



Process Improvements for Blade Property Measurements on Small-Scale Rotor Blades.

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Summer 2024

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NOTATION

Acronym	Description
PLA	Polylactic Acid
BEST	Blade Evaluation and Structural Testing
FPS	Frames per Second

ABSTRACT

This project was aimed at designing new methods to test small-scale rotor blades to determine specific properties: torsional stiffness, flexural rigidity, center of gravity, elastic axis location, and mass moment of inertia. During these tests, blades of many sizes and materials are inserted into test apparatuses to gather specific raw data. This data is converted into blade properties that are difficult to obtain accurately via simulation, especially for blades with complex construction. The methods developed in this project will be used to test current blades and future designs. The accuracy of these experimental methods was determined using segments of homogenous cast acrylic and 6061-aluminum with simple geometry. Because of the simplicity, the target results of each method can be determined using pure math and established analytical methods. The pure math results and experimental results were compared to determine the accuracy of the experiment. The methods were then modified to reduce error. The accurate information provided by the finalized methods will inform design changes for both blades and the vehicles overall. The blade data will also be used as a reference for tuning the BEST Blade Validation.

Keywords: Rotorcraft, Blades

BACKGROUND

For blade design, especially during rapid iteration, it is both time consuming and difficult to determine certain physical qualities. Prior to this project, values such as center of mass and torsional stiffness were estimated but not certain for many blades. Compared to other components that are easily analyzed in modern software, rotor blades can be made of multiple materials with complex connections and geometry. This makes it incredibly time consuming to model the blade with enough accuracy for the computer to determine the properties. And for some newer manufacturing techniques, such as 3D printing, the material geometry may be too complex for the available software.

Being able to identify accurate properties of the blades allows for better prediction of blade behavior in rotor performance simulations, optimization of the design, and overall knowledge for many applications. These methods are useful for any blade except for very heavy or large blades that may require more substantial testing assemblies.

Past methods provide an inaccurate understanding of the blade, leading to suboptimal design. These inaccuracies can lead to a longer more expensive project. This project has created consistent and relatively quick and easy ways to gather accurate data on a variety of blades. Moving forward, many blades, both currently existing and future designs, can be tested to determine the data points needed. Because they are consistent data collection methods, they do not require extensive training or modification for each test. Many blades can be tested in quick succession. It is expected that the knowledge coming from these tests will allow for an increase in blade quality and outcomes from the projects they are used for.

APPROACH

Because the blades are too complex, both in material composition and geometry, rectangular beams of aluminum and acrylic were used as replacements during the method testing stage. Because of their uniform composition and simple geometry, accurate qualities could be determined using well-established analytical methods. The geometry was determined using digital calipers, and the material properties were obtained from the manufacturers and material information websites. Once the pure math target values were determined, the physical testing methods were improved by comparing the experimental results and the target values. Relative error was used to determine the accuracy of the testing method during the iteration process. The goal of each method was to consistently have less than 5% relative error when comparing the experimental and target results. The relative error was determined by dividing the difference between the experimental result and the goal result by the target result. The percentage was then determined by taking the absolute value and multiplying that number by 100.

Measuring tapes and rulers were used to measure distances during the data collection process. Digital calipers, with an accuracy up to a thousandth of an inch, were used for measuring dimensions for CAD modeling and any other high precision applications. When structures were required, they were built out of aluminum 1"x1" t-slotted framing. Two dial indicators were used for many of the experiments to measure deflection. Weights were used to exert external forces on the blades. These weights were calibrated by the manufacturer to be exact proportions of pounds. The weights were hung using woven fishing line. The woven fishing line was chosen because of its ability to withstand forces significantly greater than expected without deforming. Hand tools were used to manufacture the test components: screw drivers, hex keys, and utility knife. There

were no adhesives used during the experiments beyond gorilla tape. The gorilla tape was used to hold the aluminum plates and tubes to the table during the 3-point bend test.

For many of the methods, at first approach after inheriting the project, there was significant error. The difference between experimental and pure math results approached a 600% difference in some instances. After determining the starting level of error, it was a matter of locating the sources of error. For some experiments, the most significant sources of error were obvious. The cantilever beam experiment, to determine flexural rigidity, originally used lasers and mirrors. The difficulty of accurately positioning the mirrors and tracing the laser path with a measuring tape led to error. Changes to the methods, replacing lasers with dial indicators, were implemented first to remove most of the error. Data points were gathered, and a new relative error was determined. Changes were made to improve the results and a new error was calculated. This would be repeated until the relative error reached less than 5%. Then improving the next method would begin.

Physical data collection sheets were developed for all blade experiments. These data sheets are used to organize raw data and perform very basic calculations. The goal being a simple and consistent data recording method that allows for readability during the calculation stage.

