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Dynamic Testing of Bovine Cortical Bone

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DYNAMIC TESTING OF BOVINE CORTICAL BONE

by
Kenton Wong

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of
the requirements of the Sally McDonnell-Barksdale Honors College.

Oxford
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Approved by

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ABSTRACT

KENTON WONG: Dynamic Testing of Bovine Cortical Bone

Bone is the primary structural element of mammalian animals. It plays a critical role in support, strength, and resilience, and has been the subject of many investigations into its material properties. The high strain rate behavior of bone has remained relatively unexplored, however, and its properties under dynamic loads perpendicular to the diaphysis of the bone are somewhat poorly understood. Bone is an anisotropic material and displays different properties depending on its orientation during testing. It is known that bone is weaker under a compressive load in the transverse direction, but the relationship has not been tested at high strain rates. A bovine femur was obtained and specimens were cut from it to be tested in a Split Hopkinson-Kolsky Pressure Bar. The test results were analyzed and compared to the literature on bovine bone tested under various other parameters. Testing found the samples to be significantly weaker than their longitudinally-cut equivalents, qualitatively confirming the anisotropic model.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 DYNAMIC LOAD CONDITIONS

The Industrial Revolution has increased the frequency and magnitude of potential dynamic loading scenarios. Heavy machinery, combustion-driven engines, and fast-moving vehicles have all contributed to an environment that, intentionally or not, has increased the likelihood of a high strain rate impact. This increased prevalence of high strain rates has led to a need for the controlled testing of various materials that may be subjected to a dynamic loading condition. Structural elements to be used in mobile vehicles are one example of materials that require such testing, to ensure their durability. This is reflected in a need for an understanding of the human body's behavior under high strain rate loading conditions, as humans operate powerful machinery at high speeds on a daily basis in addition to normal movement. Crashes, explosions, and impacts all affect organic tissues in ways that can be predicted through controlled testing.

Static loading conditions are described by the relatively stable nature of the force acting upon the system. These forces are typically present for long periods of time, or are applied gradually to the element being loaded. Some examples include buildings, bridges, and furniture. The challenge of building strong structures is still a field of research in and of itself, and methods used to test static loads are distinct from dynamic testing methods. One such example of static testing on large structures is a pile test, which measures a supporting pile's ability to hold a load. [1] These test types are typically applicable to forces of multiple kiloNewtons.

Dynamic loading conditions are used to describe any force that varies rapidly over time in its application upon the system. [2] This definition can include impacts and shock waves, but also refers to less dramatic situations as well, such as a sudden gust of wind acting on a building. Materials under dynamic loading conditions will frequently respond differently to a dynamic load than a static one. This phenomenon partially accounts for the reason that a certain amount of force applied in a shorter time to an object can cause failure, when the same object would be able to withstand the gradual application of the same amount of energy. Testing dynamic loads is more challenging than testing static loads, as the multitude of different strain rates and applications of force present a wider variety of scenarios to account for. Nevertheless, in order to better understand materials under dynamic loading conditions, these measurements and experiments are necessary.

Though the exact definitions differ somewhat, general consensus states that there exists an additional distinction in the area of dynamic testing. Classification of each dynamic test by using the strain rate provides important insight as to the speed of the test and the kind of impact the sample suffers during the test. There are three main strain rate ranges – low, intermediate, and high – of which the intermediate range is most relevant to research pertaining to the resulting impact effects on bone within the context of most incidents with machinery and other solid objects. [3] The comparative difficulty of testing within this range complicates experimentation, especially in the context of the standard Hopkinson bar apparatus. Additionally, the existence of blast effects and other potentialities for a high strain rate load condition incentivize high strain rate testing.

1.2 DYNAMIC TESTING BACKGROUND

Modern technology has accelerated human progress in many areas, notably leading to large increases in speed and power of transportation. Dynamic loads now occur with regular frequency, whether intentional or by accident, and affect materials in a different manner from static and quasi-static loads. This variance of mechanical properties has necessitated a new class of testing devices that can measure this behavior, such as the Hopkinson Bar. The behavior exhibited by materials under dynamic loads may vary with strain rate, but a general model is usually achievable to describe expected behavior under a specific set of circumstances.

The historical basis of materials science is rooted in the metallurgical advances made in the Industrial Era, where inventors frequently used the most advanced metals available for pressure vessels, steam turbines, and other mechanical devices. The rapid expansion of these technologies, as well as chambers for firearms and artillery, brought about a demand for measurements of a material's performance under specified loads. Brinell hardness tests, file tests, and Rockwell hardness tests all measured a material's respective properties, but performance under dynamic loads and high strain rates would be difficult to understand and measure until the introduction of servo-based testing machines. [4]

The Hopkinson bar apparatus is one example of a high-strain rate testing device. The first part of an apparatus is one long steel, aluminum, or composite "Incident Bar" held in place by brackets. This is acted upon by the "Striker Bar" and supported by another "Absorbing Bar," both of the same material as the Incident Bar. The Momentum Trap comes last, after the Absorbing Bar, and absorbs any excess energy from the resulting

