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Addendum to “Multiscale Response of the Human Skull to Quasi-Static Compression”

by Stephen L Alexander and Tusit Weerasooriya

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Addendum to “Multiscale Response of the Human Skull to Quasi-Static Compression”

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13. SUPPLEMENTARY NOTES As of 31 January 2019, the organization is now part of the US Army Combat Capabilities Development Command (formerly RDECOM) and is now called CCDC Army Research Laboratory.					
14. ABSTRACT The journal article titled “Multiscale Response of the Human Skull to Quasi-Static Compression” (Alexander SL, Gunnarsson CA, Rafaels K, Weerasooriya T. <i>Journal of the Mechanical Behavior of Biomedical Materials</i> ; 102, 2020) reported the nonlinear stress response of human skull bone to quasi-static compression. Power relationships were optimized to relate the local microstructure (bone volume fraction, or BVF) to the initial linear response (Young’s modulus) and subsequent failure stress at the microstructural level. These relationships were then used to calculate apparent macro-structural moduli at different scales for the initial regime before localized instabilities start to soften the material response. However, finite element simulations involving loading applied to the human head and predicting injury (skull fracture) require apparent stress-strain relations up to global failure. The present addendum derives this global stress-strain response up to final failure.					
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Preface

Alexander et al.¹ reported the nonlinear stress response of human skull bone to quasi-static compression. Power relationships were optimized to relate the local microstructure (bone volume fraction, or BVF) to the initial linear response (Young's modulus) and subsequent failure stress at the microstructural level. These relationships were then used to calculate apparent macro-structural moduli at different scales for the initial regime before localized instabilities start to soften the material response. However, finite element simulations involving loading applied to the human head and predicting injury (skull fracture) require apparent stress-strain relations up to global failure. The present addendum derives this global stress-strain response up to final failure.

¹ Alexander SL, Gunnarsson CA, Rafaels K, Weerasooriya T. Multiscale response of the human skull to quasi-static compression. *J Mech Behav Biomed Mater.* 2020;102:103492. <https://doi.org/10.1016/j.jmbbm.2019.103492>.

1. Simplified Deformation/Failure Model for Human Skull under Compression at Quasi-static Rates

The analytical model (mathematical representation of the skull response to compression) developed in this addendum is compared with the previously reported experiment from the specimen labeled as 04-09. Figure 1 plots the engineering stress measured from the experiment as a function of the engineering strain. The strain was calculated from the digital image correlation (DIC)-derived displacement fields on the left and right cameras and by averaging between the two cameras at each time point. The analytical model (*assuming a layered configuration*) was constructed in three parts. In the first part, the modulus of each layer was calculated using the power law relationship between the modulus (E) and bone volume fraction (f_{bv}) previously published¹ for cranial bone:

$$E = 8528(f_{bv})^{1.585} \text{MPa.} \quad (1)$$

The local failure stress was described by an analogous power relationship. This relationship scaled σ_0^f , which is the local failure stress of compacted bone such that $f_{bv} = 1$, by the bone volume fraction:

$$\sigma^f = \sigma_0^f (f_{bv})^k. \quad (2)$$

Here, the exponential scaling parameter, k , was specified as $k=2$ in keeping with previous publications.^{2,3} The parameter σ_0^f was identified as $\sigma_0^f = 90 \text{MPa}$ by matching to the experimental stress-strain response and indicates that the specimen, after accumulation of debris from compaction, is expected to fail at 90 MPa.