The physical actions of the tester during the testing process varies significantly between tests. Methods with hanging weights only involve the experimenter gently releasing the weights after the initial set up is complete. Other tests, like the center of mass experiment, require active engagement. The specific physical involvement of each experiment is recorded in its instructions.

When applicable, each method instruction sheet provides all equations to convert the raw data into the final desired value. For the more complicated equations, there are also written instructions. Because of risk of outliers, many values collected during the experiments are

averaged before being plugged into the equations. The amount of data points being averaged increases the accuracy of the resulting average.

Below are descriptions of the changes made to each method. The finished method can be seen in the unedited documents at the end of this paper:

- Center of gravity was the first method tested for accuracy. It reached the accuracy goal within the first test so there were no modifications to the method. The written instructions were updated to include more detail. Some of these additions being using light colored painters' tape for the best visibility and gathering multiple data points. A data collection sheet was written for the method.
- For elastic axis location data collection, the main changes were replacing the monofilament fishing line with the woven version and redesigning the 3D printed end clamp. For this method, and all others, monofilament was replaced with woven line because woven line stretches significantly less. A common source of error was monofilament line decreasing the deflection read by the dial indicators. The elastic axis is found by hanging a weight from the end of the blade. The weight is hung using fishing line attached to a 3D print. The print being designed specifically to the blade. The core concept wasn't changed but that print was updated for easier repositioning of the weight. With a larger gap for the fishing line to move in, there was a decrease in accidental shifting of the blade itself and throwing off the data.

- The main change for determining mass moment of inertia was replacing a human timekeeper with video recording at 30 fps. The process of swinging the blade from two strings and counting the duration of oscillation was not changed. However, the human with a stopwatch was replaced with a phone recording the oscillations from above. With a basic video editing software, including the one provided by the device, the video can be reviewed to determine the average oscillation duration. Because of the unpredictability of human reaction, and how much it varies between people, recording was the only viable option.
- The 3-point bend test to determine flexural rigidity was the method that required the most modification. The original method had significant error and only allowed for chordwise testing. Flap wise testing was achieved by printing blade negatives for each end of the blade. These blade negatives allowed for fixturing of the unique and complex geometry of each blade by having a rectangular box outside. The blade negatives were printed on a Markforged printer with carbon fiber internal supports. Images of blade negatives and the exact printing settings can be found at the end of this document. These heavier duty parts were required because standard PLA prints, including those with increased wall thickness and infill quality, would compress. This additional compression would be picked up by the dial indicator and cascade through the equations and throw off the calculated flexural rigidity. After the significance of reinforced printing was determined, the Markforged printing settings were added to all applicable methods. The other significant changes to the 3-point bend were also made to counter over deflection. The t-frame was placed on aluminum tubing that acted as rollers. Those rollers were placed on and taped to aluminum

sheets taped to each table. This new assembly provided both proper constraining of the blade and elimination of excess deflection from compression of the tabletop.

- The cantilever method was primarily improved and completed after the 3-point bend test. This allowed for rapid elimination of error caused by material compression. Markforged prints and metal plating were used in the same way. The notable change in this method was the replacement of mirrors and lasers with a dial indicator to measure deflection. For this test, and the other with lasers, torsional stiffness, the system was removed immediately. The laser and mirror method required tracing the length of individual beams through the air with a measuring tape and exact angling of the mirrors on the curved blade surface. Proper implementation of a dial indicator and modification of the equations was sufficient for significant human error removal.
- The torsional stiffness method was the only one not completed during the summer 2024 intern session. However, progress was made towards its completion. The in-progress instruction sheet and data sheet can be found at the end of this paper. As previously noted, the original torsional stiffness method used mirrors and lasers. These were eliminated and replaced with two dial indicators. The current design involves pulleys and woven fishing line applying torque on either side of the blade elastic axis with the same force and angle. Two dial indicators are used to record the blade rotation. Only one dial indicator is necessary but two are strongly recommend as it allows for confirmation that all positional changes are resulting from pure torsion. In the situation when the dial indicators are reading

different changes, there is deflection beyond torsion and there will be error in the results.

The other notable change was designing and building a rotating holder for the end of the blade. During the initial error determination stage, the most significant source of error was the blade being pulled by one of the weights much more. This occurred because the end of the blade was free to move. The rotating blade holder properly constrains the blade. It does over constrain the blade by holding the blade at a set length. However, it is predicted that this constraint will not cause a notable amount of error, because the test article length change with torsion is so small. At the end of the summer 2024 session, the method has yet to be tested for error amount with the rotating holder implemented.

