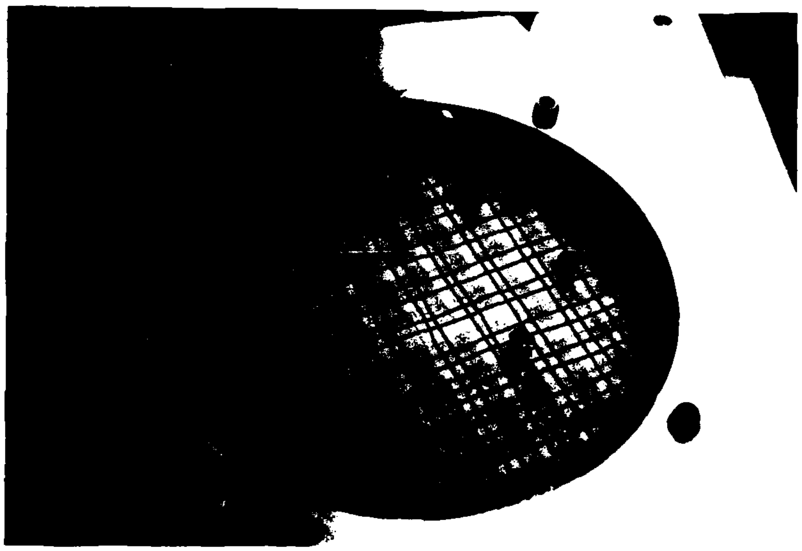
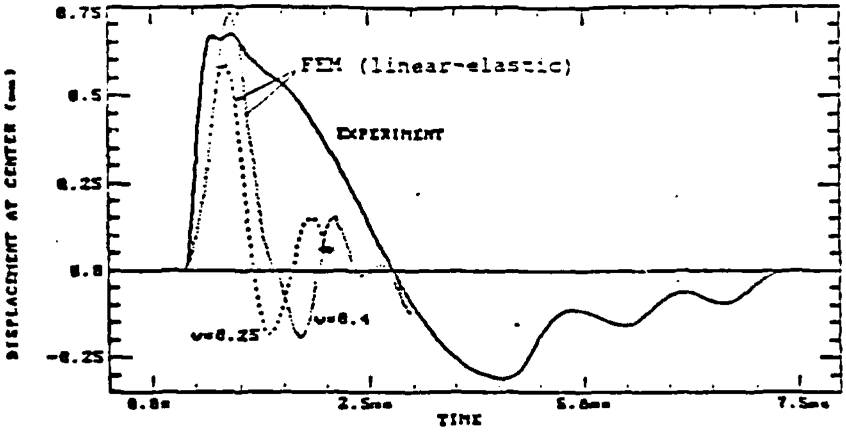


Figure 5 Picture of Formwork for RC Roof



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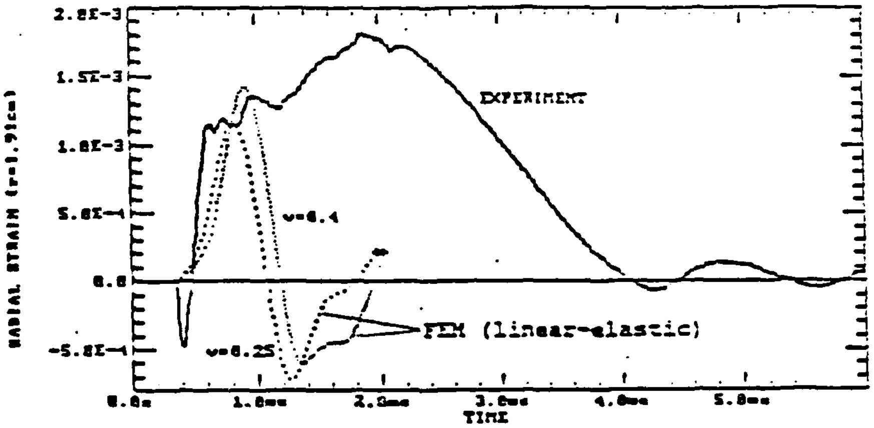

