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A DEVICE FOR MEASURING THE FLEXURAL STIFFNESS OF INSECT WINGS, OR HOW TO MAKE A WING-BAR GIZMO

Brandon S. Field[1], **Julian L. Davis**, **Evan M. Taylor**, **Louis J. Volz** and **Eric S. McCloud**: University of Southern Indiana, 8600 University Blvd., Evansville, IN 47712, USA

ABSTRACT. Flexural stiffness is an important property of many biological structures, including insect wings, but measuring it can prove challenging when the structures to be measured are small and light or have a low elastic modulus. We have designed, constructed, and tested a rugged and inexpensive device for measuring flexural stiffness. The apparatus was validated by testing with fine gage copper wire and comparing our results with those obtained from standard test equipment used for tensile testing. It is shown that results can be obtained with the wings of small butterflies. Preliminary findings on *Strymon melinus* (Hübner), the Gray Hairstreak, showed that the stiffness measurements of the butterfly wings were repeatable and therefore the testing mechanism was not damaging the wings. Little variation was found between the dorsal and ventral direction in the experimental measurements. The stiffness tester provides a simple, low cost, means to measure the flexural stiffness of small and light biological structures. This device is well within reach, and provides a means, of quality research in a small college or university setting.

Keywords: Flexural stiffness, insect wings, experimental apparatus

INTRODUCTION

Interest in the mechanical properties of insect wings has primarily been motivated by the desire to understand the mechanics of insect flight. For instance, an important application has been replicating essential features of these structures in biomimetic micro-air-vehicles (Karpelson et al. 2008). While a good portion of the work has been related to understanding the micro-scale and unsteady fluid mechanics, there is also significant interest in measuring and understanding the structural properties of the insect wings. Understanding the mechanics of insect flight may elucidate subjects as diverse as the energetics of foraging to the constraints on non-flight related wing functions (Dudley 2000).

The structural property of a wing that relates to the strength of the wing and also the deformation during flight is the flexural stiffness. The flexural stiffness of a structure is the product of Young's modulus, E, which is a material property describing the relationship between stress and strain, and the second area moment of inertia, I, which is a geometric quantity. Flexural stiffness represents the resistance to deformation under a load at a specific length along the structure. A higher flexural stiffness indicates less deflection occurs for equally applied forces. The flexural stiffness of a cantilevered structure, EI (Fig. 1) relates the displacement of the end of a structure, δ, the force applied to the beam, F, and the length from the mounted end at which the force is applied, L:

$$EI = \frac{FL^3}{3\delta} \tag{1}$$

Early examinations and cataloging of the structure of insect wings were documented by Comstock (1918) and Martynov (1925). Subsequently, Rees (1975) explored the corrugated structure and its contribution to the wing's flexural stiffness, noting that the leading edges are more strongly corrugated. Kesel et al. (1998) examined the folded structure of dragonfly and common house-fly wings, finding the overall wing experiences stress-stiffening as the folds are straightened. This result accords with the microstructure and intermolecular interactions among chitin chains in chitin microfibrils that make up the wing. Vincent & Wegst (2004) present a review showing that the mechanical properties of cuticle vary widely, spanning several orders of magnitude, depending on molecular and protein arrangements and water

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[1] *Corresponding author:* Brandon S. Field, 812-464-1882 (phone), bsfield@usi.edu.

Figure 1.—Geometry of a generic beam deflection, illustrating the measured values used to calculate flexural stiffness of a structure. Length (*L*) from the fixed end to the location at which force (*F*) is applied and the deflection (*δ*) of the structure at the force location. These three measured values are used in equation 1 to determine flexural stiffness.

content. Dirks & Taylor (2012) examined the structure of the wing veins in a locust and observed that cross-veins act to prevent the growth of cracks that form from defects in the wing material. Vein spacing and wing material properties could strike a balance between strength and weight in the wing.

