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Bending Response of Human Skull-Beams as a Function of Loading Rate and Loading-Tip Geometry

**by C Allan Gunnarsson, Stephen L Alexander, and
Tusit Weerasooriya**

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Bending Response of Human Skull-Beams as a Function of Loading Rate and Loading-Tip Geometry

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14. ABSTRACT Impacts to the head can transfer energy to the skull and brain, leading to injuries such as skull fracture and traumatic brain injury. The presence of a cranial fracture has been shown to be associated with a higher incidence of intracranial lesions, neurological deficit, and poor medical outcomes. Therefore, it is important to understand the effect of impact on the mechanical response of human skull. Thin skull-beam specimens were fabricated from a postmortem human subject donor skull. The beam specimens were loaded in three-point bend to quantify the response of the skull deformation as a function of loading history. Deformation and failure of the skull-beam during loading were quantified using digital image correlation. Pre- and posttested (27 μm^3 and 67 μm^3 voxel resolution, respectively) specimens were scanned using a micro-CT scanner for quantification of the 3D microstructure. This allows for creation of computational meshes for each specimen for computational modeling of the deformation response and failure mechanisms. Understanding the skull deformation and fracture process with associated mechanisms in this loading configuration allows for the development of mechanism-based failure criteria for use in computational modeling of the effect of indenting/impacting. The experimental techniques used and deformation and failure results are presented.					
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Contents

List of Figures	v
List of Tables	vii
1. Introduction	1
2. Methods	5
2.1 Human Skull-Beam Specimens	5
2.2 Micro-Computed Tomography	7
2.3 Bend Experiments	8
2.3.1 High-Rate Experiments	11
2.3.2 Quasi-static Rate Experiments	12
2.3.3 Experimental Setup Compliance and Specimen Apparent Stiffness	12
3. Results	14
3.1 High-Rate Experiments	14
3.2 Quasi-static Rate Experiments	16
3.3 Strain-Rate Approximation	17
4. Discussion and Limitations	18
4.1 Loading Rate Effects on Bone	19
4.2 Loading Geometry Effect	20
4.3 Specimen Fracture	21
4.4 Limitations in Analyzing the Full-Field Surface Strain Profiles	21
4.5 Rate Limitations	23
4.6 Effect of Irradiation Absorption on Bone	23
5. Conclusions	24
6. References	25

Appendix. Camera Images from Experiments and Pre- and Posttest Micro-CT Images for Each Specimen	29
List of Symbols, Abbreviations, and Acronyms	42
Distribution List	43

List of Figures

Fig. 1	(a) Skullcap used for skull-beam specimens cut from (b) donor PMHS upper skull and (c) skull-beam specimen cut from skullcap specimen including speckle pattern on side surface for DIC. Specimen B01 was closest to anterior (A), while B05 was farthest (P). Length of ruler in (b) is 15.2 cm.	6
Fig. 2	Human skull-beam specimens cut from PMHS skullcap. Photograph is of the outer surface of the specimens (the surface closest to the skin in vivo). Specimens B01 through B05 begin at the top and move down. Each specimen is approximately 4 mm wide and 75 mm long.....	6
Fig. 3	Skull-beam specimen B03 micro-CT cross-section images (y - z plane) for pretest (top) and posttest (bottom), with labels for specimen measurements. Images have been binarized so that white represents bone. Colored circles indicate common features in both scans.	7
Fig. 4	Loading tips for skull bend experiments. The blunt loading tip (right) had a large curvature (15.875 mm), while the sharp loading tip (left) had very small tip curvature (0.025 mm, detail B). The cylindrical base for each loading tip had a diameter of 31.75 mm.	9
Fig. 5	Schematic of bend experiment loading. This example includes the blunt loading tip and a micro-CT image of Specimen B03.	10
Fig. 6	High-rate experimental setup shown with blunt loading tip during experimental setup. (a) Prior to contacting the loading tip to the specimen. (b) Closeup showing contact of loading tip with the specimen prior to loading.....	10
Fig. 7	Quasi-static rate experimental setup with sharp loading tip, second camera not shown	12
Fig. 8	Base plate displacement along loading axis and loading-tip (LT) displacement histories using DIC and machine extensometer for B01	13
Fig. 9	Load vs. displacement for high-rate experiments. The failure initiation point for B03 is marked. This point is identified later (see Fig. 12) from analysis of the strain-time response. Dashed line shows the trend for the B03 response, disregarding the oscillations.	15
Fig. 10	Time series of LP camera images from B03 before and during fracture. Time stamps on the images are elapsed time from the start of the specimen loading, which is taken as 0 μ s. Labels A-F are noted on the load-time curve in Fig. 12.....	16
Fig. 11	Load vs. displacement for quasi-static rate experiments	17
Fig. 12	Load-time and strain-time response for B03. Strain data points are the maximum principal strain for each DIC image taken during loading from both the LP camera (blue) and WS camera (red). Strain-time response was bilinear, as indicated by the colored dashed lines. The	

	time at which the strain-time response increased dramatically was the failure initiation point, indicated by the vertical dotted line. Labels A-F indicate the time points for the experimental images shown in Fig. 10.	18
Fig. 13	(a) Failure load and (b) apparent stiffness as a function of loading rate. The failure load and apparent stiffness for the sharp high-rate experiment have high uncertainty due to oscillations.	19
Fig. 14	Surface strain profiles obtained for the LP camera of B01 at the time point just prior to failure using two different DIC subset sizes: (a) 73 pixel (0.304 mm) and (b) 15 pixel (0.0625 mm). The strain color map scale is the same (0.00 bottom/light purple - 0.30 top/red) for both profiles. The pixel to millimeter ratio is 0.004166 mm/pixel. Red boxes in the upper-right corners of the figure show the subset size.	22
Fig. A-1	Images from the LP camera for B01 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	31
Fig. A-2	Images from the WS camera for B01 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	32
Fig. A-3	Micro-CT images of B01 before (top) and after (bottom) the experiment.	32
Fig. A-4	Images from the LP camera for B05 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	33
Fig. A-5	Images from the WS camera for B05 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided below. Post-fracture image (b) includes red circle indicating location of fracture.	34
Fig. A-6	Micro-CT images of B05 before (top) and after (bottom) the experiment.	34
Fig. A-7	Images from the LP camera for B04 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	35
Fig. A-8	Images from the WS camera for B04 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right.	

	Post-fracture image (b) includes red circle indicating location of fracture.	36
Fig. A-9	Micro-CT images of B04 before (top) and after (bottom) the experiment.....	36
Fig. A-10	Images from the LP camera for B02 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	37
Fig. A-11	Images from the WS camera for B02 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	38
Fig. A-12	Micro-CT images of B02 before (top) and after (bottom) the experiment.....	38
Fig. A-13	Images from the LP camera for B03 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	39
Fig. A-14	Images from the WS camera for B03 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.	40
Fig. A-15	Micro-CT images of B03 before (top) and after (bottom) the experiment.....	41

List of Tables

Table 1	Comparison of different skull specimen length scales needed for the comprehensive understanding of skull fracture or failure	3
Table 2	DIC analysis parameters	11
Table 3	Experimental results summary for all bend experiments.....	14

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1. Introduction

The understanding and mitigation of head injury is an important goal among the defense research community. Over 235,000 service members were diagnosed with traumatic brain injury (TBI) from 2000 to 2011, and it is estimated that 1.7 million civilians sustain a TBI each year (Multi-agency Leadership Panel 2013). TBI can occur when external mechanical forces act on the head. These applied forces affect pressure and strain in the hard and soft tissues of the skull and brain, leading to structural and functional deficits. These mechanical forces are present during head impact events when a projectile strikes the head protection device, such as a helmet. The impact event can cause the protecting device to deform and contact the head, as in behind-helmet blunt trauma (BHBT), or the projectile can penetrate the protecting device and directly contact the head. Understanding the underlying mechanisms of head injury caused by these head impact events enables the design and evaluation of improved head protection concepts and devices. In particular, established injury thresholds would enable head protection to be directly assessed either through experimentation or simulation.

Determination of mechanical thresholds (pressure, strain, etc.) in brain cells and tissues that lead to injuries of varying intensity is ongoing, with some success (Meaney et al. 2014) while still needing further development. Meanwhile, the presence of skull fracture has been established as an indicator of reduced medical outcomes and increased likelihood of TBI (Bullock et al. 2006; Tseng et al. 2011). Therefore, computer simulation of head impact could use skull fracture as an indication that injury would likely occur under the prescribed loading conditions (Weerasooriya and Alexander 2021).

The barrier to predicting skull fracture lies in a lack of understanding of the different fracture mechanisms operating under various types of loading conditions. Ritchie et al. (2005) discussed the fracture behavior of bone in detail and put forth several toughening mechanisms that could occur in cortical bone, including deflection of cracks by microscopic osteons at cement line interfaces, initiation of multiple microcracking ahead of the main crack, bridging of uncracked ligaments, and collagen fiber crack bridging. However, many of these mechanisms are present during fracture of the highly oriented cortical bone present in load-bearing bones, such as the femur. Skull fracture may occur by different mechanisms due to the difference in the porous structure of the skull. For human skull, the change of porosity as a function of thickness from the outer surface (nearest the skin) to the inner surface (nearest the brain) follows a bell-shaped curve (Alexander et al. 2019). Following the classification of Alexander et al., the outer table and inner

table generally have porosities less than 30% while the diploe (or mid-diploe) has a porosity greater than 30%.

Another major difference between the skull and other load-bearing bones, such as the femur, is the relative isotropy in the skull. Dempster (1967) punctured decalcified human skull away from the orbital cavities and facial structures to visualize the dominant direction of collagenous fibers in the outer table. He concluded that the fibers had a random orientation in the skull. Similarly, McElhaney et al. (1970) could not discern dominant directions in the histology of each of the three cranial layers. These findings are supported by recent observations (Alexander et al. 2019) that used high-resolution microcomputed tomography (micro-CT) visualization of the canal structure within the tables of the human skull. This lack of a dominant structural direction in cranial bone is in sharp contrast to load-bearing bones, such as the femur, which possesses a highly anisotropic substructure and has shown mechanical response and fracture behavior to be highly dependent on loading orientation (Sanborn et al. 2016; Weerasooriya et al. 2016).

There are not many experimental studies focused on how the structure of the skull deforms and fractures during blunt or penetrating loading, which would allow incorporation of fracture mechanism-based injury threshold models into computational methods to accurately predict behavior of the skull during indentation loading. The mechanical response of the adult human skull during bending has been investigated using thin skull-beam specimens loaded in three-point bending (Hubbard 1971; Verschueren et al. 2006; Delille et al. 2007; Motherway et al. 2009; Rahmoun et al. 2014). They found that fracture initiation occurred in tension on the inner surface of the specimens, with elastic moduli ranging from 2.3 ± 1.2 GPa (Verschueren et al. 2006) to 9.69 ± 2.32 GPa (Hubbard 1971). The mechanical response of the adult human skull during indentation loading was studied by the authors previously (Gunnarsson et al. 2021) using skullcap specimens to preserve the 3-D skull geometry. However, both loading rate and loading-tip geometry likely cause different types of failure in the human skull during head impact, as presented by Weerasooriya and Alexander (2021). The above-mentioned experimental studies did not investigate the effect of loading-tip geometry on the skull; the bend studies did not include both quasi-static and high rates (>1 m/s) in the same study.

In skull fracture studies at low and high rates, it is possible to load skull specimens at four levels of length scales: (1) small coupon-scale experiments with either uniaxial or simple shear idealized loading, (2) skull-beam-scale bending experiments, mainly by indenting/impacting, (3) skullcap-scale indenting/impacting with an impactor/indenter, and (4) skull-scale or component-scale indenting/impacting. Each scale experiment provides different aspects for

acquiring and building the needed comprehensive understanding of skull failure through HEMC (hybrid-experimental-modeling-computational) concepts. Each length scale specimen has different advantages and disadvantages, which are identified in Table 1.

Table 1 Comparison of different skull specimen length scales needed for the comprehensive understanding of skull fracture or failure

	Coupon-scale	Skull-beam-scale	Skullcap-scale	Skull-scale or component-scale
Load-displacement measurement?	Detailed measurements	Detailed measurements	Detailed measurements	Failed/not failed diagnostics only as a function of velocity
Full-field displacement/strain measurement?	Detailed measurements on coupon surfaces, enabling visualization of failure process as a function of time under idealized loading	Detailed measurements on skull-beam surfaces, enabling visualization of failure process as a function of time	Can observe full-field displacement and failure initiation and patterns only on the back surface , but not inside the specimen	Not possible
State of loading?	Idealized uniaxial or simple shear loading, which does not represent actual/real multiaxial loading	Multiaxial loading which may represent actual/real loading, but specimen is not completely multiaxial	Multiaxial loading, which may represent actual/real loading, but not to the extent of full skull component	Multiaxial loading representing actual/real loading
Possible to observe multiple mechanisms of failure and transition of failure mechanisms?	Yes, but forces to only one dominant mechanism	Yes, can be observed during failure process in situ also complementing with corresponding full-field measured displacements	No. Models and computational concepts can only be optimized from load-displacement response. Harder to stop loading with just initiated failure.	Not possible; postmortem observation only. Very difficult to obtain a fractured skull showing just failure initiation.
Possible to use multiple specimens and suitable for statistical studies?	Smaller specimen size, thus multiple specimens can be harvested for statistical studies	No, because smaller number of specimens, but suitable for understanding failure with quantified structural details	Fewer specimens, thus expensive for statistic studies and also to interrogate the source of variability in the structure	Fewer specimens, thus not possible for comprehensive statistic studies except for comparing different subjects; and to interrogate the source of variability from structure, as chemistry of the bone also changes from one subject to another.

