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# FLEXURE OF CRANIAL SUTURES*

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**Abstract**—Beam samples containing cranial sutures were prepared from embalmed and unembalmed cranial bone and were tested to determine their flexural stiffness and strength. With the aid of layered beam theory, the flexural stiffnesses of beams containing cranial sutures were compared to hypothetical layered cranial bone beams which did not contain sutures. The bending stiffnesses and strengths of cranial sutures were found to be generally the same as comparable layered cranial bone structures. Embalmed samples were slightly stiffer and stronger in bending than unembalmed samples.

## INTRODUCTION

THE DEVELOPMENT and refinement of mechanical and mathematical head injury models will include consideration of increasingly detailed structural features of the head. Such features include cranial sutures whose ability to transmit the effects of trauma could significantly affect the response of the head to mechanical trauma.

Cranial sutures are junctions between the cranial bones (Fig. 1), and are regions of bone growth and remodeling in cranial development. Structurally, sutures are zones of collagenous fibers bridging two adjacent bone surfaces. The interlinking sutural interfaces are geometrically complex, and their configuration varies with site in a single skull and from skull to skull. The extent and character of the sutural interlinking could greatly effect a suture's mechanical behavior. Other significant factors could be age (or extent of cranial development) and the effect of embalming.

The role of the sutures in the mechanics of head injury is not well understood. Unterharnscheidt and Sellier (1966) characterized the sutures as being less capable of transmitting bending moments than cranial bone, but they gave no data to support this conclusion. Suture failure in dynamic head injury situations does not appear to be common. Gurdjian *et al.* (1952) did not note any occurence of suture failure. However, under slow loading conditions, as in crushing injuries, diastasis of the sutures has occured (Messerer, 1880).

In the present study, samples containing cranial sutures were taken from fresh and embalmed skulls, were prepared as beams, and were tested to determine their bending stiffness and strength. With the aid of layered beam theory (Hubbard, 1971), the flexural stiffness of beams containing cranial sutures was compared to hypothetical layered cranial bone beams which did not contain sutures.

## EXPERIMENTAL TECHNIQUE

Eleven beams containing cranial sutures (sample 1-3 through 11-3) in their mid-region were cut from one embalmed calvarium. The location of these beams is shown in Fig. 1. Two more suture beam samples (sample 1-7 and 2-7) were cut from the posterior part of the sagittal suture of a second embalmed calvarium. Samples from both calvaria were milled to tested shape with a Unimat SL. All

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machining was performed on the surfaces perpendicular to the inner and outer bone surfaces. The embalmed samples were stored at room temperature in closed glass bottles containing damp gauze to maintain sample moisture.

Seven beams were taken at autopsy which were oriented perpendicular to the sagittal suture and located from 1–3 in. posterior of the bregma. The samples were stored at $-10°C$ in closed plastic bags and were filed to tested shape without the samples thawing. Again, care was exercised during sample preparation not to excessively load the samples or modify the inner and outer bone surfaces.

From the suture beams prepared, two embalmed samples (1-7 and 2-7) and two unembalmed samples (117 and 121) were selected as being effectively straight, uniform layered cranial bone beams with sutures in their mid-regions. These selected beams were loaded in three-point bending in the apparatus shown in Fig. 2 at various span lengths from 0·875 in. to 2·000 in. The samples were loaded repeatedly with no evidence of sample weakening or degradation. The embalmed samples were supported on the inner table and loaded at mid-span on the outer table (normal orientation). These samples were also inverted and loaded on the inner table (inverted orientation). The unembalmed samples were tested in the normal orientation.

The remaining beams were loaded to failure in four-point bending with a minor span of 1 in. and a major span of 2 in. Load was applied to the minor span through a block that was free to rotate, insuring that the suture in the beam mid-region was subjected to pure bending. For both three- and four-point testing, the load transmitted through the beam sample was monitored by an Instron tension–compression load cell and the movement of the loading apparatus was followed by a linear variable differential transformer (LVDT). The load displacement signals were displayed on a trace-storing oscilloscope, and photographs of the stored traces constituted the data records.

In addition to the above tests, a device shown in Fig. 3 was developed to allow small segments of cranial bone containing sutures to be tested for maximum moment carrying capability. The cranial bone segments were machined from 1½ in. dia. bone plugs taken at autopsy and stored in closed plastic bags at $-10°C$. The beam segment was bonded into the fixture with quick-setting acrylic adhesive and then tested in four-point bending. Only the maximum load was recorded.