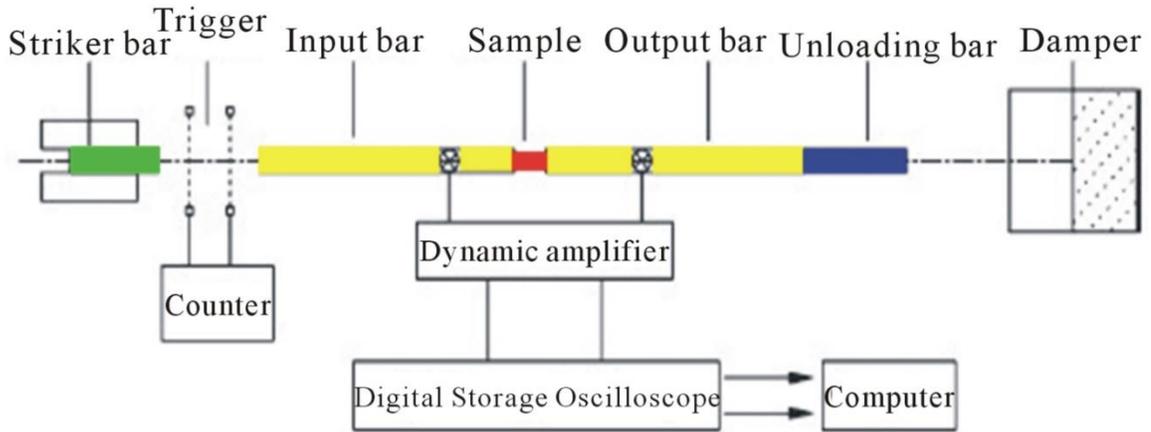


Figure 1. Generalized Hopkinson Bar Setup. Photo Credit: Scientific Research, Inc.

impacts. With an oscilloscope linked to strain gages on both Incident and Reflective rods, it is capable of testing materials in strain rates ranging from 300 s^{-1} to 5000 s^{-1} . [5] This allows researchers to simulate conditions similar to blasts, shock waves, and other very rapid applications of force to the material. Though the Hopkinson bar testing apparatus has unique drawbacks in its operation, it remains an efficient and economical solution for testing rapid compression on materials, especially those with small specimen sizes. There also exist Hopkinson Bar variants and setups that allow for tensile testing as well.

The Hopkinson Bar apparatus (see fig. 1, fig. 2) was chosen for these tests in part due to its versatility in strain rate testing, the small sample size required to get a good measurement, and the availability of the machine in comparison to other testing devices.



Figure 2. Hopkinson bar setup in the testing facility.

The strain rate versatility arises from the fact that different types of bars can be used as impact and absorbing bars. Additionally, as long as the sample size diameter or width (in case of a prismatic sample) is smaller than

the bar diameter, it can be tested in the setup. Overall, the Hopkinson Bar promised a solid result with low input requirements.

1.3 HIGH STRAIN RATES ON BONE

Most devices capable of high-speed impact interact with humans in one way or another, typically through the operation of powerful machinery. Mechanical devices are often operated at speed or can fail rapidly, initiating a high strain-rate impact upon other objects. When humans or other animals are involved, the result is a potential injury, depending on several factors. In order to approximate the effects of a high strain-rate impact on organic tissues, it is necessary to test these tissues under laboratory conditions. Thus, a bovine femur was obtained from a local butcher shop, the samples of which were to be tested in an apparatus under a moderately high strain rate.

Every macroscopic living organism is composed of different tissue types and extracellular matrices. Bone is one extracellular matrix found in vertebrate animals, and has evolved to compose the central load-bearing elements in most animals. Bone itself, however, is not a uniform matrix. There are two main types of bone tissue – compact and “spongy” bone. Whilst compact bone tissue draws its name from the densely packed osteoclasts that make up the matrix, spongy bone has a branching cross-section opening into holes which better allow arterioles, venules, and nerves access to the cells within the matrix. [6]

Compact (cortical) and spongy (trabecular or cancellous) bone should be looked at as two different materials, as they usually exhibit different characteristics and fulfill different purposes. However, the two are difficult to separate in macroscopic bone

structures. Compact or cortical bone comprises the outer layer of bone structures, and shields the weaker spongy bone with its higher strength. [7] Additionally, the transition from compact bone to spongy bone occurs on a spectrum, with some bone tissue falling in between the classifications. At some point there exists an intermediate bone tissue that could be argued to fall outside the main classifications. There is also a significant presence of marrow, which is a soft substance unsuited to dynamic testing and therefore must be separated from the bone itself.