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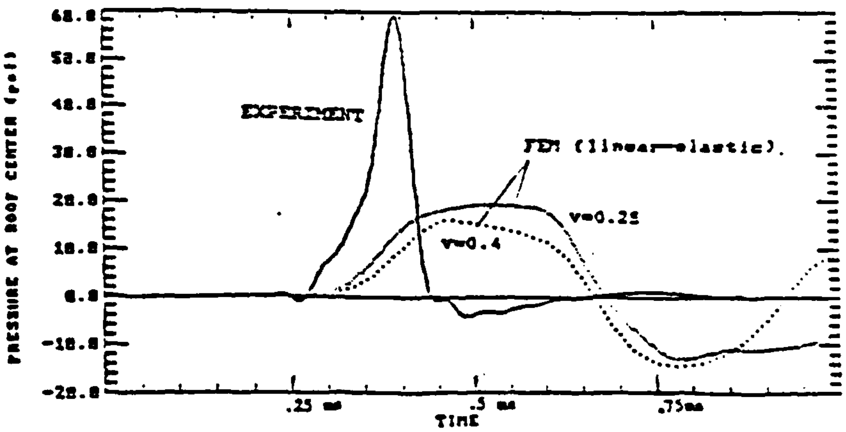


(c)

Figure 6 Experimental Results in Comparison with Numerical Results (Elastic Structure).

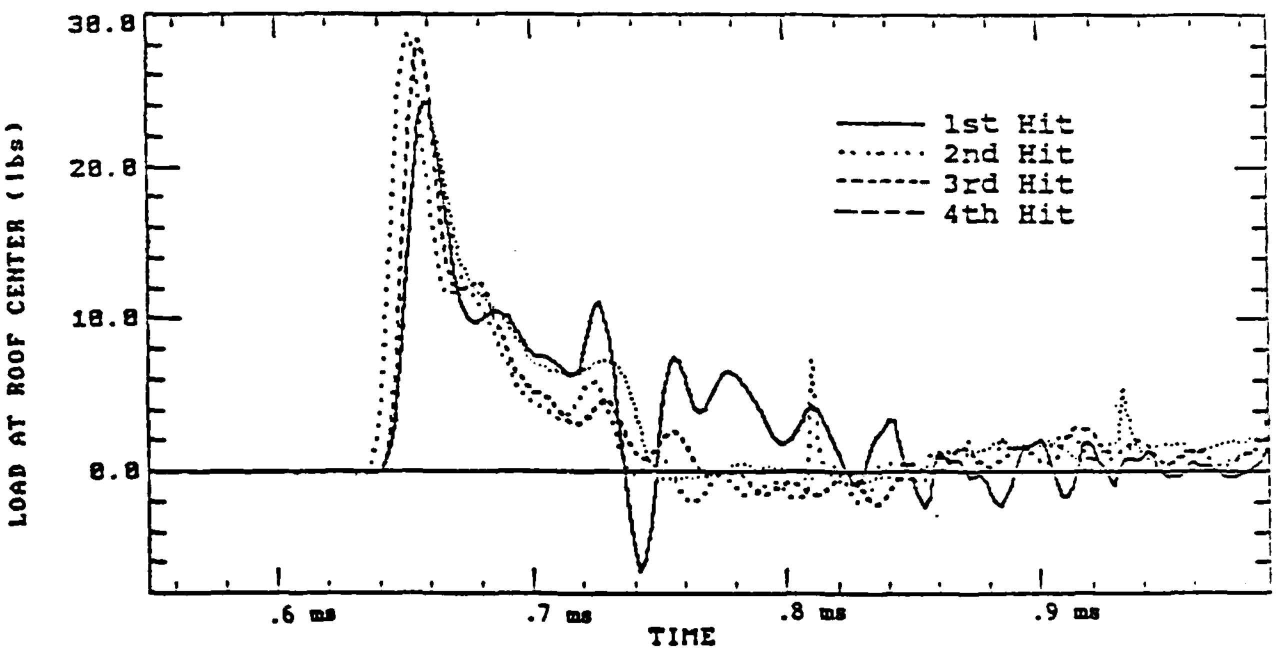


Figure 7 Loading History (First 4 Hits)