Table 1 Comparison of different skull specimen length scales needed for the comprehensive understanding of skull fracture or failure (continued)

	Coupon-scale	Skull-beam-scale	Skullcap-scale	Skull-scale or component-scale
Microstructure quantification?	Easier to quantify structure with standard micro-CT	May need higher resolution and higher power specialized micro-CT for larger-scale specimens to obtain resolution on the scale of skull-pores	May need higher resolution and higher power specialized micro-CT for larger-scale specimens to obtain resolution on the scale of skull-pores	Harder to quantify structure with high-resolution micro-CT. Can quantify using clinical CTs, only providing thickness variation of the skulls.
Postmortem (PM) analysis of surface and internal structure?	Specimens can be recovered for PM micro-CT studies after loading	Specimens can be recovered for PM micro-CT studies after loading	Good for PM studies, but very difficult to stop experiment at crack initiation	Good for PM studies, but very difficult to stop experiment at crack initiation
In situ loading with observation of internal structural changes using a micro-CT?	Can be loaded in situ in a micro-CT to understand detailed internal deformation and failure	Need more specialized loading platforms for in situ studies of failure as a function of time	Possible with great difficulty and cost, requiring design of specialized loading systems	Not possible
Suitable to use for material modeling and calibration of existing material models?	Yes, for uniaxial deformation and failure model parameters, but may not be applicable for multiaxial loading situation	Yes, for mechanism-based failure models incorporating multiple simultaneous mechanisms operating at different locations and/or the possible transition from one mechanism to another during failure	Yes, for mechanism-based failure models allowing optimization to load-displacement, but blindly assuming the dominant failure mechanisms inside the specimen	Only used for final validation of an existing computation scheme with material models that have already been calibrated at lower length scales

In the present study, the deformation and fracture behavior of the human skull by indentation/impact loading was investigated at slow (Instron rate) and high rate (Hopkinson bar rate) using skull-beam specimens, thus providing in situ full-field deformation within the inner and outer surfaces of the skull specimen, also showing the possible critical transitions in failure mechanisms within the specimen, which was not available at our skullcap studies (Gunnarsson et al. 2021; Weerasooriya and Alexander 2021). The coupon-scale skull studies (Boruah et al. 2017; Alexander et al. 2020a; Brown et al. 2021) do not impose to loading of multiaxial stress state, and also each study is restricted to one dominant mechanism. In comparison, in full skull-scale studies (Rafaels et al. 2015; Weisenbach et al. 2018) even though they are multiaxial loading, there are not enough measurements in

these experiments to use them to incorporate or validate failure models. In addition, in the current skull-beam study, the loading-tip geometry effect was investigated by using two indenters/impactors to represent either BHBT (blunt) or sharp indenting/impacting events. During loading, the full-field deformation of the beam specimen surfaces was measured using digital image correlation (DIC). This enabled a unique opportunity for quantitative visualization of the process of damage initiation and propagation within the inner structure of the skull. After failure, loading was removed and the posttest skull-beam structure was scanned with the micro-CT. This posttest micro-CT scan allowed for a direct comparison with the pretest micro-CT scan, identifying the effect of loading on the skull structure and allowing for in situ observation of fracture processes at the microstructural scale. The results of this study are used to understand human skull deformation and transition of fracture from one dominant mechanism to another during slow and high-rate indentation loading so that the observations and measurements could be incorporated into computational modeling of head impact events (Alexander et al. 2020b; Weerasooriya and Alexander 2021).

2. Methods

2.1 Human Skull-Beam Specimens

The experiments reported here were conducted in compliance with the US Army Combat Capabilities Development Command Army Research Laboratory Policy for Use of Human Cadavers for Research, Development, Test, and Evaluation under the guidance and oversight of the DEVCOM Army Research Laboratory's Human Cadaver Review Board and the ARL Safety Office. Five skull bend specimens, labeled B01 through B05, were extracted from the right parietal skull bone of an adult postmortem human subject (PMHS), ARL-2017-0021, age 74 years. A bone pathology saw (Exact 312, Exact Technologies, Inc.) was used to cut the skull approximately at the ear line; the upper skull was then cut to fabricate a skullcap specimen. Figure 1a shows the skullcap specimen extracted from the upper skull of the PMHS donor (Fig. 1b). The skullcap specimen was hand sanded until the cut surface was flat. The skullcap was then cut into slices to create thin beam specimens; each specimen was approximately 4 mm (0.175 inches) wide (x-axis in Fig. 2) and 75 mm (3.0 inches) long (z-axis in Fig. 2). A typical skull-beam specimen is shown in Fig. 1c, with speckle pattern already applied to the side surface. The specimens were cut parallel to the left to right axis of the skullcap—that is, the specimen long dimension (z-axis) is approximately parallel to a line running from the left to right ear. The specimen width dimension (x-axis) is along the anterior-posterior axis (front to back).

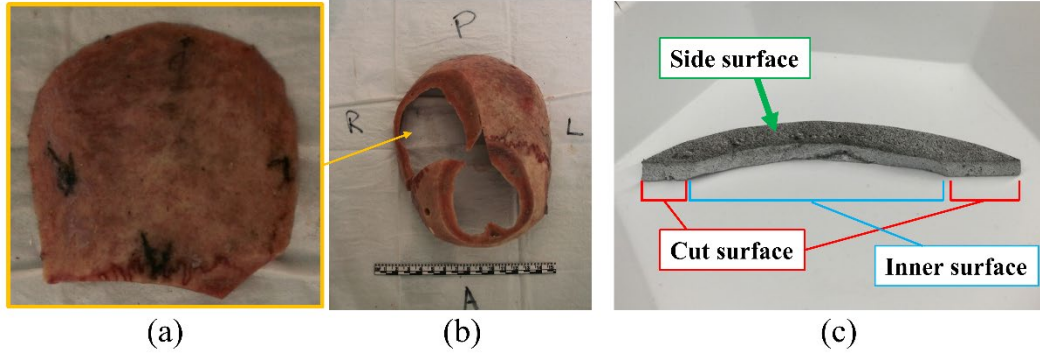


Fig. 1 (a) Skullcap used for skull-beam specimens cut from (b) donor PMHS upper skull and (c) skull-beam specimen cut from skullcap specimen including speckle pattern on side surface for DIC. Specimen B01 was closest to anterior (A), while B05 was farthest (P). Length of ruler in (b) is 15.2 cm.

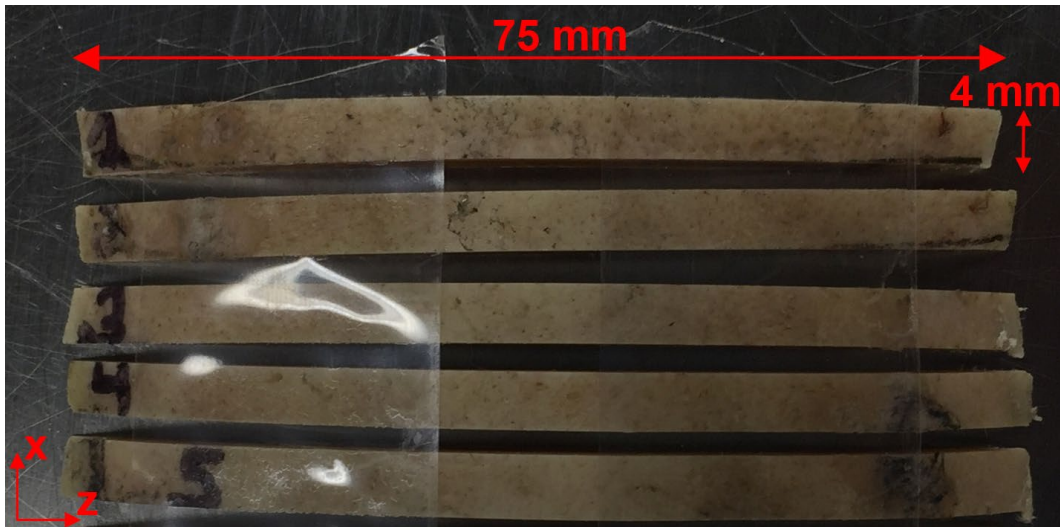


Fig. 2 Human skull-beam specimens cut from PMHS skullcap. Photograph is of the outer surface of the specimens (the surface closest to the skin in vivo). Specimens B01 through B05 begin at the top and move down. Each specimen is approximately 4 mm wide and 75 mm long.

All five specimens were similar in length and geometry, as they were all extracted from the same skull at the same location next to each other and are shown in Fig 2; B01 is at the top, B02 is second from the top, and so on. B01 is the most anterior of the skull-beam specimens and was the closest to the coronal suture, which separates the parietal and frontal skull bones. In the figure, there are two pieces of clear tape that were used to keep the specimens parallel as well as maintain a gap between them during micro-CT scanning.

These five specimens were used as they were approximately symmetric along the z-axis relative to the loading point. The distance between the inner and outer surfaces, normal to the top (skin-side) surface at the loading point, is referred to as

the specimen thickness (Fig. 3), while the distance between the loading point and the cut surface along an axis normal to the cut surface plane is referred to as the specimen height (Fig. 3). The specimen height and thickness for these specimens were 11.2–11.5 mm (0.453–0.441 inch) and 6.3–6.8 mm (0.248–0.268 inch), respectively. The specimen length was the total length of the specimen along the z-axis, while specimen span was taken as the specimen length along the z-axis where the specimen was not contacted by the base plate.

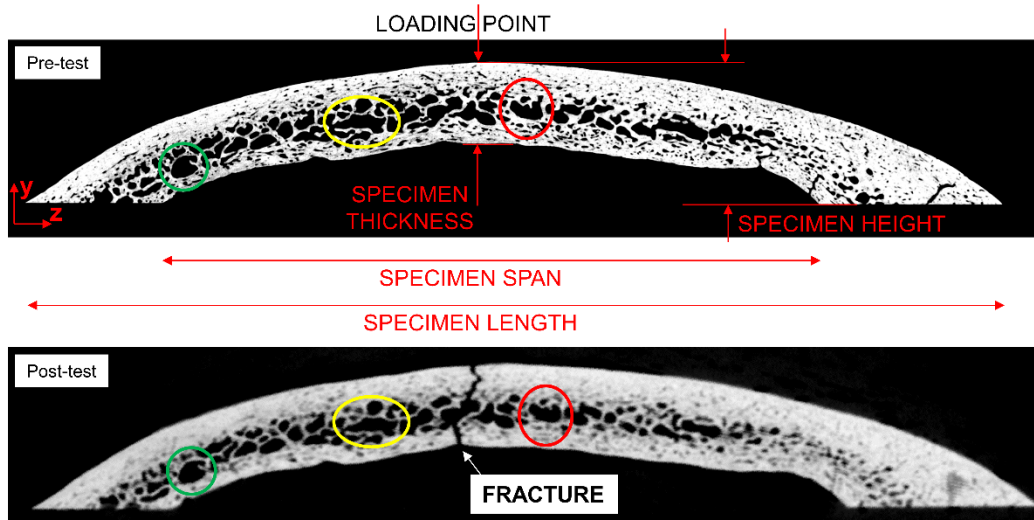


Fig. 3 Skull-beam specimen B03 micro-CT cross-section images (y-z plane) for pretest (top) and posttest (bottom), with labels for specimen measurements. Images have been binarized so that white represents bone. Colored circles indicate common features in both scans.

The specimens were stored frozen after fabrication. Prior to micro-CT scanning or mechanical testing, the specimens were thawed to room temperature and hydrated in Hank's Balanced Salt Solution (HBSS). For mechanical testing, the specimens were removed from HBSS and blotted dry to eliminate any fluid and allow for application of the speckle pattern.

2.2 Micro-Computed Tomography

The skull-beam specimen's geometry and microstructure were quantified prior to loading using a micro-CT scanner (Northstar XRD 1620), with isotropic voxel size of $27.1 \mu\text{m}^3$; X-ray source settings of 160 kV and 260 μA (41.6 W) with no filter were used for all specimens. The specimens were sealed inside a plastic container and wrapped in HBSS-saturated gauze to maintain hydration during micro-CT scanning. The micro-CT scan images were reconstructed into an image stack along the width dimension (x-axis). The specimens were also posttest scanned with the micro-CT scanner at voxel resolution of $66.5 \mu\text{m}^3$. Typical reconstructed cross-section images for specimen B03 are shown in Fig. 3, for both pretest and posttest scans. Several colored markers are used to illustrate common features in both scans,

indicating that they are showing the same cross section. Similar pictures for the other specimens are in the Appendix.

2.3 Bend Experiments

The five skull bend specimens were loaded in a three-point bend configuration using a loading tip. The loading tip contacted the specimen at the approximate center of the specimen span on the specimen outer surface; this is referred to as the loading point and corresponds to approximately the maximum specimen height. All five specimens were loaded to failure. Two different loading-tip geometries were used to understand what effect loading geometry had on specimen mechanical response, deformation, and failure behavior. Both were made of Al-7075. The first loading-tip geometry (Fig. 4, right), referred to as the blunt loading tip, was a half cylinder with diameter of 31.8 mm (1.25 inches) and tip curvature radius of 15.875 mm (0.625 inch). The second tip geometry (Fig. 4, left), referred to as the sharp loading tip, had a triangular prism geometry; the two sides tapered to the tip at 20° and the tip edge in contact with the specimen during loading had a very small curvature radius of 0.025 mm (0.001 inch). The two loading tips are shown in Fig. 4, along with geometry details. A steel base plate was used to support the specimen cut surfaces during loading; a thin layer of vacuum grease was used between the base plate and the specimen to reduce friction. A schematic of the experimental configuration, with the blunt loading tip, is shown in Fig. 5. The sharp loading tip had to be remachined after each use, as the experiment caused the loading tip to be slightly blunted.

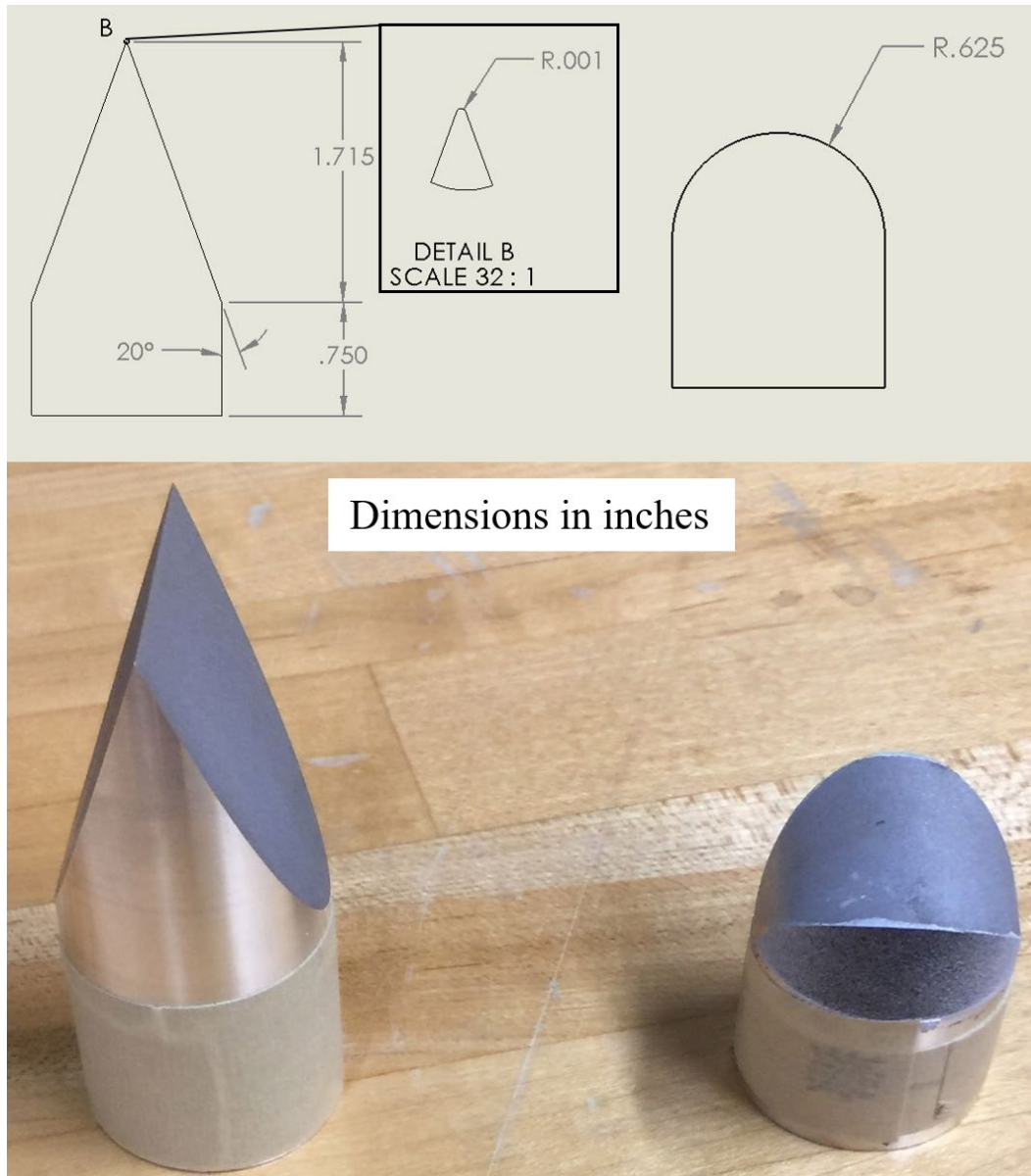


Fig. 4 Loading tips for skull bend experiments. The blunt loading tip (right) had a large curvature (15.875 mm), while the sharp loading tip (left) had very small tip curvature (0.025 mm, detail B). The cylindrical base for each loading tip had a diameter of 31.75 mm.