Given the limitations of bone samples, predictable difficulties arise in determining which type of bone tissue is being studied in the experiment. Nevertheless, cortical and

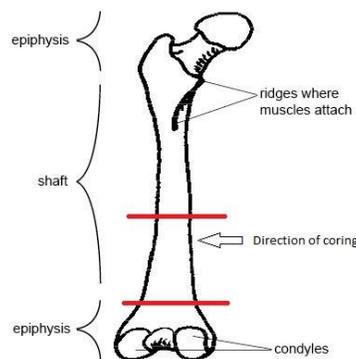


Figure 3. Generalized animal femur, with cut sections and coring direction illustrated. Photo Credit: Wikibooks.

trabecular bone regions are typically affected as a singular structure. The samples used were cut so as to provide as little variance in the tissue composition as possible. Bovine femurs have a thick region of cortical bone, owing to the large weight that they have to support, and thus aid the creation of specimens for testing. Unlike the study by Cloete, Paul, and Ismail, the specimens were cored perpendicular to the central

shaft of the bone (see fig. 3). This coring direction allows for testing of bone's properties transverse to the long axis of the bone. [8]

A summary of bovine bone's suitability as a test surrogate in place of human bone has been given by Cloete et al. There exist differences in the thickness of cortical bone and the microstructure of the cells, but consist of the same extracellular matrix and are similar enough to yield a good approximation of mechanical properties. Additionally,

bovine bone offers significantly fewer difficulties in regards to acquisition and ethical clearance.

1.4 POTENTIAL DISEASES IN BONE

The testing of a bovine bone in the high strain rate Hopkinson Bar carries some risk of contamination with potentially biohazardous material. An examination of possible transmissible diseases was warranted, along with recommendations for sanitary procedures regarding the storage, testing, and disposal of samples, as well as proper disinfection of the Hopkinson Bar.

The Virginia Cooperative Extension, a collaborative effort between Virginia Tech and Virginia State University, has compiled a list of zoonotic diseases transmissible from cattle to humans. These diseases have several potential transmission vectors, including feces, blood, or unpasteurized dairy products. Some of the more common diseases included ringworm, *E. Coli*, and Cryptosporidiosis. However, few diseases are transmissible through contaminated bone. [9]

Anthrax, while rare, is one potentially fatal disease that can be carried by livestock. Anthrax is a bacterial disease that spreads via highly persistent spores. Anthrax spores may be found in contaminated soil, undercooked meat, or direct exposure through a wound in the skin. Despite its deadly nature and ability to survive in contaminated areas for decades, anthrax is a rare disease, even in livestock. Since the beef bone sample was considered food-grade at time of purchase, the possibility of contamination with anthrax spores is extremely low. Nevertheless, these potential transmission modes were taken into consideration when designing the handling protocol for the samples. [10]

Another rare but serious disease is listeriosis, carried by the bacteria *L. monocytogenes*. This disease is preventable in livestock with good feed practices, but it is difficult to determine the quality of the bone sample sources' food. Typical transmission to human hosts involves ingesting contaminated meat or unpasteurized dairy products. Most humans are resistant to contracting the disease, although immunosuppressed, pregnant, or taking antacids can contract this disease. Potential effects of an infection include spontaneous abortion and septicemia. Due to these serious symptoms, listeriosis must be considered when testing beef bone samples. [11]

E. Coli is the third and possibly most serious disease that has a bovine transmission vector. Although harmless strains of *E. Coli* exist in the digestive tract of humans and livestock alike, disease-causing strains can rarely be transmitted through asymptomatic cattle. Humans usually contract these strains through consuming undercooked food or water, particularly ground beef from infected cattle. Once introduced to a human host, *E. Coli* can also spread via human-to-human contact. It causes abdominal cramping, bloody diarrhea, and occasional life-threatening kidney and blood disease in the elderly, children, and immunocompromised. Due to this combination of stealth among animal hosts, transmissivity in humans, and potential life-threatening symptoms, *E. Coli* was the primary focus of the handling protocol. [12]

It is important to note that the aforementioned diseases are almost exclusively encountered through a fecal-oral route, or by ingesting infected tissue. The potential for a contaminated bone source to transmit any disease to humans is extremely remote. However, bone's nature as a biological substance necessitates some protective protocols. The protocol developed needs to take the test setting into account, proceed with means to

minimize the risk from the maximum number of diseases, and treat surfaces exposed to the bone appropriately.

The Center for Disease Control has developed a set of protocols that address the proper disinfection protocols of hand-operated non-sterile equipment. [13] This is known as low-level disinfection procedure, and involves the treatment of exposed surfaces with a disinfectant appropriate for killing or displacing contagions and contaminants. Based on the table provided by the CDC, isopropyl alcohol (70%) was chosen as the disinfecting agent, to clear surfaces exposed to the sample before and after the testing was complete. Additionally, alcohol is not an electrolyte, which should ensure that it does not interfere with the electrical readings gathered by the oscilloscope during testing. Personal protection equipment involved sterile gloves (latex or nitrile), long pants, closed-toe shoes, and optional 95% efficiency or greater surgical mask. These precautions were taken to further minimize the risk of exposure to a pathogenic agent from the bone sample.

