Finite Element Analysis of a Beetle's Forewing

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Abstract

Mechanical properties of biological materials are often studied for information that can be used to improve the design of synthetic biomaterials. Beetles have been examined due to the availability of millions of different species and their long process of evolution, which has selected for beetles with properties adapted to their surroundings. In order to gain insights that might improve the design of lightweight composite structures, we analyzed the structure and mechanical properties of the *Allomyrina dichotoma* beetle's wing. Finite element analysis (FEA) was performed on a male and female forewing to determine where the stresses occur in the forewing. Two, two-dimensional cross-sections of the wings were created in COMSOL Multiphysics. The resulting von Mises stress and the normal and shear stresses were analyzed from an applied loading. From these figures, lower stress levels were shown on the female forewing in comparison to the thinner male wing design. The von Mises and normal stress plots show the most stress around the outside edges, with minimal stress towards the middle of the wing. Additionally the results show low levels of shear stress around the whole part, with only one area of concentrated stress. These results demonstrate that the female forewing design is a better model for most lightweight composite structures unless a more economical, lighter design is needed, in which case, the male forewing is a better model.

Introduction

Lightweight composite structures have many different applications in medicine, aeronautics, and construction engineering. One potential source of information that might improve the design of lightweight composite structures is found in nature, specifically with beetles. With over six million species and a long evolutionary history, each species of beetle has adapted to its unique surroundings. The beetle's forewing is of particular interest because the beetle is a flying creature and everything on the beetle must be as light as possible. In addition, the beetle's forewing is its main defense against foreign elements or creatures. This is especially important for the female *Allomyrina dichotoma* beetles because they do not have a horn like the male species. These characteristics make a beetle's forewing a useful model for lightweight composite structure design.

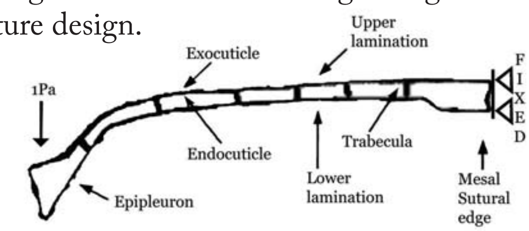

Figure 1 Cross section of a beetle's forewing with key characteristics and finite element analysis constraints and forces labeled. Re-drawn from Ref. 1.

The beetle's forewing is comprised of several parts (reviewed in Ref. 1; Figure 1). The outside of the wing is the exocuticle, which is mainly comprised of proteins. The top and bottom layers of the wing, called the upper and lower laminations, are comprised of chitin fiber and protein layers. The chitin layers found towards the middle of the wing are called the endocuticle and are connected to the trabeculae. These trabeculae are found in the void lamination, which creates a sandwich plate structure. Other important features of the beetle's forewing are the epipleuron, which is the outside edge of the wing, and the mesal sutural edge, the opposite edge.

For this study, a two-dimensional (2D) representation of the beetle wing was examined to explore the stresses found from an applied load. Since male and female beetles have different forewing thicknesses, male and female models were tested and compared with each other.

Methods

Creation of 2D CAD figure

We created a 2D CAD model in SOLIDWORKS DWGEditor (Dassault Systèmes Solid Works, Cambridge, MA) by importing a previously published model of the beetle forewing scaled to the reported size dimensions (1). We generated models for both the male and female beetle forewings because their lengths and heights differ slightly by gender. By picking key points in the figure, the cross section was traced with the line and curve options in SOLDIWORKDS DWGEditor. This step simplified the cross section, eliminating unnecessary details that would be too computationally intensive for the FEA. These drawings were then exported as AutoCAD 2000 ASCII DXF files.

COMSOL Analysis

After creating the 2D profile of the beetle's forewing, the profile was imported into COMSOL Multiphysics 3.4 ((COMSOL AB, Stockholm, SE). For this 2D profile, we used the 2D plane stress option. The profile was imported into COMSOL as curves, which we fit to an area. This area was converted into a mesh, which was refined two times, creating a fine mesh for this profile. The computation time was slightly increased due to the mesh refinement. The meshes are shown in Figure 2a and 2b.

We used the meshes we created to assign profiles. A different material was created for both the male and female forewing profiles. To define a new material, the user must define several material properties including the modulus of elasticity, Poisson's ratio, a thermal coefficient and density and thickness of the material. We identified an approximated value for the modulus of elasticity in previously published work (2). We obtained and calculated the remaining values needed from previously published data (1). More specifically, we calculated the area of the forewing from the tensile test results (force/stress) reported in reference (1). We calculated the volume of the wing by multiplying this area by the previously reported thickness values (1). From here, we calculated the density of the forewing by dividing the volume by the previously reported mass (1). These values are shown in Table 1. The thermal coefficient and Poisson's ratio values were left at the defaults since they do not affect the stress on the forewing. For future study, the Poisson's ratio could be analyzed and calculated from experimental values (2).

