FATIGUE-RESISTANT COMPOSITE BEAM BASED ON THE MICROSTRUCTURE OF BONE

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Abstract

Holes in engineering structures are sources of stress concentrations that often lead to failure. Previous research has shown that the microstructure and composition of bone reduces this stress concentration by varying fiber orientation, diameter, and density. These findings led to the fabrication of a biomimetic plate which when uniaxially loaded and compared to a similar homogeneous plate, was found to have increased static strength. This project continued this research by determining the requirements needed to fabricate a fiber composite biomimetic beam that will be cyclically loaded to test the fatigue life of the beams.

Introduction

There was a lot of previous research done in this area that will serve as a background for this project. This research dealt with quantifying the composition and microstructure of the area surrounding a foramen on a bone, and applying this microstructure to a biomimetic plate. A foramen is a naturally occurring hole in a bone that serves as a passageway for arteries and veins. From a macroscopic scale, bones appear to be uniform in structure. On a microscopic scale, bones are actually a composite structure consisting of discontinuous fibers. These fibers are called osteons, and are the basic microstructure of bone. It has been determined that the osteon orientation varies across bone. In long bones, osteonal fibers run parallel to the long axis of the bone, in the longitudinal direction of principal stress. However, there are regions of transverse osteons oriented perpendicular to the cortex at the apex of the foramen, as shown in Figure 1.

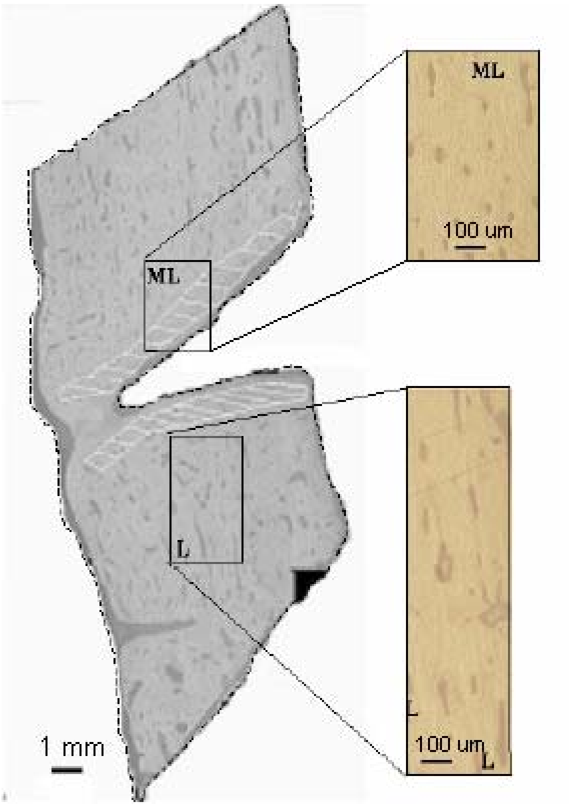


Figure 1. A parasagittal section through a centrally located foramen. At top right, ML denotes the transverse osteons located around the foramen. At bottom right, L denotes the longitudinally oriented osteons. These osteons are much longer than the transverse osteons around the foramen.[1]

Foramen, like holes in other structures, are subjected to stress concentration where crack initiation frequently occurs and crack propagation could be critical to the health of the structure. It has been discovered that the local microstructure around the foramen, notably the osteon alignment, mitigates this stress concentration. This led an investigation of microcrack damage in bone when cyclically loaded. This project, titled *Damage About Natural and Drilled Holes in Bone*, compared the damage around a foramen to a drilled hole in bone. This was done by cutting and shaving a long bone, namely an equine third metacarpus containing a foramen, into beams. A hole of the same size and shape of the foramen was drilled into these beams. These beams were then cyclically loaded for 60,000 cycles, and the foramen and drilled hole were subjected to the same strain severity. This resulted in distinct morphometric differences around the foramen and drilled holes, shown in Figure 2.