1.5 HYPOTHESIS

Bone is a semi-crystalline structure, consisting of millions of osteocytes that simultaneously support the load of an animal's body while allowing vital nutrients, blood cells, and oxygen to flow into and out of the marrow located in the bone's interior [14]. Bone has evolved in Earth's gravity to support a vertical load, and though horizontal impacts are still common in nature, bone is said to be an anisotropic material, meaning that the strength of the material is dependent on the direction in which it is tested. In order to validate this assertion, the testing of horizontal loads in the dynamic range should reveal that bone is not as strong in that direction. Moreover, a high strain rate

impact means that a greater amount of stress will be transferred to the bone, yielding a more severe stress-strain curve in the higher-loaded samples. Every sample should be thoroughly shattered under strain rates above 1000 s^{-1} achieved by an aluminum bar. Finally, the bone is imperfect and has been in storage for some time. The data collected will most likely correspond to fatigued, or older, bone, which will be shown by a lower maximum strength. References to the bone's position and direction assume a vertical femur, as though the individual was standing upright.

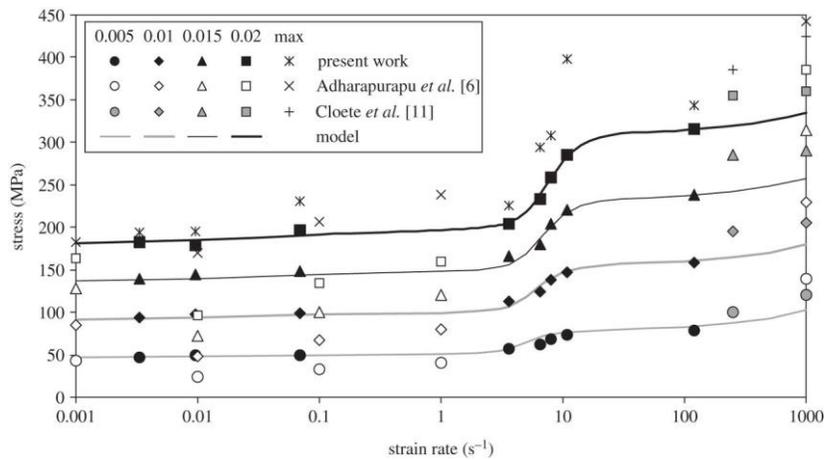


Figure 4. Cloete et al.'s findings for vertically-loaded cortical bone at various strains and rates. Photo Credit: Royal Society Publishings.

2. PROCEDURE

2.1 BONE SOURCING

Bovine bone can be found within only a few fields, the most significant of which is undeniably the meat industry. Because of this, the bone selected was sourced from a local butcher shop, freshly cut from a carcass. The bone was wrapped in butcher paper and stored in a freezer for approximately 8 weeks prior to the cutting of samples, but the transportation to and from the workshop was accomplished using a cooler and dry ice. The bone was then machined into standard Hopkinson-type specimens of approximately 6 mm radius and cylindrical length of 8 mm, though these dimensions varied somewhat. The specimens were also kept on dry ice until their testing approximately 48 hours later.

Frozen storage was the standard protocol for the bone and machined samples, due to the relative ease of storage in sub-zero conditions and the preservation of bone's mechanical properties under those conditions [15]. Desiccation, while effective at preserving certain tissue types and reducing risk of contamination, was not pursued due to its requirement for specialized equipment not readily available. Alternatively, the bone could have been sterilized through heat. However, this would result in an increased brittleness in the bone samples, through a change in the structure of the bone itself. The bone sample was frozen by default and would therefore be less likely to deviate from the structure it had already assumed if the sample were kept in that condition.

Specimens were cut using a custom coring bit on a drill press. After cutting, the bone specimens were briefly thawed in water and the marrow was removed where possible. The samples were then filed to more closely yield a cylindrical shape and even

cylinder surface. Despite filing, initial tested samples still had some marrow attached to them, which yielded poor results in the Hopkinson bar. Further tests all had the marrow removed from the bone in order to ensure uniformity and produce valid and applicable test results. Despite attempts to file the bone samples to a uniform length, the unevenness of the samples caused several tests to yield less applicable data than was desirable.

2.2 TESTING

Testing was performed on an aluminum rod Split-Hopkinson Pressure Bar setup, which was additionally loaded with a sacrificial copper pulse shaper to help ensure that the resulting loading ramp would be slower and more consistent. The Hopkinson Bar had strain gages on its incident and reflected bars that output data to an oscilloscope, and a high-speed camera with high-luminosity lights additionally recorded the impact. First, samples with some additional marrow were tested, revealing that the marrow's presence effectively ruined the data collected through the destruction of the sample. Subsequently, effectively pure bone samples were tested, which yielded much better data but was still subject to the confounding issue of an uneven contact surface. Further tests leveled off the contact surface as much as possible with the use of a hand file. Gloves were worn for the duration of the tests. After each battery of tests, the surfaces in contact with the bone were sanitized. Simple Green was used in place of isopropyl alcohol, as it accomplished the same cleaning purpose and was more readily available.