RESULTS

The final relative error for each experiment is listed below:

Center of Gravity: 0.14%

Elastic Axis: 2.79%

Mass Moment of Inertia: 3.45%

3-Point-Bend: 4.30%

Cantilever: 1.32%

Torsional Stiffness: Method not completed.

Every method finished reached the goal of being under 5% relative error. The methods with the most error, 3-point-bend and mass moment of inertia have the most complex set up or

rely particularly on human perception. The increase in error is expected from these factors. The center of gravity method is, by far, the most technically simple, and the most accurate.

After performing the tests with both acrylic and aluminum, distinct applications for each material were identified. Aluminum was most useful during initial method determination. That was the stage where significant changes to how components of the assembly were set up, were made, or the entire method was fundamentally changed. The aluminum, being much more rigid than the acrylic, was used to plan out the design without the inconvenience of flexing. The acrylic was used for tests that required deformation because it deforms like actual rotor blades. With the aluminum being much too stiff, the acrylic was used for tests, like torsional stiffness, where deflection needed to be read by the dial indicators.

CONCLUDING REMARKS

The improvement of data collection methods will allow for a more accurate understanding of individual blades. With a proper understanding of a rotor blade's properties, more informed design decisions can be made, reducing cost and duration of a project while improving the result. The method improvements also allow for more blades to have data collected with more ease.

The most consistent improvements made were changing fishing line type, reinforcing 3D prints, and integrating dial indicators. The relative error was determined and minimized by using simple pieces of aluminum and acrylic as stand ins for the more complex rotor blades. The goal for each method was less than 5% relative error. This goal was achieved for all completed methods.

FUTURE WORK

The most significant flaw with these methods is that many of them are limited by the blade size. A significantly large or heavy blade will not be testable with the current test apparatuses.

However, the methods and their accuracies are reliable, so the methods could be properly scaled to accommodate larger blades. The quality of data is also limited by the measuring equipment used. The main equipment used to collect data was an iPhone 13s camera for moment of inertia, and standard digital calipers and dial indicators for other methods. Theoretically, with a higher frame rate camera and more precise measuring equipment, the relative error could be further reduced. Constructing more rigid permanent test apparatuses would also decrease error from faults in the assembly.

Future contributors to this project will finish the torsional stiffness method and modify instructions, or the methods themselves, as the scope of blades to test increases. Changes and improvements based on more experience with a variety of blades is expected.

ACKNOWLEDGEMENTS

I would like to acknowledge the Idaho Space Grant for the support they have provided me. This internship opportunity would not have been possible without what they do.

I would also like to acknowledge my mentors Carl Russell and Gianmarco Sahragard-Monfared for providing invaluable insight into my project and engineering overall. William Warmbrodt and the entire Aeromechanics team have also been incredibly supportive, both by providing this opportunity and facilitating an incredible learning experience.

APPENDIX A

Method Instruction and Data Collection Sheets

Center of Gravity – BEST Data Collection – Guide

Setup:

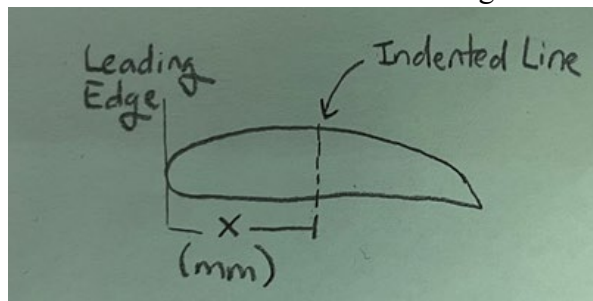
1. Place an X-ACTO blade in a vise, leveled along the long axis, and tightened in place, using a bubble level. A longer blade type may be required for significantly wider blades or segments.
2. Label each blade section with sharpie (if not already done) so it can be matched to data as needed. "Sectioned" means the blade piece is cut from a larger blade.
Ex: "OverallBladeLabel_BladeSegment_DateofSectionCutting_ExperimenterName"
3. Apply a piece of tape to the flatter side of the section (generally the lower surface of the airfoil). Do not use multiple pieces of tape as the knife can get caught in the gaps. Painter's tape is usually used for this experiment. Only place the tape where the blade will likely touch the blade and try to make it even on either side. Place the lightest weight tape possible on the blade. Using lighter tape helps avoid changing the center of gravity. Color wise lighter tape also allows the indent line to be much more visible.

Procedure:

1. Balance the blade section on the X-ACTO knife, tape side down. Make sure the segment is resting on both ends of the knife. Once the blade is balanced apply pressure to blade to score. Try to avoid indenting into the rotor blade itself. Press the blade evenly across the length of the X-ACTO knife. Do not run your finger back and forth across the blade surface as anything besides pushing down shifts the blade and ruins the indent clarity.



