EFFECT OF A PROTECTIVE DEVICE IN THE REDUCTION OF HEAD INJURY

by Werner Goldsmith, Professor of Applied Mechanics, and Tawfik Khalil, Research Assistant, University of California, Berkeley, USA

The severity of a head injury is unquestionably related to the history of one or several mechanical parameters, in particular stress and/or displacement produced at some critical position of the cranium as the result of a collision or an impulsive type of loading. An initial effort to provide a rationale for this situation has resulted in the specification of a highly simplified model of the human head involving the axisymmetric loading by the impact of steel spheres on elastic, thin-walled spherical shells composed of either aluminum or lucite filled with water. [1][2][3] Closed-form solutions of the governing differential equations for this system, obtained by standard eigenvalue techniques for loading histories actually measured on a corresponding mechanical replica, were in excellent agreement with measured strains on the inside and outside of the shell as well as with pressure variations at a number of interior stations as ascertained by the output of tourmaline crystal transducers. [3] In addition, a finite element solution for this situation was found to be in excellent accord with both the experimental data and analytical prediction as shown in Fig. 1 and 2, for the midsurface strains and pressures at various non-dimensional radii $\tilde{r} = r/R$, with R as the shell radius and r as the distance from the center, respectively.

The finite element representation utilizes the equation of motion in rectangular Cartesian coordinates for a homogeneous, isotropic elastic continuum in the form

$$[M] \ddot{\vec{u}} + [K] \vec{u} = \vec{F}(t) \qquad (1)$$

where [M] is the inertia matrix, [K] is the stiffness matrix, $\vec{F}$ is the force vector, $\vec{u}$ is the displacement vector and a dot denotes differentiation with respect to time t. The discretization in space is accomplished by means of Hamilton's Principle and results in second-order ordinary differential equations. [1] These in turn are integrated step by step by means of a computer program utilizing a Newmark Beta integration scheme. [4][5] This code has been extended to provide numerical solutions for the response of multi-component concentric shell systems under axisymmetric impact conditions so as to permit an examination of the efficacy and value of protective coverings in reducing the amplitude and/or duration of history of the field variables produced by such loading. In all instances, the human skull and brain have been simulated by a spherical aluminum shell 7.4 inches in outside diameter and 0.141 inches thick filled with water so as to provide a constant base for this examination.

A physical model consisting of the previous spherical shell nesting inside two concentric hemispherical shells composed of Styrofoam and aluminum with inside diameters of 7.4 and 8.4 inches and thicknesses of 0.5 in. and 0.22 in., respectively was constructed and tested under axisymmetric impact conditions. The system components were glued together by means of rubber-cement. This artificial configuration was not intended to represent a head-helmet combination, but was chosen only for the purpose of further validating the computer code as applied to multi-layered systems. SR-4 SPB2-12-12 or SPB3-1212 semiconductor strain gages were mounted with epoxy cement on the inside and outside of the two metal shells at various stations in the ϕ-direction which is that along a great circle of the shell containing the impact axis and which measured circumferential strain. The transducers located on the interior of the innermost shell were waterproofed by coating with a silicone rubber compound. Piezo-electric tourmaline crystal pressure transducers were flexibly suspended at predetermined stations along the axis of the interior cavity and measured the pressures in this domain when filled with water. The location of these devices is indicated in Fig. 3.

One-half inch diameter steel spheres were projected radially against a sandwiched crystal transducer attached to the system that permitted the measurement of the pressure input. [1][3] Two types of loading situations were employed: in the first, the spheres were dropped from a height of 53 inches through a guiding tube to insure proper contact, corresponding to an initial velocity of 17.5 ft/sec, while in the second, the spheres were propelled by means of an air gun at velocities of about 43.5 ft/sec. These conditions were utilized for the determination of the strains and of the pressures, respectively; however, in each instance the input pulse was monitored and the transducers were calibrated. The signals were recorded on Tektronix oscilloscopes with a bandpass in excess of one megahertz. Triggering was accomplished by the signal from the input transducers. The capacitance for the tourmaline crystal circuits was augmented by the addition of parallel capacitors to provide for adequate low frequency response. [3] A schematic of the pneumatic gun apparatus and the instrumentation is shown in Fig. 4.

Figs. 5, 6, and 7 present a comparison of the numerical results and the experimental data for circumferential strains from several locations on the outside and on the inside of the inner and outer metallic shells as well as the measured input when no water was present in the cavity. In general, the correlation is quite satisfactory, although there are individual differences both in amplitude and frequency of the record, particularly at later times. These discrepancies are partially attributable to failure to incorporate the precise physical boundary condition employed, that were intended but did not quite represent an unrestrained system, the possibility of significant local inhomogeneities in the Styrofoam spacer that would affect strain signals immediately below such voids, and some uncertainties concerning the actual dynamic properties of this spacer that were required for the calculations. In addition, some inhomogeneities in the properties of the outer aluminum shell may have been introduced by the casting process and the degree of contact between the three concentric shells may not have been totally uniform.