## RESULTS AND DISCUSSION

Eleven embalmed and fourteen unembalmed samples containing cranial sutures were tested and studied. This number of samples is too small to draw strong conclusions concerning the mechanical response of sutures and the factors which might effect this response. However, the results point to conclusions about cranial sutures which are significant to researchers in head injury. Further study and experimentation should lead to refinement and expansion of these preliminary findings.

The compliance (mid-span deflection due to a unit load) of two embalmed and two unembalmed suture beam samples was determined for a range of span lengths in three-point bending. The primary objective for these compliance determinations was to compare the flexure stiffness of cranial sutures with that of layered beam theory for the calculation of the flexure response of layered cranial bone. The suture beams used in the multi-span compliance determinations were selected as being effectively straight, uniform layered cranial bone beams with sutures in their mid-regions. Based on measurements of layer thicknesses on either side of the sutures and on assumed material properties for the compact and porous bone material in the beams, the layered beam theory was used to calculate the flexural response of a hypothetical layered cranial bone beam of the same structure as the suture beam samples, but without the sutures. Compari-

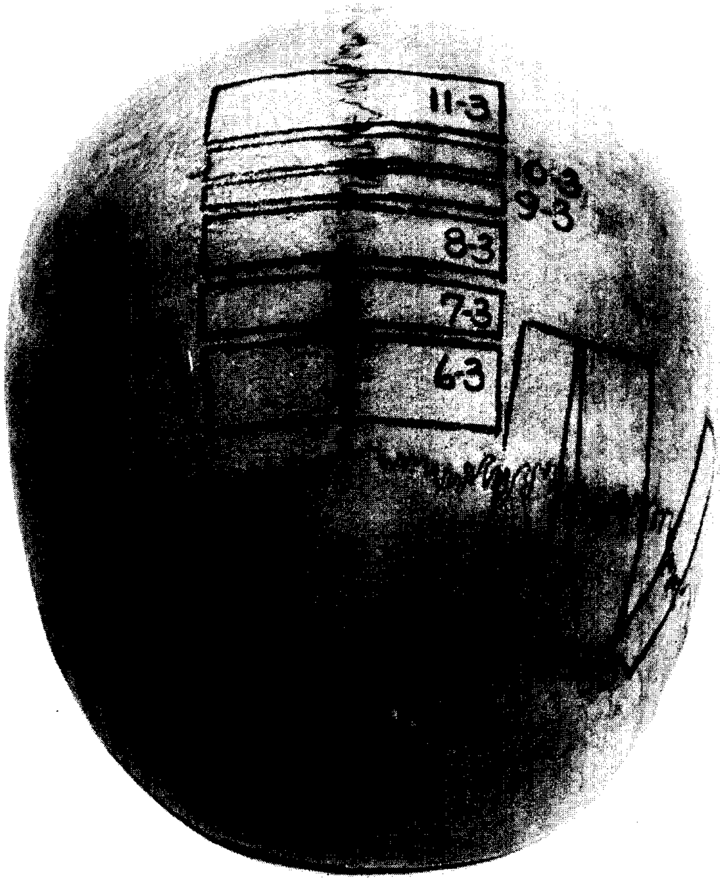

Fig. 1. Calvarium with suture beam locations.