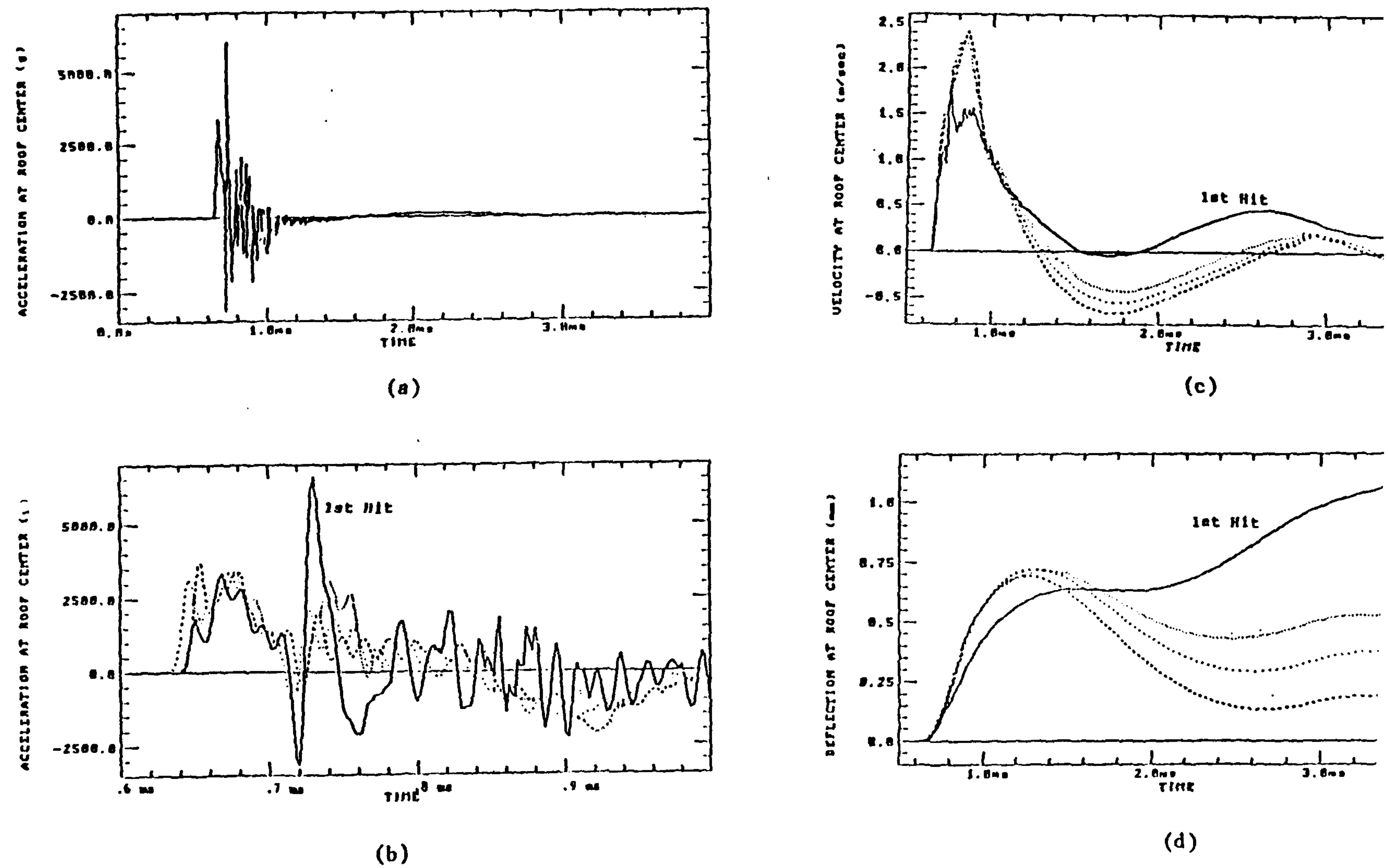
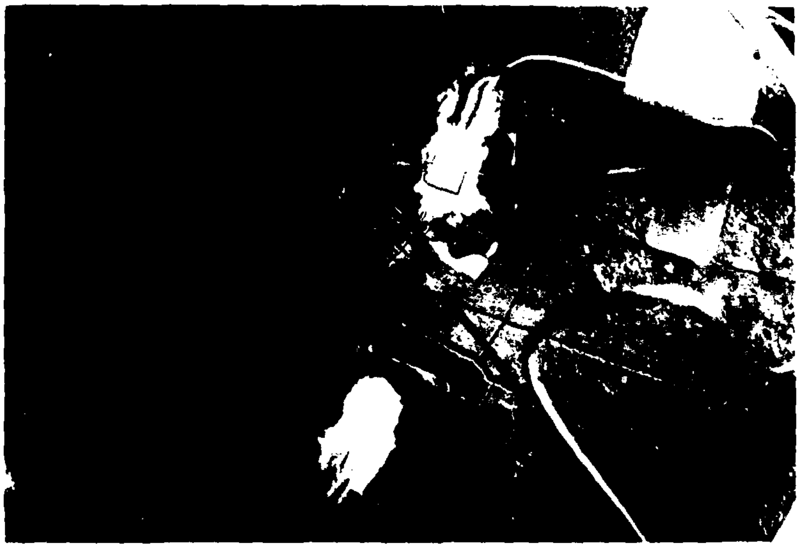


