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COMPARISON OF HUMAN SKULL AND SPHERICAL SHELL VIBRATIONS--IMPLICATION TO HEAD INJURY MODELING

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A resonance comparison was made between the experimental response of a dry human skull and the analytical response of a spherical shell model which was geometrically and materially similar. Poor agreement was observed. An analysis of the model revealed that the shell uniformity approximately doubles the effective stiffness in comparison with the skull. The model elastic modulus was adjusted to bring its resonances into closer agreement with those of the skull. Although the "effective" modulus is 50% lower than the elastic modulus of cranial bone, the adjustment brings model predictions of skull fracture into close agreement with human cadaver data.

IN RECENT YEARS much effort has been directed to head injury investigation by mathematical modeling. The primary objective of this work is to explore injury mechanisms with an eventual goal of providing for adequate protection against accidental head impact. Among the numerous head models which have been suggested, the deformable spherical shell appears to be the most scientifically acceptable simple model for head injury studies [1].

By insuring gross geometric and material property similarities between the spherical shell model and the human head, the impact response and skull fracture studies were expected to yield results in close agreement with available human cadaver data. This, however, was not the case. The model predictions of skull fracture loads were typically twice the observed level. It is hypothesized that the uniform spherical model is structurally stiffer than its skull counterpart. To assess this hypothesis, the vibratory resemblence between the dry human skull and the closed spherical shell model is investigated through nondestructive mechanical impact testing.

The resonant frequencies and mode shapes of two dry human skulls are compared with geometrically and materially matched shell models. It was noted that the skull resonant frequencies were consistently lower than those of the shell model. If, however, an "effective" cranial bone elastic modulus ($E = 32.6 \times 10^5$ kPa) was used in the mathematical model, accurate similarity was achieved between the skull and the model. This adjustment in material property also brought the model prediction of skull fracture into close agreement with experimental cadaver data.

In the following text, a brief description of the study is presented in four main points. More details are provided in references [2 and 3].

1. Head Injury Simulation by Mathematical Modeling: Mathematical simulation of head injury is concerned with applying continuum mechanics principles to a geometrically and materially representative head model to determine its response to impact. One model is shown in Fig. 1, in which the skull is represented by a spherical shell. The exterior surface of the shell is encased by a soft tissue layer simulating the scalp. A compressible fluid, representing the intracranial contents, occupies the cavity. The impact responses of this model, in addition to two other model configurations, are fully analyzed and presented in reference [1]. The solution provides deformation histories, stresses, and strains throughout the model. Load levels at which skull fracture and/or brain injury may occur are extrapolated from the mechanical response (Fig. 2). The data presented in Fig. 2 are based on a load duration of 4 ms. Skull fracture is assumed to initiate at a strain level of 0.5% in tension or 1.5% in compression. Brain damage is hypothesized to occur when the fluid pressure simulating the brain is reduced by one atmosphere. It was noted that skull fracture loads are strongly dependent on the impact area. Such dependence, however, was not observed for brain damage by tensile intracranial pressure.

