Fatigue-Resistant Composite Beam based on the Microstructure of Bone

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Introduction

Previous research (Garita & Rapoff ASME SBC 2003) discovered that bones have a reduced stress concentration at naturally occurring holes (called a foramen) by varying its composition. It was discovered that composition determined stress and strength distributions near foramen that in turn caused a reduced stress concentration at the foramen This knowledge lead to the design, fabrication and testing of lightweight plates that mimicked the compositional and mechanical properties distributions, increasing the static strength performance found near the foramen. It was also learned that the internal micro-architecture of the bone in the vicinity of the foramen also increased its resistance to crack formation and crack propagation under cyclic loading. This project will use this to determine the beam composition and fabrication process needed to make fiber composite beams with similar microstructure to bone.

Beam Composition and Dimensions

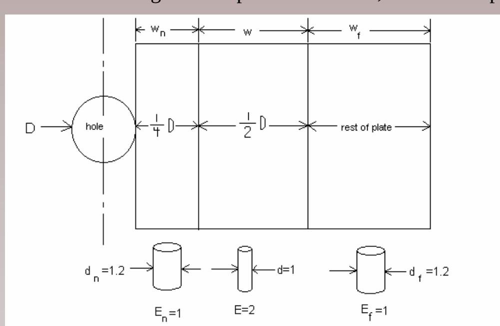
This project consisted of several steps to determine the beam composition and dimensions. The first was to determine the proper materials that could mimic bone. From a macroscopic scale, bones appear to be uniform in structure. On a microscopic scale, bones are actually a composite structure consisting of discontinuous fibers. These fibers are called osteons, and are the basic microstructure of bone. It was also determined that there was an osteon diameter gradient across the bone. It was from this knowledge that the idea of using fiber composite material could be used. The fibers of the composite material can mimic the osteons in the microstructure of bone; osteons are likened to fibers in fibrous composites. From previous research, it was further found that the elasticity across a bone varies. Bones adapt to the presence of a foramen. This research showed there is a compliant region near the foramen and a stiffer region some distance away. This led to the notion that two materials were needed to mimic bone – a compliant one for the area around the foramen and a stiffer one for a distance away. With this knowledge, calculations were done to find the correct osteon diameter ratios and stiffness ratios that would mimic bone.

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

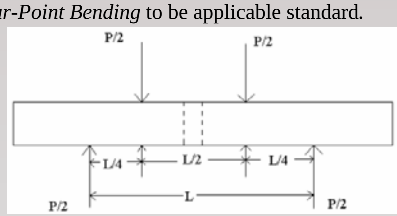
Material 1 is more compliant and therefore used for the area around the hole. After researching a lot of materials, a PAN-based carbon fiber material and an S-Glass fiberglass material were found to have the closest desired ratios.

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

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.



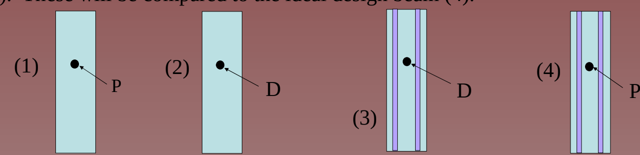
From this it was determined that the fiberglass would be used around the foramen and at a distance away from the foramen with the carbon material in between. The next step was to find the proper ASTM Standard that applied for this project. The standard entitled *Standard Test Method for Flexural Properties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



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 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.

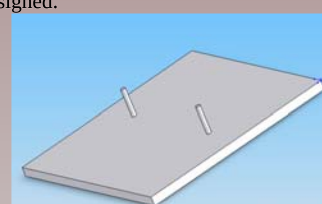
Fabrication Process

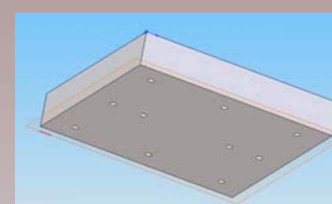
Now that the composition of this beam was determined, the other beam designs in order to compare results needed to be determined. The decision was made to fabricate three other beams to compare: a homogeneous beam with a preformed hole (1), a homogeneous beam with a drilled hole (2), and a heterogeneous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



P = preformed hole; D = drilled hole. The darker strips indicate a different material.

A preformed hole is one that is formed in the beam during the fabrication process rather than having it drilled in after. After these beams have been cyclically loaded the results can be compared. Beam (4) can be compared to beam (1) to test whether the modulus of elasticity gradient increases fatigue life. The only variable that will be different is the composition, so its effect can be tested. This is also true when comparing beams (2) and (3). Beam (4) can also be compared to beam (3) to test whether the preformed hole increases fatigue life. The osteon orientation and density changes around a foramen giving it greater static strength and fatigue life. By comparing beam (4) to beam (3), it can be determined whether preforming a hole increases fatigue life. To further solidify this claim, beam (1) and beam (2) can be compared to each other. The holes will be preformed during the fabrication process, however to do this, a new fixture needed to be designed.





The above left image 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. It was previously determined (Garita & Rapoff, 2003) that the osteons are oriented in a transverse direction which may increase the toughness of this region. 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. The above right image is the top plate was also designed containing holes at the same location as the protruding pegs. 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. This process was completed to get an idea of how it worked. Four layers of material were layered onto a fixture and put it in the hot press. After the process was over, a composite that measured 0.76 mm in thickness was made. It was then determined that it will take approximately 68 layers to generate a composite that is 14.5 mm thick.

Future Work

The next step in this process is to start fabricating all four of the beam designs. 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.

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