In a search for a relationship between flexural stiffness and other morphological parameters, Steppan (2000) constructed a wing bending apparatus to measure the flexural stiffness profiles of dried wings from ten different species of butterflies. The testing apparatus was a loading bar which pushed down on a wing that was mounted horizontally by mounting one or two mm of the basal attachment regions of the wings between two glass microscope slides. This loading bar applied a line load on the wing, perpendicular to the wing span, to mimic the aerodynamic loading that occurs on a wing in flight. Deflection of the wing was determined by measuring the displacement of the bar with a linear variable differential transformer attached to the loading bar. Force was measured by a transducer that appears to have been connected directly to the loading bar.

Combes & Daniel (2003a) measured the flexural stiffness of sixteen different insect species in both the span-wise and chord-wise directions by pushing with a pin on a single point, located 70% of the way along the wing length. The pin was mounted on a flexible beam that was used to measure displacement and instrumented with a force transducer that measured the force pushing on the wing. In the second part of the study (Combes & Daniel, 2003b), they used a laser to illuminate the wing before and after deformation, and optical analysis was used to measure the displacement profile across the wing. By assuming various stiffness profiles and matching the displacement results, the local stiffness values of the wing were determined.

Measurement of small forces (on the order of millinewtons) and displacements (on the order of tens of micrometers) are needed to determine the flexural stiffness of insect wings. However, the expense of equipment typically used can be a road block to collecting these data and all of the studies cited here required force transducers and other expensive measurement equipment: an apparatus similar to the ones reported in these studies could cost as much as $15,000.

This paper describes a rugged, simple to use, and inexpensive apparatus for measuring the flexural stiffness of butterfly wings. The apparatus was designed, tested and implemented with less than $1000 for materials purchased. The apparatus was constructed to use an analytical balance, which is equipment typically found in a biology or chemistry laboratory. Machining time was provided free of charge by the departmental machinist, and would have added a few hundred dollars to the overall cost. This design and procedure provide an easily accessible and affordable opportunity for more biomechanical measurements of flexural stiffness of insect wings, and may find additional applications with other biological materials with small stiffness such as feathers or small bones.

METHODS

Design of wing bar testing apparatus.—The test apparatus was constructed to measure the flexural stiffness of a butterfly wing in bending mode (Fig. 2). The load applied to measure the flexural stiffness was applied in a line force, along a line perpendicular to the major branches of the medial and cubital veins. The three species that this device was designed to test were the *Strymon melinus* (Hübner) or Gray Hairstreak, *Cupido comyntas* or Eastern Tailed Blue, and *Celastrina ladon* or Spring Azure. The wings of all these species are similarly sized, however larger species could easily be tested within the apparatus device. Maximum size is limited only by the traverse length of the micromanipulator stage.

The apparatus consisted of an analytical balance to measure the applied force and a pair of orthogonally-mounted micromanipulators (Model number NT37-936, Edmund Scientific,