The curves clearly show a reduction in strain level by a factor of about ten from the outside to the interior aluminum shells at stations remote from the impact point having the same circumferential angle ϕ. The presence of bending dominates the response of both shells within a polar cap angle of 60° and diminishes at more distant positions. The oscillations in the strain evident for the inner shell appear to be more regular than for the outer cover; this may be partially due to the fact that the former is a complete shell whereas the latter is only hemispherical and reflections may thus distort the pattern of the wave progression.

A repetition of the experiment and corresponding numerical analysis for the system was conducted under identical loading conditions when the cavity was filled with water. The strains in the outer shell appear to be slightly smaller than those shown in Fig. 5, but exhibit the same general pattern. The strains on the outside and inside on the inner shell appear to be reduced by a factor of two relative to the data of Figs. 6 and 7 as the result of energy dissipation within the field. Fig. 8 shows a comparison of the calculated and measured pressures in the fluid due to pneumatically-driven projectile impact. Considering the level of the pressures produced, the correlation is quite excellent. In particular, the general process of wave propagation noted in References [1][2] and [3] along the impact axis is reproduced, with initial tension occurring near the contrecoup point as the result of radiation back into the fluid from the more rapidly travelling wave in the inner shell. Thus, the main purpose of the comparison of the response of the system has been achieved, and the computer program was now applied with confidence to the analysis of nested shell structures whose mechanical properties conform as closely as possible to the human cranial system covered by two different devices that are actually utilized for the purpose of reducing head injury.

One of the most crucial requirements for the proper functioning of the computer program was the use of the appropriate dynamic elastic constants representative of the components of the structure to be analyzed. In the previous models, which consisted of aluminum, water and Styrofoam, only the latter was tested quasi-statically both in tension and compression at a rate of 0.0037 sec^{-1} in a standard commercial Instron machine. In the following analyses of head-helmet combinations, two actual helmets were numerically simulated: the first consisted of an outer layer of steel in intimate contact with an adjacent interior layer composed of fiber-impregnated epoxy, in turn supported by a series of cloth straps that were simulated by a cotton shell; the second resembles a motorcycle helmet with an outer layer of a different composite of fiberglass embedded in a matrix. Quasi-static tension tests at rates ranging from 0.00007 to 0.27 sec^{-1} were similarly executed on the two composites cited; it was found that their "elastic" constants were relatively insensitive to the rate of loading within the test domain. The necessary constants for aluminum, steel, water, bone [6], scalp [7] and cotton [8] were selected from the literature. The values of these parameters are given in Table 1.

The two head-helmet combinations were analyzed by imposing on both an axisymmetric loading equivalent to the impact of a $\frac{1}{2}$-in. diameter steel sphere travelling at a velocity of 1000 ft/sec. From momentum considerations and numerous previous experiments, [3][4] this loading can be very closely represented by a sine-squared input with a force amplitude of 94,400 lb and a duration of 50 microseconds. The first structure was represented by a six-layer system consisting of five nested concentric shells surrounding the brain which, in the inward direction, represent the steel shell, the epoxy-fiberglass combination, the cotton lining, the scalp and the skull, respectively. The second unit consisted of an outer fiberglass-matrix shell, a Styrofoam lining, the scalp, skull and the brain, respectively.

The mid-surface circumferential strains at two positions of the outermost shell, at four stations on the skull and the pressures at seven stations in the brain are shown in Figs. 9, 10, 11 and Figs. 12, 13, and 14 for the two helmets respectively. In the first case, the strains in the skull are actually larger than those in the helmet, although the stress level is smaller by virtue of the considerably smaller modulus. In the second head-helmet combination, where the elastic constants of the outer shell and of the skull are comparable, the strain levels in the outer covering are higher by a factor of about twenty. With respect to potential brain damage, the first helmet leads to the production of consistently higher fluid pressures by a factor of about 5 at all stations than the second helmet; this effect is due to the cushioning provided by the Styrofoam that is not present in the first combination. In contrast to the solutions for a two-component system, the initial pressure variation at the contrecoup point is still compressive, attesting to sufficient dispersion and a slower propagation rate of the wave through the outer layers to prevent the radiation of tensile components back into the brain from this position.

It is concluded that the addition of a protective covering can reduce the amplitude of the pressure pulse in the brain by a factor of 10 relative to the bare head. Furthermore, a combination consisting of a hard outer shell with a soft, energy-dissipating interior lining is more effective than for a helmet composed solely of a hard exterior even for pulses with durations as short as those analyzed here. This effect is expected to be even greater for pulses with longer durations.