Quantity of testing was unfortunately limited, due to the fact that the coring bit used in the machining of specimens was destroyed after making twelve, of which five were deemed suitable for testing.

3. RESULTS

Testing was completed on 5 different samples that were marrow-free but had varying degrees of evenness on the test surface. This resulted in some samples snapping very quickly under the load, limiting the useful data obtained from those tests. Nevertheless, the data captured from the majority of the specimens were useful. The tests had average strain rates ranging from around 2617 s^{-1} to 3576 s^{-1} . Samples were tested at 10 PSI, using the aforementioned aluminum bar and pulse shaper. The stress-strain curves fit the brittle model, with a parabolic trajectory that peaked rapidly and then dwindled down. As expected, strain rate increased rapidly over the course of the test before failure occurred. All bone samples were shattered upon testing. The resulting video footage showed very little deformation before failure, though two of the samples exhibited some movement as a result of their uneven contact surface with the bar.

There was considerable variance in the strain rate that the specimens experienced. Nevertheless, all were tested under the same loading conditions and stayed within or around 1000 s^{-1} of each other. The variance is explainable, due to the different shapes of the specimens, and to an extent, the different originating sections that the specimen itself was machined from. The data on one of the specimens were suspect, with an abnormal

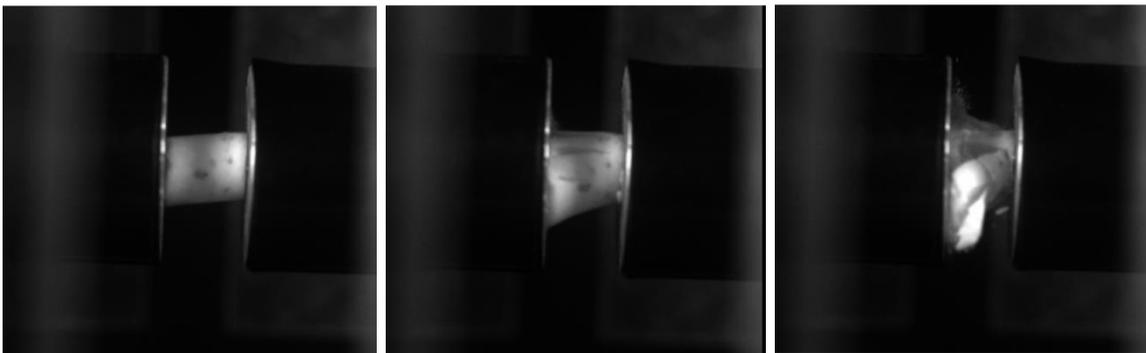


Figure 5. Still frames from sample 2's test.

stress-strain curve and a stress pulse graph considerably incongruous with the other specimens (compare the charts in fig. 6). The four other specimens were all within a similar range and were favored in the analysis of these results. The aberrant specimen's data was discarded.

The stress-strain rate curves of the different specimens are all displayed in figure 8 below. The maximum stress varies considerably, from less than 20 MPa to over 50 MPa. There is also variation in the rate of stress increase, with Sample 1 showing significantly slower increase per strain rate. Sample 2 provides the stress maximum across all samples. This ceiling is considerably lower than that of longitudinal samples from a similar bovine femur. This supports the claim that bone is an anisotropic material, even under dynamic loading conditions. Most deviation in the specimens is due to the variance between their shapes and sizes, pointing again to the imperfect machining process. Nevertheless, the maximum stress appeared be much smaller than some reported values from the field of orthopedic biomechanics. [16] This may be attributed to the near-frozen state at which the bone samples were kept prior to the experiment, which likely

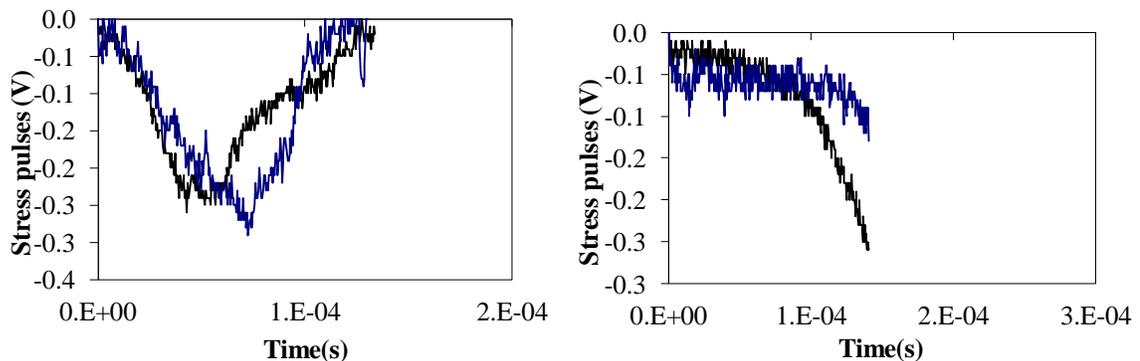


Figure 6. Favorable and aberrant stress pulse alignments (sample 1, left, and discarded sample, right).

caused pores in the microstructure to swell. The samples also followed a brittle stress-strain curve rather than a ductile stress-strain curve, which was expected.

