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# FRACTURE MECHANICAL ANALYSIS OF HUMAN SKULL

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## Abstract

We provide, in this work, estimation of critical value of stress intensity factor of the human skull ($K_{IC}$). Our research assists examinations concerning dynamic effects exerted on human skull (cracks, etc.).

*Keywords:* fracture mechanics, human skull, stress intensity factor, finite elements.

## 1. Introduction

The understanding of the mechanical behavior (stress-strain characteristics) of human bones is indispensable to ensure the success of operations and the compatibility of prostheses. There are two main groups of characteristics in the focus of our interest. The first one is the relation between stresses and strains: the second one is the load-bearing capacity of the material.

Application of classical mechanics and its constitutive equations is sufficient to solve several problems. Assuming homogeneous, isotropic, elastic behavior, for example, determination of Young modulus and Poisson ratio is enough for the characterization of the material (though the time dependent behavior cannot be described in this most simple way). Using constitutive relations different from elasticity, number of material parameters increases and broad range of features and aspects of behavior can be modelled.

Classical theories, however, are not really reliable in predicting the crushing of the material — that is fracture in our case. They consider the fracture as a stress or strain limit state, acting exactly the same way in the whole representative volume. The real situation, as proved by numerous experiments, is just the opposite: fracture is initiated by a local discontinuity, an opening bond, dislocation, a micro-crack, etc., and the propagating opening up of the initial crack leads to the global crushing of the material. So the fracture process can be described by understanding the conditions of crack initiation and propagation.

Approaching the problem of fracture from this point of view, methodology of fracture mechanics should be used and its material parameters are to be determined by laboratory experiments.

## 2. Material Parameters of Fracture Mechanics

Fracture is meant as the splitting of a solid body leading to the loss of its load-bearing capacity. The physical cause of fracture is the opening up of atomic or molecular bonds due to external loads and/or internal stresses causing free surfaces this way. Fracture is a continuing process of crack initiation and propagation while energy dissipation phenomena (heat and sound emission, stress-caused phase changes, etc.) are activated.

In the linearly elastic fracture mechanics, quantitative description of fracture condition is based on the assumption that the stress–strain behavior is linear until fracture. The initial crack in the material is regarded as a cut having $\rho \cong 0$ radius, and the increased stress in its peak is given as

$$\sigma_{\max} = \alpha_k \sigma_N \,, \tag{1}$$

where $\sigma_{\max}$ = ultimate stress
$\sigma_N$ = nominal stress, calculated from the external loads
$\alpha_k$ = shape factor, depending on the shape of the cut and of the analysed body

Assuming an elliptical cut, and taking the limits $\rho \to 0$ and $\sigma_{\max} \to \infty$, stress and strain fields at the peak of the crack can be described by the following mathematical form:

$$\sigma_{ij} = \frac{1}{(2\pi r)^{\frac{1}{2}}} \left[ K_{\mathrm{I}} f_{ij}^{\mathrm{I}} + K_{\mathrm{II}} f_{ij}^{\mathrm{II}} + K_{\mathrm{III}} f_{ij}^{\mathrm{III}} \right] . \tag{2}$$

The intensity of stress increase at the peak is characterised by the $K_{\mathrm{I}}$, $K_{\mathrm{II}}$ and $K_{\mathrm{III}}$ factors that are independent of the polar coordinates, $r$ and $\Theta$. The dimensionless $f_{ij}$ functions depend only on $\Theta$. The stress intensity factors, $K_{\mathrm{I}}$, $K_{\mathrm{II}}$ and $K_{\mathrm{III}}$, belong to the different types of the possible displacements of crack surfaces (*Fig. 1*).

Type I is a simple opening up due to tension, with the edges of the crack symmetrically moving away from each other. Type II is a longitudinal shearing when the edges slip on each other in the plane of the crack. Type

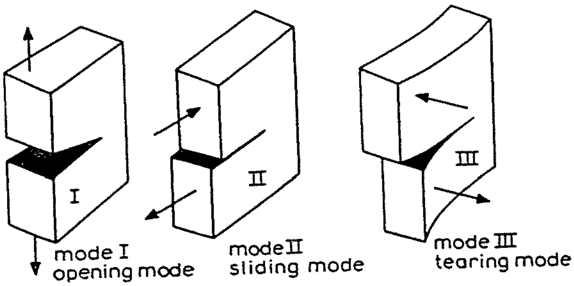


*Fig. 1.*

III — crosswise shear — is due to non-planar shear when the edges move orthogonal to the direction of crack propagation.

Type I is the most important one from practical point of view: it is characteristic for structures subjected to tension, bending or internal pressure. So this type can well be applied for the fracture analysis of human skull.