Figure 8 Experimental Results of RC Structure.



(a) Ceiling

(b) Roof

Figure 9 Failure Mode of RC Roof

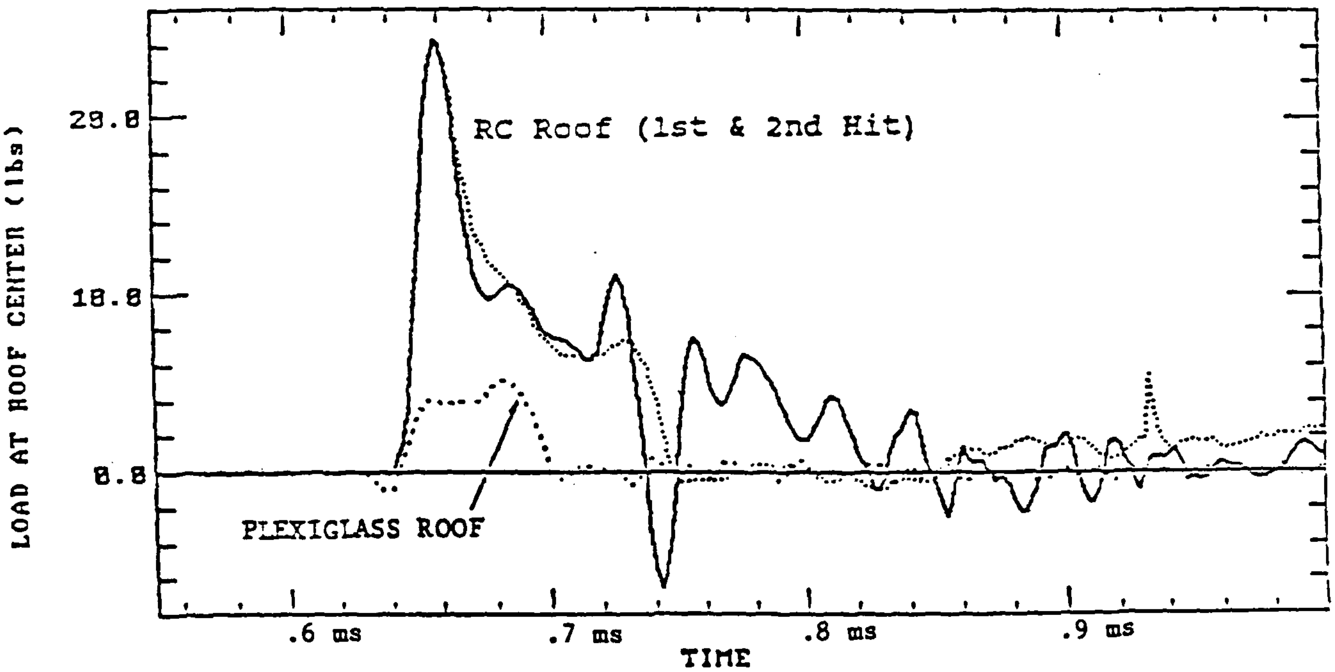
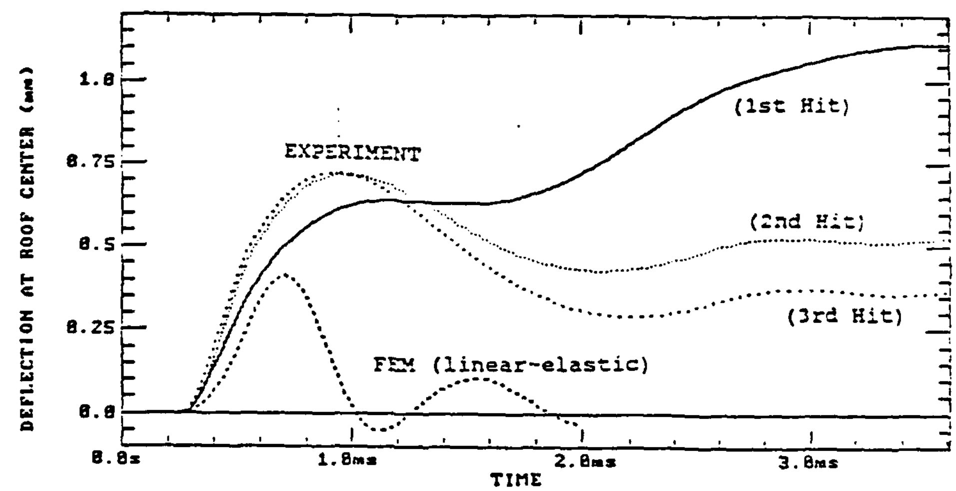