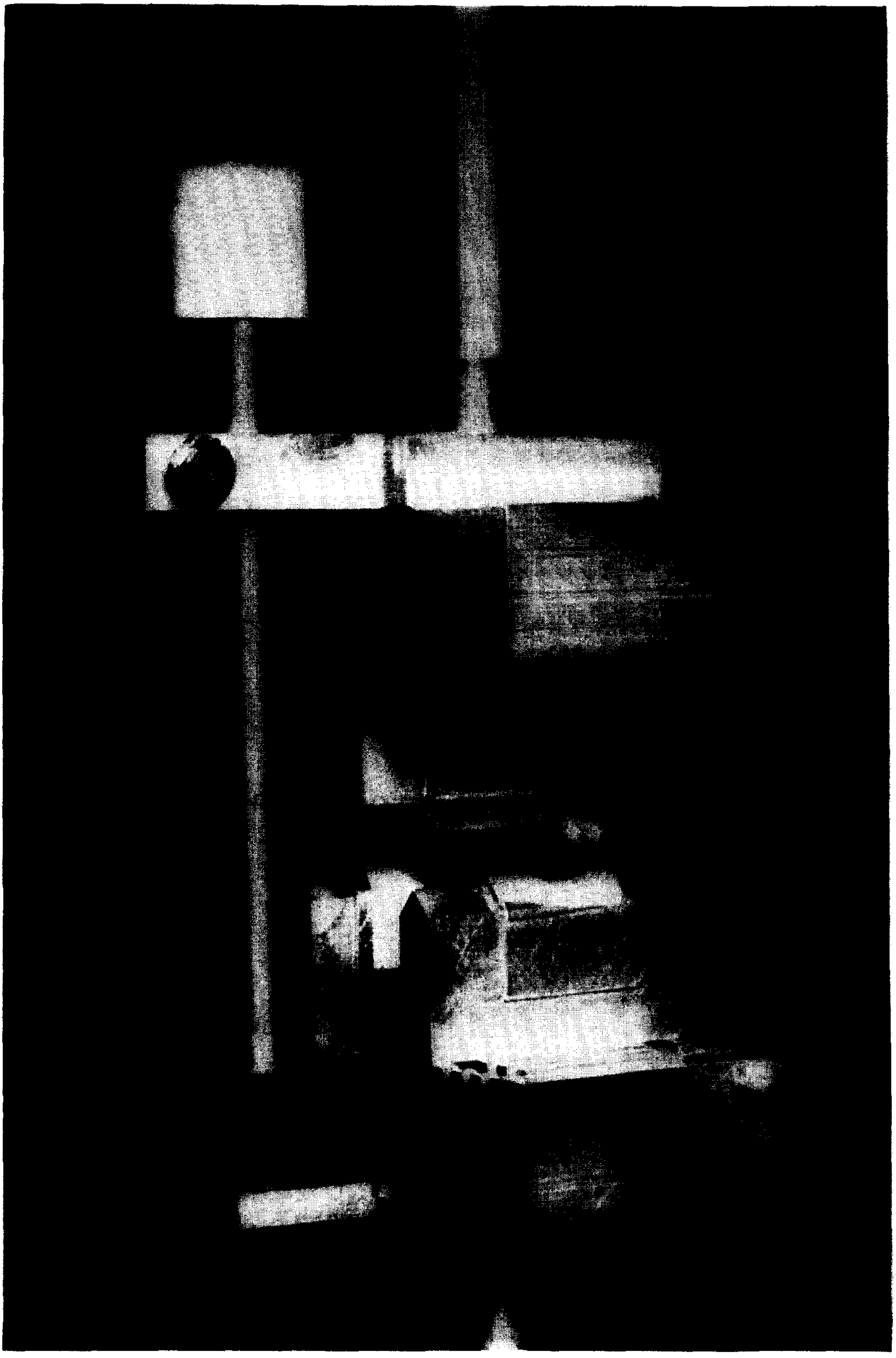

Fig. 2. Three-point bending apparatus.