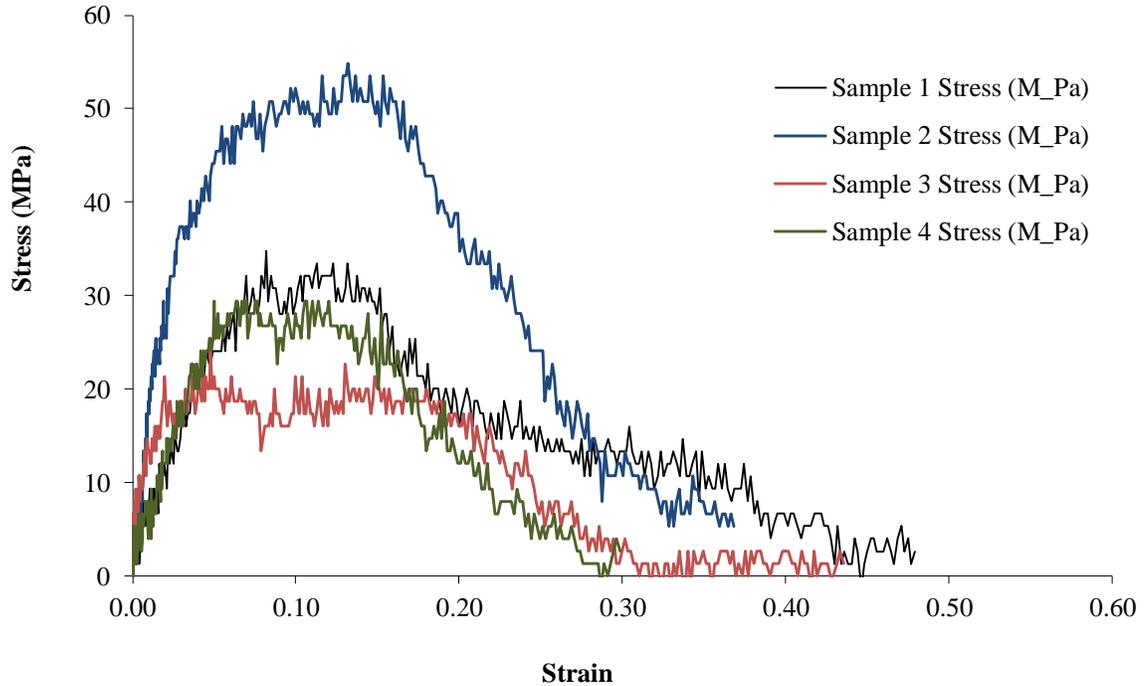


Figure 7. Combined stress-strain sample curves.

The low stress ceiling was most likely caused by an increase in porosity, due to the aforementioned frozen state of the bone. Therefore, these samples' behavior most closely matches that of old or osteoporotic bone, due to the low maximum stress. [17] Apparent density of the samples was comparable to normal bone, but the mass was measured before the sample would have had a chance to thaw. It is possible that some water was still trapped in the pores of the microstructure, adding mass that did not ultimately contribute to the samples' compressive properties. Each curve appears to match the ceramics model of a rapid increase in strain rate followed by a peak stress, although there is no abrupt loss of data. This indicates that the failure in the specimens

was progressive and that pressure generated by the Hopkinson Bar was maintained for longer than expected.

The average strain rates of each specimen varied widely but were all over 2000 s^{-1} . This strain rate is not typically found in natural impact events, but rather corresponds more closely with blast effects, shock waves, and supersonic impacts. The strain rate varied with the condition and position of each specimen in the Hopkinson Bar, with the highest average value coming from Sample 1 at 3576 s^{-1} and the lowest average value coming from Sample 4 at 2120 s^{-1} . The highest strain rate previously tested on bovine bone specimens was around 2500 s^{-1} , due to the small chance of bone structures encountering such a rapid load in everyday use. However, the interesting find of lowered maximum stress may be a function of this extremely high strain rate, in addition to the anisotropic character of bone.

Table 1. Average sample strain rates.

Sample	Strain Rate (s^{-1})
1	3576
2	2617
3	3093
4	2120

Typically, materials get stronger under higher compressive strain rate, and a reversal of this trend would be unexpected. Testing at different conditions is needed to show whether this trend holds in different circumstances. Using longitudinal samples under identical testing conditions would bring clarity to the trend, or possibly reverse it.

Though the chart is more applicable to low- and moderate-strain rates, the sample's stresses have been plotted against their strain rates for the purpose of comparison to Cloete et al's graph (fig. 4). In the comparable region, it appears that the tested bone is significantly weaker, with stresses below 50 MP even at 1000 s^{-1} making up the majority of the results. Sample 2, the highest-strength sample, never approaches the 100 MPa mark that other data points support. While this result is consistent with the hypothesis of

lower strength, it seems unlikely that bone would experience such a precipitous drop in strength from a horizontal load. Once again, storage methods and contact surface probably contributed to the drop. Additionally, the presence of trabecular bone as well as cortical bone also decreases the sample strength. Some trabecular bone was almost certainly present due to the coring methods used.