TABLE 1. ELASTIC CONSTANTS EMPLOYED IN THE NUMERICAL ANALYSIS

Material	E, Young's Modulus psi	μ, Poisson's Ratio	ρ, Mass Density lb-sec^2/in^4
Aluminum	10.6×10^6	0.33	2.59×10^{-4}
Steel	30.0×10^6	0.29	7.25×10^{-4}
Water	$3.17 \times 10^{5*}$	--	9.45×10^{-5}
Brain	3.0×10^5	--	9.95×10^{-5}
Styrofoam	522	0	2.82×10^{-6}
Cotton	6×10^5	.15	7.2×10^{-5}
Fiberglass-Epoxy, Helmet 1	1.4×10^5	.176	9×10^{-5}
Fiberglass in Matrix Helmet 2	2.09×10^6	0.138	2.48×10^{-4}
Bone	1.44×10^6	.2	1.9×10^{-4}
Scalp	4.3×10^4	.1	1.1×10^{-4}

* For the fluids, the bulk modulus K replaces E and μ.

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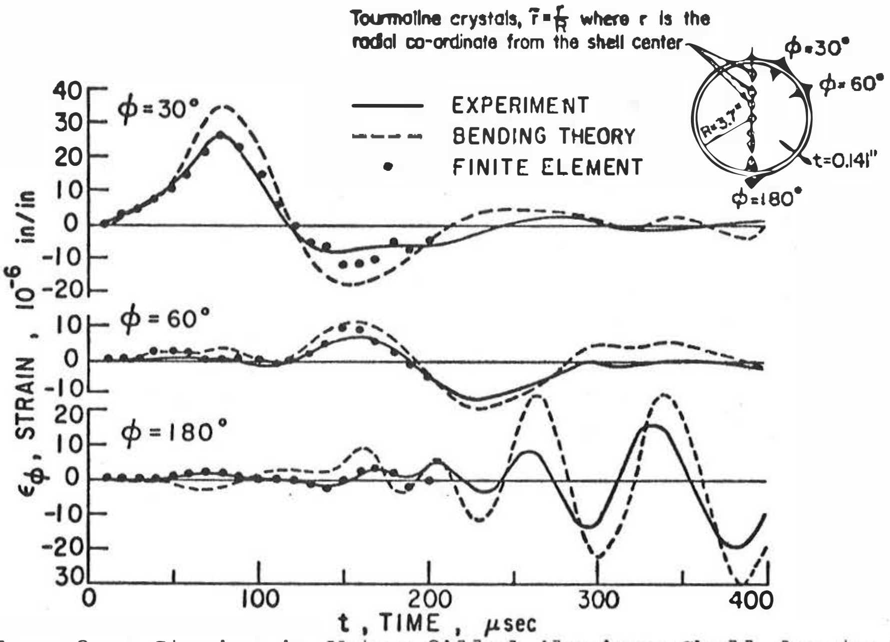


Fig. 1 Mid-surface Strains in Water-filled Aluminum Shell due to Impact by a $\frac{1}{2}$-in. Diameter Steel Sphere with a Velocity of 7.5 ft/sec.

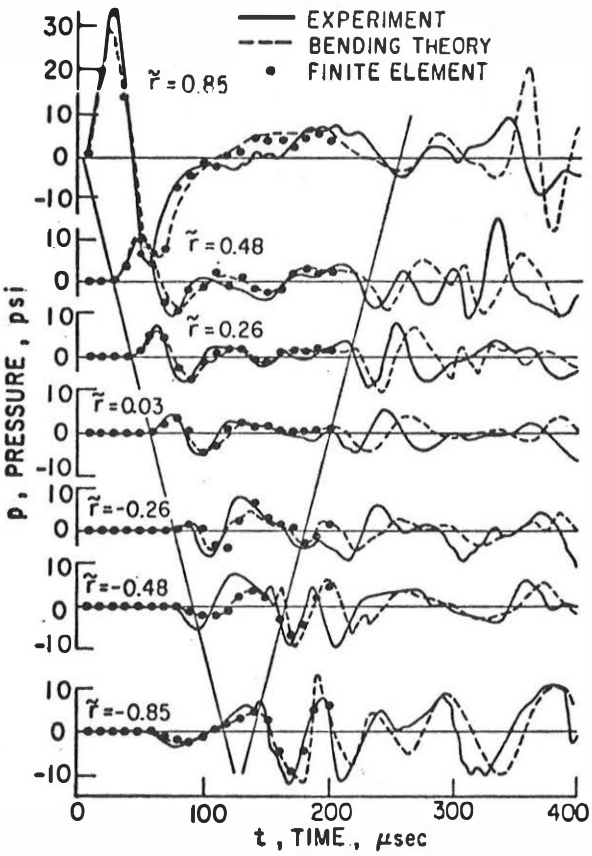


Fig. 2 Fluid Pressures for the Case shown in Fig. 1.