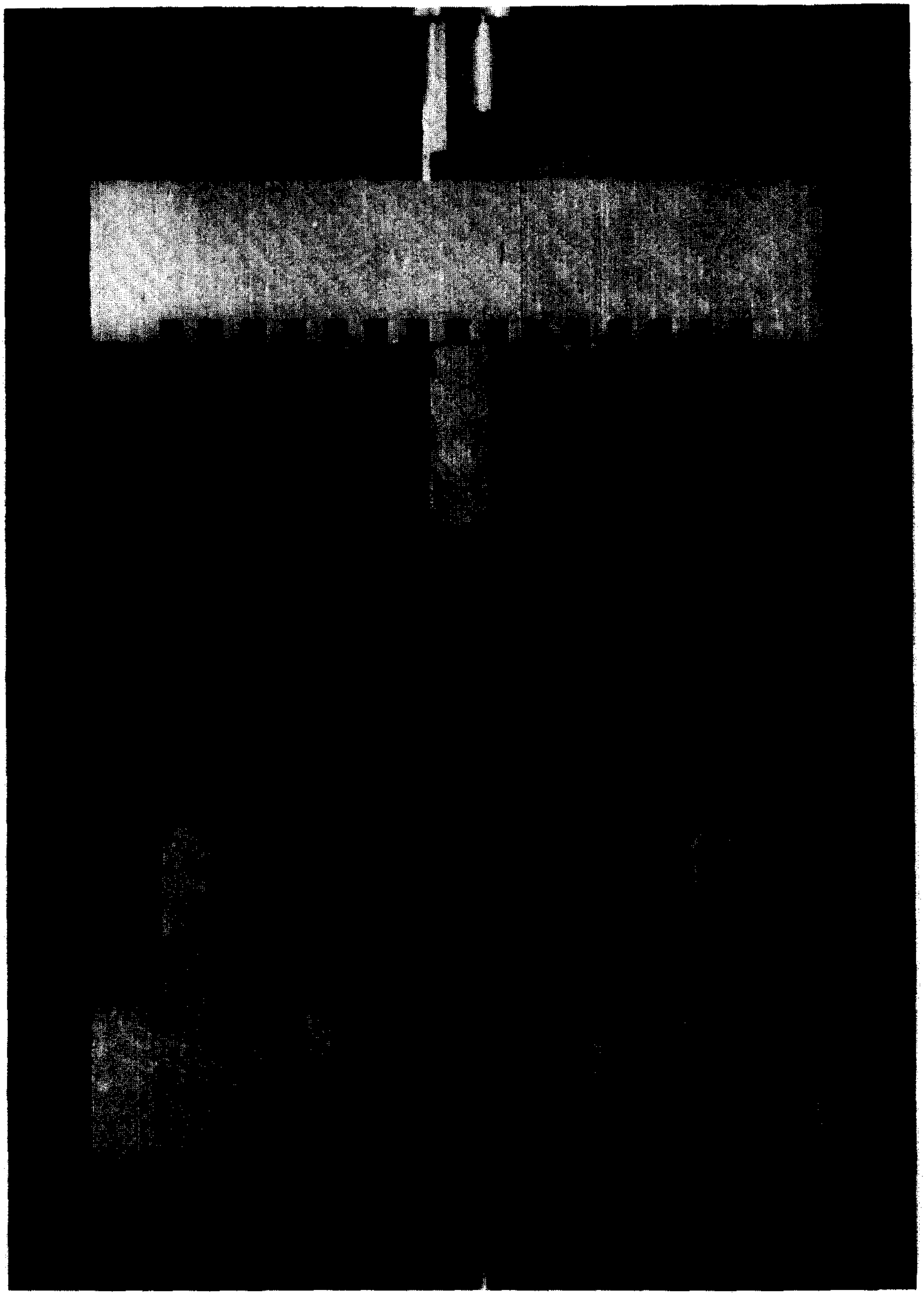

Fig. 3. Apparatus for four-point bending of suture beam segments.

sons of these hypothetical layered beam responses yield an understanding of the effect of sutures on the flexural response of cranial bone. For data presentation and analysis, beam width was incorporated with compliance into a compliance parameter, (mid-span deflection × beam width/mid-span load, $\delta w/P$).

The results of three-point bending tests and hypothetical layered beam calculations are shown for cranial suture beam samples 1-7, 2-7, 117, and 121 in Figs. 4, 5, 6, and 7 respectively. The embalmed samples, 1-7 and 2-7, were tested in both normal and inverted orientations. The effect of beam orientation on compliance was negligible for sample 1-7 (Fig. 4). Sample 2-7 (Fig. 5) was consistently more compliant when tested in the normal orientation than in the inverted orientation. The unembalmed samples were tested in the normal orientation only.

Embalmed suture beam 1-7 (Fig. 4) was more compliant than the hypothetical layered beam at the shorter span lengths but slightly less compliant at the longer spans. Embalmed suture beam 2-7 (Fig. 5) was more compliant than the hypothetical layered beam throughout the tested span range. Both unembalmed

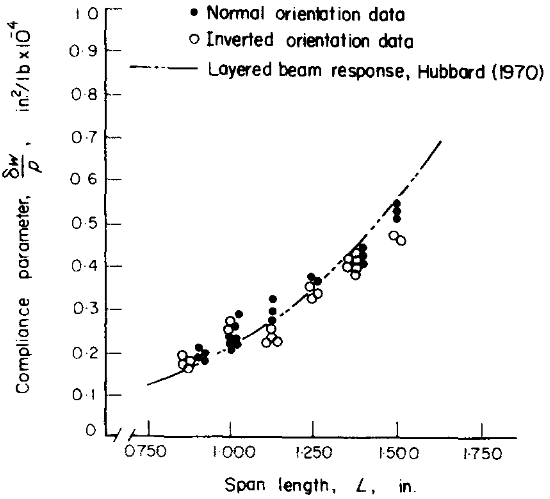

Fig. 4. Compliance parameter vs. span length; embalmed cranial suture beam 1–7.