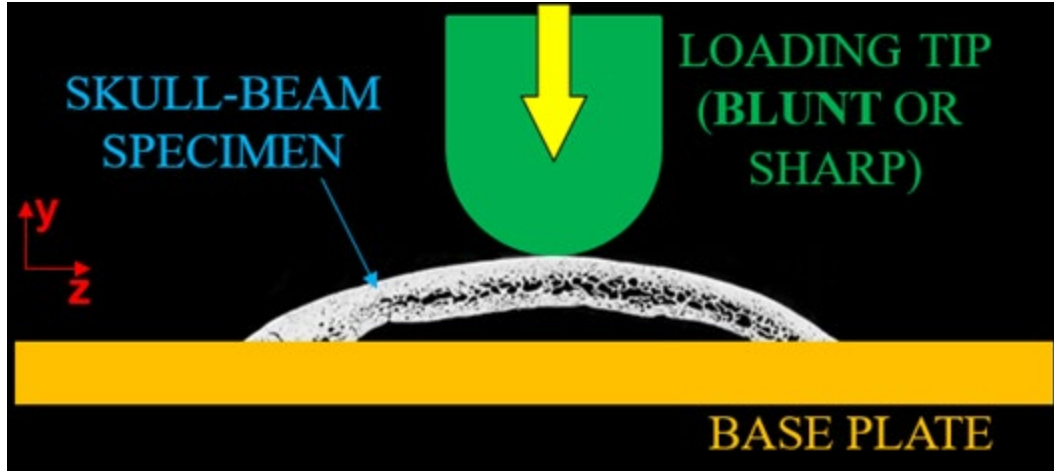


Fig. 5 Schematic of bend experiment loading. This example includes the blunt loading tip and a micro-CT image of Specimen B03.

It is necessary for the loading tip to be in contact with the specimen over the entire specimen width (which was defined as the x-axis in Fig. 2). A closeup of the high-rate experiment with blunt loading tip and specimen is shown in Fig. 6b, illustrating complete contact between loading tip and specimen across the specimen width. The specimen is not centered in the loading tip for imaging purposes; the specimen surface was closer to the loading-tip surface to prevent blurring of the specimen surface by the loading-tip surface for the loading point camera. This full-width contact condition was obtained for all five bend experiments.

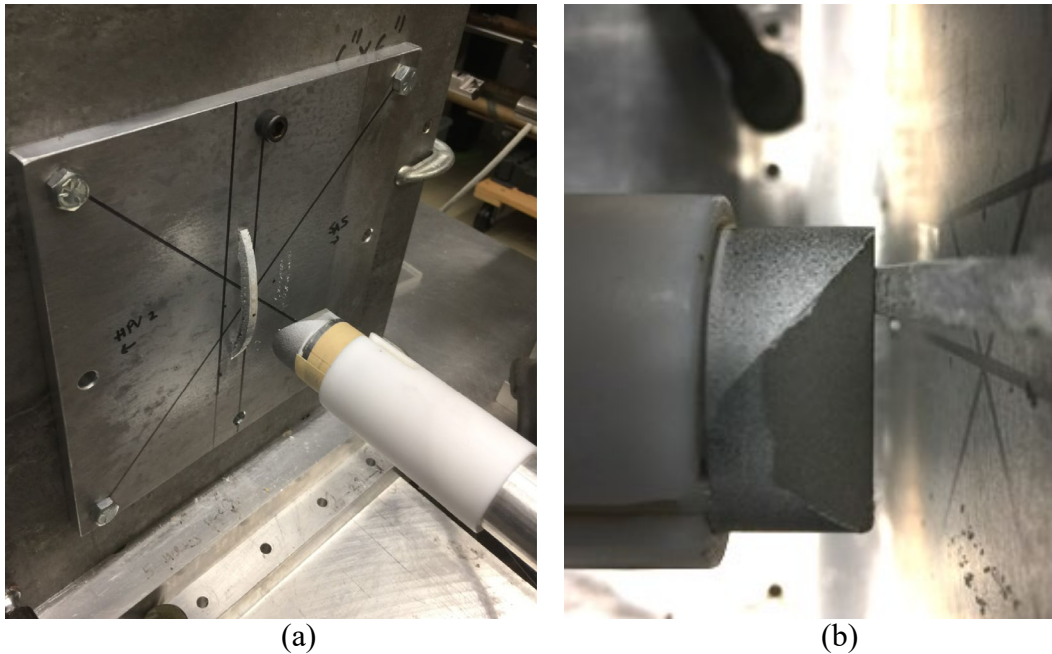


Fig. 6 High-rate experimental setup shown with blunt loading tip during experimental setup. (a) Prior to contacting the loading tip to the specimen. (b) Closeup showing contact of loading tip with the specimen prior to loading.

The two specimen side surfaces were imaged during loading. The imaging for one specimen side was focused at the loading point (LP) to give high spatial resolution of specimen deformation and strain; this camera is referred to as the LP camera. The imaging for the opposite specimen side captured the whole specimen (WS) surface and is referred to as the WS camera. DIC commercial software (Correlated Solutions Inc, VIC-2D) was used to postprocess the speckle images to create full-field strain and deformation measurements across the camera's area of interest (AOI). For the WS camera, this included the entire specimen side surface, as well as the loading tip and the base plate, while the LP camera contained AOIs on the specimen at the loading point and the loading tip. The DIC postprocessing parameters are summarized in Table 2.

Table 2 DIC analysis parameters

Spec. ID	Subset size (px)		Step size (px)		Subset area (mm ²)	
	LP camera	WS camera	LP camera	WS camera	LP camera	WS camera
B01	151	45	15	2	0.3965	0.8135
B02	15	9	1	1	1.5019	3.7721
B03	15	11	1	1	1.3092	6.1474
B04	151	43	15	2	0.4118	0.7755
B05	151	43	15	2	0.4295	0.7801

The bend experiments were performed on human skull specimens at two different loading rates, quasi-static and high rate, using both loading-tip geometries. The high-rate loading experiments were performed using a modified split Hopkinson pressure bar (SHPB) setup. The quasi-static rate loading experiments were performed using a standard test machine (Instron 8871).

2.3.1 High-Rate Experiments

Two high-rate bend experiments were performed, one for each of the loading-tip geometries. A modified SHPB setup was used, with an incident bar and the loading tip at the bar-specimen interface. The incident bar and loading tips were made of Al-7075, with a diameter of 31.75 mm (1.25 inches). The loading tip was attached to the incident bar using a plastic sleeve. Instead of a traditional transmission bar, the beam specimens were supported by the steel base plate, which was normal to the incident bar axis. Two high-speed cameras (Photron SA5, 100K fps, 128 × 376 pixel image size for the WS specimen surface and Shimadzu HPV2, 250,000 fps, 312 × 260 pixel image size for the LP specimen surface) recorded the specimen side surfaces during loading. Each camera also captured the loading-tip motion. The high-rate loading experimental setup is shown in Fig. 6a for the blunt

loading-tip specimen. Tape was used to hold the specimen in place on the base plate and was removed prior to loading.

2.3.2 Quasi-static Rate Experiments

Three quasi-static rate bend experiments were performed using a universal test machine (Instron 8871), with the loading tip connected directly to the machine actuator. Two experiments were performed with the blunt loading tip and one with the sharp loading tip. A pair of high-resolution framing cameras (FLIR, 12.3 MP) imaged both specimen surfaces during loading. All three quasi-static rate experiments were conducted at a constant displacement rate of 0.005 mm/s (0.012 in/min). The experimental setup is shown in Fig. 7.

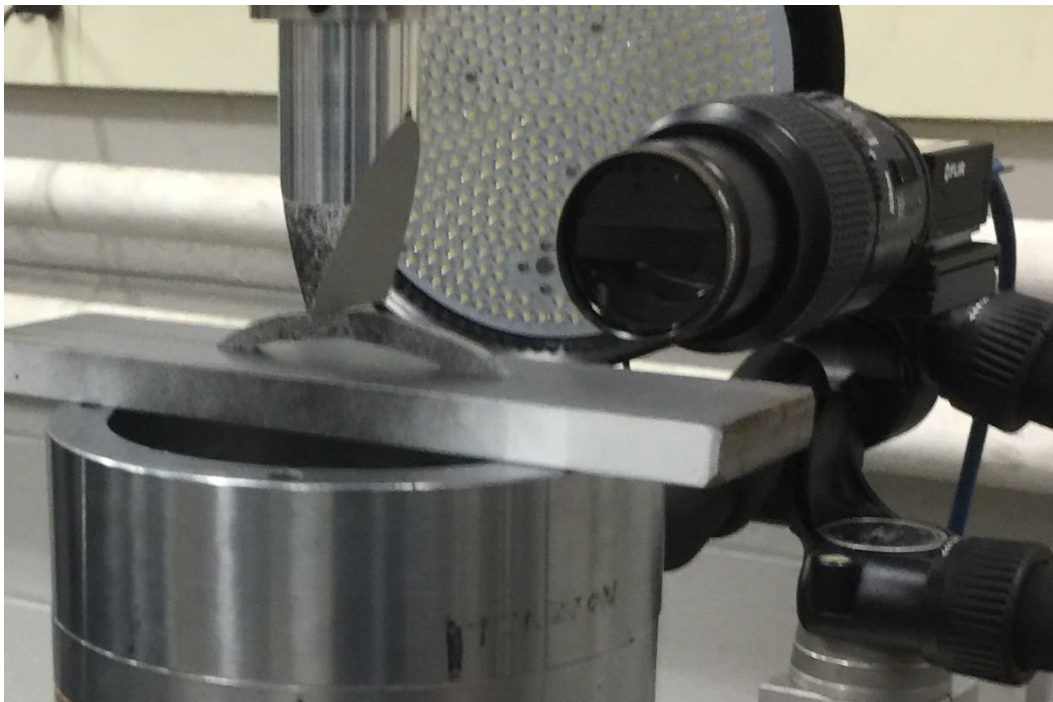


Fig. 7 Quasi-static rate experimental setup with sharp loading tip, second camera not shown

2.3.3 Experimental Setup Compliance and Specimen Apparent Stiffness

The loading-tip displacement was measured in two ways: using the test machine's internal extensometer and using optical measurement of the loading-tip displacement using 2-D DIC. Frequently, there is compliance of the loading train (fixtures, load cell, etc.) as they deform slightly, causing an error in the machine extensometer data. DIC was used to measure the actual loading-tip displacement to eliminate any error due to this compliance. A comparison of the loading-tip displacement, using both the machine extensometer and DIC of the loading tip, is shown in Fig. 8. For these experiments, the two measures were virtually identical.

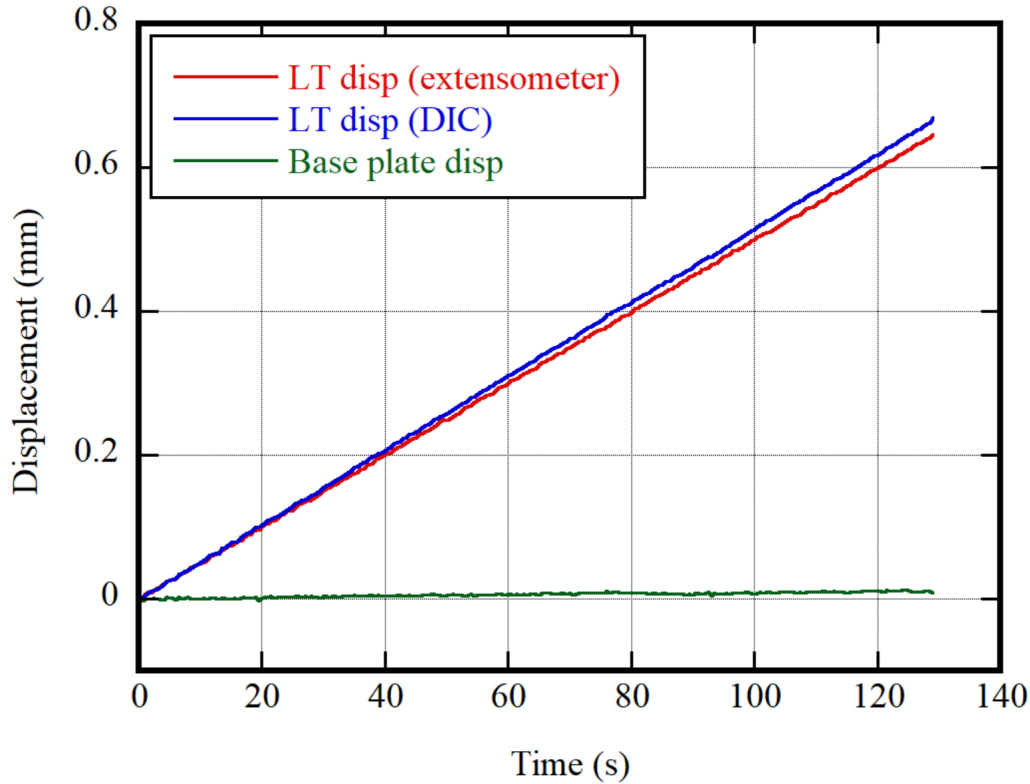


Fig. 8 Base plate displacement along loading axis and loading-tip (LT) displacement histories using DIC and machine extensometer for B01

In the quasi-static experiments, the steel base plate was placed across a hollow cylindrical fixture and could deform in the loading direction (Fig. 7). However, the amount of deformation of the steel plate was predicted to be negligible compared to the deformation of the bone. The region of the plate under the specimen was speckled and imaged with the WS camera during loading to determine if the base plate could be approximated as perfectly rigid or experienced deformation (compliance). DIC analysis of the base plate indicated that it deformed minimally (Fig. 8). Therefore, no correction to the loading-tip displacement due to base plate deformation is necessary. In the high-rate experiments, the base plate was well supported by a solid frame and was therefore also approximated as perfectly rigid.