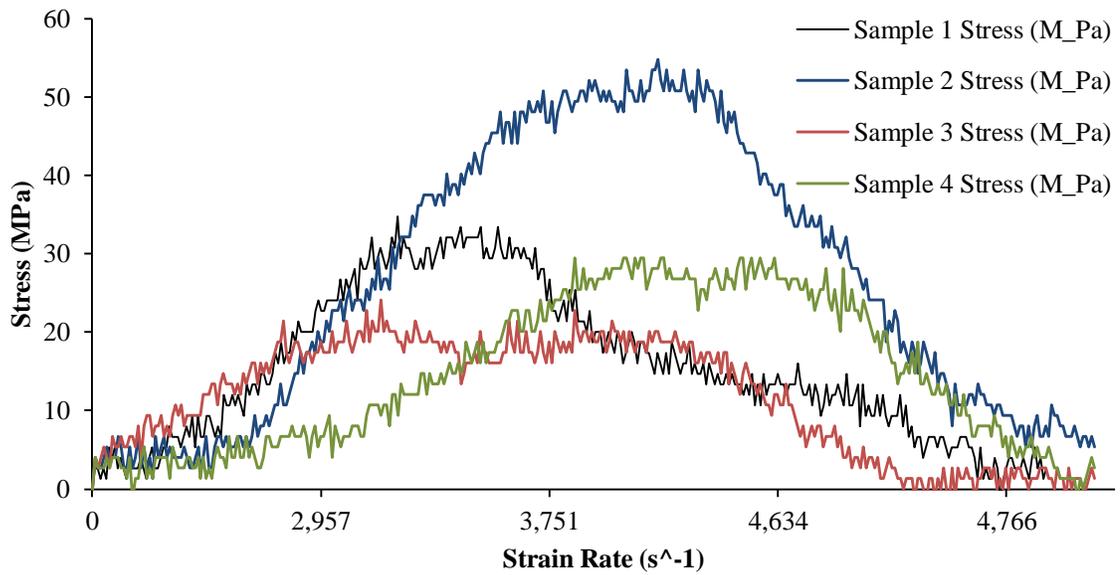


Figure 9. Stress-Strain Rate Sample Curves.

4. DISCUSSION

4.1 STRESS INVESTIGATION

The single most unexpected result of the tests was the bone samples' maximum stress. The limits established by multiple other studies were not even approached during the testing of these samples. As previously stated, some reduced maximum stress is consistent with the anisotropic hypothesis. However, the magnitude of the reduction is surprising and contrary to some reported values in other literature. [18] The reduced toughness of the bone samples merits further discussion and investigation.

The significant difference between cortical and trabecular bone strength is one potential answer for why the bone may have failed at such low strain rates. While cortical bone can frequently withstand loads in excess of 100 MPa, trabecular bone can be much more fragile, with vertebral trabecular bone possessing a yield stress as low as 1.5 MPa, especially after fatigue effects have occurred. [19] The bone in a bovine femur will have a much larger section of cortical bone than a spinal vertebra due to the different purposes of each structural element, but the majority of the interior bone is still made up of the trabecular tissue type. [20] The specimens used for testing were cored from the femur without regard to the differing regions of bone – the only component intentionally removed was the marrow. Given that trabecular bone makes up the majority of the tissue in the bone itself, it is reasonable to assume that it could have accounted for the majority of the tissue in the sample as well. The presence of both tissue types would change the application of the data gained from a specific investigation into the properties of cortical bone into more of a general test for high-speed impact effects on femurs. The cortical

region could be more independently tested along a horizontal axis by grinding down the specimen after coring it, or using alternate machining methods.

One potential factor in the lower strength of the tested samples may lie in their method of machining. The coring bit used was a metal pipe with an inner diameter of 6 mm, with teeth filed into the contact end to help cut into the bone. The bit was attached to a drill press, which was used on the frozen femur to cut the required specimens. However, the specimens were heated by the friction created by the drill press and partially thawed, although they were refrozen as soon as cutting had finished. The disruption of the extracellular matrix may have compromised the structural integrity of the sample, either through the effects of thawing and refreezing or through the biting and digging action of the coring bit. The bit had difficulty cutting through the cortical region, often failing to find purchase on the surface of the bone. This machining method stands in contrast to Zimmerman et al's procedure, which cut specimens with a water-irrigated low-speed saw. While some alteration to the microstructure is unavoidable, certain cutting techniques may be more desirable than others. Testing whether the cutting method altered the test results would involve simply changing the process used to cut the samples, then running the test under the same conditions.