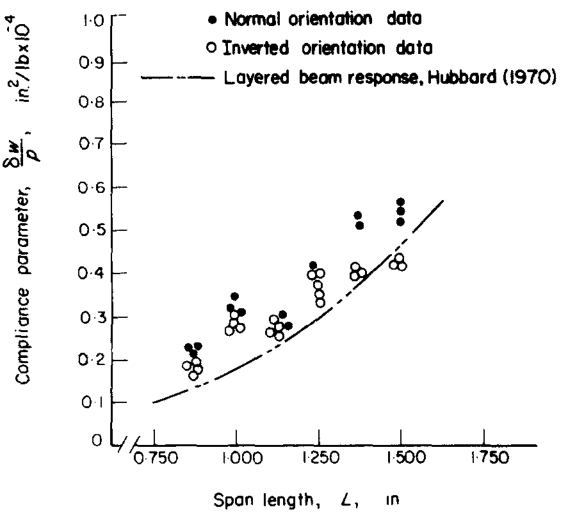

Fig. 5. Compliance parameter vs. span length; embalmed cranial suture beam 2–7.

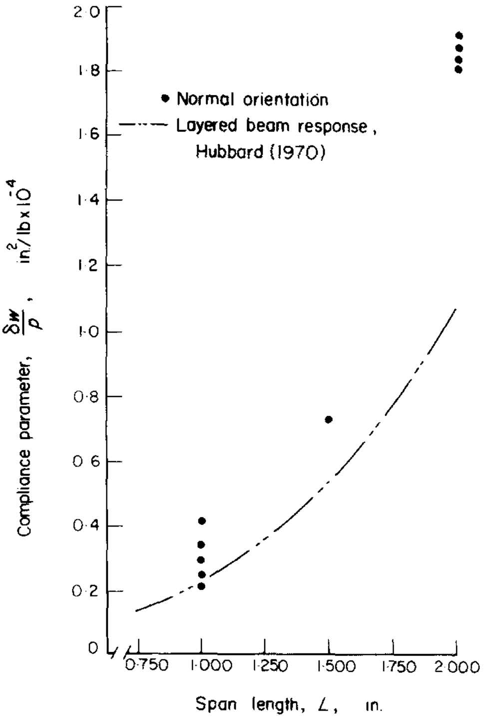

Fig. 6. Compliance parameter vs. span length; unembalmed cranial suture beam 117.

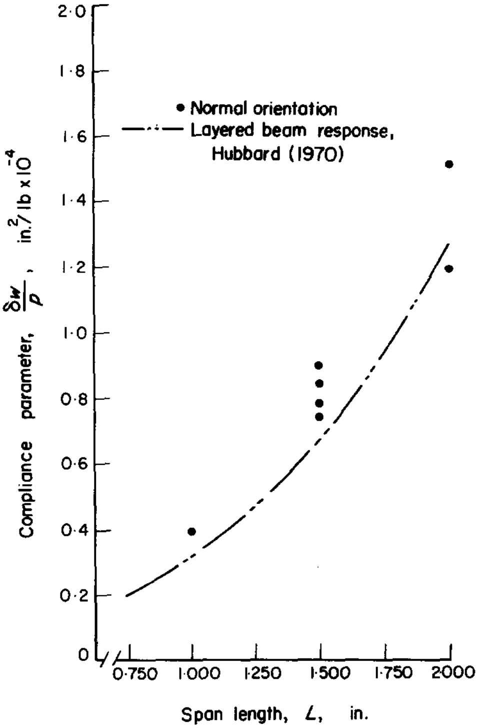

Fig. 7. Compliance parameter vs. span length; unembalmed cranial suture beam 121.

suture beam samples were more compliant than the corresponding hypothetical layered beam, sample 117 to a greater extent than sample 121 (Figs. 6 and 7). These results indicate that both embalmed and unembalmed cranial sutures are slightly more compliant to flexure about an axis along the sutures than the 'equivalent' layered cranial bone structures. In addition, it appears that unembalmed sutures are more compliant than embalmed sutures. However, the overall reversible flexural response of cranial sutures is not greatly different from that of layered cranial bone.