Deformation of the loading tip was also evaluated, visually and using DIC. The blunt loading tip experienced minimal deformation and was assumed to be rigid. The sharp loading tip was observed to blunt slightly during loading approximately 0.01–0.03 mm; this was quantified after loading using a caliper to measure total indenter length at two locations: where the specimen contacted the loading tip and where there was no specimen contact. This required remachining of the tip after each loading to ensure consistent loading-tip geometry but was negligible considering the displacement measurement, which was 0.6–1.0 mm.

The apparent stiffness for each specimen was calculated by applying a linear fit to the initial portion of the specimen load as a function of loading-tip displacement data. This apparent stiffness represents an approximation of the structural stiffness of the skull-beam specimen. For these experiments, the initial linear loading history was used to determine apparent stiffness, between approximately 50 and 100 N for the quasi-static loading rate and 0.5 kN to maximum load for the high loading rate.

3. Results

The load-displacement response and specimen failure for the high-rate and quasi-static experiments are presented in Sections 3.1 and 3.2, respectively, and are summarized in Table 3. Section 3.4 describes how an approximate strain-rate was determined for each experiment. The Appendix contains experimental images from the timestep just prior to failure (referred to as the pre-fracture image) and just after failure (referred to as the post-fracture image). The post-fracture images have the failure location marked.

Table 3 Experimental results summary for all bend experiments

Spec. ID	Loading rate type	Loading tip	Failure load (kN)	Loading rate (kN/s)	Disp to failure (mm)	Disp rate (mm/s)	Apparent stiffness ^a (kN/mm)	Strain-rate ^b (/s)	
								LP Camera	WS Camera
B01	Quasi-static	Blunt	0.1377	0.0014	0.603	0.005	0.283	0.00045	0.00019
B02	High	Blunt	1.498	4302.6	0.92	3558.5	1.283	517	612
B03	High	Sharp	0.840	NA ^c	0.66	3386.4	NA ^c	459	578
B04	Quasi-static	Sharp	0.2204	0.0018	0.889	0.005	0.355	0.00020	0.00036
B05	Quasi-static	Blunt	0.1508	0.0017	0.6755	0.005	0.344	0.00009	0.00011

^a See Section 2.4.3 for details on calculation of apparent stiffness.

^b Strain-rate is approximate. Details on calculation provided in Section 3.3.

^c For Specimen B03, there were too many oscillations to determine a loading rate and apparent stiffness.

3.1 High-Rate Experiments

Two skull-beam specimens were loaded at high rate using a modified SHPB setup, one with each loading tip. Both specimens exhibited brittle mechanical response, with the load generally increasing to failure. There was little to no permanent deformation around the loading point, such as denting or cupping, and the specimen height was approximately unchanged prior to fracture.

The load vs. loading-tip displacement for both high-rate experiments is shown in Fig. 9. For both, the load fluctuated as it increased to a maximum (failure) load before the catastrophic load drop, corresponding to sudden (unstable) fracture of

the specimen into two pieces. The oscillations in the load data prior to the failure load are most likely related to measurement noise and are likely not indicative of actual load decreases experienced by the specimen. This noise is associated with the small signal-to-noise ratio of a large diameter bar, and the large mismatch in impedance between specimen and loading tip, which caused the incident and reflected signals to be very similar. The failure load for the blunt geometry experiment was lower than the sharper geometry experiment, and the displacement to failure load was larger.

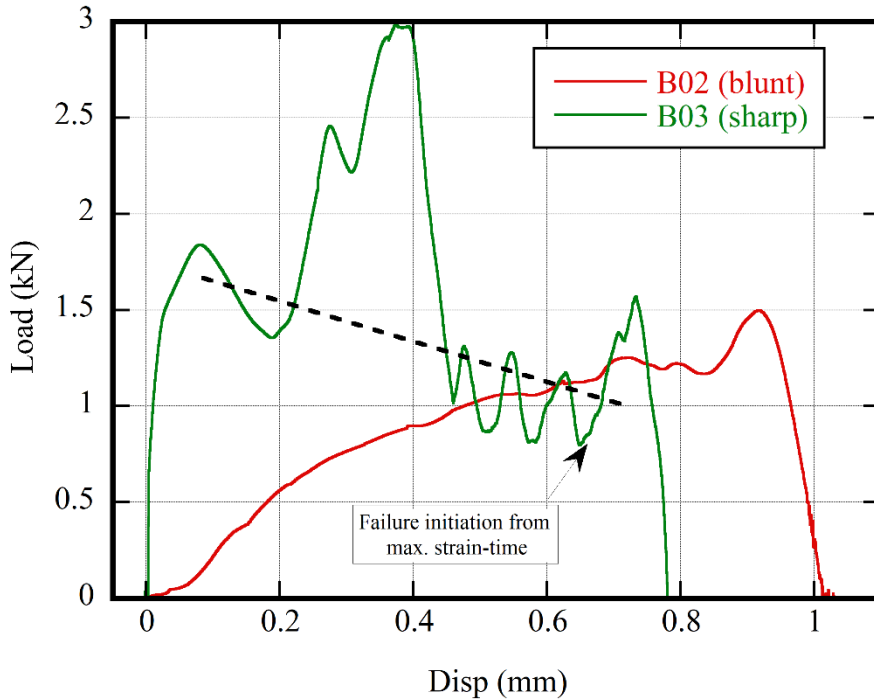


Fig. 9 Load vs. displacement for high-rate experiments. The failure initiation point for B03 is marked. This point is identified later (see Fig. 12) from analysis of the strain-time response. Dashed line shows the trend for the B03 response, disregarding the oscillations.

In B03, the fracture clearly initiated at the inner table and propagated toward the outer table. This fracture sequence is seen in the time series images from the LP camera, as shown in Fig. 10. However, no such conclusion could be made for B02 from the experimental images, as presented in the Appendix. For this specimen, the WS camera was too zoomed out to clearly visualize the crack. In the LP camera, the crack is seen at a large pore pointed in the direction of the loading point and the outer table. However, because the pore is positioned at the bottom of the images, it is not discernable whether there was also a crack going from the inner table to the pore, or if the crack initiated at the pore itself.

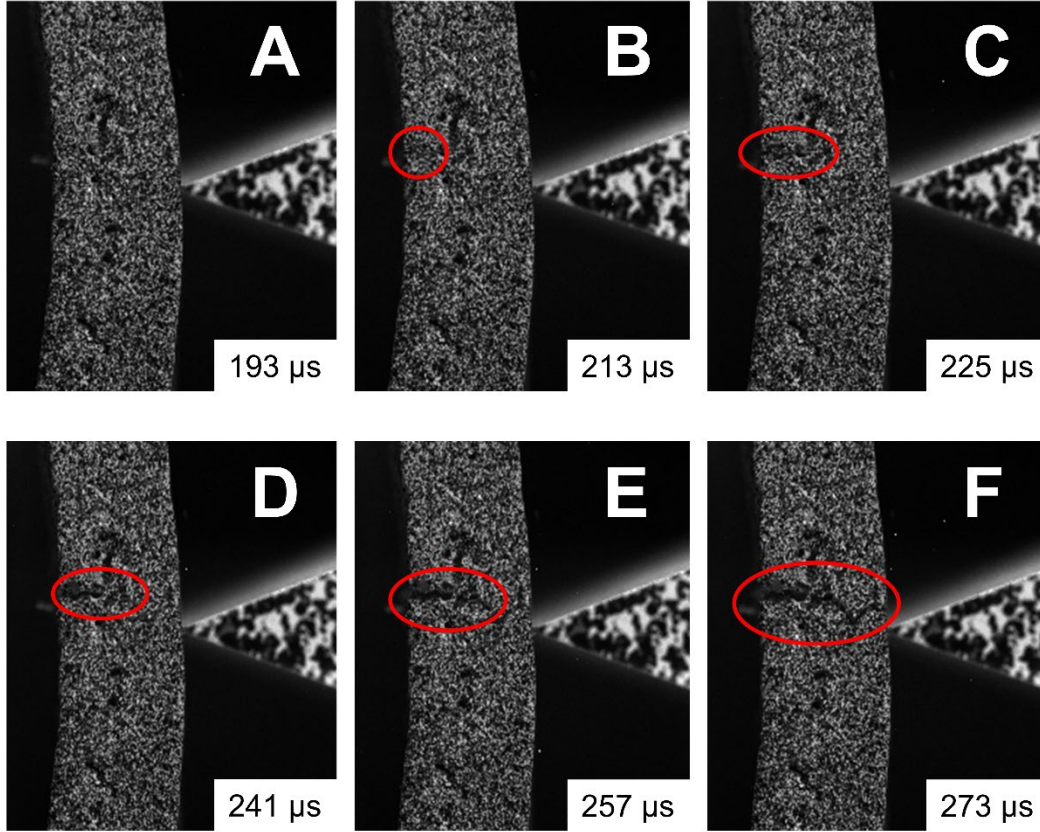


Fig. 10 Time series of LP camera images from B03 before and during fracture. Time stamps on the images are elapsed time from the start of the specimen loading, which is taken as 0 μ s. Labels A-F are noted on the load-time curve in Fig. 12.

3.2 Quasi-static Rate Experiments

The load versus loading-tip displacement for the three quasi-static rate experiments is shown in Fig. 11. The load increased to a maximum (failure) load and then experienced sudden failure and broke into two pieces. The failure loads for the two blunt geometry experiments were very similar and lower than the sharp geometry experiment. The location of fracture initiation and the direction of fracture growth could not be determined because the specimen fractured between the pre-fracture and post-fracture images.

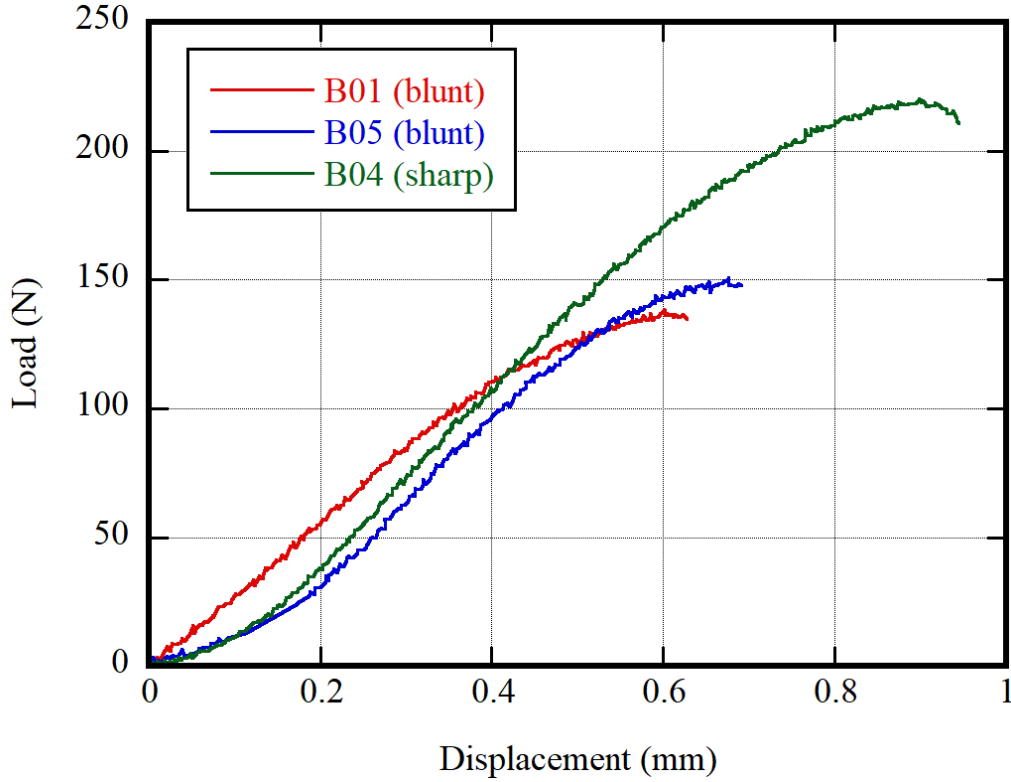


Fig. 11 Load vs. displacement for quasi-static rate experiments

3.3 Strain-Rate Approximation

The maximum principal strain was obtained for each camera image from the DIC strain profiles. The Lagrange strain tensor and the default filter size of 15 were used. Then, the maximum principal strain was plotted as a function of time, and a linear fit provided an estimate of the strain-rate during loading. The strain-rates provided here represent a conservative estimate; the actual strain-rate is likely larger, since the maximum principal strain can change based on DIC postprocessing parameters (discussed in Section 4.4).

The maximum principal strain for both cameras is shown, along with load, as a function of time in Fig. 12 for specimen B03 as an example. The max strain increased approximately linearly during loading until failure, after which the strain and strain-rate increased dramatically (Fig. 12, dotted lines). A linear fit to the data strain history before the failure provided an estimation of the strain-rate. The intersection of the before failure and after failure response is taken as the failure point and shown in Figs. 9 and 12. The strain-rates obtained for all five experiments were similar for both cameras and were tabulated in Table 1.