## 3. Experimental Results

Four specimens were taken from a human skull to determine the critical value of stress intensity factor with the help of uniaxial tensile test (according to Type I). *Fig. 2* shows the arrangements of the experiments.

Single cuts were applied on two specimens while double cuts were made on the other two. The exact geometrical data are given in *Fig. 3*. Uniform force distribution was ensured by the elements glued to the edges and had hinges to ensure uniaxial loading, too.

Opening up of the cracks was followed by extensometers glued on the specimens. They were placed in all cases in such a way that the deformation of crack peak, and the opening up of the crack edges could be registered.

Single-cut specimens were evaluated with the help of the expression and shape factor given by BOWIE (1972). The critical value of stress intensity factor:

$$K_{\mathrm{I}} = \frac{P}{tw}\sqrt{a}F_{\mathrm{I}}(\alpha, \beta, \gamma) \,,$$

where

$$\alpha = \frac{a}{w}, \qquad \beta = \frac{w}{2H}, \qquad \gamma = \frac{t}{w}, \tag{3}$$

where $a$ is the length of the crack, $w$ is horizontal and $H$ is vertical measurement of the plate, $t$ is the thickness of the analysed body and $P$ is the external force.

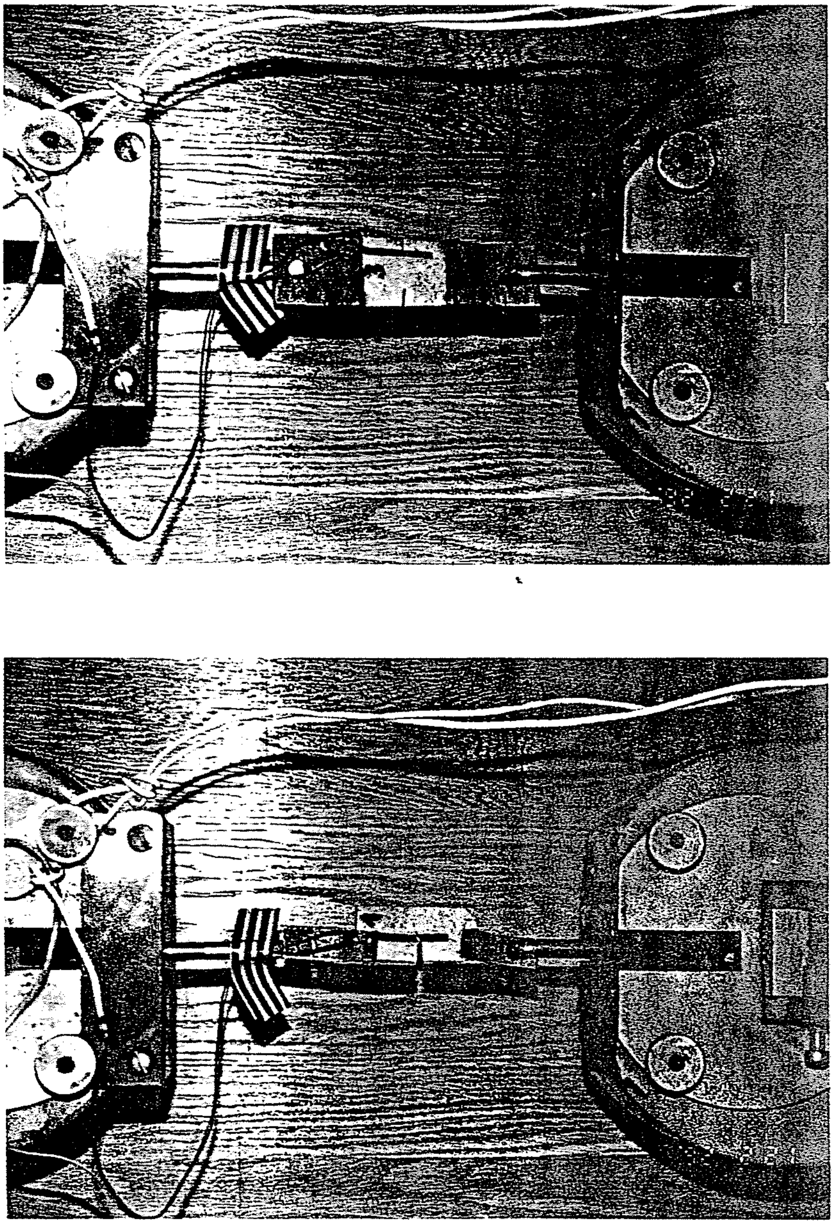

*Fig. 2.*

Shape factor and critical stress intensity in the case of double-cut specimens was calculated as suggested by NISITANI (1975). The critical