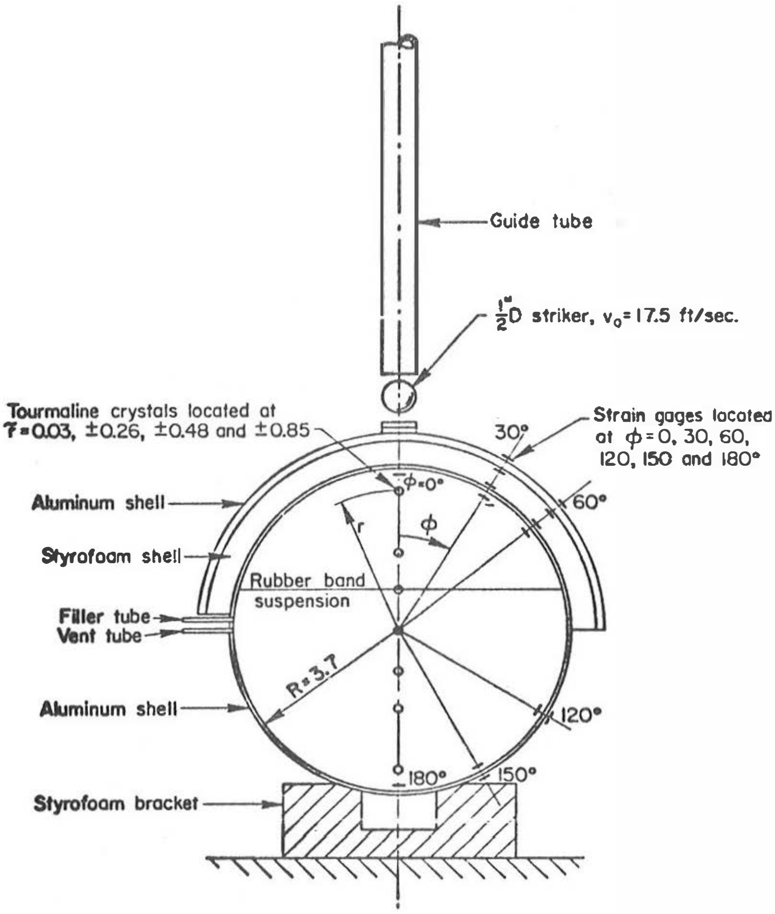


Fig. 3 Schematic of the Drop Test Apparatus

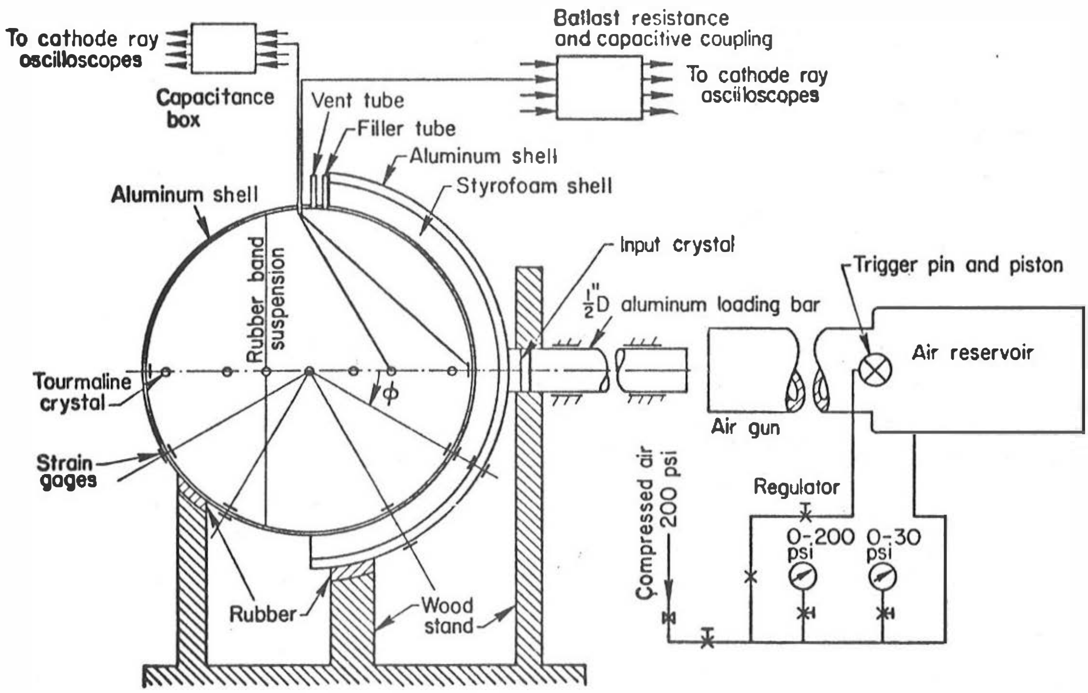


Fig. 4 Schematic of the