After defining the material, we applied boundary conditions. For these tests, the mesal sutural edge was held fixed. This edge was selected since it is where the wing attaches to the beetle. A 1 Pa follower load was then applied to the epipleuron, the opposite edge. The value of 1 Pa was chosen due to it being large enough that a deformation was visible but not enough to have the profile fail. Applying the force on the opposite edge of the forewing produces the maximum moment at the fixed constraint. For reference, Figure 1 shows where the fixed and the 1 Pa load boundary conditions were applied. With the loads applied, the solve function of COMSOL was used to view the results from the boundary conditions.

Table 1 Values used to create materials in COMSOL

	Male	**Female**
Mass[1] (g)	0.151	0.160
Stress Applied[1] (MPa)	130.7	127.9
Force Applied[1] (kN)	28.1	35.6
Area[2] (mm^2)	215	278
Thickness[1] (μm)	54.0	69.7
Volume[2] (mm^3)	11.6	19.4
Density[2] (kg/m^3)	13,000	8,250
Shear Modulus of Elasticity[3]	1 GPa	

[1] Reported in (1);
[2] Calculated from values in (1)
[3] Estimated from (2)

More specifically, COMSOL solves the equilibrium equations of linear elasticity, $\nabla \bullet \sigma = 0$, where σ is the Cauchy stress tensor and $\nabla \bullet$ is the divergence operator. For an isotropic material, the constitutive relation is given, using the index notation, by

$$\varepsilon_{ij} = 1/E\ [(1 + \nu)\sigma_{ij} - \nu\delta_{ij}\sigma_{kk}] \qquad (1)$$

where ε_{ij} is the ij component of the strain tensor, ν is Poisson's ratio, and E is Young's modulus. Further explanation can be found in COMSOL's help files and documentation.

Results and Discussion

Von Mises stress

After 0.5 seconds, COMSOL solved the model and displayed the von Mises stress. The von Mises stress is a scalar stress value used to predict material failure. To compute the von Mises stress, COMSOL uses the Cauchy stress relationship. Figure 2c shows the results for the female forewing, while Figure 2d shows the

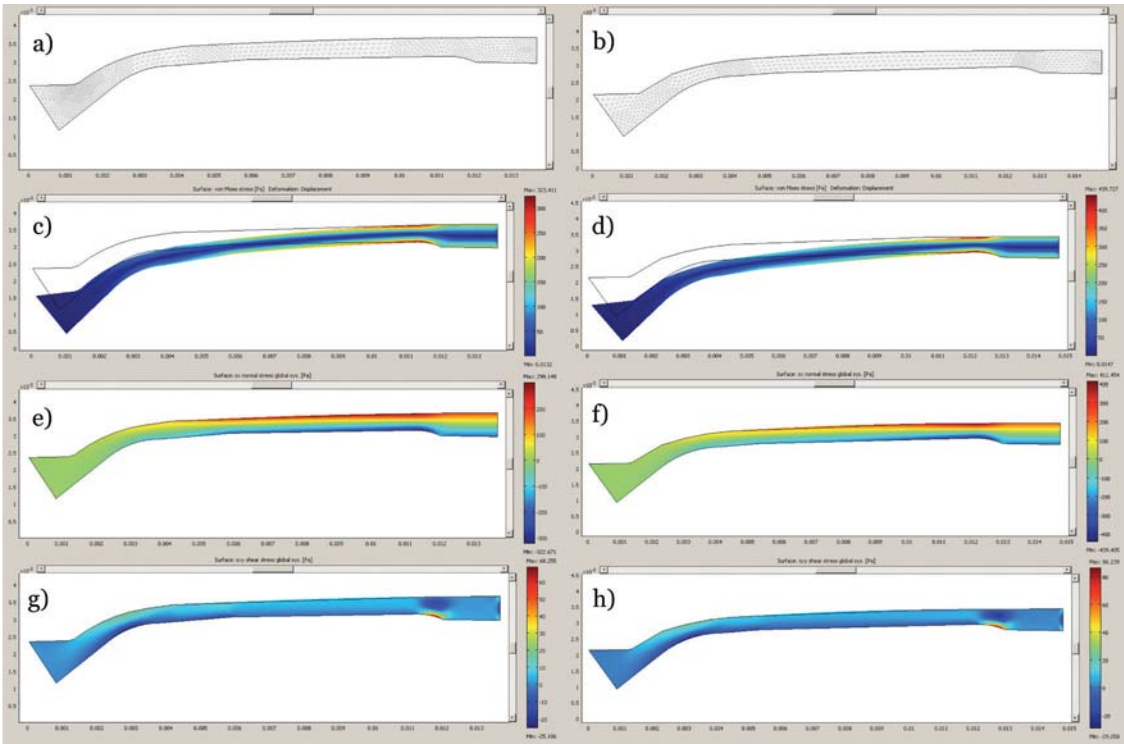

Figure 2 Comsol Stress Analysis. The finite element mesh of the a) female forewing and b) male forewing; Von Mises stress deformation due to 1 Pa load on the c) female forewing and d) male forewing; Normal stress deformation due to 1 Pa load on the e) female forewing and f) male forewing; Shear stress deformation due to 1 Pa load on the g) female forewing and h) male forewing.