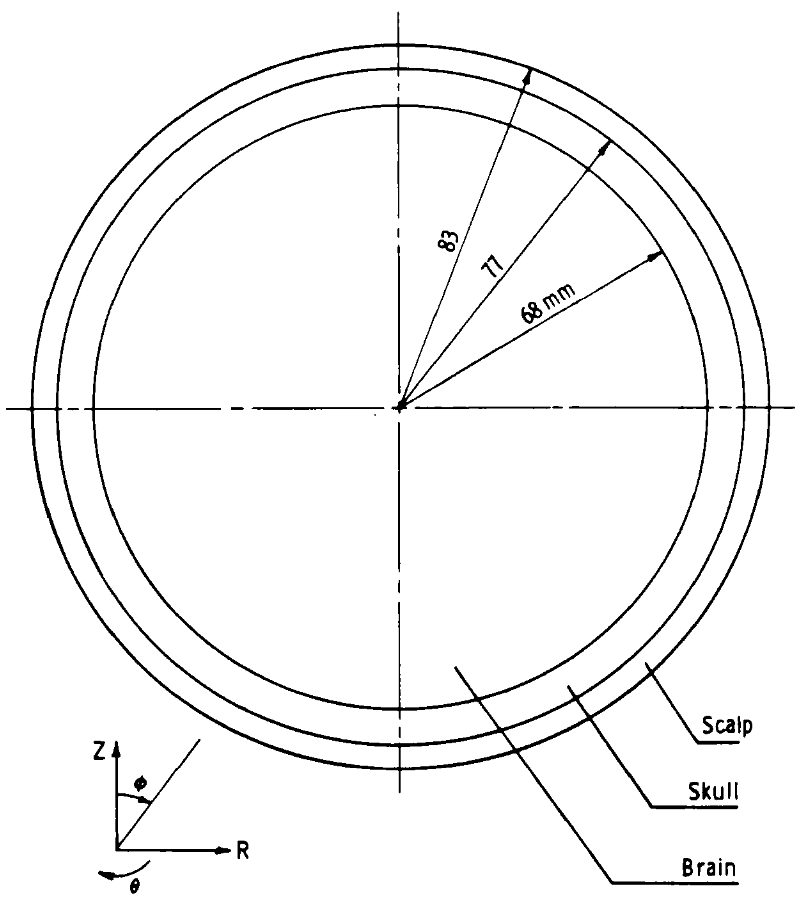

Fig. 1 Spherical head model.

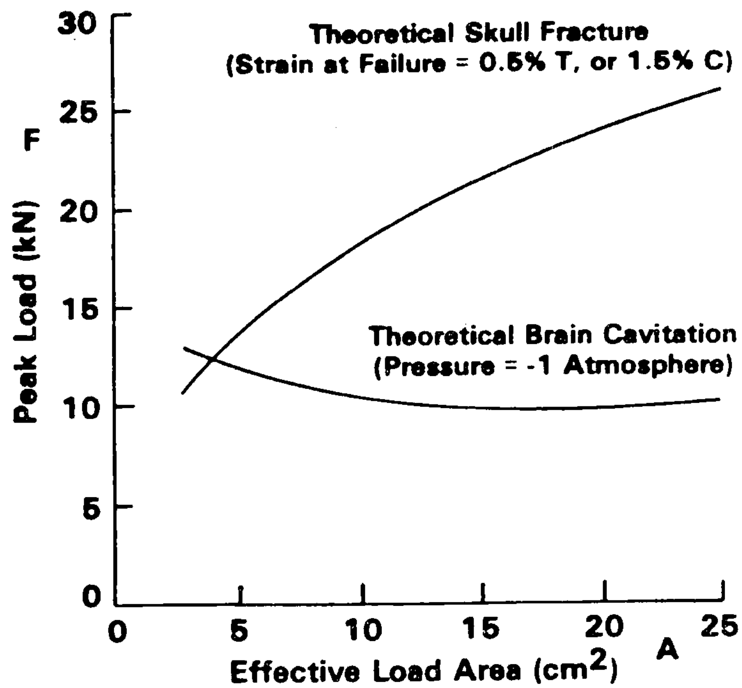

Fig. 2 Model predictions of skull fracture and brain damage loads.

Validation of the mathematical model is necessary to establish its credibility. At the present time, skull fracture prediction of the model is compared with available human cadaver skull fracture data, as will be shown in the following section. Validation of model predictions for brain injury is not attempted due to the lack of experimental data on mechanical injury parameters.

2. Comparison of Experimental Skull Fracture Data with Spherical Shell Model Prediction: Skull fracture mechanisms and associated mechanical parameters (i.e., peak force, peak acceleration, maximum strain, etc.) have been extensively investigated. For the purpose of this study, cadaver skull fracture data relating frontal impact area to load levels producing skull fracture are summarized from approximately 200 tests [3]. Both the average and associated range of skull fracture data (Fig. 3) exhibit an increase with the contact area. A linear regression analysis of the average data was performed to correlate skull fracture load and contact area: F (kN) = 4.2 + 0.6A (cm^2), with F being the peak force and A representing the contact area.

Comparing the average experimental and theoretical skull fracture data (Figs. 2 and 3) reveals that the model overestimates skull fracture loads by as much as a factor of two. It is apparent that the uniform spherical shell model is structurally too rigid when composed of material identical to that of cranial bone. A calibration of the theoretical skull fracture curve is necessary to reduce the model stiffness to match that of the skull. A resonance comparison between the skull and the model is the basis for developing a structurally effective mathematical model. This will be discussed in the next two sections.