Pneumatic Gun Test Arrangement

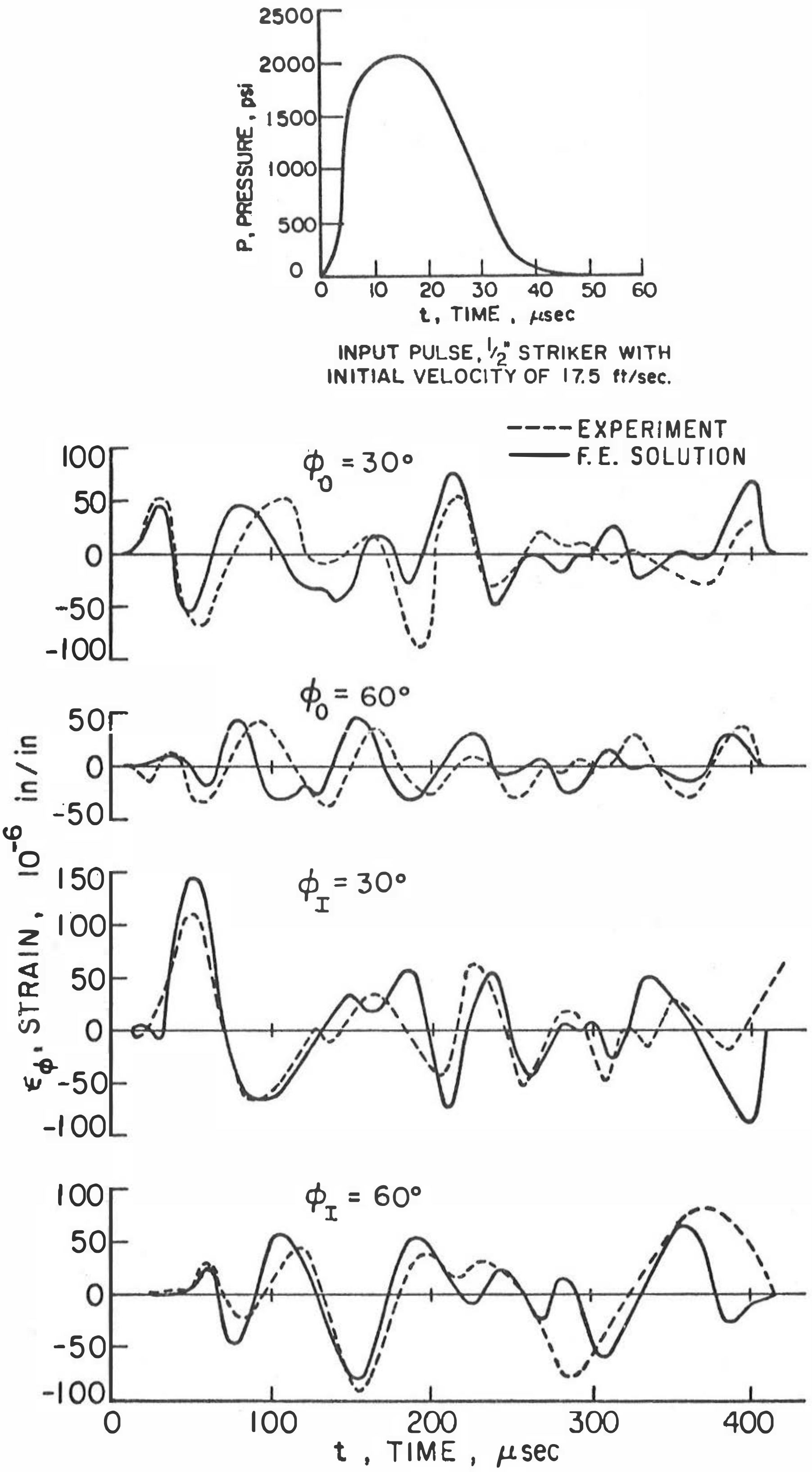
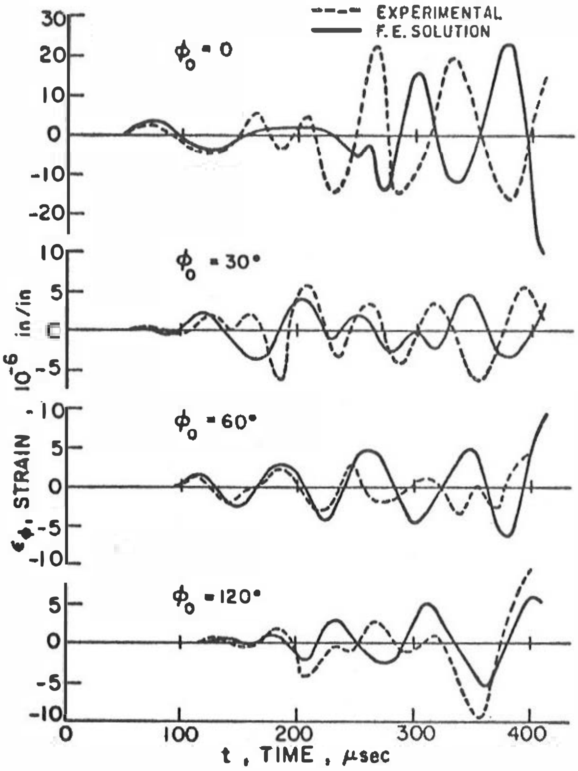
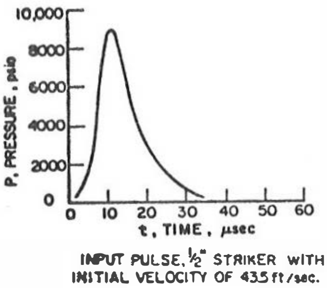