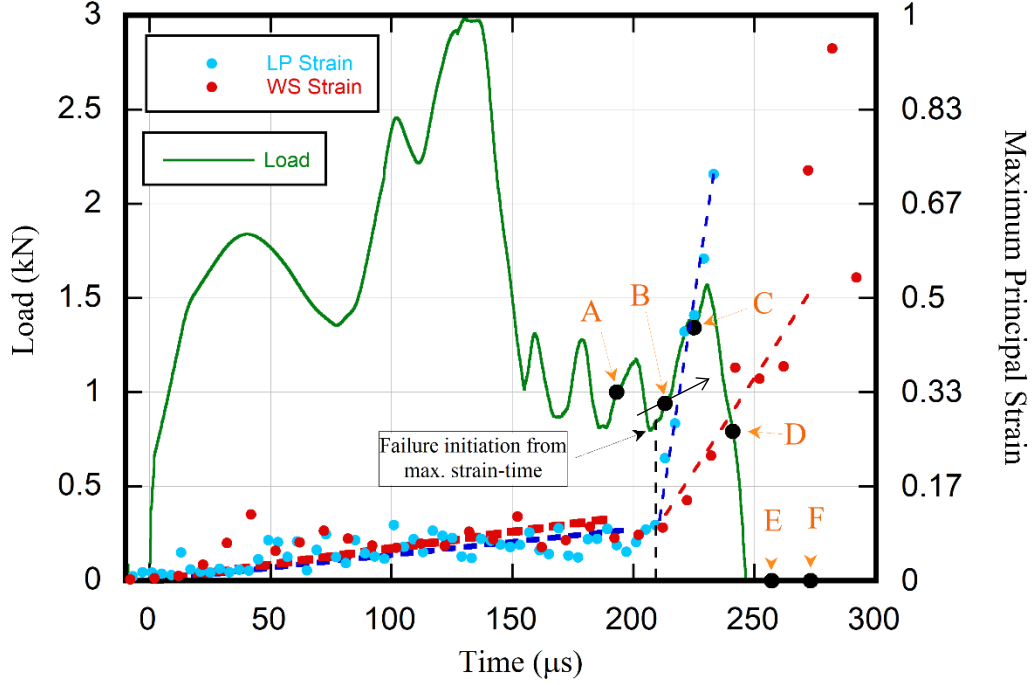


Fig. 12 Load-time and strain-time response for B03. Strain data points are the maximum principal strain for each DIC image taken during loading from both the LP camera (blue) and WS camera (red). Strain-time response was bilinear, as indicated by the colored dashed lines. The time at which the strain-time response increased dramatically was the failure initiation point, indicated by the vertical dotted line. Labels A-F indicate the time points for the experimental images shown in Fig. 10.

4. Discussion and Limitations

This study characterized the mechanical response of human skull to bend loading as a function of loading rate and loading geometry. The results obtained from this study will be used to implement skull deformation mechanisms into finite element models as well as providing a simulation validation data set for models developed to represent human skull. Computational limitations restrict the amount of detail, such as pore structure, that can be accurately represented in a full head and head protection model. As a result, solid elements often represent portions of the skull that are porous. Therefore, it is important to utilize microstructurally inspired material models for these elements, which intrinsically account for the porous nature of skull, to improve the biofidelity of the model over simply using parameters derived for pure bone. Thompson et al. (2016) recently demonstrated that modeling the Gottingen minipig skull with a 10-layer system, using experimentally determined material properties for each layer, made a significant difference on the peak pressure experienced in the brain during simulations of head impact. However, it may not be feasible to incorporate multilayer models in large-

scale simulations; therefore, it is important to have models that are validated to represent the skull as a structure.

The response of human skull to bend loading reported here was performed on specimens obtained from a single skull, and therefore is not representative of all human skulls. In addition, the donor skull was acquired from an elderly PMHS, and therefore may not be representative of the mechanical response of a military service age relevant human skull.

4.1 Loading Rate Effects on Bone

The dataset here is based on a limited number of samples, so drawing definitive conclusions about the effect of loading rate for all human skulls is not possible. However, for this small dataset, it appears that the loading rate has a strong influence on both failure load and apparent stiffness for human skull in bending. Figure 13 shows the failure load (a) and apparent stiffness (b) as a function of loading rate for both loading geometries. Verschueren et al. (2006) reported a similar rate effect, with modulus and bend strength increasing with increasing loading rate, although their range of loading rates was much smaller (3 orders of magnitude compared with the 6 covered here).

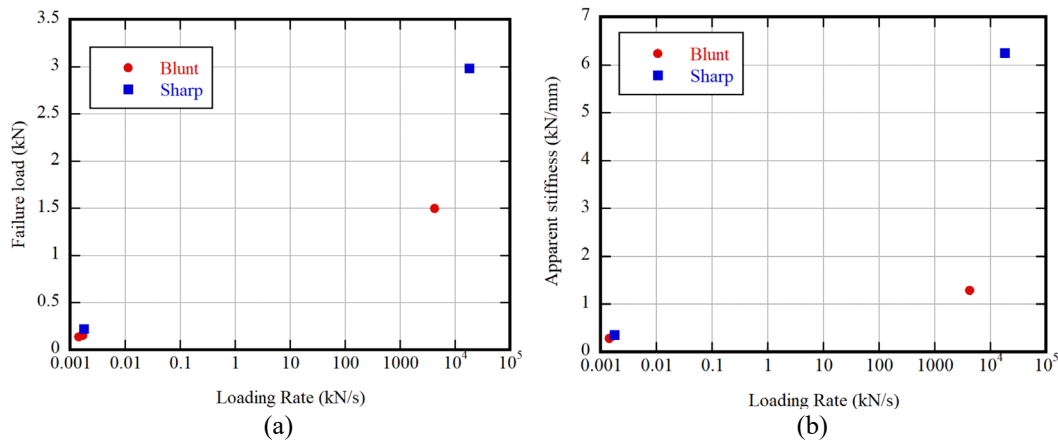


Fig. 13 (a) Failure load and (b) apparent stiffness as a function of loading rate. The failure load and apparent stiffness for the sharp high-rate experiment have high uncertainty due to oscillations.

Other research on the bending response of human skull has indicated similar ranges of results for the full thickness of human skull in three-point bend. While differences in specimen structure, geometry, and morphology do not allow for direct comparison, their results suggest that the results reported here are reasonable. Motherway et al. (2009) conducted three-point bend experiments on adult human skull at three velocities between 0.5 and 2.5 m/s. That study reported failure loads

at the 2.5 m/s velocity of 1300–1800 N. Rahmoun et al. (2014) conducted quasi-static (10 mm/min) three-point bend experiments on adult human skull. They, inexplicably, did not report failure loads; however, they did report an average apparent stiffness of approximately 500 N/mm for 7-mm-wide specimens, which suggests that the approximately 300 N/mm reported here for 4-mm-wide specimens at quasi-static rate is reasonable. Delille et al. (2007) conducted three-point bend experiments at a quasi-static (also 10 mm/min) loading rate on adult human skull. They reported a wide range of failure loads from 200 to 1800 N, with an average of about 900 N for 14-mm-wide specimens; this range suggests that the 170-N average reported here at the quasi-static loading for 4-mm-wide specimens is reasonable.

Research on the compressive response of human skull has observed similar loading or strain-rate effects. Karkar et al. (2018) performed quasi-static and high-rate compression experiments on formalin preserved elderly (79–86 years) adult human skull. They reported a significant increase in modulus as the strain-rate increased from quasi-static to high. Zhai et al. (2020) performed compression experiments on fresh frozen adult (70–74 years) human skull at three different strain-rates, including high-rate (625/s), and two orientations, radial (thru-thickness) and tangential (in-plane). They found significant increases in elastic modulus and strength as strain-rate increased.

4.2 Loading Geometry Effect

The dataset here is based on a limited number of samples, so drawing definitive conclusions about the effect of loading geometry is not possible. In these experiments, the specimens loaded with the sharp loading tip (B03, B04) had failure localized close to the loading tip, while the specimens loaded with the blunt loading tip (B01, B02, B05) all had failure localized at a large pore farther away from the loading tip. This can be observed in the WS and LP post-fracture images of the Appendix. The sharp loading-tip specimens appeared to have similar large pores in the area of the loading point, suggesting this effect was not due to a randomized absence of large pores in those two specimens. This suggests there was a failure localization effect based on the loading geometry, although the small sample size limits the strength of this conclusion. Delille et al. (2007) loaded 380 human skull specimens in three-point bending at a quasi-static rate (0.17 mm/s) using a relatively blunt loading tip (2.5-mm radius of curvature) and reported that failure initiated at pores on the inner surface away from the loading tip in only about 6% of the experiments. For the remaining specimens, failure was through the center of the specimen near the loading tip.

In the present study, the effect of the loading geometry on the failure load was unclear. At quasi-static rate, the loading geometry appeared to have had an effect on the failure load, which was higher for the sharp loading tip. However, this effect was not observed at high-rate. There are at least two possible explanations why the failure load was higher for the sharp loading tip in the quasi-static experiments. One explanation could be that the specimens loaded with the blunt loading tip failed at large pores where the strain was concentrated, as noted previously, which could have caused lower failure loads. In addition, the sharp loading tip may not have been sharp enough to induce the shearing failure mechanism, which would have reduced the failure load.

Specimen response was relatively brittle for both geometries, with linear load increase preceding a sudden specimen failure. Significant local deformation, denting, or cupping of the specimen at the loading point was not observed for either loading geometry.

4.3 Specimen Fracture

The location of fracture initiation and the direction of propagation were only clearly observed in B03 (Fig. 10), which was a high-rate experiment. Fracture initiation could not be discerned in the images from the other high-rate experiment (B02), as detailed in Section 3.1. For the quasi-static experiments, the specimen fractured during the time elapsed between the images.

4.4 Limitations in Analyzing the Full-Field Surface Strain Profiles

Nonuniform, discontinuous specimens subjected to a nonuniform stress state, such as the experiments documented here, will produce strain distributions that are nonuniform. Strain gradients will occur around microstructural features such as voids that produce stress concentrations. Optical measurements of strain in specimens that contain strain gradients are sensitive to DIC analysis settings, such as subset size and step size (Jones and Iadicola 2018). Subset size dictates the area over which DIC performs spatial averaging; larger subset sizes produce strain data averaged over a larger area. This has the effect of decreasing the magnitude of strain in areas that have strain gradients, if the subset size is not small enough. If the strain magnitude increases as the subset size decreases, it is likely that the DIC analysis may not be capturing the highest magnitude strain.

Here, the strain data for both cameras showed subset size dependence. Figure 14 shows two strain profiles for the LP camera of B01 at the time point just prior to failure, using two different subset sizes (73 and 15 pixel). The strain distribution

and areas of strain localization across the specimen are similar; however, the strain magnitudes for the large subset profile (Fig. 14a) are lower than the small subset profile (Fig. 14b). The strain magnitude color map scale is the same for both profiles.

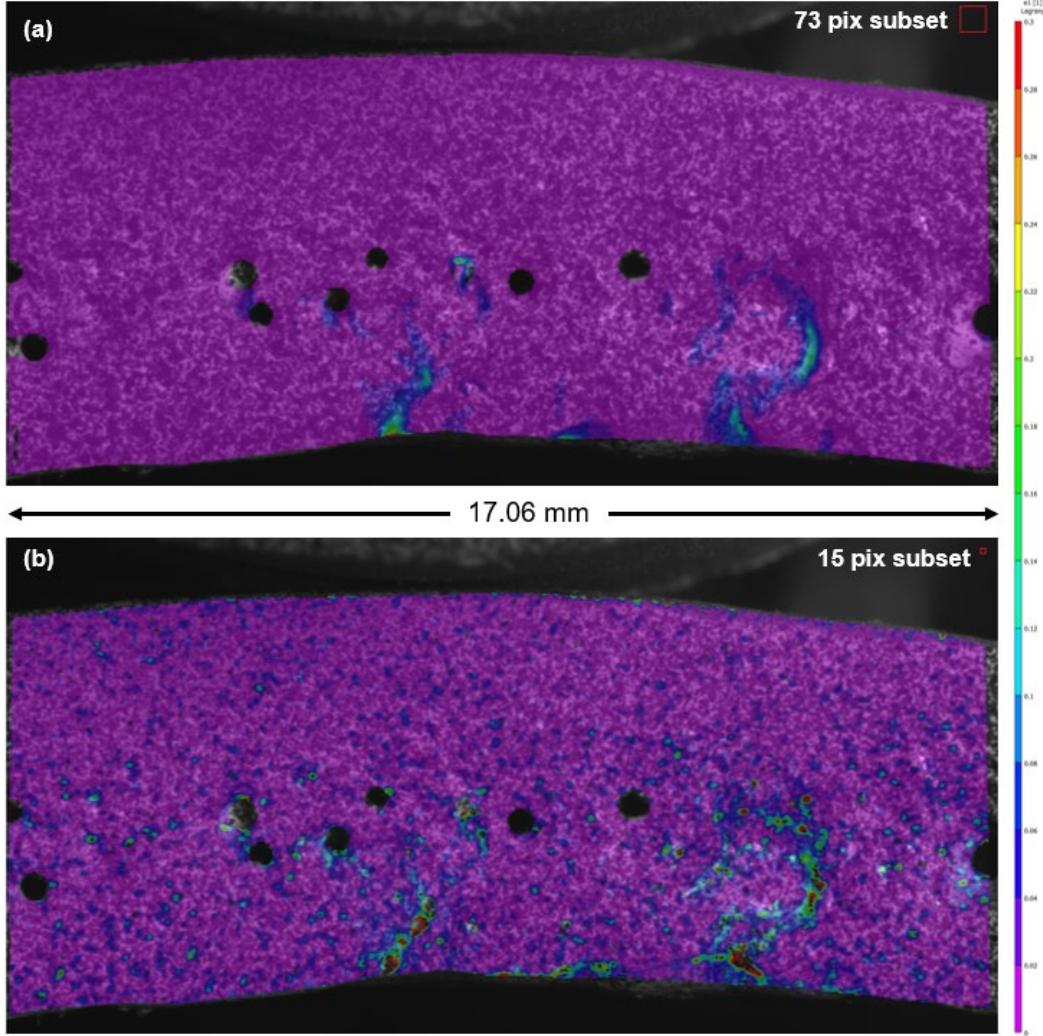


Fig. 14 Surface strain profiles obtained for the LP camera of B01 at the time point just prior to failure using two different DIC subset sizes: (a) 73 pixel (0.304 mm) and (b) 15 pixel (0.0625 mm). The strain color map scale is the same (0.00 bottom/light purple - 0.30 top/red) for both profiles. The pixel to millimeter ratio is 0.004166 mm/pixel. Red boxes in the upper-right corners of the figure show the subset size.

Therefore, the strain profiles reported here may not represent the maximum strain experienced by the specimen, and it is possible that larger strain magnitudes exist, such as around the sharp curves, pore edges, or trabecular structure of the skull. However, these strain profiles provide a comparison tool to evaluate the results of computational simulation of these experiments. It is important to ensure that similar spatial averaging is being performed in the simulation to obtain a meaningful

“apples to apples” comparison. This may be done by controlling subset and mesh size so that both are similar.

The strain profiles in the Appendix for each experiment show similar strain distribution and magnitudes across both cameras, with strain concentration at approximately the same locations. This suggests that the strain field is approximately constant through the specimen width.