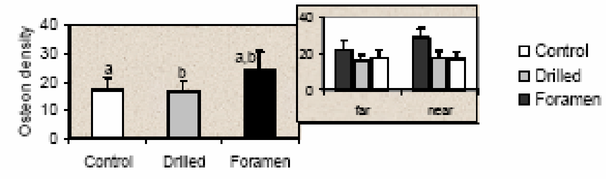


Figure 2. Microstructural differences between the foramen and drilled hole in bone. The osteon density is higher around the foramen then the drilled hole.

Osteon density was significantly greater around the foramen than the drilled hole, and porosity in the region near the foramen was nearly twice what it was in a region away from the foramen. The osteon diameter near the foramen was also found to be larger than it was a distance away from the foramen. This led to distinct differences in the amount of damage around the foramen and drilled holes, shown in Figure 3.

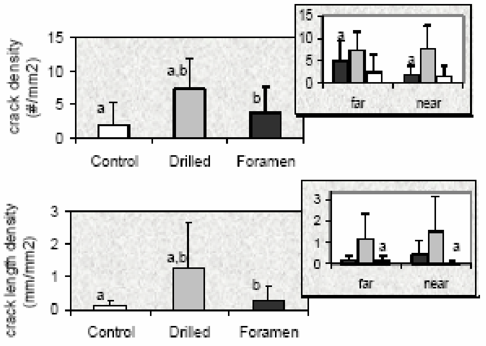


Figure 3. Microdamage around the drilled hole and foramen. The crack density, and crack length density was much greater around the drilled hole.

Crack density was much greater around the drilled hole than the foramen. Crack length density around the drilled hole was nearly twice what was found around the foramen. This agreed with the previous findings – that the osteon alignment and density around the foramen led to a mitigation of stress concentration. The higher osteon densities and smaller osteon diameters translate into a higher packing of osteons near the foramen leading to crack arrestment and deflection.[2]

From previous research, it was further found that the elasticity across a bone varies. Bones adapt to the presence of a foramen. G¨otzen et al. (2001) investigated the foramen in a horse metacarpal bone, deriving mechanical properties from experimental measurements of porosity, mineral density, principal material directions, and the degree of anisotropy. They found a compliant region near the foramen and a stiffer region some distance away, compared with normal bone properties away from the hole, shown in Figure 4.

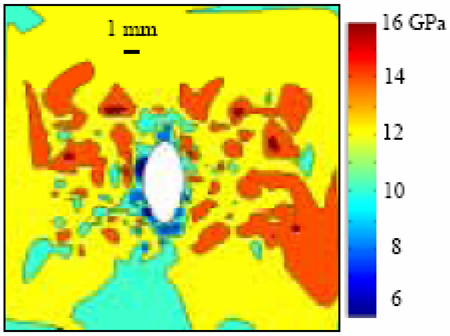


Figure 4. Modulus of elasticity of the region surrounding the foramen in a bone. This shows that the bone is stiffer at a region away from the foramen.

Structural optimization using biological variables (mineral density, porosity, and orthotropy orientation) indicate that the material distribution plays an important role in minimizing stress failure at the foramen.[3]

This work was continued by fabricating a plate that mimicked the microstructure of bone. This biomimetic plate was made with polyurethane and had discrete rings around a hole. Each ring had its own modulus of elasticity matching that of a bone. This meant the plate had an elasticity gradient mimicking the composition of bone. A homogeneous plate with similar geometry was also fabricated and the two plates are shown in Figure 5.

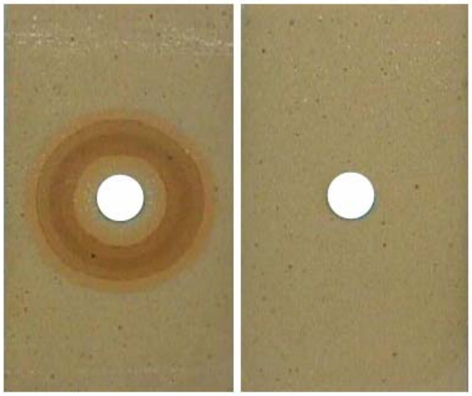


Figure 5. On the left is the heterogeneous plate with discrete rings each with their own modulus of elasticity. On the right is the homogeneous plate. These plates were uniaxially loaded and it was found that the static strength of the heterogeneous beam was twice that of the homogeneous beam.