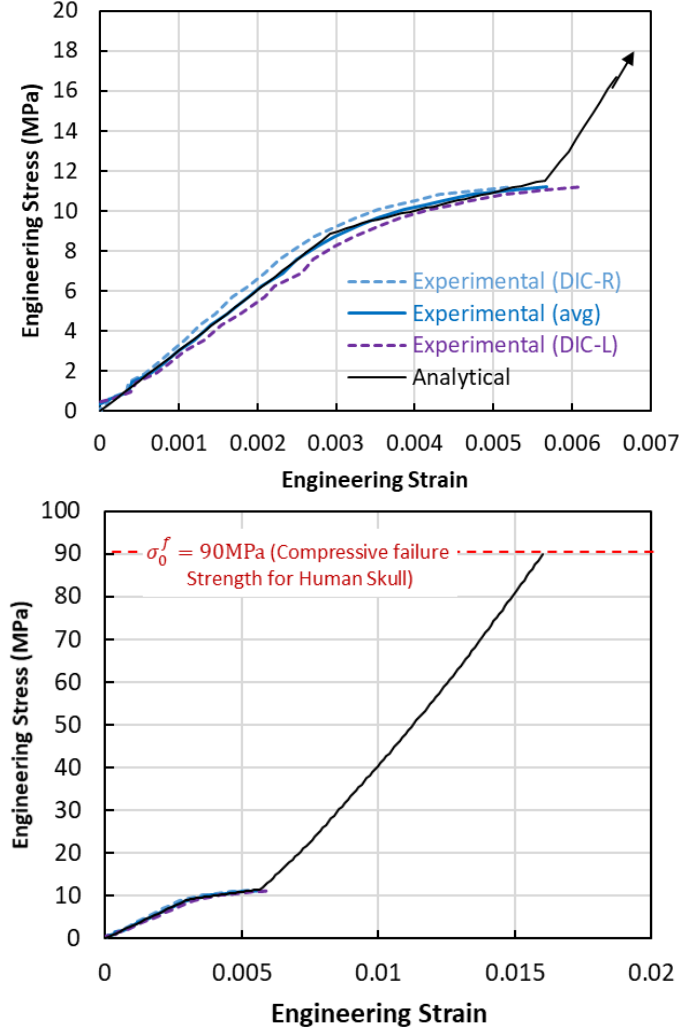


Fig. 1 The stress-strain response from the experiment and analytical model for the initial response (top) and to failure (bottom). Experimental strain was measured from the DIC-derived displacement fields from the left camera (DIC-L), right camera (DIC-R), and as an average between these two cameras at each time point (avg).

The analytical model can be described by the following:

$$\sigma \text{ (MPa)} = \begin{cases} 2984.9\varepsilon, & (0,0) \leq (\sigma, \varepsilon) < (9.0 \text{ MPa}, 0.0030) \\ 946.0\varepsilon + 6.1, & (9.0 \text{ MPa}, 0.0030) \leq (\sigma, \varepsilon) < (11.9 \text{ MPa}, 0.0061). \\ 7454.1\varepsilon - 33.5, & (11.9 \text{ MPa}, 0.0061) \leq (\sigma, \varepsilon) < (90 \text{ MPa}, 0.0166) \end{cases} \quad (3)$$

Note that the model describes the stress response to 90 MPa ($\varepsilon=0.0166$), after which the specimen is predicted to fail under compression (plane stress). The three different regimes of this model are shown in Fig. 2 and in comparison to the experimental stress-strain response. We assumed a piecewise linear relationship for the three regions in order to make implementation into finite element simulations easier.

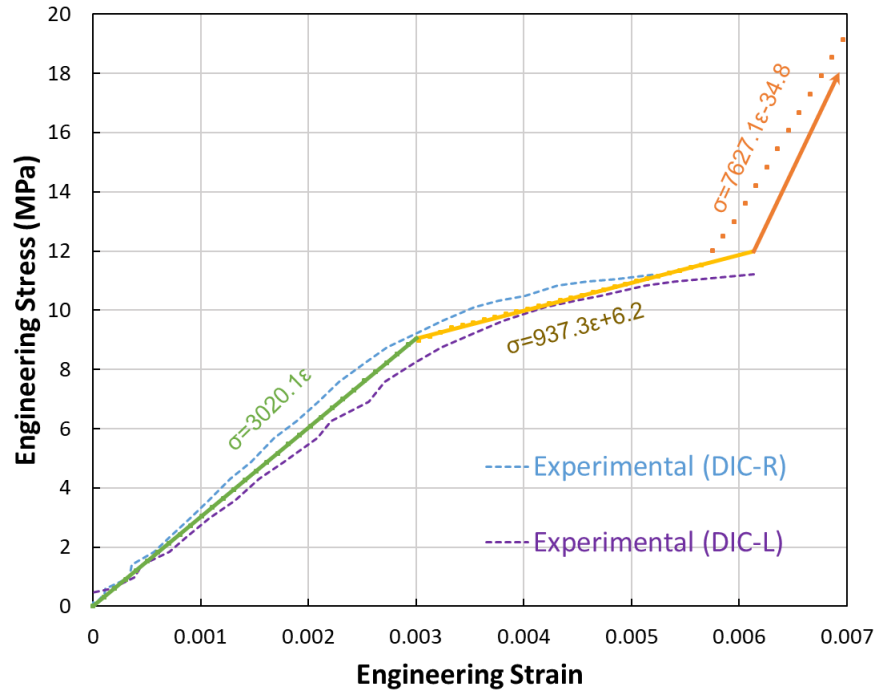


Fig. 2 The engineering stress-strain response in the small-scale regime, with the tri-linear model plotted with the experimental stress-strain curve (as in Fig. 1)

2. References

1. Alexander SL, Gunnarsson CA, Rafaels K, Weerasooriya T. Multiscale response of the human skull to quasi-static compression. *J Mech Behav Biomed Mater.* 2020;102:103492.
<https://doi.org/10.1016/j.jmbbm.2019.103492>.
2. Gibson LJ, Ashby MF. *Cellular solids: structure and properties.* Cambridge (UK): Cambridge University Press; 1997.
3. Morgan EF, Unnikrisnan GU, Hussein AI. Bone mechanical properties in healthy and diseased states. *Annu Rev Biomed Eng.* 2018 June 4;20:119–143.

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