Increased porosity due to ice formation in the bone was mentioned earlier as another potential cause of the sample's decreased stress maximum. The microstructure of both trabecular and cortical bone is riddled with pores of various sizes, which reduces weight in a functional bone. During the removal of the marrow, the samples were immersed in non-freezing water, which would have freely flowed into these pores. Once marrow was removed, the bones were refrozen, which would turn the water into ice and

force it to expand. Any water still trapped within the bone would have encountered the connections of the bone matrix. While the expansion could have simply followed the channels that the water originally flowed into, it is also likely that additional stress concentrations were introduced into the bone samples, especially in areas where pores are narrow and restrictive such as the cortical bone. This would translate into a decreased threshold for failure, in addition to the ductile-to-brittle effect that cold temperatures often have on materials.

The dynamic response of the samples was somewhat different than some other composite materials. In one study of an apparently isotropic glass/graphite/epoxy composite, the material was found to have practically uniform energy absorption across all tests. [21] The bone samples were naturally not machined the same way, but could have been expected to have similar energy absorptions due to their similarity of origin (i.e., all specimens being cored from the femur). Instead, the strain rate variance is more indicative of a range of energy absorption that probably contains the relevant data. Alternatively, the variation in porosity depending on the region that the specimens were taken from would also change the energy absorption. Multiple factors are at work in the variance in response. Nevertheless, since pultrusion [22] is not an option for machining organic specimens, research involving bone may be forced to work with this energy absorption variance.

4.2 RECOMMENDATIONS

While the overall research project yielded good results, there exist several opportunities for improvement in future studies of bone's dynamic properties. Human bone may be sourced at additional expense and caution, to more accurately model

dynamic effects on humans. Alternatively, other mammal bones could be used to obtain a more general dynamic model of bone or to investigate the strength of certain species' bones. Further testing could be intermediate-strain-rate range, relying on either a polycarbonate tube or a specialized striking mechanism in order to more slowly apply the force onto bone samples. In order to model different types of bones, density tests and mineral tests might be conducted on the source to investigate the nature of the samples before testing. Denser bone samples would yield results more applicable to young and healthy bone.

As for the samples themselves, the custom coring bit developed to cut into the bovine femur was effective, but only able to yield samples suitable for testing in a single direction. Future studies could machine a rectangular prismatic specimen from the bone to enable testing along the vertical axis as well as the horizontal axis. Samples also encountered difficulty with marrow removal, as both some marrow was able to stay on the specimens and some specimens' surfaces became uneven after filing the marrow away. The easiest solution to this problem would be to simply cut all marrow-bearing parts of the bone away, an action which was unavailable during the preparation and testing phase.

Sample count was also quite low, relative to the amount of surface area available on the femur section. This is, to an extent, a mark of the difficulty in replacing the coring bit that was broken while coring samples. Future studies could create a more effective bit and core as many samples from a single femur or other bone as necessary. The possibility also exists for a machine other than the Hopkinson bar to be used. This would cause additional difficulty in procuring appropriately sized samples, and setting other

parameters to fit within the bounds of whatever machine was eventually used. However, additional testing with different devices would either strengthen or disprove the current viscoelastic model established mainly via Hopkinson bar testing.

Improvements in the Hopkinson bar technique may be achievable through use of one of the intermediate strain rate testing devices pioneered by Cloete et al. These encompass the specialized striker discussed earlier, but also indicate use of a unique wedge bar apparatus that was specifically developed for lower strain rate ranges. This may improve the viscoelastic model. An alternative to the compressive testing would be a test of bone's elastic or torsional properties, given that frequent stresses occur at the ends of bone members. However, Hopkinson fracture bar setups require different test equipment and it may be simpler to use an alternate testing device. There would also be additional difficulties in machining specimens to the appropriate dimensions for such a test.

5. CONCLUSION

Bone is an integral material in every vertebrate animal, but testing is often difficult and inconclusive. The involvement of biological agents must be carefully managed, to prevent contamination and minimize risk of disease. Cortical bone has different mechanical properties from trabecular bone and can be difficult to distinguish and separate. Additionally, bone is most often loaded at moderate strain rate, which presents challenges due to the general lack of universally accepted equipment for moderate strain rate analysis. With these limitations and obstacles in mind, every effort was made to surmount the difficulties encountered and generate useable data to test the hypothesis. However, the unified nature of the tested samples, the high strain generated by the Hopkinson bar, and the frozen storage method of the samples must be taken into account by those who would apply this data.

In summary, the bovine bone samples behaved in the same manner as expected of a crystalline matrix material, additionally confirming the anisotropic model. The samples displayed a considerably lower maximum stress than most other literature, likely owing to the frozen storage method of the samples between machining and testing. The experiment would have benefitted greatly from additional marrow-free specimens, which were unable to be machined after the destruction of the custom coring bit. More data is needed to confidently contradict earlier studies on similar bone tissue in regards to the samples' maximum stress. The potential for a better understanding of gunshot wounds, blast effects, and other extremely rapid loading conditions cannot be ignored. The more intimate knowledge of this bone orientation's behavior under high strain rate is also

valuable in helping to develop a better understanding of the human body's main structural element.

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