Figure 10 Comparison Between RC Roof and Plastic Roof



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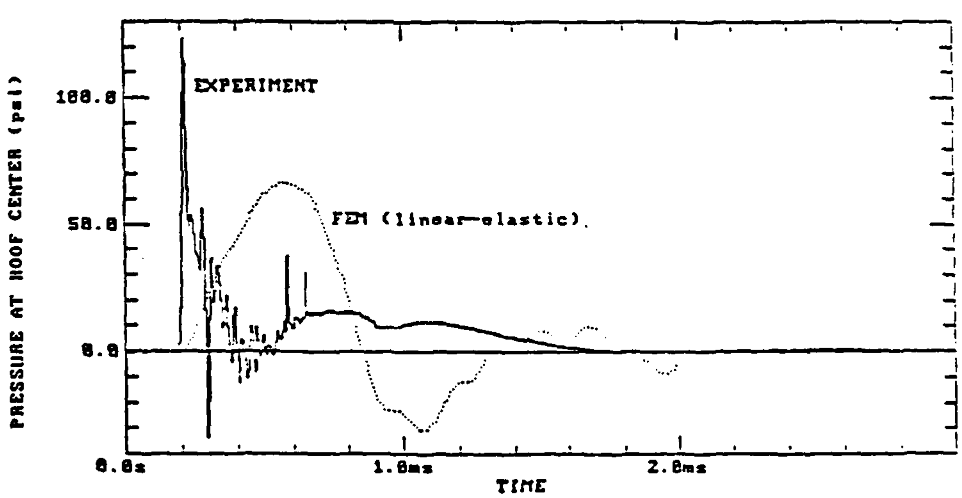

(b)

Figure 11 Experimental Results in Comparison with Numerical Results (RC Structure).