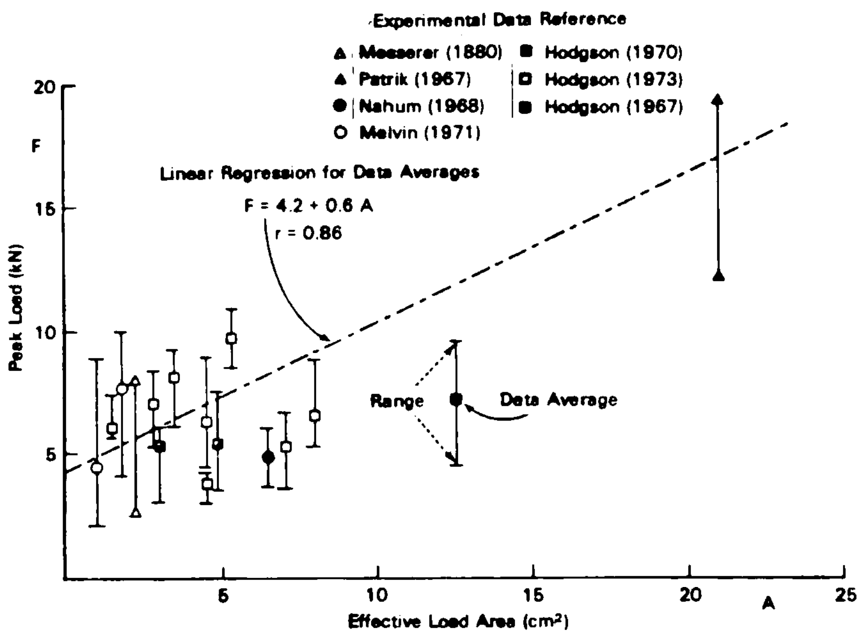

Fig. 3 Frontal cadaver head impacts which demonstrate the dependence of fracture load on the effective contact area. (The average and range of fracture loads are shown for each experimental study).

3. <u>Resonance Comparison Between the Human Skull and the Spherical Shell Model</u>: The resonant frequencies and mode shapes of two dry human skulls are determined experimentally [2] by Fourier transformation techniques. Osteometrically, one skull corresponds to that of a fiftieth percentile male and the other is representative of a fifth percentile female skull. The skull resonance frequencies are arranged in an ascending sequential order (Table 1), which does not necessarily indicate similar vibratory motion [2].

Two spherical shell models are constructed to simulate the gross geometry and cranial bone properties of the tested skulls. The frequency equations of spherical shells are used to determine the models' resonant frequencies [3]. A comparison between the resonant frequencies of the fiftieth percentile male skull and its model counterpart is shown in Fig. 4. The resonant frequencies Ω_n are nondimensionalized with respect to the mean shell radius R_m and the material wave velocity $C_p = \sqrt{E/\rho(1-\nu^2)}$. The data of Fig. 4 and a similar analysis of the fifth percentile female skull confirm our hypothesis that the model is structurally stiffer than the skull.

Table 1

SUMMARY OF RESONANT FREQUENCIES OF TWO DRY HUMAN SKULLS

Mode No. n	Resonant Frequency f, Hz Skull 1 50 Percentile M	Skull 2 5 Percentile F
1	0	0
2	1385	1641
3	1786	2344
4	1903	2969
5	2449	3477
6	2857	4453
7	3386	5000
8	3523	
9	3845	
10	4069	
11	4245	
12	4636	