4.5 Rate Limitations

The indenter tip velocities used here for high-rate are lower than typical BHBT events, so it is likely that the high loading rates are lower than experienced by the skull during a BHBT event; the apparent stiffness and failure loads reported here at high-rate may not be representative of the skull mechanical response during BHBT events.

4.6 Effect of Irradiation Absorption on Bone

The skullcap bone specimens used here for blunt indentation loading experiments were first scanned using micro-CT to understand their structure and orientation. The micro-CT process causes the bone to absorb a radiation dosage during exposure to the X-ray beam in the micro-CT. There are studies that suggest irradiation exposure may alter the mechanical properties of bone due to degradatory effects on the collagen (Anderson et al. 1992; Hamer et al. 1996; Currey et al. 1997; Cornu et al. 2000; Vastel et al. 2004; Barth et al. 2010, 2011). Specifically, irradiation causes radiolysis of water, which can induce collagen cross-linking, decreasing plasticity and increasing brittleness (Colwell et al. 1996). Most studies report a significant effect from irradiation dosage on the plastic collagen material properties with negligible effect on elastic properties. Barth et al. (2010) reported significant reduction in bending strength, plasticity, and fracture toughness in human cortical bone with increasing irradiation dosage, but no effect on bending stiffness. Currey et al. (1997) reported significant decreases in bending strength, work to fracture, and impact energy absorption with increasing irradiation dosage in human bone; however, the elastic modulus was unchanged. These studies have concerned the X-ray exposure of bone in high-power X-ray equipment, such as a synchrotron, with irradiation dosages of approximately 10^2 – 10^3 kGy. However, the irradiation dosages that bone specimens receive in low-power micro-CT scanning ($\sim 10^{-1}$ – 10^0 kGy) are typically well below the dosages shown to cause degradation of plastic mechanical properties in human bone (Gunnarsson et al. 2018).

5. Conclusions

The mechanical response of human skull to three-point bend loading was quantified as a function of loading rate and loading tip-geometry. Loading rates differed by approximately 6 orders of magnitude between quasi-static (~ 0.005 mm/s) and high-rate ($\sim 3,000$ mm/s). The effects of loading-tip geometry were quantified by changing the radius of curvature by approximately 3 orders of magnitude between the blunt and sharp indenters. Micro-CT imaging with a voxel resolution of approximately $25\text{ }\mu\text{m}^3$ was used to quantify the skull structure prior to loading. Damage initiation and subsequent propagation were identified by observing micro and macro cracks, and comparing the pre and post scan images. In-situ optical DIC methods were used to measure the full-field deformation of the skull during loading, which enabled visualization of how failure occurs inside the skull during loading.

Failure generally occurred in the inner table or lower diploe at locations of large pores. Experimental images confirmed that fracture initiated at the inner table in one of the experiments, although fracture may have also initiated at the inner table for some of the other experiments.

Increasing the loading rate by approximately 6 orders of magnitude increased both the failure load by about 600% and apparent stiffness by about 300%. The effect of increasing the sharpness of the loading tip (decreasing the radius of curvature) was not as clear. At quasi-static loading rate, using the sharp indenter increased the failure load by 53% and the apparent stiffness by 15% relative to the blunt indenter. At high-rate, the failure load decreased using the sharp indenter compared to the blunt indenter.

The loading-tip effect at quasi-static rate was unexpected and could indicate that the sharp loading tip was not sharp enough to induce the shear failure mechanism. The unexpected loading-tip effect could also have also been connected with the phenomenon observed in this study that the experiments with blunt loading tip failed at large pores where the strain was concentrated. Failure at large pores rather than near the center of loading could be indicative that failure in these specimens was premature with lower failure loads and underlines the microstructural-dependence of the mechanical response of the skull.

The experimental results reported here provide a unique dataset allowing for incorporation of fracture initiation mechanisms into computer models, and subsequent validation of these models, improving the injury predictive capability through computer simulations of head impact.

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**Appendix. Camera Images from Experiments and Pre- and
Posttest Micro-CT Images for Each Specimen**

Contained within are images from the whole specimen (WS) and loading point (LP) cameras taken during the experiments at time points just prior and just after fracture, referred to as pre-fracture and post-fracture, respectively. The two cameras are looking at opposite sides; for the quasi-static rate experiments, the left side of the LP profile corresponds to the right side of the WS profile, and vice versa. For the high-rate experiments, the indenter tip is visible in the image at the right for the LP profile and at the left for the WS profile; the top to bottom orientation is the same for both cameras.

The pre-fracture images include the principal strain (ϵ_1) contours derived from digital image correlation (DIC) analysis, with the parameters that were listed in Table 1. The strain scales vary among the different experiments; however, the scales are the same for both cameras of the same experiment. In the post-fracture images, a red circle has been added to indicate the location of the fracture.

This appendix also contains micro-CT images of the specimen taken prior to the experiment (pretest) and after the experiment (posttest). The micro-CT technique was described in Section 2.2. The micro-CT images provided here are cross-sectional images that have been binarized so that white represents bone. Microstructural features present in both the pre- and posttest images are identified with color-coded circles. These common microstructural features verify that the pre- and posttest images are at approximately the same cross section within the specimen.

A.1 Quasi-static Rate, Blunt Loading Tip (B01)

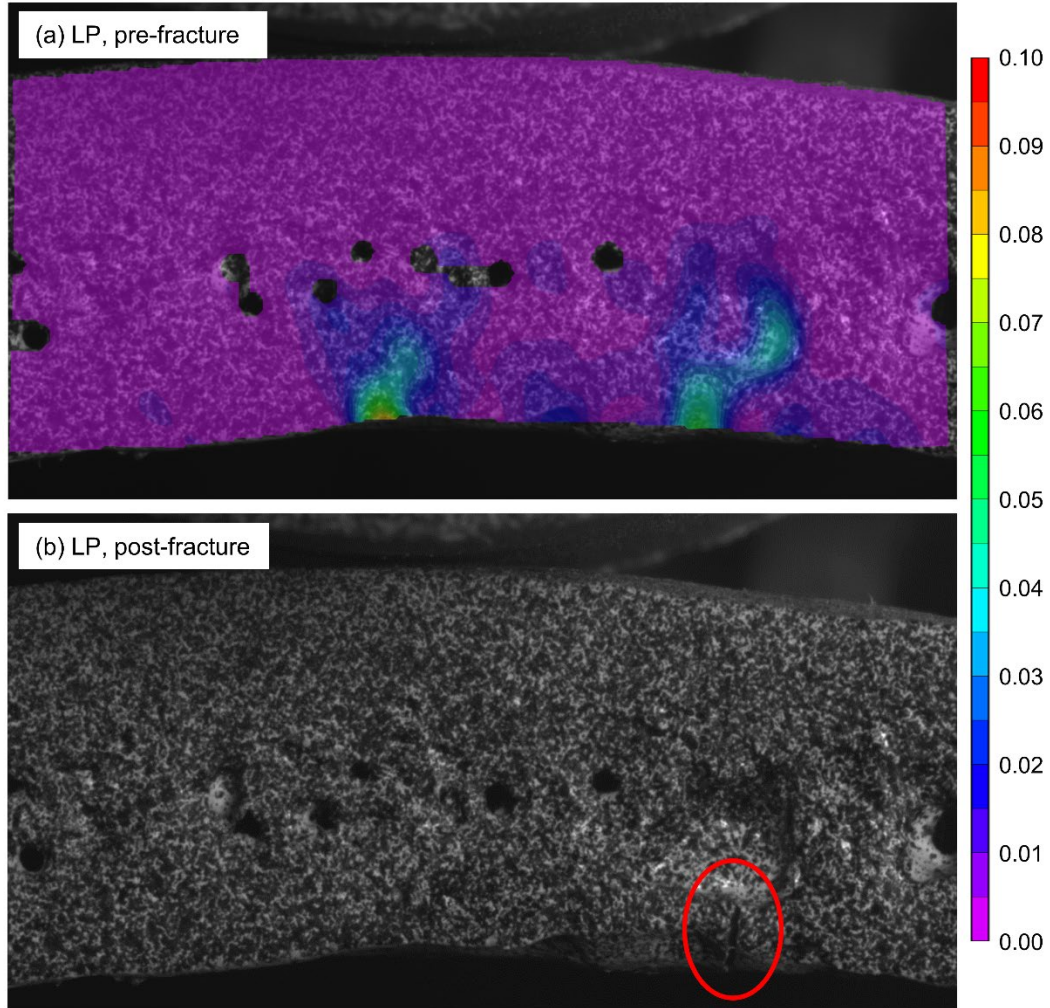


Fig. A-1 Images from the LP camera for B01 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

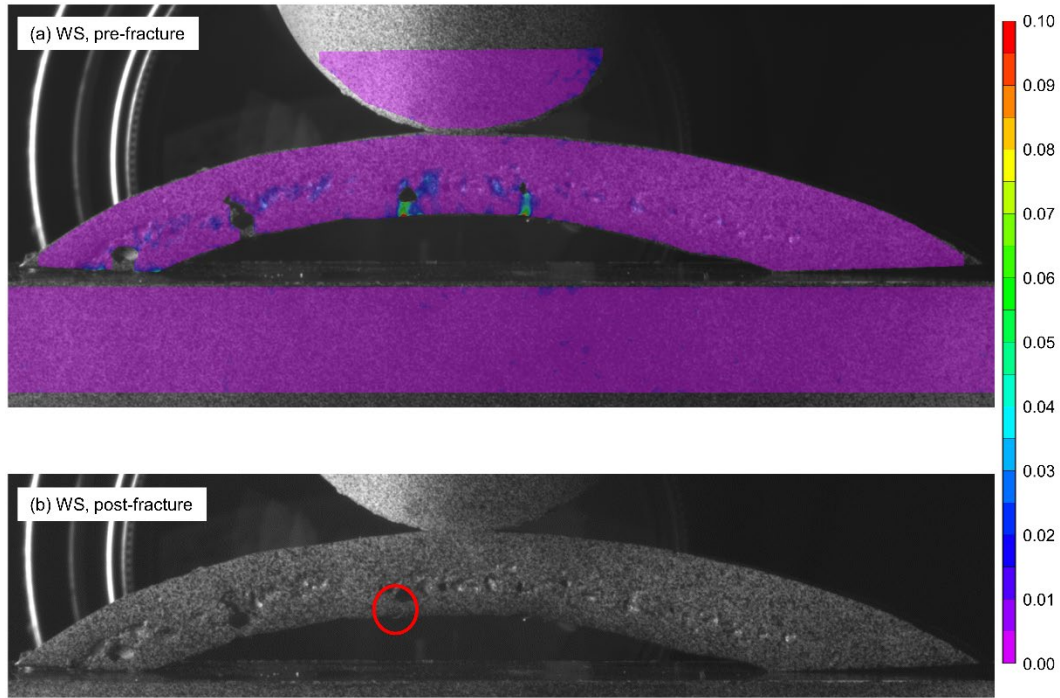


Fig. A-2 Images from the WS camera for B01 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

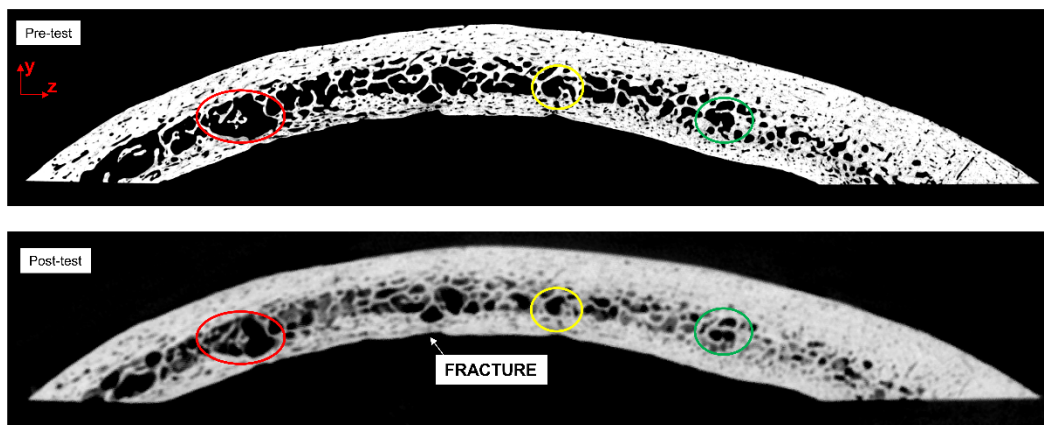


Fig. A-3 Micro-CT images of B01 before (top) and after (bottom) the experiment

A.2 Quasi-static Rate, Blunt Loading Tip (B05)

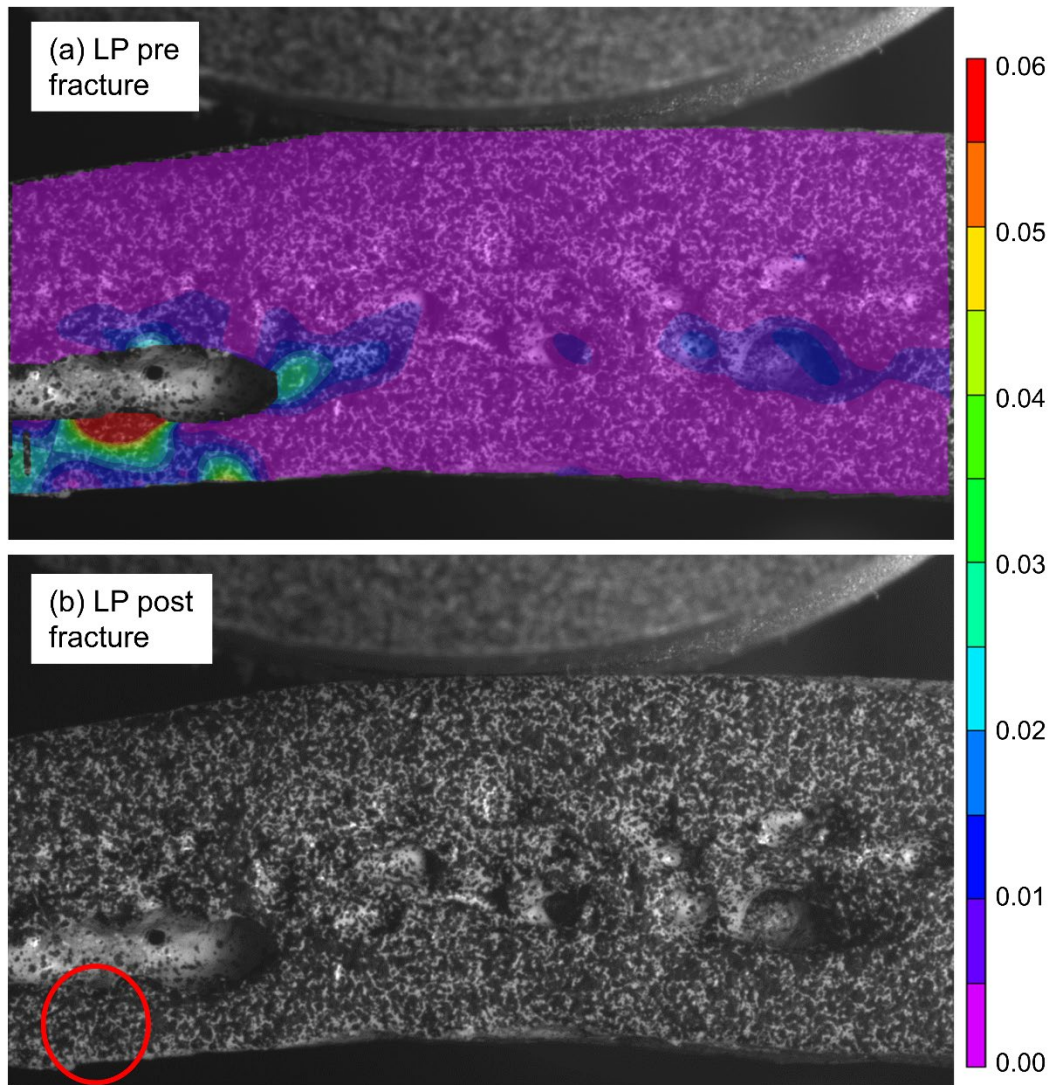


Fig. A-4 Images from the LP camera for B05 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