Both of these plates were tested in uniaxial tension. The results showed that the inhomogeneous plate had twice the static strength of the homogeneous plate and had the same weight. The elasticity gradient across the inhomogeneous plate reduced the stress concentration on the hole, increasing its load carrying capacity. A second observation was also made from these results. The homogeneous plate fractured at the hole, which was to be expected given the stress concentration around the hole. The inhomogeneous plate fracture some distance away from the hole. The stiffer region away from the hole attracted more of the load, deflecting it away from the hole. This also aided the load carrying capacity of the plate[4].

Methods

This biomimetic plate showed that the load carrying capacity of a structure with a hole can be increased by introducing an elasticity gradient. This research failed to account for the microstructure of a bone in its analysis. The earlier research showed that osteons vary in orientation, density, and diameter around the foramen in bones to reduce the stress concentration around this hole. This biomimetic plate was not fabricated to analyze its microstructure – while the elasticity varied across the plate, the microstructure remained constant. This project consisted of several steps to determine the beam composition that would mimic bone and its dimensions. The first was to determine the proper materials that could mimic bone. Given that it was determined that there is an osteon diameter gradient across bone, the idea of using fiber composite materials could be used. The fibers of the composite material can mimic the osteons in the microstructure of bone. Furthermore, two materials with different fiber diameters could be used to mimic the different sized osteons in bone. Since it was also determined that there is a modulus of elasticity gradient across bone, the notion of using two fiber composite materials is solidified. Two materials with different elasticities could be used to mimic the elasticity gradient across bone.

With this knowledge, calculations were done to find the correct osteon diameter ratios and stiffness ratios that would mimic bone. The ratios needed to mimic bone are shown in Figure 6.

Characteristic	Material 1	Material 2
Fiber Diameter	1	1.2
Modulus of Elasticity	2	1

Figure 6. The material ratios needed to mimic the microstructure of bone and also have proportional modulus ratios.

Appendix A shows the calculations to find the correct osteon diameter and Appendix B shows the calculations to find the correct modulus of elasticity ratios. After researching materials, a PAN-based carbon fiber material and an S-Glass fiberglass material were found to have the closest desired ratios, as shown in Figure 7.

Characteristic	Fiberglass:Carbon Ratio
Fiber Diameter	1.2:1 – 1.3:1
Modulus of Elasticity	1:2.93

Figure 7. Fiberglass:Carbon ratio, the closest ratio that could mimic bone.

The material properties are given in Appendix C. The fiber diameter for the carbon fiber ranges from 7.6 – 8.6 µm which is why the ratio also ranges. The next step was to determine the proportion of each material that would mimic bone. After reviewing the composition of bone, the desired proportionality was found.

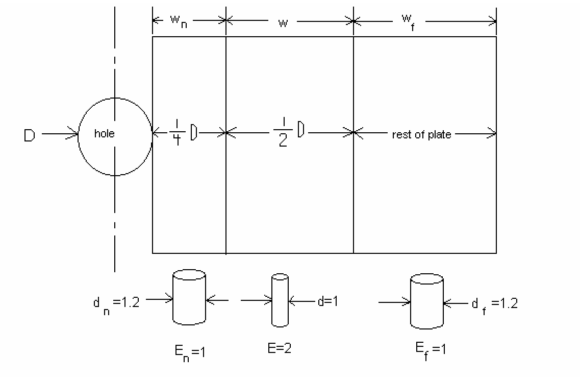


Figure 6. The composition of the biomimetic beam, mimicking the composition of bone. The bone is stiffer at a region away from the hole. The fiber diameter also gets smaller at a region away from the hole, before it gets larger far away from the hole. This is a similar composition to bone.

From this it was determined that the Fiberglass would be used around the foramen and at a distance away from the foramen with the Carbon material in between. The next step was to find the proper ASTM Standard that applied for this project. The standard entitled *Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics by Four-Point Bending* to be applicable standard. The test method for this standard is shown in Figure 8.