Fig. 5 Comparison of Experimental and Computed Outer Shell Strains for the Three Component System (empty shell) due to the Loading shown. Subscripts "O" and "I" denote outer and inner surfaces, respectively.



← Fig. 6 Comparison of Experimental and Computed Inner Shell Strains on the Outside Surface for the System and Loading shown in Fig. 5.



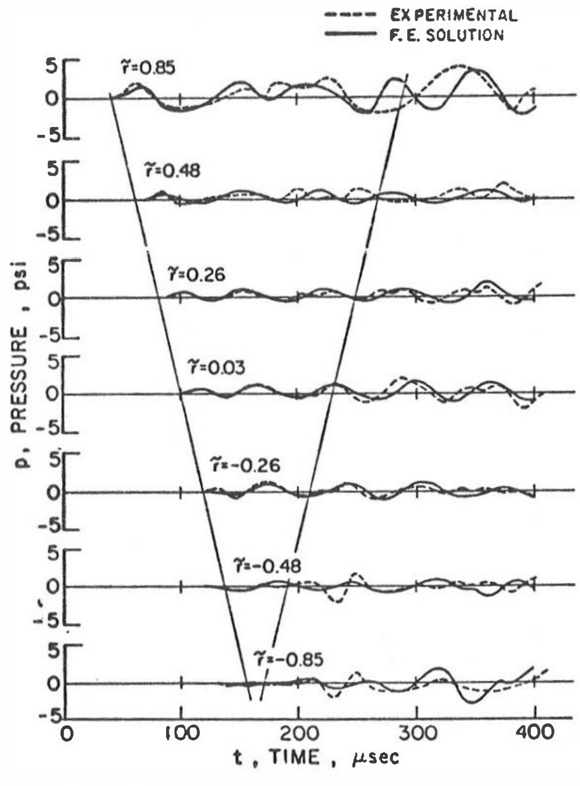


Fig. 8 Comparison of Experimental and Computed Fluid Pressures for the Four-Component System due to the Loading shown.

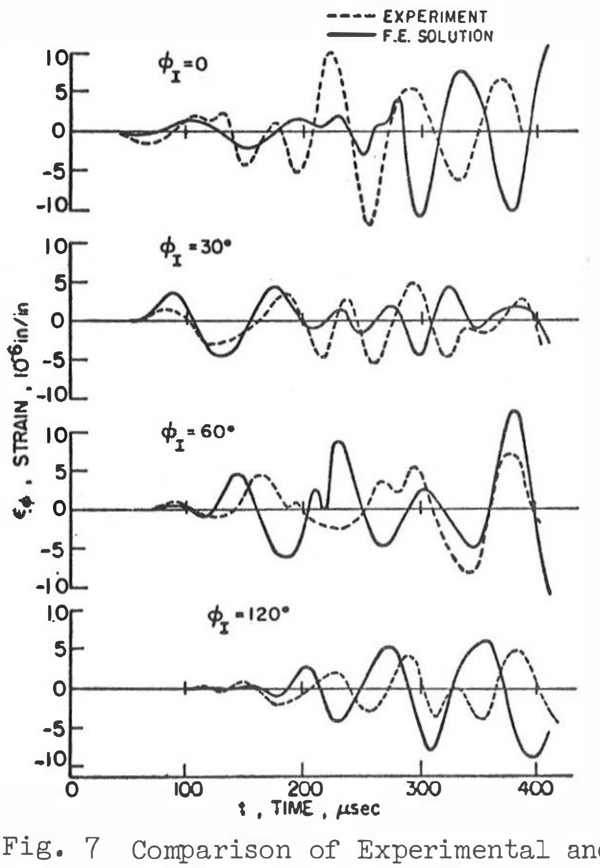
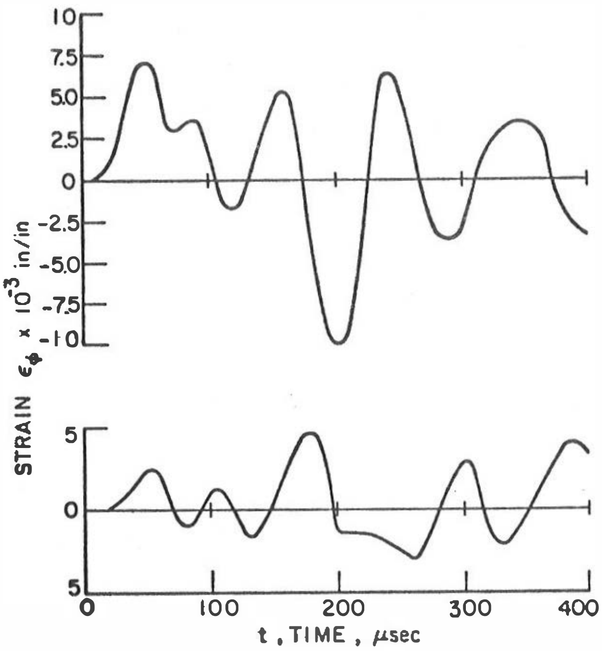