results for the male forewing. The outlined shape is the original profile for comparison against the deformed shape with the color-coded, stress levels. As shown on the scale on the right side of each figure, the female forewing experiences 323 Pa, which is significantly less stress than the male forewing of 440 Pa. This follows the prediction that the stress on the female forewing would be less due to it being thicker. These figures also show that the high points of the stress occur at the area where the forewing tapers off the most near the mesal sutural edge.

Stress in the x-direction and plane

To understand the location of the maximum tensile and compressive stresses, the settings were changed to view the normal stress in the x-direction and x-plane. For the profiles, the x-axis is the same as the x-direction. These results are shown for the female and male forewing in Figures 2e and 2f, respectively. To simplify the figures, only the original profile is shown. For Figure 2e, the maximum normal stress is 298 Pa and the minimum is -323 Pa, and for Figure 2f, the maximum normal stress is 411 Pa with a minimum of -439 Pa.

Comparing Figures 2e and 2f to 2c and 2d reveals that the maximum stress for the von Mises stress is almost the minimum stress on the normal stress plots. This means that the maximum stress that the beetle forewing experiences is compressive.

As expected, the top of the profile is in tension and the bottom of the figure is in compression. Figures 2e and 2f also reveal that the difference in maximum tensile and compressive stresses is the same for both male and female forewings in spite of their differences in size and thickness.

Shear distribution

Another important design consideration is how much shear stress the profile experiences. Even though an object is able to withstand the normal forces, the object may fail due to the amount of shear stress acting on it. With this in mind, a plot of the amount of shear stress in the forewing was created for both female and male forewings, shown in Figures 2g and 2h, respectively. As with Figures 2e and 2f, only the original shape of the forewing is shown.

Analysis of the figures reveals that the maximum normal and shear stresses occur in the same location. For Figure 2g, the maximum shear stress is 68.3 Pa with a minimum of -25.1 Pa, and Figure 2h has a maximum shear stress of 86.2 Pa with a minimum of

-29.1 Pa. As anticipated, the amount of shear stress the profile experiences is significantly less than the normal stress it experiences. It is also important to note that the shear stress, τ_{xy}, in Figures 2g and 2h is the shear stress on the plane perpendicular to the y-axis. This can be slightly different from the plane of the outer edge of the profile. Theoretically, there should be no shear stress at the outer edges of the profile, and the shear stress should increase the further it is away from the edges. With a thin forewing, there is not as much of an increase in shear stress. The figures also show that both forewings experience the same amount of negative shear stress; however the maximum shear stress vastly differs between the male and female forewings.

Potential differences with biological forewings

It should be noted that there is a region of very little stress in the middle of both of the forewings. This is the void lamination, which for simplicity was left as being purely void. In actuality, this area is filled with trabeculae for structural support. Prior research has investigated the structure of the chitin and protein layers and shown that there is a special interlacing between the two that creates a higher strength in the material (1,3,4). With COMSOL, there was no easy way to represent this structure. Therefore, the structure was left out of our simulations. This absence is a limitation of this method of analysis because the presence of the trabeculae would cause less deformation in the forewing. However, this simplification does not interfere with the interpretations of the comparisons between male and female forewings because trabeculae are present in similar amounts in both sexes.

Even with these limitations, COMSOL showed that there are many advantages to this design. The void lamination region in the beetle's wing model is advantageous for many reasons. Without having the chitin and protein layers in that region, it decreases the overall weight of the wing. Even though it creates more normal stress on the upper and lower laminations of the wing, it allows the wing to experience a lower maximum shear stress.

Comparison of parameters between male and female

From the figures it appears that the female *A. dichotoma* beetle forewing design is the optimal structure. Even though prior literature (1) has found it to be slightly heavier, the thicker upper and lower laminations prove to make it an advantageous design. As shown in the figures, the female forewing design creates a significantly lower normal stress and a lower shear stress.

Conclusions

To conclude, we examined properties of male and female beetles' forewings to gain insights into how their design differences impact stress tolerance. Due to a beetle's need to fly and given that the forewings are on the outside of the exoskeleton, each wing needs to be light and strong. The results showed that the female forewing has a design that experiences less stress overall than the male forewing and that the majority of the stress for both occurs near the mesal sutural edge. Therefore, we concluded that the female forewing design is a better model for most lightweight composite structures unless a more economical, lighter design is needed, in which case, the male forewing is a better model for design.

Future research could examine how the profile would perform with additional loads applied to it. 3D FEA may also reveal additional differences between the male and female forewing.

Acknowledgements

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