2. Measure distance from score mark to leading edge, using calipers, and record the value. Measure of the center of the indent line as that is the average distance.



3. Repeat steps 2-4 for each blade section. Input the results and other required information into the experiment specific paper data sheet. It is highly recommended but not required to take multiple indents of the same piece and average the results.

PROCESS IMPROVEMENTS FOR BLADE PROPERTY
MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Date:

Data Collection:

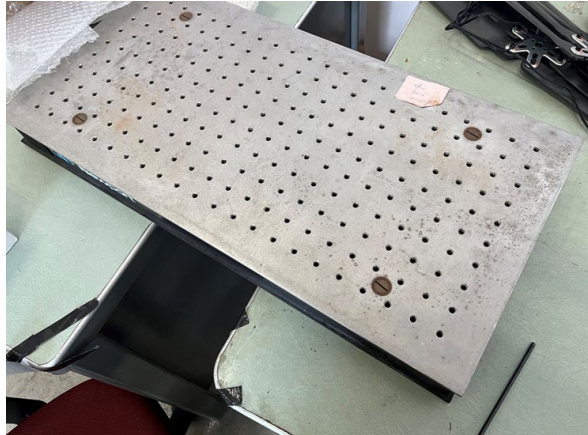
Center of Gravity – BEST Data Collection Sheet

Blade Section Name "OverallBladeLabel_BladeSegment_DateofSectionCutting_ExperimenterName"	Center of Gravity

Elastic Axis – BEST Data Collection - Guide

Setup:

1. Place a bolt plate onto the table.



2. Suspend blade by the root using a set of 3D printed blade root negatives. Clamp the 3D print to a flat surface to hold the blade root in place during testing. The exact set up does not matter if it is stable, and 2 dial indicators can be fit under the blade. It is highly recommended to print the blade root on the Markforged with the below settings. With normal PLA printing, the negative will deflect and throw off the results.

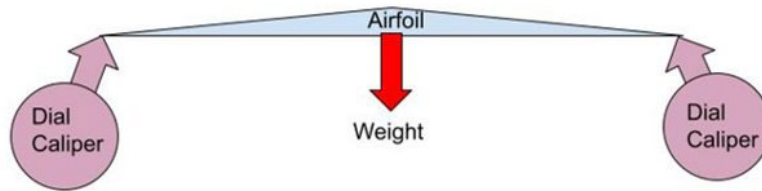


3. Use a 3d printed blade negative clamp that fits the specific blade geometry of where you want to find the elastic axis. The clamp will only fit onto a specific section of the specific blade.



4. Place one dial indicator on the leading edge and one caliper on the trailing edge and record the starting positions. The dial indicators are held using magnetic clamps. The dial indicators must have the same angle and be placed on mirrored locations on the airfoil.



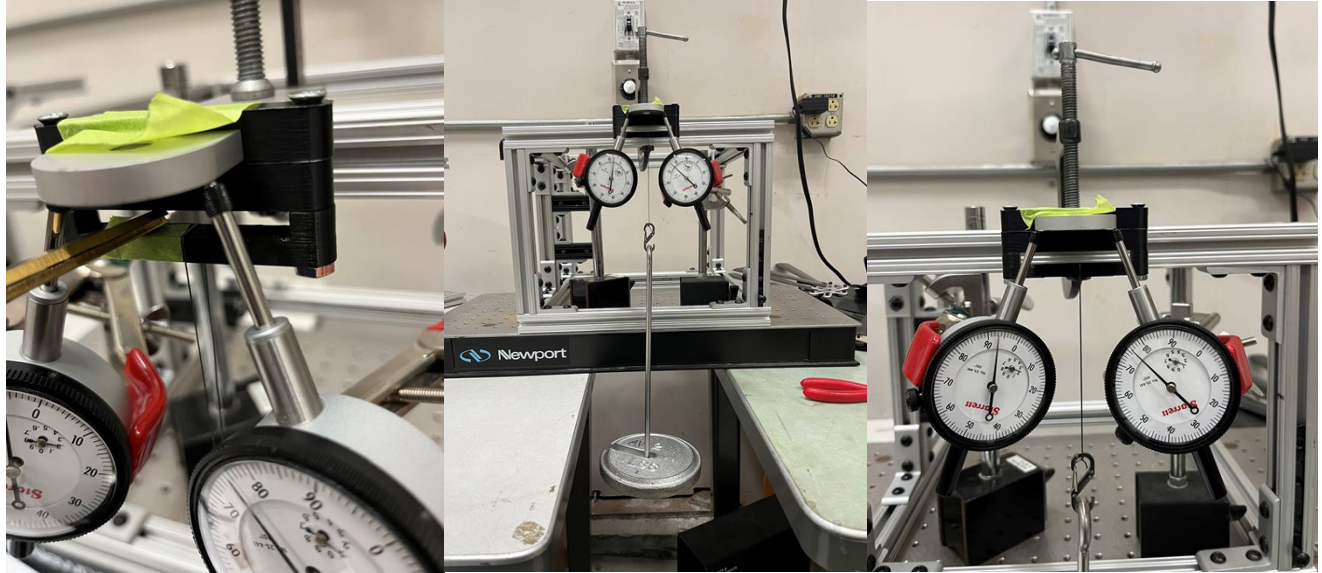


Procedure:

1. Hang a small carabiner from the clamp using fishing line. Hang the 1lb weight holder from the carabiner using woven fishing line. The weight should be able to move along the length of the clamp.



2. Record the initial dial positions. When recording dial positions, make sure eye is level with center of dial to get proper reading.
3. Add a 2lb weight without changing the string position.
4. Record the final dial positions and calculate deflection.
5. Remove the 2lb weight and shift the string position based on the deflection results.
6. Repeat steps 2-5 until both dial indicators have changed the same amount, once this happens the load is in pure bending and no torsion is involved, this is the location of the elastic axis. Record the position of the elastic axis by marking where the weight is hanging from on the clamp. The airfoil negative side can be used to find the position on the airfoil itself.
7. Use a marker or piece of tape to mark the final string position in case it shifts during measurements. This also allows the assembly to be disassembled without losing data.



*These photos were taken during the testing period; that is why the “blade” is a piece of aluminum and there is tape attached.

Markforged Blade Negative Settings:

*Every setting not listed can be assumed default

- Material: Onyx
- Reinforcement Material: Carbon Fiber
- Triangular Fill
- 37% Fill Density
- 4 Floor and Roof Layers
- 2 Wall Layers

PROCESS IMPROVEMENTS FOR BLADE PROPERTY
MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Date:

Data Collector:

Blade:

Elastic Axis – BEST Data Collection Sheet

Left Dial Initial Position	Right Initial Position	Left Final Position	Right Final Position	Left Deflection (Δ)	Right Deflection (Δ)

Moment of Inertia – BEST Data Collection – Guide

*Must find the center of mass and elastic axis using other experiments first.

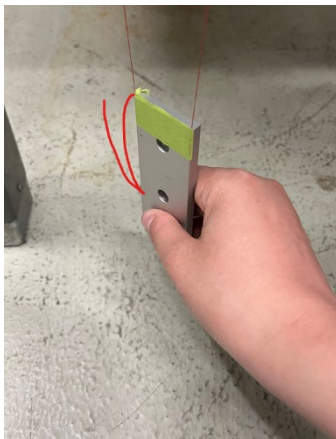
Setup:

1. Use a digital scale, accurate to a hundredth of a gram, to record the mass of the blade section.
2. Suspend blade section from two strings, each equal distance from the quarter cord (d). The strings can be connected to the mount with tape and to the blade section with tape or glue. Avoid applying excess glue that may modify the blade properties. The strings should be placed on the same side of the blade segment, the flatter underside, and have as little contact with the piece as possible. It does not matter which side of the blade is facing upwards.
3. Ensure blade is level, along both top axes, using a right angle. The longer the string length (L) the better. The string length is measured from the top of the blade section to the bottom of where the string is fixtured above.

Procedure:

1. Create a pendulum movement on the blade by starting at a slight angle. Take a video from directly above so the timing of the oscillations can be determined later. The angle does not impact the results. The more oscillations recorded, the more data points.
2. Look over the recorded video record the duration of each oscillation down to 0.01s.
3. Average the oscillation time to find the average time.
4. Use the below equations to calculate the mass moment of inertia.

*I can be translated to be about the center of gravity or elastic axis using the below equation. This is called the Parallel Axis Theorem. Center of gravity and elastic axis are found from other experiments.



The red line is 1 oscillation.

m = mass g = gravity (386.089 in/s²)

d₁ = distance from center of gravity (CG) to quarter cord (QC)

d₂ = distance from CG to elastic axis (EA)

d = distance of the strings to the quarter cord

p = average time for one rotation

L = string length

$$[1] I_{QC} = \frac{m \cdot g \cdot d^2 \cdot p^2}{4\pi^2 L}$$

Source 1 determined these equations by referring source 4.

$$[2] I_{CG} = I_{QC} - md_1^2$$

$$[3] I_{EA} = I_{QC} - m(d_1^2 - d_2^2)$$

*The quarter cord is always ¼ of the blade segment in from the leading edge.

It is always measured from the widest part of the blade segment.