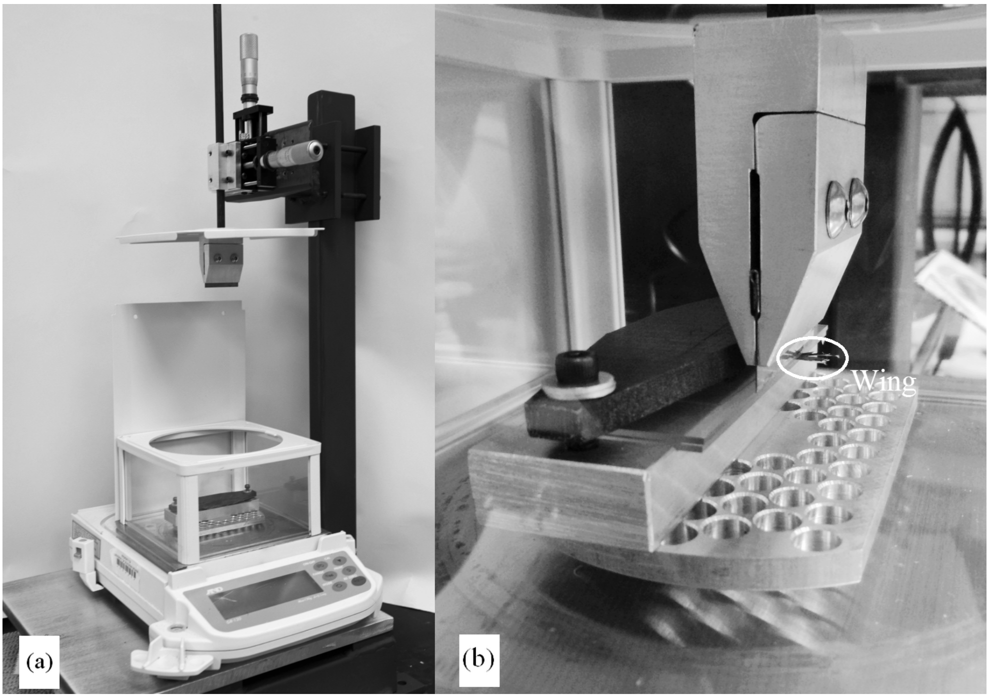

Figure 2.—(a) Photo of the wing bar testing apparatus with the micromanipulator stages visible. The enclosure of the balance was modified to reduce the distance between the wing and the micromanipulators and to minimize any potential effect of vibrations. (b) The wing-bar and a wing mounted in the glass slides. The mounting device that held the slides was inserted in place of the balance pan, and the holes drilled in the aluminum support matched the weights of the mounting device and balance pan.

Tonawanda, NY) to provide displacement in the horizontal (along the wing) and vertical (pressing on the wing) directions. The micromanipulators had 0.01 mm resolution marks, and were mounted to translational stages that were attached to an arm that was suspended above an aluminum plate and steel base for the balance. This arm and base were fabricated in the machine shop from rectangular steel bar stock and an aluminum plate of 13.5 mm thickness. Two aspects of the construction were critical for repeatable and accurate data: the overall sturdiness of the arm and the right angle that the arm formed with the base. Attached to the translating stages was an 8.0 mm diameter carbon fiber rod that extended downward to the balance and held a dulled, single-edged razor blade that provided the line force to the wing. The razor blade was slightly dulled so that there was no chance of slicing the wing, but it was still sharp enough to provide a narrow application of the load distributed across the anterior-posterior axis of the wing. The tall sliding wind screens of the analytical balance were removed and replaced with shorter ones to decrease the distance between the wing and the micromanipulators (Fig. 2a), reducing any potential vibrations in the rod.

Tested wings were glued between two glass microscope slides with cyanoacrylate glue as per Steppan (2000). The pan of the balance was replaced with a mounting device that held the slides by a piece of Bakelite (5 mm thickness) screwed to an aluminum block (11.4 mm). The screws passed through the aluminum block and into a perforated aluminum plate (5.4 mm) that served as a modified balance pan (Fig. 2b). On its bottom side, the modified pan had a milled conical protrusion that matched the dimensions of the pin from the original balance pan. The holder was aligned on the modified balance pan so that the edge of the holder passed over the center of the pin of the balance pan. Two aspects of the construction of the slide holder were critical, first that the mounting device was a sufficient replacement for the balance pan, in both total weight (not too much heavier) and in the mounting connection. The second critical aspect of the holder was that the slide and the wing be held sturdily and orthogonal to the razor blade supplying the force. Other than these critical aspects, the specific details of the wing mounting device are not critical.

Testing Procedure.—Butterfly wings and copper wire specimens used for validation were first mounted between a sandwich of two glass slides, the edges of which were kept flush to each other. Cover slips were used as spacers between the glass slides as needed and no more than 1 mm of the wing base was used to glue the wing between the two slides in the sandwich. After the glue set, the mounted wings were checked to insure flatness and perpendicular alignment of the leading edge to the edge of the glass slides. Straightened pieces of soft copper wire (16 AWG and 24 AWG, ca. 20 mm length) were mounted in a similar fashion. The mounted specimens were then screwed into the holder on the modified balance pan.

Screws were tightened on either end of the holder to fix the slide and specimen sandwich in place as well as to fix the holder to the modified balance pan. After measuring the length of the specimen, the micromanipulators were used to position the razor blade wing bar over different percentage distances along the span. At each distance where measurements were collected, the wing bar was carefully moved into a position in which it was just touching the specimen and the balance displayed a zero reading. Then, five to seven displacements of the wing were made by using the micromanipulators to advance the wing bar downward in 10 μm increments. At each of these successive deflections, the scale was read and the resulting *EI* was estimated from the slope of the linear regression of force on deflection following Equation 1.