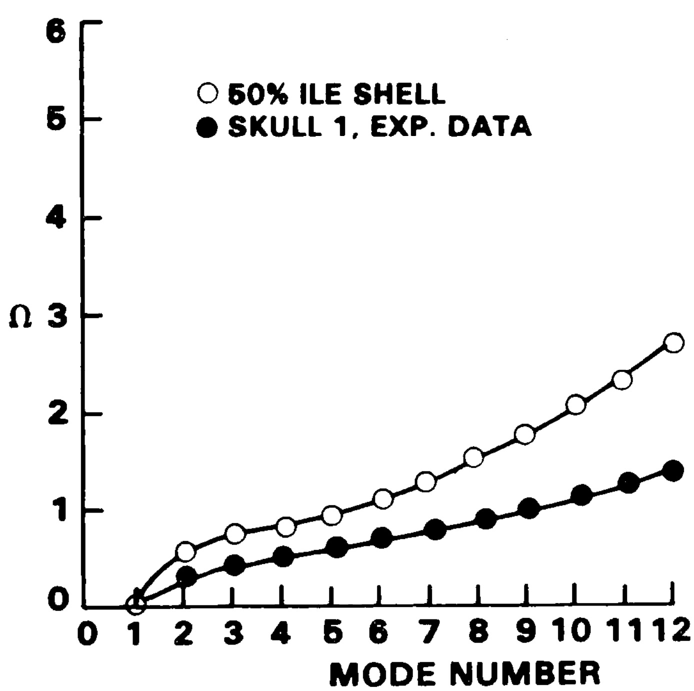

Fig. 4 Comparison between the resonant frequencies of the fiftieth percentile skull and its spherical shell model.

4. <u>Development of a Structurally "Effective" Spherical Head Model:</u> Fig. 4 shows that the resonances of the model are consistently higher in amplitude but parallel to those of the skull. It is also apparent from the resonance equation of the spherical shell ($\Omega_n = f_n \cdot R_m \cdot 2\pi/C_p$) that a linear scaling of the model resonances can be accomplished by either adjusting the material wave veloctiy C_p ($C_p = \sqrt{E/\rho(1-\nu^2)}$) or the shell radius R_m. Since the model is expected to possess a degree of geometric similarity to the prototype, and only minor adjustments can be made in the material density ρ to maintain mass similarity, a scaling of the elastic modulus E is used to adjust the model resonances to match the corresponding skull data.

An "effective" elastic modulus ($E = 32.6 \times 10^5$ kPa) is computed based on matching the experimental resonances of the two skulls with those of the models. The predicted elastic modulus is approximately 50% that of cranial bone. The reduction in the shell elasticity linearly reduces the model prediction of skull fracture (Fig. 5) into closer agreement with cadaver experimental data. The effect of reducing E by 50% on the interior fluid pressure is an increase of only 5%.

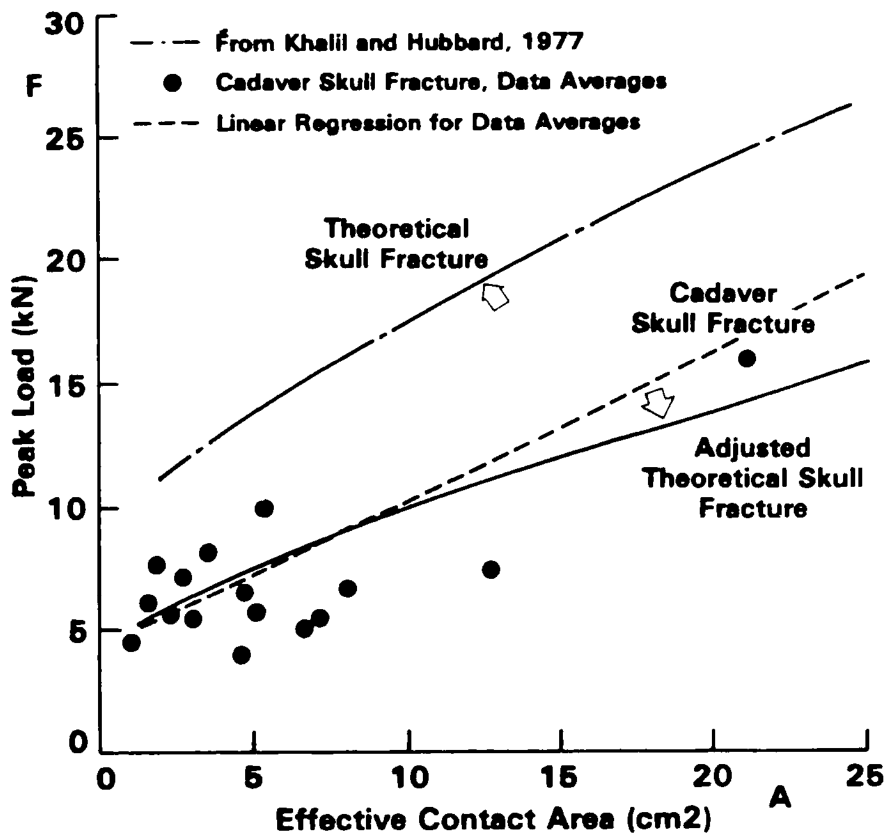

Fig. 5 Variation in peak force head tolerance with contact area (theoretical and experimental data).

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