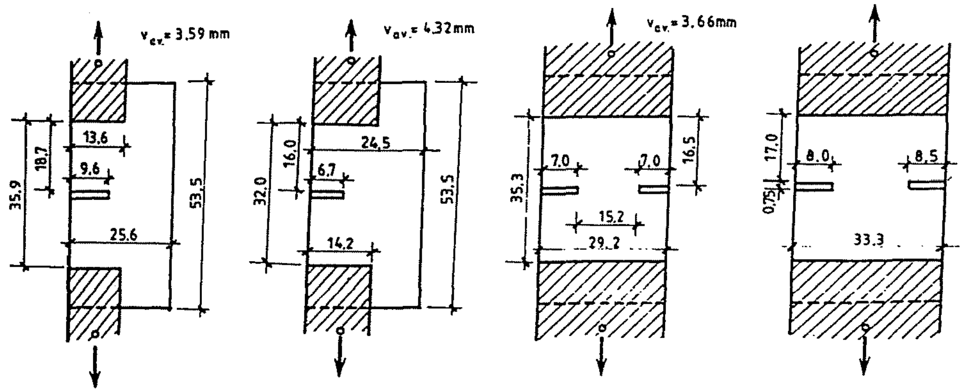


*Fig. 3.*

value of stress intensity factor is

$$K = \sigma\sqrt{\pi a} F_{\mathrm{I}}(\alpha) \,, \tag{4}$$

where

$$F_{\mathrm{I}}(\alpha) = 1.122 - 0.154\alpha + 0.807\alpha^2 - 1.894\alpha^3 + 2.494\alpha^4 \,, \tag{4/a}$$

and

$$\alpha = \frac{2a}{w} \,.$$

In this case, $a$ and $w$ represent the same characteristics as in *Eq.* (3), $\sigma$ represents external distributed loading.

*Table 1* summarises the results based on the above expressions.

**Table 1**

Critical value of stress intensity factor measured on cut specimens

| | $K_{\mathrm{IC}}\left(\mathrm{Nmm}^{-\frac{3}{2}}\right)$ |
|---|---|
| single-cut specimen | 33.41 – 20.38 |
| double-cut specimen | 23.91 - 17.27 |

According to the experimental results, the critical value of stress intensity factor determining the fracture limit is:

$$23.74 \pm 6.99\,\mathrm{Nmm}^{-\frac{3}{2}} \,.$$

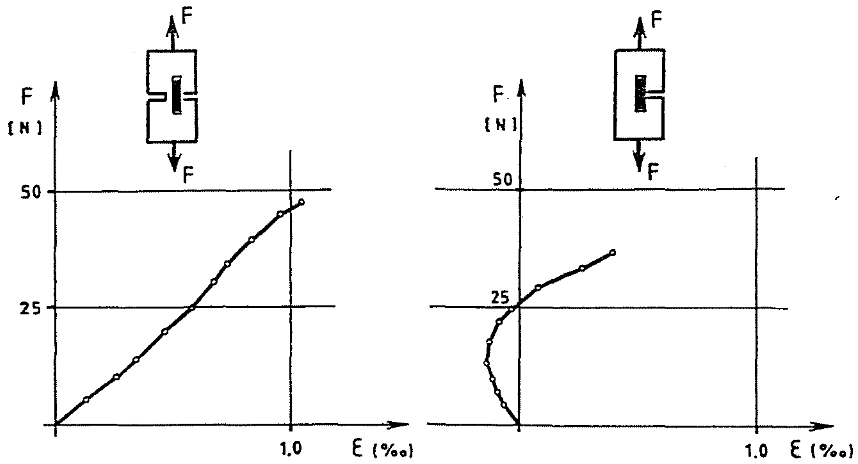


*Fig. 4.*

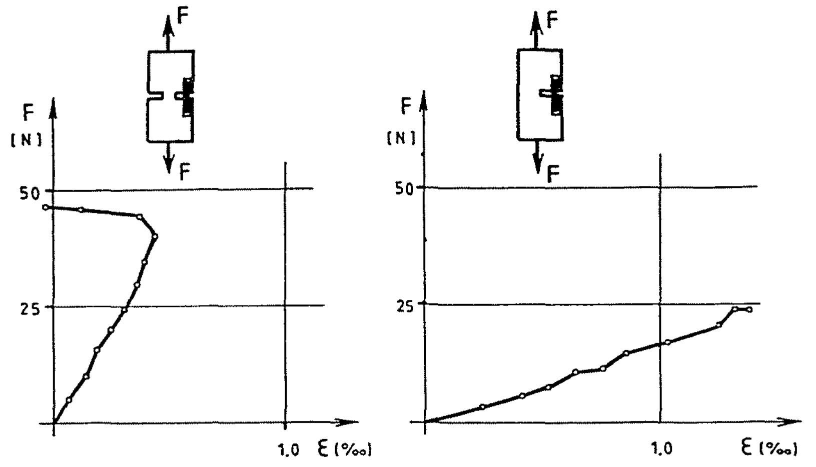


*Fig. 5.*

Process of crack opening and propagation can be followed on the force–displacement graphs registered during the experiments. Deformation of crack tip is illustrated by *Fig. 4*, *Fig. 5* shows the opening up of crack ends.