It should be noted that Equation 1 was derived assuming a *linear elastic* response of a structure (Callister 1994). If the structure modeled using this equation does not behave linearly or elastically, the equation cannot be used to derive the flexural stiffness (the product *EI*). Any non-linearity would mean that the deformations had surpassed the elastic range or that the wing had been damaged in the testing procedure, in which case the wing data would have to be discarded.

Validation Experiments.—To confirm that the device could accurately measure the properties of samples, five samples of copper wire were tested, using a slightly modified procedure with small pieces of the wire as spacers between the slides instead of glass coverslips. Measuring force and displacement on a copper wire allowed for the calculation of Young's modulus, *E*, since the area moment of inertia, *I*, can be calculated for cylindrical wire from its diameter and the slope of the force deflection curves obtained can be substituted into Equation 1 to solve for *E*. Samples of the same wire were subjected to tensile testing in an Instron (UTM, model 5592-F1, Grove City, PA) 10 kN tensile tester and the slopes of the early elastic region of the stress-strain curve were used to estimate Young's modulus. According to isotropic theory, the modulus should be the same in tension or bending (Beer et al. 1992); however, in real metals the elastic modulus varies depending on the crystallographic orientation (Callister 1994).

RESULTS

Copper Wire.—For copper wire, the relationship between applied force and deflection was strongly linear across distances between 7 and 22 mm and deflections between 10 and 50 μm (Fig. 3). Since the slopes of the force-deflection curves increased slightly at distances closer to the mounting fixture, the calculated values of *E* decreased accordingly. Tensile testing of samples taken from a different part of the same copper wires generated values between 52 and 83 GPa with 3 of 4 tests yielding values between 78 and 83 GPa (Fig. 4). The value for the isotropic elastic modulus of pure copper was found to be 110 GPa (Beer et al. 1992), which is also shown in Fig. 4. The range of the anisotropic elastic moduli was found to be 67 to 191 GPa (Callister 1994). The elastic moduli calculated from the measured force-displacement ranged from 72 to 106 GPa.

Butterfly Wings.—Representative force-deflection data from the hind wing of *Strymon melinus* (Hübner), the Gray Hairstreak, show strong linearity at distances between 3.20 and 9.59 mm from the mounting fixture and over deflections from 10 to 250 μm (Fig. 5). This linearity in force-displacement was found in every wing that was tested, indicating that the wings were within the linear elastic region of deformation. Therefore, Equation 1 could be

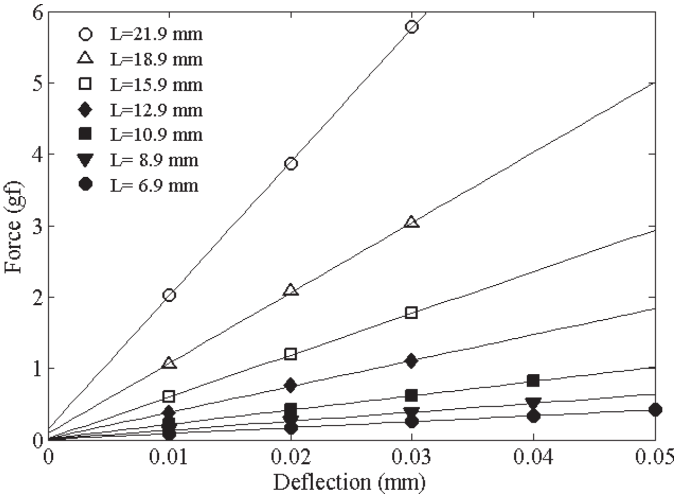

Figure 3.—Force vs. deflection for a series of tests on one copper wire at varying lengths, *L*. The linearity of the force-deflection curves confirms the validity of Equation 1. Linear beam theory is appropriate for this application. Forces reported in gram-force (gf), because the analytical balance measured in gram-force.

used validly to determine the flexural stiffness, *EI*. In addition, a series of dry wings were tested multiple times bending in the dorsal and ventral directions, to verify that no hysteresis effects could be observed from multiple trials of bending the same wing. If the wing were damaged by the device while it was being tested, subsequent tests on the same wing would yield different results. This was not the case (Fig. 6), and the device seemed capable of bending the wings without causing damage.