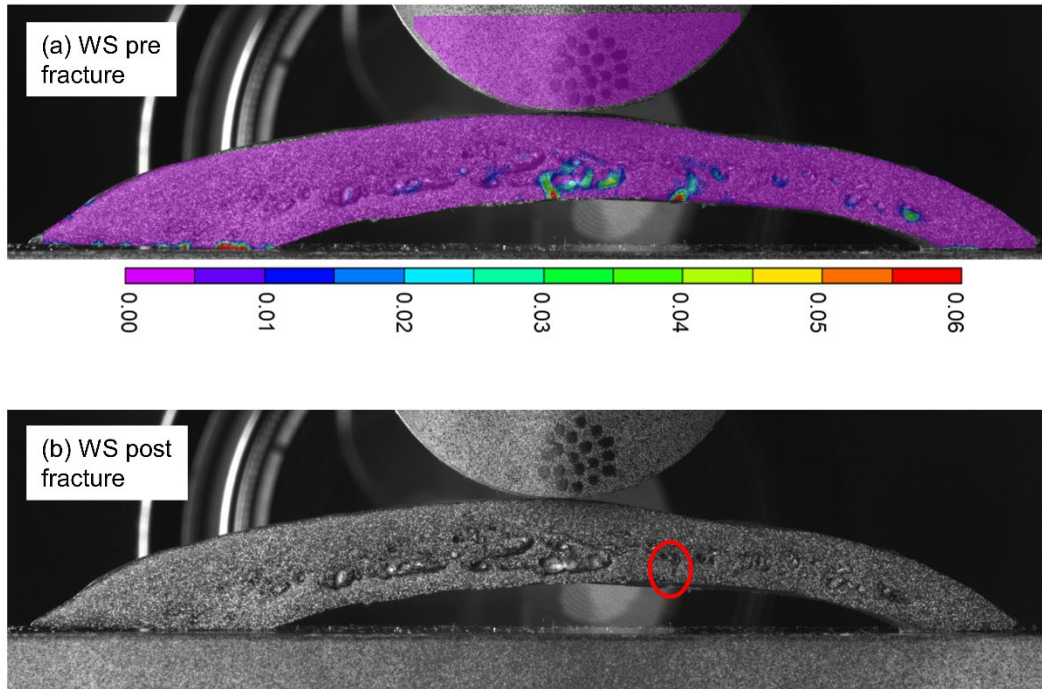


Fig. A-5 Images from the WS camera for B05 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided below. Post-fracture image (b) includes red circle indicating location of fracture.

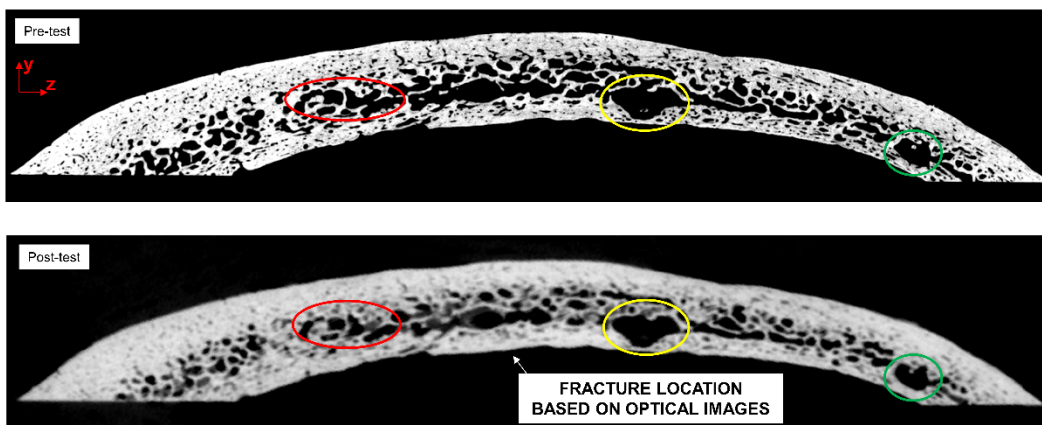


Fig. A-6 Micro-CT images of B05 before (top) and after (bottom) the experiment

A.3 Quasi-static Rate, Sharp Loading Tip (B04)

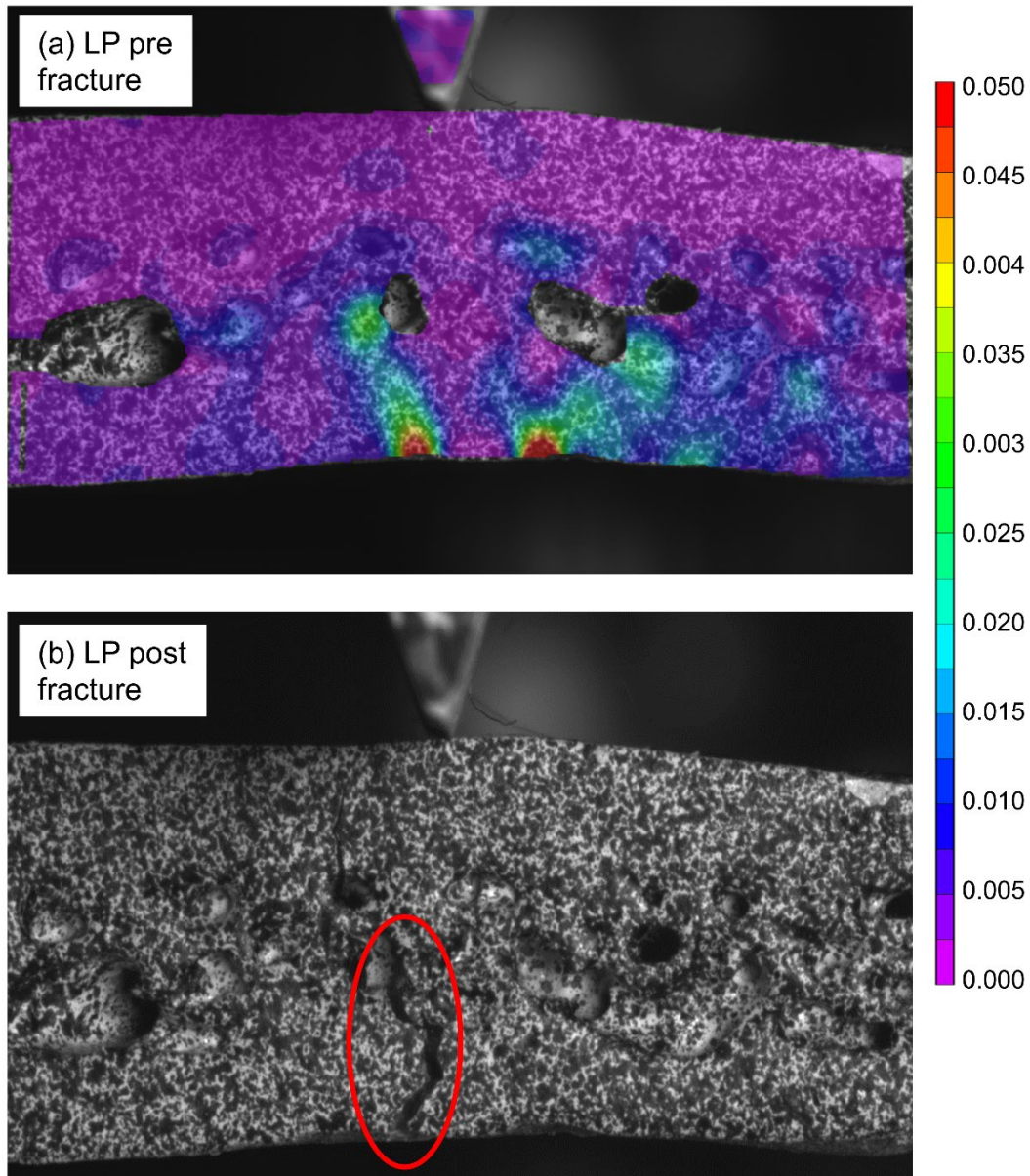


Fig. A-7 Images from the LP camera for B04 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

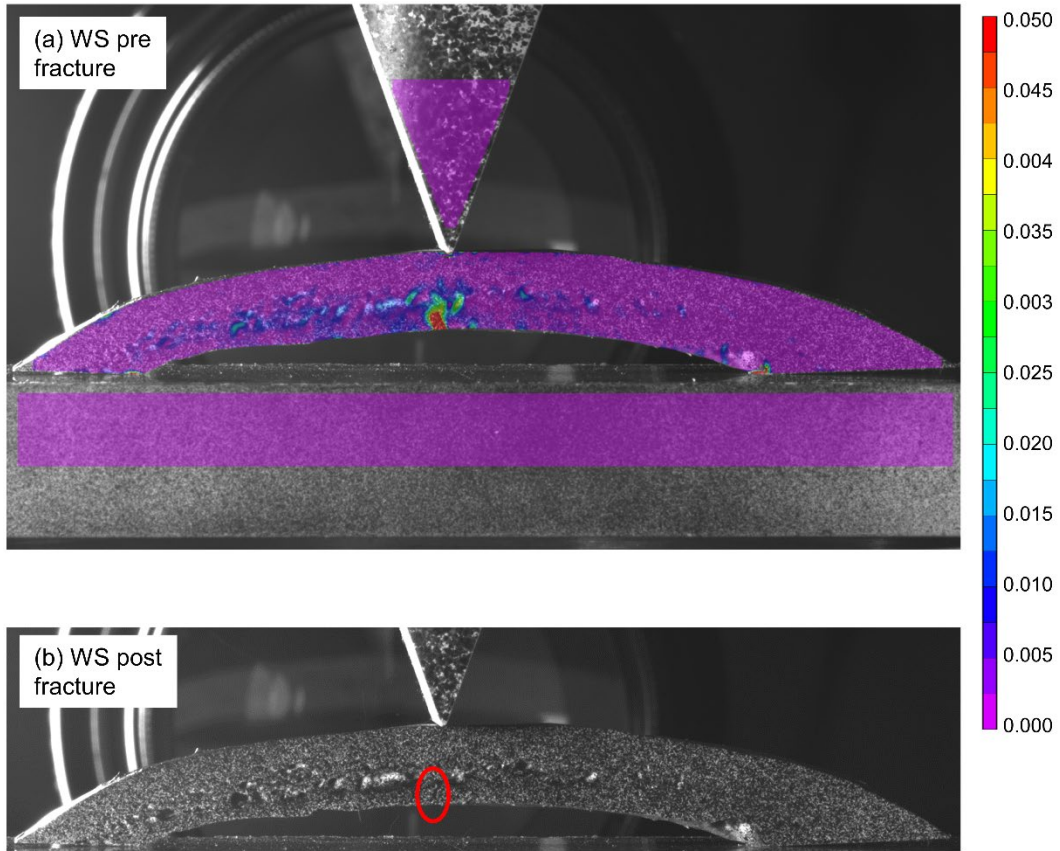


Fig. A-8 Images from the WS camera for B04 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

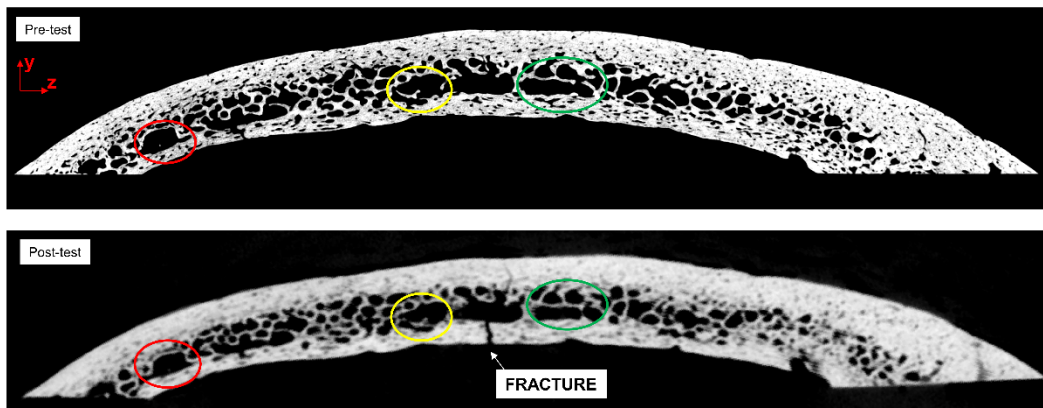


Fig. A-9 Micro-CT images of B04 before (top) and after (bottom) the experiment

A.4 High-Rate Blunt Loading Tip (B02)