Fig. 7 Comparison of Experimental and Computed Inner Shell Strains on the Inside Surface for the System and Loading Shown in Fig. 5.



← Fig. 9 Midsurface Outer Shell Strains of the Six-Layer Head-Helmet System due to Impact by a $\frac{1}{2}$-in. Diameter Steel Sphere at a Velocity of 1000 ft/sec.

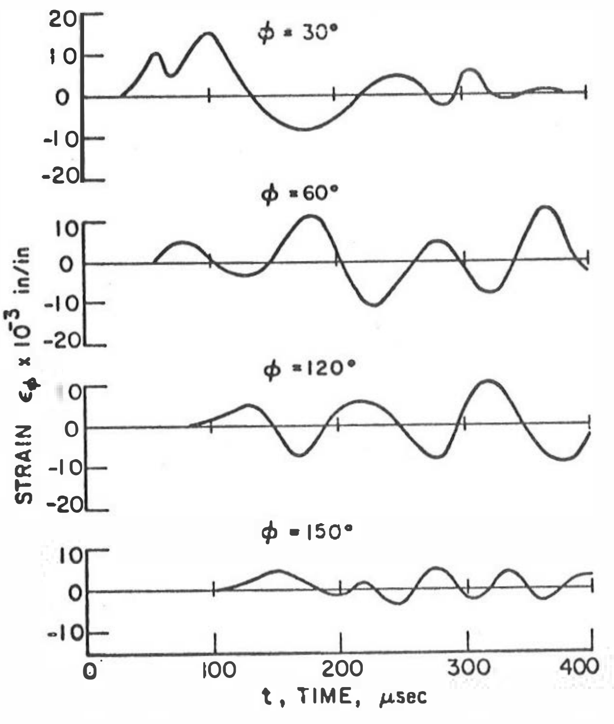


Fig. 10 Midsurface Inner Shell Strains for the System and Loading of Fig. 9.

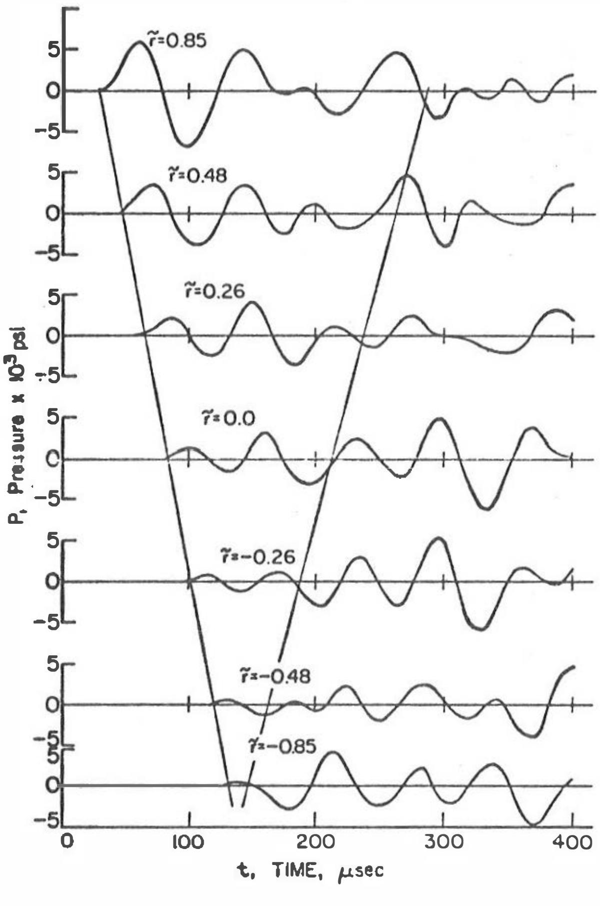
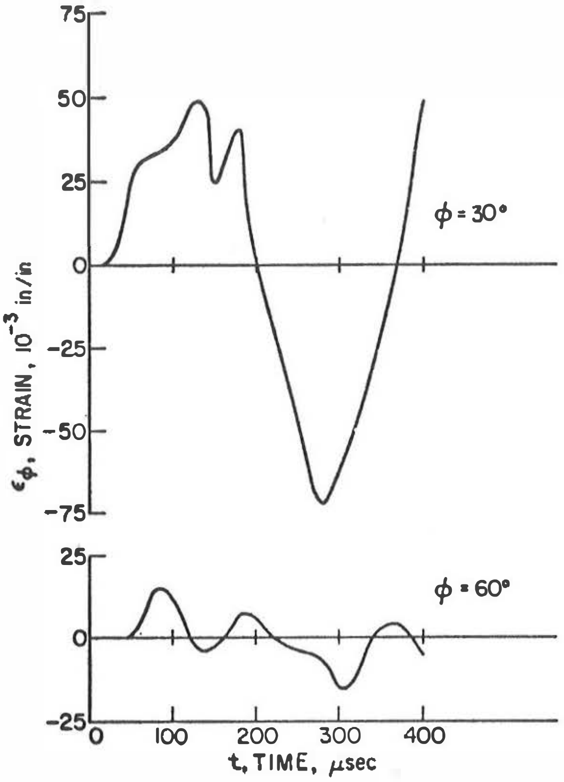