*If comparing the inertia from the above equations to a SOLIDWORKS model, divide the I_{xx}, I_{yy}, or I_{zz}, by the length along that axis. The above equations are the inertia of a sliver of the length.



Sources:

- [1] Determination of HART I Blade Structural Properties by Laboratory Testing (pg 5)
- [2] Determination of HART I Blade Structural Properties by Laboratory Testing (pg 6)
- [3] Determination of HART I Blade Structural Properties by Laboratory Testing (pg 6)
- [4] Hughes, G. W.: The Trifilar Pendulum and Its Application to the Experimental Determination of Moments of Inertia. ASME Paper 57-SA-51, 1957.

PROCESS IMPROVEMENTS FOR BLADE PROPERTY
MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Name:

Date:

Blade Segment Name:

Mass Moment of Inertia – BEST Data Collection Sheet

Blade Segment Mass (m) =

String Length (L) =

Distance of the strings to the quarter cord (d) =

Distance of CG to QC (d_1) =

Distance of CG to EA (d_2) =

Sample #	Oscillation Time (s)	Sample #	Oscillation Time (s)	Sample #	Oscillation Time (s)	Sample #	Oscillation Time (s)

Average Oscillation Time:

3-Point Bending – BEST Data Collection – Guide

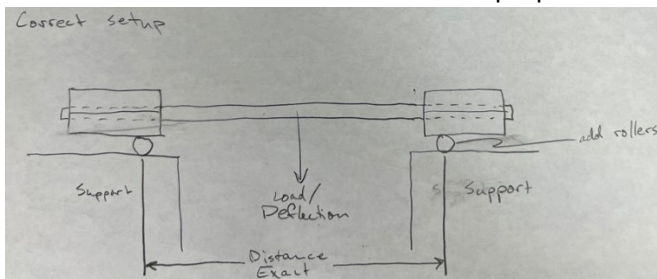
Test apparatus often require assembly as they are disassembled when not in use.

Setup:

1. Place full blade between the t-slot frames. Loosen the frames and push them together while retightening to clamp down on the blade. Blade will rest on the bottom of the frame, so it doesn't slide down. It does not matter where it is clamped if the data collection can occur. A blade root negative to hold the blade during flap wise testing. This is required to prevent twisting from the weight that throws off the deflection. The blade negative must be printed on the Markforged with the printing specifications listed below. If printed with normal PLA, the negative will deflect and throw off the results.



2. Place rollers with the same outer diameter underneath the t-slot frames. The rollers must be resting on metal plates. Use gorilla tape to tape the rollers to the plates and the plates to the tables. The exact plates and rollers do not matter. Using metal is critical for getting accurate deflection. Aluminum works well for this purpose.



3. Place dial indicator above the blade in the middle of the test section to measure deflection.
 - a. Place a magnetic clamp on a bolt plate between two tables.
 - b. Clamp the dial indicator into the clamp.
 - c. Position the dial indicator so it is contacting the top of the blade towards the center.Because the beam deflection will cause the indicator to extend back towards zero, the indicator must be placed so it is indented before any weight is added. Without this, it will zero mid-experiment and the data will be unusable.

4. Tie woven fishing line around the beam to hang the weights from. Move the fishing line as close to the indicator without being underneath it. When underneath, the fishing line indenting throws off the deflection measurements.
5. Measure the distance between the centers of the rollers (testing section, L). Measure with calipers or a measuring tape.
6. Record the original deflection.

Procedure:

*Do not touch the tables, shift weight on them, or modify them in any way during data collection.

1. Place load (F) in the middle of the testing section, take it off, and put it back on. Do this three times before recording any data. This allows the test setup to settle and helps remove initial outlier data points.
2. Continue to add load to the middle of the test section and remove it until desired number of deflection data points is measured. Weight a few seconds after adding weight to record the deflection.
3. Use Equation 1 to use find EI with each data point.
4. Average the EI values to find the most accurate EI.

$$[1] EI = \frac{F * L^3}{48 * \Delta}$$

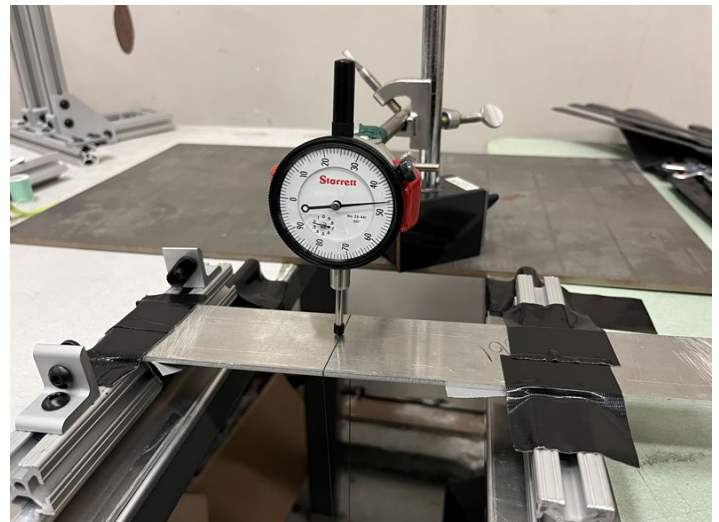
Equation 1. EI

Δ = Deflection

L = Distance between T-slot frames

F = Load

EI = Flexural Rigidity = Elastic Modulus * Inertia



*Photos taken during testing with an aluminum beam rather than a blade.