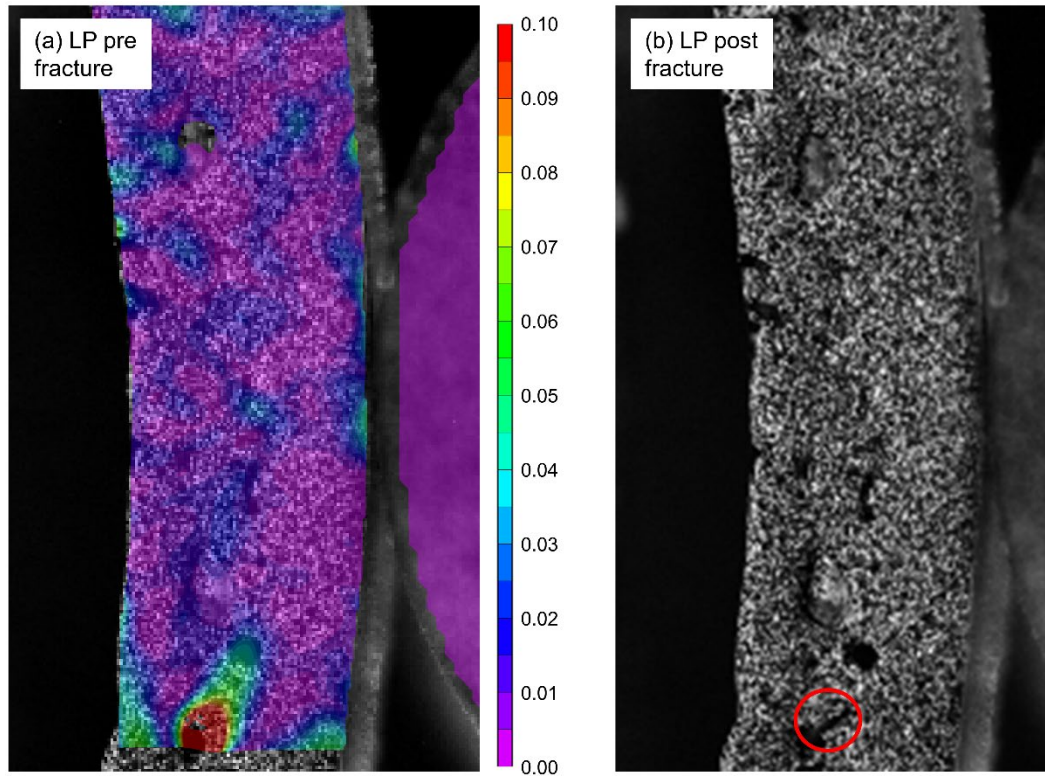


Fig. A-10 Images from the LP camera for B02 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

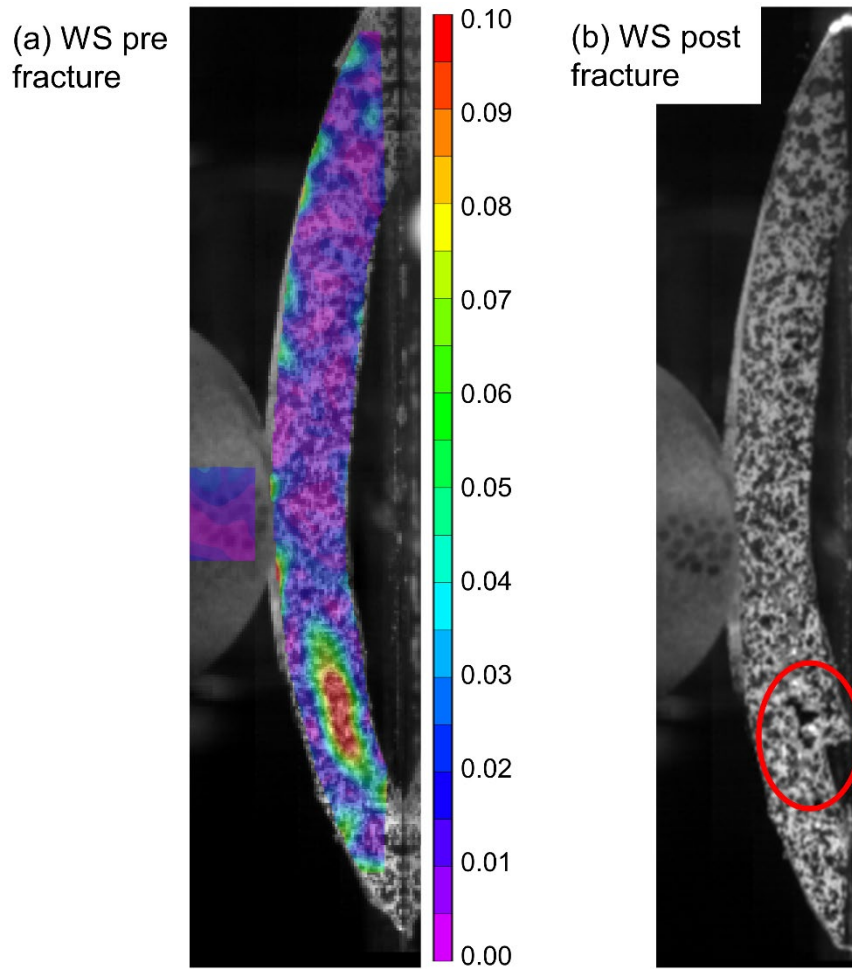


Fig. A-11 Images from the WS camera for B02 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

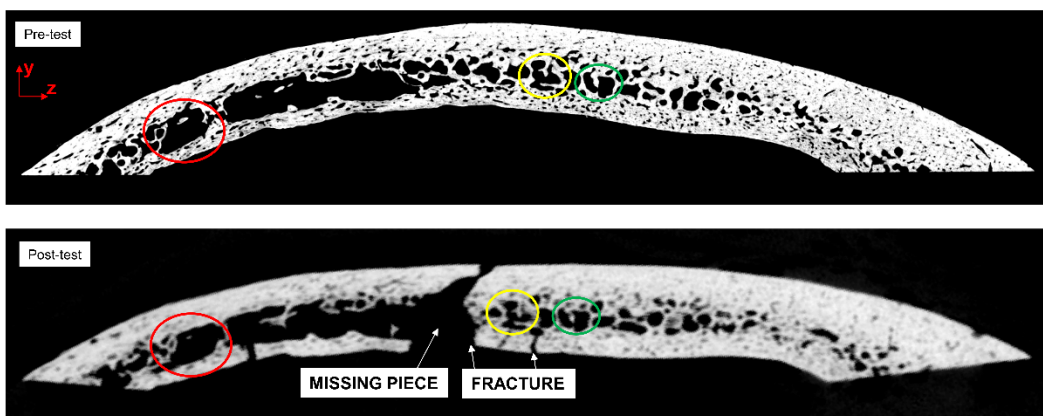


Fig. A-12 Micro-CT images of B02 before (top) and after (bottom) the experiment

A.5 High-Rate Sharp Loading Tip (B03)

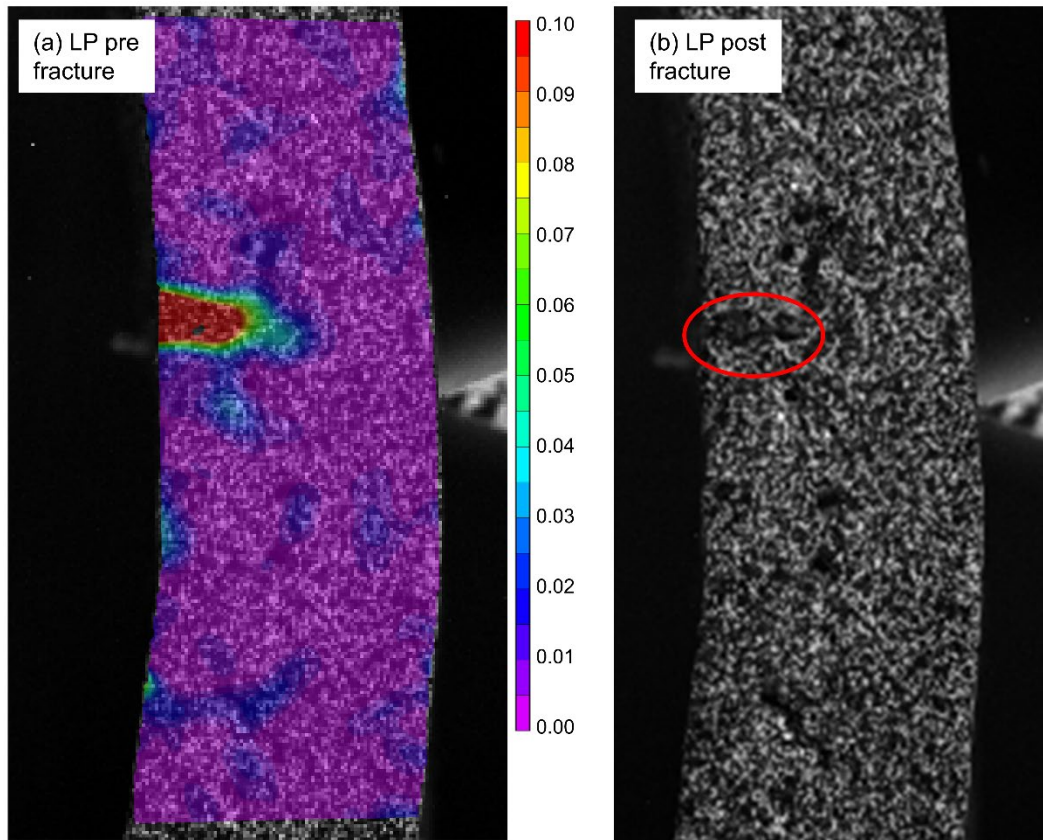


Fig. A-13 Images from the LP camera for B03 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

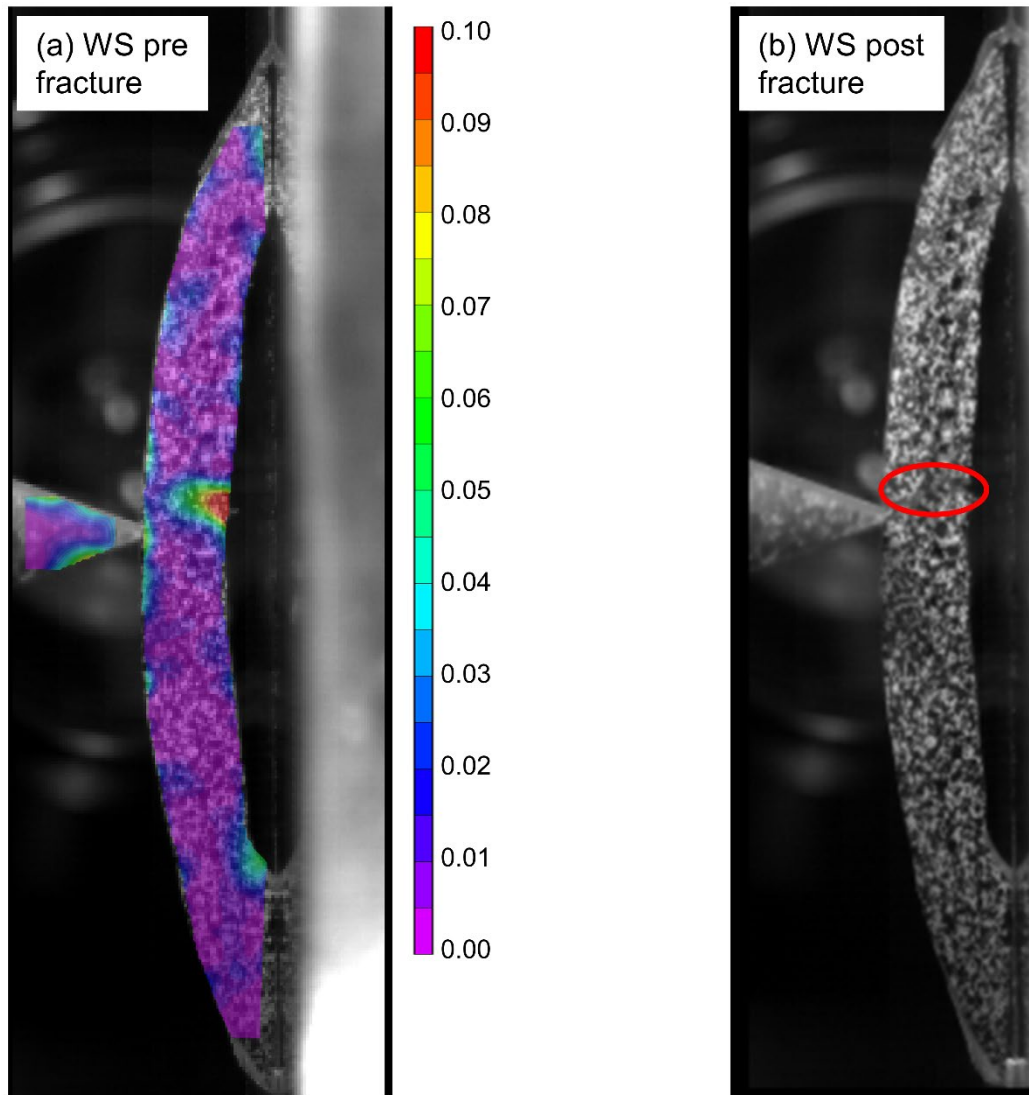


Fig. A-14 Images from the WS camera for B03 at timepoints immediately before and after fracture. Pre-fracture image (a) includes DIC-derived contour of maximum principal strain, with color legend provided on right. Post-fracture image (b) includes red circle indicating location of fracture.

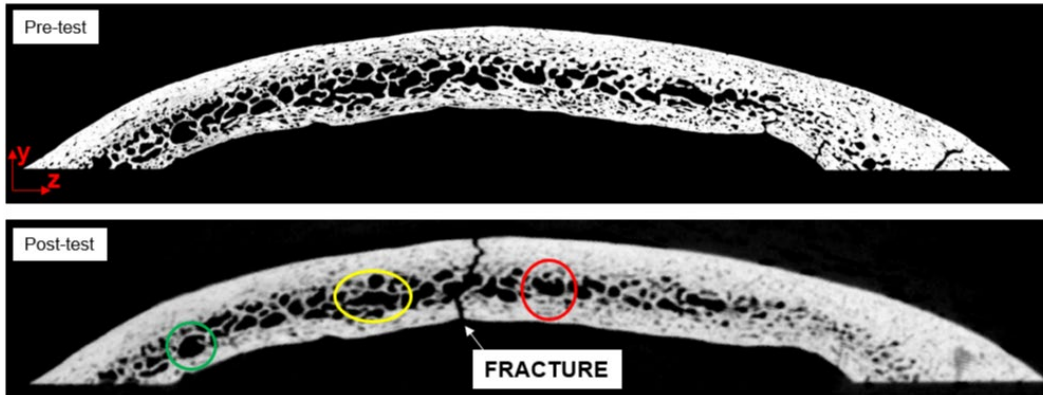


Fig. A-15 Micro-CT images of B03 before (top) and after (bottom) the experiment

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
AOI	area of interest
ARL	Army Research Laboratory
BHBT	behind-helmet blunt trauma
CT	computed tomography
DEVCOM	US Army Combat Capabilities Development Command
DIC	digital image correlation
fps	frames per second
HBSS	Hank's Buffered Saline Solution
LP	loading point
LT	loading tip
PMHS	postmortem human subject
SHPB	split Hopkinson pressure bar
TBI	traumatic brain injury
WS	whole specimen

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