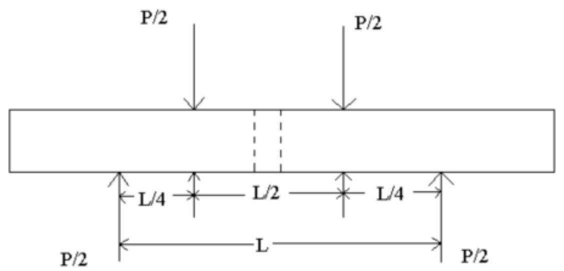


Figure 8. ASTM Standard that applies to the testing of the biomimetic beam, and also gives the proper dimension ratios.

This standard also specified the dimensions needed for the beam. It gave that the ratio between the distance 'L' and the thickness could not exceed 16:1, and that the width could not exceed ¼ of the distance 'L'. Given that the working area in the hot press is 304.8 x 304.8 mm, the beam dimensions need to be: length – 228.6 mm, width – 57.2 mm, and thickness – 14.5 mm. The next step was to determine the hole diameter size in the beam. To make sure the stress concentration from the edge of the beam didn't overlap with the stress concentration from the hole, we set the hole a distance of 3 diameters from the edge, giving a hole diameter of 9.5 mm.

Now that the composition of this beam was determined, the other beam designs in order to compare results needed to be determined. The decision was made to fabricate three other beams to compare: a homogeneous beam with a preformed hole (1), a homogeneous beam with a drilled hole (2), and a heterogeneous beam with a drilled hole (3). These will be compared to the biomimetic beam (4), as shown in Figure 9.

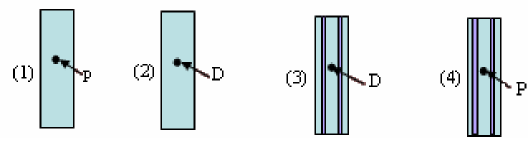


Figure 9. The three beams that will also be fabricated to compare to the fourth beam to determine whether fatigue life has been increased.

The biomimetic beam can be compared to the homogeneous beam with a preformed hole to test whether the modulus of elasticity gradient increased fatigue life. A preformed hole is one that is formed into the beam during the fabrication process. The only variable that is different between the two beams is the composition makeup. Therefore, it can be determined if the biomimetic composition chosen to mimic bone actually did mimic the superior qualities of bone. The osteon orientation and density changes around a foramen giving it greater static strength and fatigue life. By comparing the heterogeneous beam with the preformed hole to the heterogeneous beam with a drilled hole, it can be determined whether preforming a hole increases fatigue life. To further solidify this claim, the two homogeneous beams can be compared to each other. The homogeneous beam with the preformed hole should have a longer fatigue life than the beam with the drilled hole. To fabricate these beams a fixture that could be put into the hot press needed to be designed and fabricated. A schematic for the fixture can be seen in Appendix D.

A fiber composite plate was fabricated to get a sense of the fabrication process. Fiber composite material was laid onto the existing hot press fixture. Once the material is layered onto the bottom plate, the top plate is put on to compress the material before it is put in the hot press. The material is then put into the hot press, which heats up and compresses the material until it meshes into a composite. Four layers of composite material were used and after the process was over, a composite that measured 0.76 mm in thickness was made. From this it was determined that it will take approximately 68 layers to generate a composite that is 14.5 mm thick. One problem will occur when fabricating the beams with preformed holes. To mimic this property, composite layers will be wrapped around the pegs, giving the fibers a transverse orientation. This causes the problem that there will be a fiber rich area around the peg. To combat this, sections of the material being layered adjacent to the peg will be cut out. This way, the extra fiber and resin from the material wrapped around the peg will seep into the cut out region, alleviating the fiber rich area.

Future Research

The foundation for fabricating these composite beams has now been laid. The next step in this process is to start fabricating these beams with the different compositions. Within this step, it must be determined how the materials will be layered for the heterogeneous beam so that they mesh together forming the beam. When this is completed the beams can be tested by a four-point-bend test to see whether the fatigue life has been increased. This will be determined by cyclically loading the beams and seeing how many cycles it takes to break each beam. A second method for analyzing these beams will be to stop them at a set amount of cycles, section them, and quantify the damage to the beams. The desired results are that the heterogeneous beams with the preformed holes have a longer fatigue life and show less damage at the same severity of cyclic loading than the other beams.