These graphs indicate that the process was nearly linear until fracture. $F$ is the external load and $\varepsilon$ is the strain. This means that the effect of stress changing due to physiological reasons in the skull is easy to calculate if the actual stress is also known.

## 4. Analytical Evaluation of Fracture

A two-dimensional finite element plate model was applied to determine the critical stress intensity factor analytically. The program used in the calculations assumes linearly elastic, isoptropic material; geometrical finitisation is done by eight-noded isoparametric elements. In the recent analysis only traditional elements were used; singular or mixed elements were not applied. *Fig. 6* introduces the interpolation method used in determining the stress-intensity factor. (The distance from crack tip, measured on the horizontal axis, is represented here.) Considering a small domain around the crack tip, the $K_{\mathrm{I}}$ factor (that belongs to the first fracture type) can be calculated from the well-known expression (see, for instance, OWEN (1983)):

$$K_{\mathrm{I}}\begin{bmatrix}(2x-1)\cos\frac{\Theta}{2}-\cos\frac{3\Theta}{2}\\(2x+1)\sin\frac{\Theta}{2}-\sin\frac{3\Theta}{2}\end{bmatrix}=4G\sqrt{\frac{2\pi}{r}}\begin{bmatrix}u\\\nu\end{bmatrix}, \qquad (5)$$

where $x=\dfrac{(3-\nu)}{(1+\nu)}$
$\nu$ = Poisson ratio
$G$ = shear modulus
$u$, $v$ : translations of the point having the polar coordinates $r$ and $\Theta$.

As measured in simple tension tests, the shear modulus was $3400\,\mathrm{N/mm^2}$ and the Poisson ratio was 0.24 in the calculation of the plate problem.

Comparing the $K_{\mathrm{I}}$ values given by the interpolation and measured in the experiments, toughness of the real material is evidently larger than estimated by the purely theoretical model.

The most likely reason of this fact is due to the microstructure of the bones. Instead of homogeneous and isotropic behavior as assumed in the theory, real bones behave like composite materials on the micro-scale, and it increases the resistance against external loads.

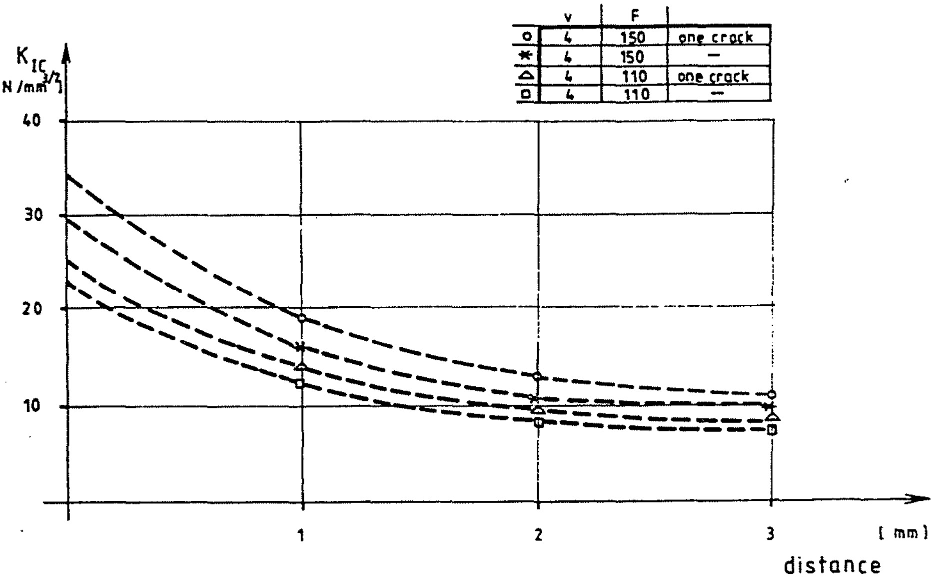


*Fig. 6.*

## 5. Summary

Experimental results, together with analytical calculations supporting them, prove that the fracture-mechanical material parameters can properly be used in the analysis of the behavior of human bones. The critical value of stress intensity factor indicates a fracture limit state; compared to this value, effects of stress increase due to pressure changes in the skull can more accurately be interpreted.

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