Flexural stiffness was found to vary across the wingspan, in general increasing distally. Some variation in flexural stiffness was ob-

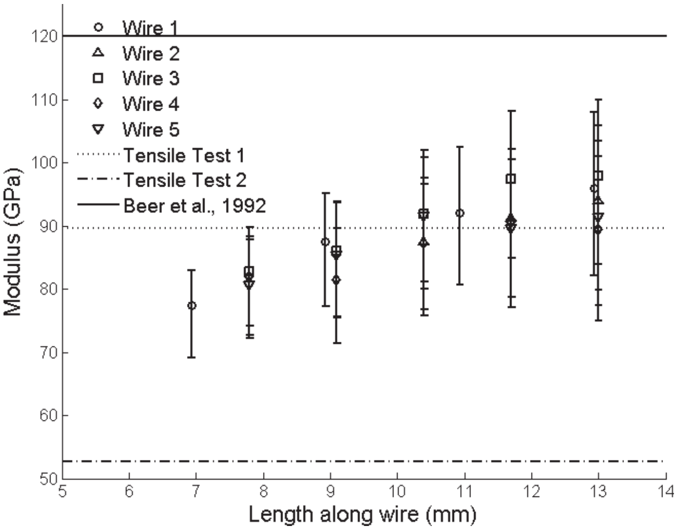

Figure 4.—Elastic modulus, *E*, for four different copper wires, measured at different lengths along the wire. The straight lines represent the elastic modulus for a different section of the same wires, measured in a tensile test, or given in a textbook. The error bars on the data points represent the total uncertainty for each point as determined by the cumulative effect of all measurements.

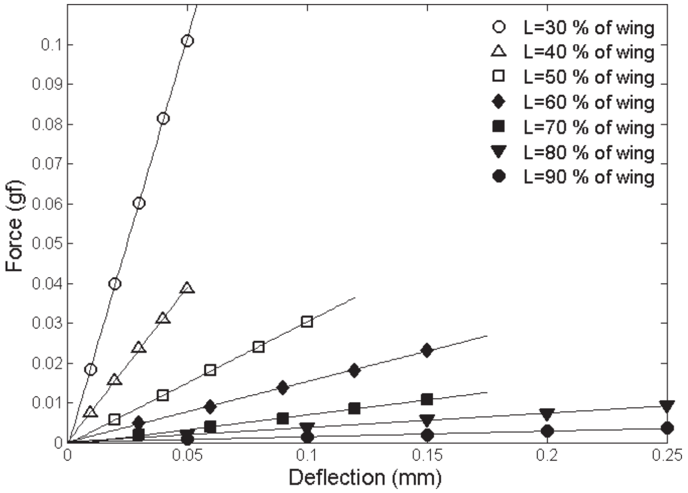

Figure 5.—Representative force-deflection data for a wing of a Grey Hairstreak butterfly at increasing lengths from the wing mount. The linearity of the wing deflections is evident in this plot, and every wing tested had a linear force-deflection relationship. Forces reported in gram-force (gf) because the analytical balance measured in gram-force.

served between tests on the dorsal and the ventral side of the wings, but no final conclusions can be made without more testing.

DISCUSSION

A testing apparatus (Fig. 2) has been developed and validated that can be used to measure small forces and displacements. The apparatus was constructed from inexpensive or available equipment, and its design could easily be replicated by researchers at any size institution. The force measurement was performed on an analytical balance, which was already available, and the wing-holding mount was made to be removable so that the scale's use was not hindered. By using the balance a force gage was not required; a force gage of sensitivity similar to the balance, such as those used by other researchers (Combes & Daniel 2003b; Smith et al. 2000; Steppan 2000), can cost approximately $2000. This is not the first instance of this cost-reducing procedure: Mountcastle & Daniel