References

1 Garita, Barbara & Rapoff, Andrew. *Fibers About a Natural Hole in Bone: Osteon Trajectories About the Equine Metacarpus Nutrient Foramen*.

2 Garita, Barbara & Rapoff, Andrew. *Damage About Natural and Drilled Holes in Bone*.

3 Huang, J., Venkataraman, S., Rapoff, A., & Haftka, R.T. *Optimization of Axisymmetric Elastic Modulus Distributions around a hole for Increased Strength*.

4 Buskirk, S., Venkataraman, S, Rapoff, A., & Ifju, P. *Functionally Graded Biomimetic Plate with Hole.*

Appendix A: Determination of Osteon Diameter Ratios

Osteons vary in diameter depending on the location on the bone. Previous research (Garita & Rapoff ASME SBC 2003) quantified this and came up with the following graph:

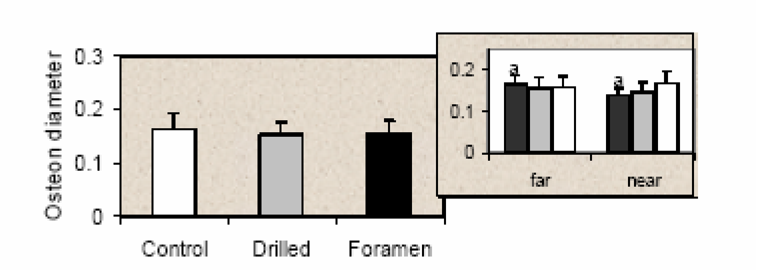
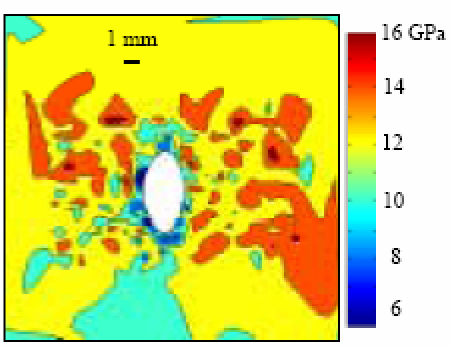


Figure 1. Osteon Diameter at Different Locations Across Bone.

This right side graph shows the osteon diameter at a distance far away from the foramen and near the foramen. The letter 'a' indicates that there is a significant difference between the two bars with the associated letters. This means that there is a significant difference between the osteon diameter near and far away from the foramen. Looking at these graphs, the approximate ratio of far:near osteon diameter was found to be 1.2:1. This was used to determine the osteon diameter ratio needed for the biomimetic beam.

Appendix B: Determination of Modulus Ratios

Previous research (Rapoff, Fontanel, Venkataraman, 2003) quantified the elasticity of a bone and the resulting spatial variation in longitudinal elastic modulus shown in Figure 1.



The white hole in the middle of the figure represents a foramen. The region directly around the foramen is blue, and at a distance away from the foramen changes to red. Using the scale, the modulus ratio of the bone near foramen:away from foramen is therefore approximately 2:1. This is how the modulus of elasticity for the materials in the fiber composite beam was determined.

Appendix C: Material Properties for Fiber Composites

The following appendix gives the material properties of the 4 materials that were considered. Materials were considered based on suitability as well as price.

	PAN-based Carbon		Fiberglass	
Characteristic	HM	HS	E Glass	S Glass
Diameter (µm)	7-10	7.6-8.6	8-14	10
Young's Modulus (GPa)	390	250	70	85

HM and HS stand for High Modulus and High Strength respectively, while E Glass and S Glass are just two different types of Fiberglass. After running the calculations, the two materials that yielded the closest to desired ratios were the High Strength PAN-based Carbon and the S Glass Fiberglass.

Appendix D: Schematic of Fixture

To make a composite with a preformed hole in it, a new fixture had to be manufactured. This fixture would have the ability to layer material around a protruding cylinder, so that while the fiber composite was being manufactured in the hot press, the material would form around this cylinder. This would create the effect of a preformed hole, similar to that of a foramen.