Embalmed and unembalmed beams and beam segments containing cranial sutures were loaded to failure in bending. The results are summarized in Fig. 8 in which the failure moment is plotted against the section modulus at the suture. The section modulus is defined in simple beam theory as the second moment of the beam cross-sectional area, taken about the 'neutral axis', divided by the beam half-thickness and is used in an effort to account for the variability in sample cross-section. The samples failed either by separation through

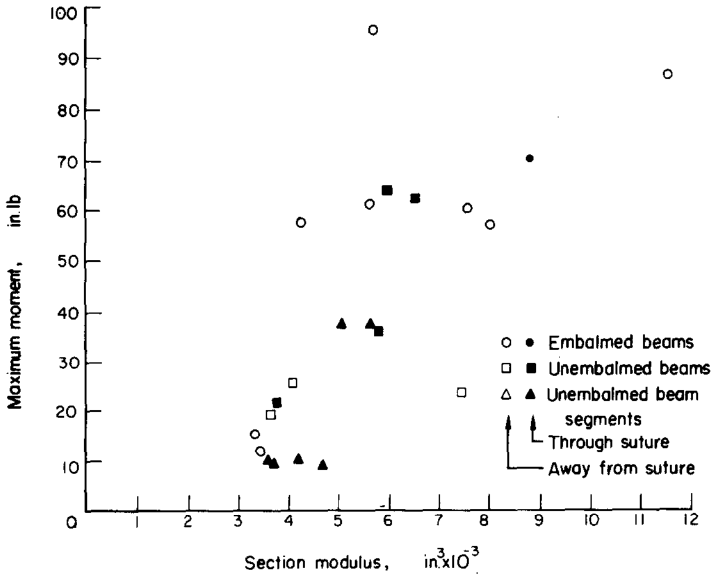

Fig. 8. Maximum moment vs. section modulus for failure of cranial sutures.

the sutural membrane (represented by solid data points) or by fracture of the sample away from the suture (open data points). Of nine embalmed suture beams tested, only one failed by suture separation, indicating that the embalmed sutures were generally at least as strong in bending as the adjacent cranial bone. Four of seven unembalmed suture beams failed by suture separation. Comparison between embalmed and unembalmed suture beam results indicates that embalming tends to strengthen cranial sutures. All of the six unembalmed suture beam segments failed by suture separation. Due to the beam segment loading technique, there was little chance for failure away from the suture. Therefore, consistent failure by suture separation is not surprising.

For homogeneous beams of different cross-sections which fail at a given maximum stress, the failure points, when plotted on a maximum moment vs. section modulus diagram such as Fig. 8, would fall on a straight line through the origin whose slope would be the failure stress level. With this in mind but realizing that a homogeneous material failure stress concept is not truly valid for the complex structure of sutures, it is interesting to note the relationship between failure moment and section modulus for failure by suture separation (Fig. 8). These data points (solid) indicate a definite positive correlation between failure moment and section modulus, which means that the section modulus of a cranial suture beam sample is a geometric indicator of maximum moment transfer capability. Other significant indicators of suture strength could be quantities which describe the character of suture interlinking and the maturity of the suture. Although the suture samples were of different character, as is obvious for the embalmed beams from Fig. 1, attempts to relate parameters which describe their character to mechanical response were not successful. After more detailed study, it is likely that the interlinking of sutures can be quantitatively described and related to measured response.

Hubbard (1971) has determined the bending strengths of layered cranial bone beams. Comparison of his results with those of the present study indicate that cranial sutures are generally as strong in bending as layered cranial bone of the same total thickness. This conclusion is strengthened by the occurrence of suture beam failure due to fracture of the layered cranial bone adjacent to unfailed sutures.

## CONCLUSIONS

Cranial sutures are a significant element in skull structure and knowledge of their mechanical response should be included in the study of traumatic head injury. This paper presents results of a first study of cranial sutures and methods for further study of their flexural response.

Results of multi-span, three-point bending tests indicate that

(1) cranial sutures are slightly more compliant than equivalent layered cranial bone structures, and

(2) unembalmed cranial sutures are more compliant than embalmed sutures.

Results of failure testing in bending of cranial suture samples indicate that

(1) embalmed cranial sutures are generally at least as strong in bending as the adjacent cranial bone;

(2) embalmed sutures are stronger in bending than unembalmed sutures;

(3) a positive correlation exists between the moment causing suture separation and the section modulus of a suture beam sample, and

(4) cranial sutures are generally as strong in bending as comparable layered cranial bone structures.

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