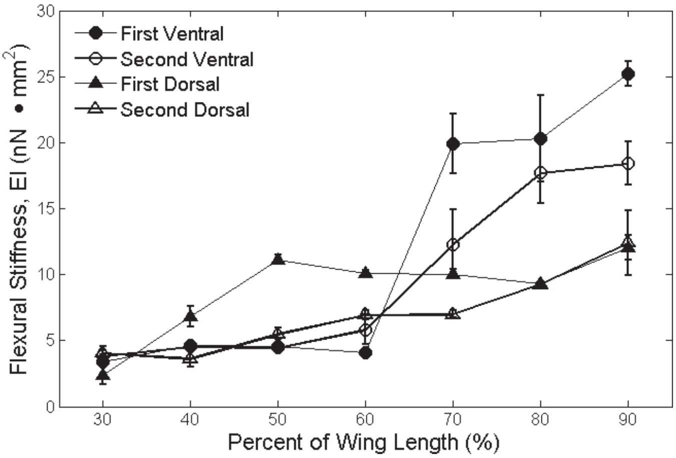

Figure 6.—Flexural stiffness measurements at different percentages of the total wing length along a Grey Hairstreak butterfly wing. This figure shows that there is little change in flexural stiffness with respect to the order in which each side of the wing, dorsal versus ventral, is tested first. The same stiffness profiles are observed, indicating that no damage is done to the wings by the testing procedure.

(2010) used an analytical balance to measure the force applied to a bending wings by mounting a pin to the pan of the balance and lowering the wing onto the pin. Two stages with manipulators were obtained for approximately $700, which allowed for positioning the deflection bar and applying the deflection; previous researchers have also used linear translators to apply deflection to the wings, and quotes for similar equipment exceeded $10,000. The cost of the raw materials for the present apparatus was $55; in our case the manufacturing was provided gratis by the departmental machinist, but labor time could add $500 to $1000 to the total cost. A trained undergraduate student operator can test as many as eight wings a day on this apparatus.

Validation of this apparatus has been performed with copper wire. Force-deflection data were found to be linear, confirming that elastic modulus can be calculated using Equation 1. Furthermore, the calculated values of the elastic modulus in bending, E, compared well to the values of the elastic modulus found in tensile tests and textbook values (Fig. 4). For a homogeneous material, the elastic modulus should be the same under tension and bending, but this is not always the case.

Steppan (2000) tested ten different species of butterflies in his wing bar apparatus. The stiffness patterns of the dry wings from all the different species (which he reported in tabular form) differed from each other, but when they were normalized and averaged across all the species, the profiles (presented in a plot) showed a peak in stiffness around the 50% location. Bending the wings in the dorsal or ventral direction made little difference in the stiffness profiles for most of the tested species. Stiffness patterns from fresh and dry wings from *Vanessa cardui* (L.), the Painted Lady, were tested and the dried wings were found to have higher stiffness than the fresh wings, although the shapes of the stiffness pattern along the length of the wing remained similar to each other. The shape of the preliminary stiffness profiles that were found with the present apparatus showed agreement with some of the species that Steppan tested, and little difference was found between pushing from the dorsal or ventral direction in the preliminary data (Fig. 6). However, the results presented here from bent wings are not sufficient to draw any conclusions.

The flexural stiffness measurements made by Combes & Daniel (2003a, 2003b) were done by applying a force at a single point, 70% along the wing. Flexural stiffness was highly correlated with the size of the wing, but not with the vein patterns. Observing the spatial deflection optically, they determined the flexural stiffness profiles for two species. They noted, however, that their force-deflection curves were nonlinear. By applying a line load to the wing, we only observed linear force-displacement curves (Fig. 5). In a separate study of wing flexing, Combes & Daniel (2003c) demonstrated the inertial forces in the flapping wings are much more significant for deformation than the aerodynamic loading. This indicates that aero-elastic models need not be coupled to correctly model the deformations of a flapping wing, and implies that the structural properties of the wing are the most important element in understanding the motion and aerodynamics of an insect wing. To that end, an inexpensive testing device that can measure structural properties may be a help to other researchers in both mechanical and aerodynamic aspects of insect flight.

The design of the apparatus and testing method permits flexural stiffness testing in different directions and of different parts of the wing by varying the mounting direction of samples being affixed between the glass slides. Flexural stiffness tests can be performed on any small material that can be mounted under the wing bar, and the scale and manipulator resolutions are such that many biological samples could be reasonably tested.

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