Fig. 11 Brain Pressures at Various Non-dimensional Radii for the System and Loading of Fig. 9.



← Fig. 12 Midsurface Outer Shell Strains of the Five-layer Head-Helmet System due to Impact by a $\frac{1}{2}$-in. Diameter Steel Sphere at a Velocity of 1000 ft/sec.

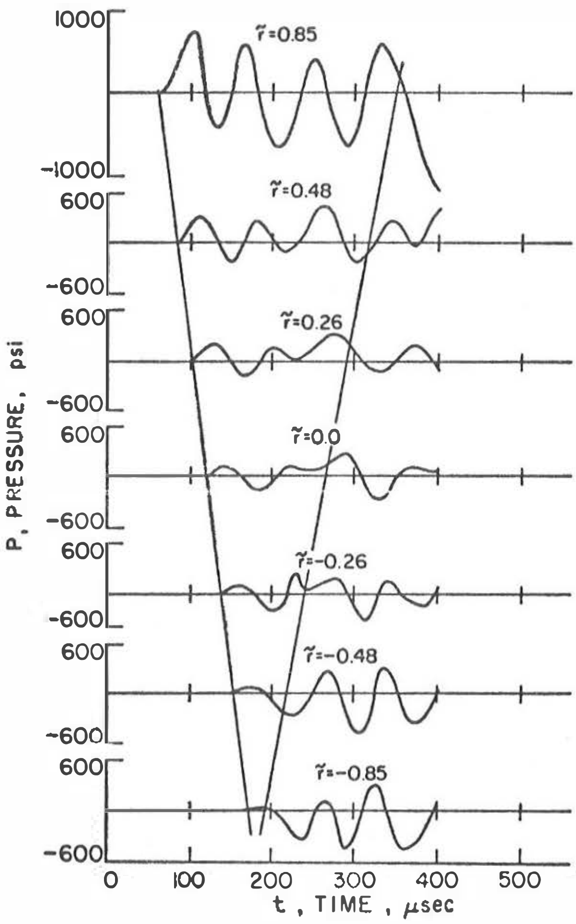


Fig. 14 Brain Pressures at Various Non-dimensional Radii for the System and Loading of Fig. 12.

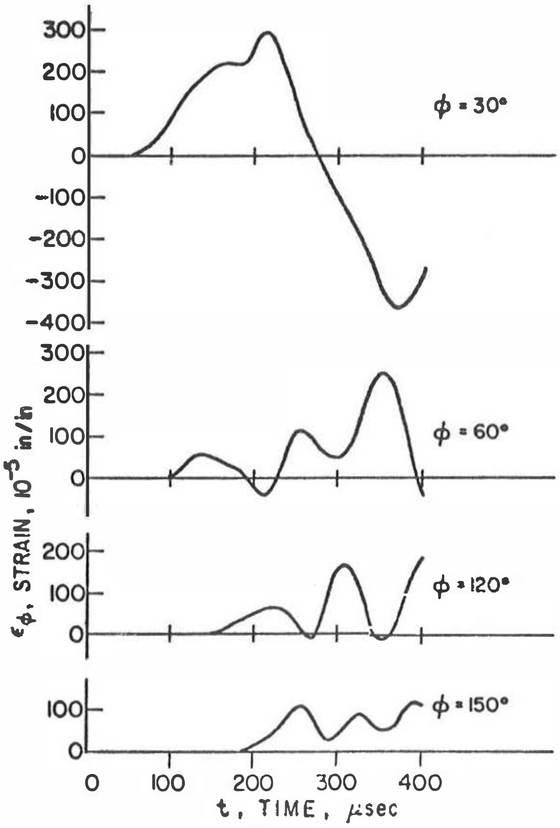


Fig. 13 Midsurface Inner Shell Strains for the System and Loading of Fig. 12.