[1] Determination of HART I Blade Structural Properties by Laboratory Testing (pg 10)

Markforged Blade Negative Settings:

*Every setting not listed can be assumed default

- Material: Onyx
- Reinforcement Material: Carbon Fiber
- Triangular Fill
- 37% Fill Density
- 4 Floor and Roof Layers
- 2 Wall Layers

Blade:

[illegible]

Cantilever – BEST Data Collection – Guide

Setup:

1. Place a steel plate between two tables. It must be steel to avoid over deflection.
2. Place the blade root in a blade specific negative and clamp it to the steel plate so it is hanging off the plate perpendicularly. It must be firmly attached to the plate, so it does not shift beyond deflecting when a load is applied. The blade root negative must be printed on a Markforged with the settings listed below. If it is printed with normal PLA, the negative will over deflect and throw off the results.



3. Using a magnetic adjustable clamp, place a dial indicator over the end of the blade. It must be indented prior to any additional load being applied. Since the dial indicator is measuring from above, the measured value will decrease as load is applied to the blade. Make sure the fishing line is closer to end of the blade than the dial. If the dipping of the blade due to weight pushes the fishing line into the indicator, it will throw off the results.



*Photos taken during testing with an aluminum beam rather than a blade.

Procedure:

1. Add a load to the blade, 3lb works, by hanging it from the blade end clamp. Record the dial indicator position. Make sure to wait 30+ seconds before recording the position; this allows the weight to settle and will significantly eliminate data error. There is an increase in relative error of 3%+ without waiting the full time.
2. Remove the 3lb weight and record the indicator position.
3. Subtract the indicator positions to get the deflection.
4. Calculate EI using W , L , δ , and the below equation:

If weight and dial indicator are being added to the end of the beam:

$$EI = W(L)^3 / (3 * \delta)$$

δ = Deflection

EI = Flexural Rigidity

W = Load/Weights

L = Length of Beam



*Photos taken during testing with an aluminum beam rather than a blade.

Markforged Blade Negative Settings:

*Every setting not listed can be assumed default

- Material: Onyx
- Reinforcement Material: Carbon Fiber
- Triangular Fill
- 37% Fill Density
- 4 Floor and Roof Layers
- 2 Wall Layers

PROCESS IMPROVEMENTS FOR BLADE PROPERTY
MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Date:

Data Collector:

Blade Name:

Length of Beam (L):

Cantilever – BEST Data Collection Sheet

Load (W)	Deflection (δ)	Load (W)	Deflection (δ)

Torsional Stiffness – BEST Data Collection – Guide

*For proper set up of this experiment, the elastic axis of the individual blade must be identified. This can be done through the elastic axis experiment in this collection. The elastic axis informs requirements of the blade specific 3D prints used in this experiment. It is recommended to read below to understand these requirements and print the proper pieces before beginning.

*It is possible to conduct this data collection using one dial indicator rather than two. However, it is not recommended as using two dial indicators on either side allow for confirmation that the deflection values are purely from twisting. If the deflection differs between the dial indicators, the test assembly is imbalanced and non-twist deflection is causing error in the raw data.

*The t-frame test assembly dimensions may need to be modified if there is significant variation in the blade's length, both by being shorter and longer. This means having extra 1" t-frame on hand can assist in keeping up the testing rate.

Setup:

1. Suspend the blade by one end using a blade specific negative 3D print. The blade negative must be print on the Markforged with the printing specifications listed below. If printed with normal PLA, the negative will deflect and throw off the results. A clamp(s) is used to hold the blade to the t-frame.
(Insert photos)
2. Attach a clamp to the blade, the attachment should have two pieces of woven fishing lines, each the same distance from the elastic axis on each side of the blade. The clamp is a 3D printed negative of the specific blade. The clamp has holes for the fishing line to be tied too. These holes must be equal distance from the elastic axis. The clamp is placed on the very end of the blade. The angle of the fishing line and external weight applied need to be mirrored so the forces cancel out and only the moment effects the blade.
(Insert photo of the clamp)
3. Attach the rotating blade holder to the opposite beam using clamps. Use the L-brackets attached to the t-frame inside the rotating blade holder to hold the clamp just added in the previous step. This will allow the blade to rotate without unintended horizontal deflection.
(Insert photos of rotating section)
4. A pulley system should be set up to allow for weights to hang off the attached fishing line. The weights hang off the fishing line using a knotted loop.
(Insert photo of tied in weight)
5. 2 dial indicators held by magnetic stands must be placed on either side of the blade. The dial tips being placed equal distance from the elastic axis. This is done so only one equal angle is read and plugged into the below equations. To decrease potential error from collision, it is recommended to place the dial indicators on the two sides opposite of the strings.
(Insert dial indicator drawing here)

Procedure:

1. Put on and remove the same set of weights until the desired amount of data points are reached. Chose weights that cause notable amounts of deflection but are as light as possible; overly heavy weights are unnecessary and can increase error while trying to position them. Release the weights to hang freely together. Stop the weights from swaying as much as possible without pulling them and causing additional deflection. Wait ~30s after applying the weights to collect data. Taking data without waiting significantly increases error as it takes some time for the deflection to settle.

2. Average the deflection to get “x”.
3. Use equation 2 listed below to calculate the change in angle.
4. Use equation 3 the calculate the torque “T”.
5. Use equation 1 to calculate the torsional stiffness “GJ”.

$$[1] GJ = \frac{L}{\frac{\phi}{T}}$$

$$[2] \phi = \arctan\left(\frac{2x}{d}\right)$$

$$[3] T = w * d$$

Summarized:

$$GJ = \frac{L}{\frac{\arctan\left(\frac{x}{d}\right)}{w * d}}$$

GJ = Torsional Stiffness

J = Polar Inertia

G = Modulus of Rigidity aka Shear Modulus

Derived from $E = 2G*(1 + \nu)$ for isotropic materials

ϕ = Angle of Twist (radians)

T = Torque

b = Base

d = Distance of fishing line from elastic axis.

L = Length of the Blade between the Fixed Points

w = Load (sum from both fishing lines)

x = Averaged Horizontal Deflection

If you want to check the value:

- G can be found on the internet for the specific material
- $J = b * 2d(b^2 + (2d)^2)/12$ for a rectangle
- $E = 2G*(1 + \nu)$ for isotropic materials (including the acrylic used to verify this method)
 - ν = Poisson's Ratio

Math References:

[1] Determination of HART I Blade Structural Properties by Laboratory Testing (pg 10)

PROCESS IMPROVEMENTS FOR BLADE PROPERTY MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Markforged Blade Negative Settings:

*Every setting not listed can be assumed default

- Material: Onyx
- Reinforcement Material: Carbon Fiber
- Triangular Fill
- 37% Fill Density
- 4 Floor and Roof Layers
- 2 Wall Layers

Reference Photos:

(Insert general reference photos)

PROCESS IMPROVEMENTS FOR BLADE PROPERTY
MEASUREMENTS ON SMALL-SCALE ROTOR BLADES.

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Date:

Data Collector:

Blade:

Torsional Stiffness – Data Collection Sheet

Modulus of Rigidity (G):

Base (b):

Height/2 (d):

Beam Length (L):

Load (w) (Sum from both lines)	Dial Indicator 1 Position (x_1)	Dial Indicator 2 Position (x_2)	Average Deflection (x)

REFERENCES

- Benham, P. P., Crawford, R. J., & Armstrong, C. G. (1996). *Mechanics of Engineering Materials* (2nd ed.). Longman Group.
- The Engineering Toolbox. (2023, September 11). *Modulus of Rigidity*. Engineering ToolBox. https://www.engineeringtoolbox.com/modulus-rigidity-d_946.html
- Jung, S. N., & Lau, B. H. (2012, August). *Determination of HART I Blade Structural Properties by Laboratory Testing*. In NTRS - NASA Technical Reports Server. Retrieved from https://rotorcraft.arc.nasa.gov/Publications/files/Jung_CR_2012-216039.pdf
- MatWeb. (n.d.-a). *Aluminum 6061-T6; 6061-T651*. MatWeb. <https://www.matweb.com/search/DataSheet.aspx?MatGUID=b8d536e0b9b54bd7b69e4124d8f1d20a&ckck=1>
- MatWeb. (n.d.-b). *Overview of materials for Acrylic, Cast*. MatWeb. <http://www.matweb.com/search/datasheet.aspx?bassnum=O1303>
- McMaster-Carr. (n.d.). *Clear Ultra-Scratch-Resistant Cast Acrylic 12" x 12" x 1/8"*. McMaster. <https://www.mcmaster.com/8536K131/>