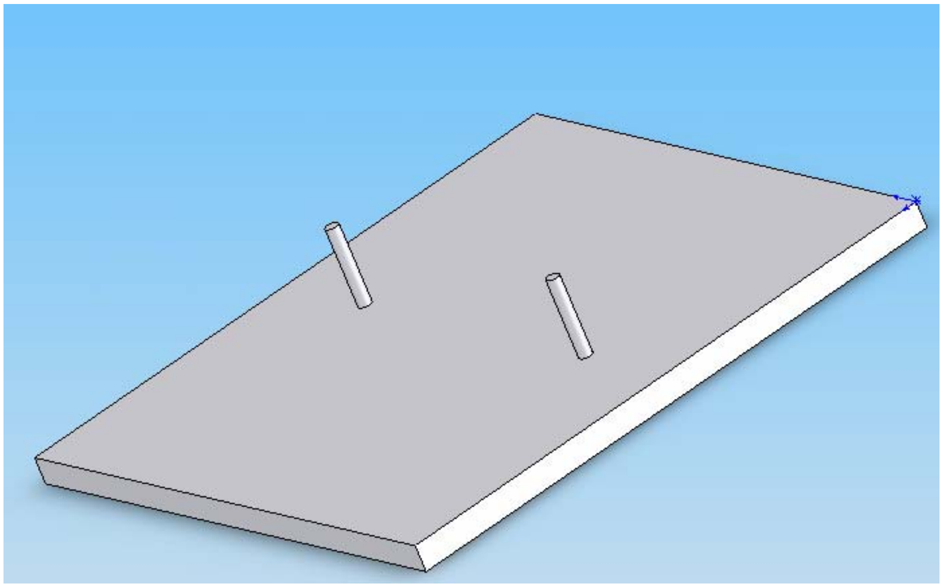


Figure 1. A schematic of the bottom plate of the fixture.

This is the bottom plate of the fixture. The material is layered on this plate. To create a preformed hole, the material can be layered around either of the protruding pegs. The preformed hole mimics the foramen in bone. There is enough room between the two pegs to fabricate a beam with no hole, so this beam can have a hole drilled into it.

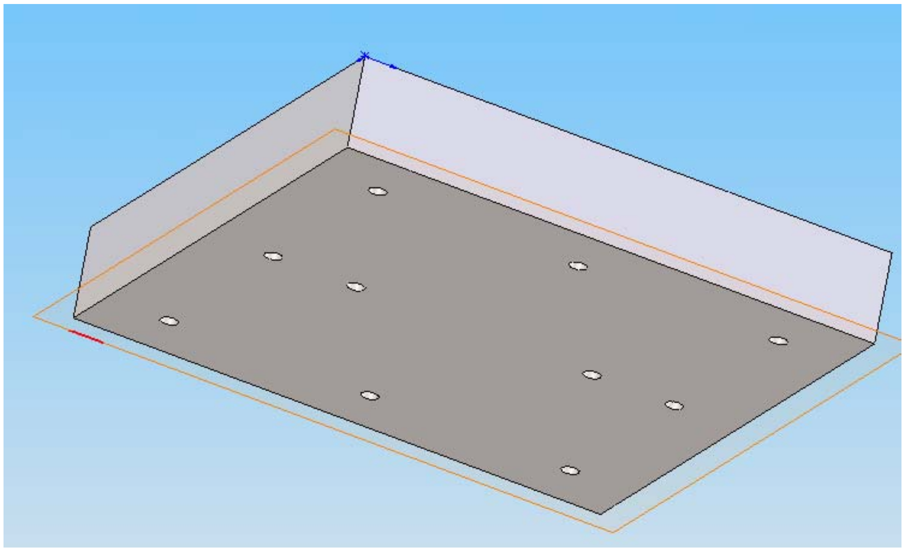


Figure 2. A schematic of the bottom plate of the fixture.

The top plate contains holes at the same location as the protruding pegs so the two surfaces will sit flush. Once the material is layered onto the bottom plate, the top plate is put on to compress the material before it is put in the hot press. The material is then put into the hot press, which heats up and compresses the material until it meshes into a composite.