Teaching with Midwest’s Boomilever

1st Edition
A “Hands-On” Laboratory Adaptable to Grades 6 - 12
Written by Bob Monetza

Introduction
This Teacher’s Guide is designed to introduce model building of cantilevered structures to teach principles of physics and engineering design in hands-on exercises, culminating in a classroom competition of creative design. The Boomilever project is based on a competitive Science Olympiad event. The information and materials presented with this kit are similar to the “Boomilever” event in the Science Olympiad competition program and may be a used as a starting point to prepare students to develop competitive structures. Note that rules published by Science Olympiad or any other organization are not reproduced here and are subject to change. Rules presented in this Guide do not substitute for official rules at sanctioned competitions; check the rules in use at formal competitions for differences.

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Part 1 - Introduction

A **Boomilever** is a **cantilevered beam** or **truss**, a structure that extends out from a base and supports a load. Cantilevers come in many forms and serve many functions, but the common characteristic is that they extend beyond their supports to hold a load or resist a force. Typical examples range from coat hooks and sign brackets to mobile cranes and tower cranes used in construction. Cantilevered beams may be counterweighted beams that are supported at a balance point, like playground teeter-totters and bascule lift bridges. They may also be rigidly attached to a wall or base that is stiff enough to resist the overturning force, or torque, resulting from the force applied at the far end of the beam. Sign brackets, industrial jib cranes, masts of sailing ships, and self-unloading conveyers on freighter ships work this way. A Boomilever is this latter type of structure.

The physical principles that will be explored are the balance of forces and moments, the internal and external structural stresses, and the bending and buckling of structural components. The goal of the design work is to produce a structure that has the capacity to support a load as efficiently as possible. Students should draw conclusions about the suitability of their designs, and the reliability and economy of the final structure.
The Boomilever project is structured as follows:

- A hands-on activity in which students will construct and test a common design which is included in the kit. While not intended to be a creative activity, this exercise will provide an opportunity to learn construction techniques and allow every student to build a testable structure. Testing of the finished structure will demonstrate the structural principles described above. Test results for a set of Boomilevers may be summarized and analyzed to show the variance in reliability of the structures.

- An explanation of some of the details and options of Boomilever design and construction, and materials selection. Also included are some useful forms for data logging and analysis.

- An experimental design, in which the students must apply the principles and techniques from the previous two sections to build a Boomilever for a different set of problem conditions. This section is intended to be an inquiry activity or experiment utilizing scientific method, and staged as an in-class competition. A teacher may require a formal written report of the experiment.

- An informal presentation of basic structural concepts suitable for middle school and high school, and may be presented in part or in whole at the discretion of the teacher, based on class time available and the grade level of the class.

- Additional information on advanced structural principles including static analysis, bending, section properties, deformation, and stability under load. These are advanced engineering concepts; however, the presentation here is only a brief, informal introduction intended to foster an intuitive grasp of the engineering and to reinforce the Boomilever testing observations.

The materials in this lesson are relevant to the following National Science Content Standards, Levels 5-8 and 9-12:

- **Unifying Concepts and Processes**, understanding of form and function, measurement, evidence, and explanation

- **Science as Inquiry**, the understanding and ability to do a scientific inquiry

- **Physical Science**, understanding of motions and forces

- **Science and Technology**, abilities and understanding of technological design

- With supplemental practical applications and historical examples, the Science in Personal and Social Perspectives and History and Nature of Science content standards can be tied into this exercise as well.
Boomilevers are Everywhere!

Construction Crane
Photo by Liz Monetza

Street Light
Photo by Liz Monetza

Projecting Store Sign
Photo by Liz Monetza

Cantilevered Street Sign
Photo by Liz Monetza
Part 2 - Boomilever Construction

Included in the kit is a set of full-scale drawings for an example Boomilever, and information for assembling and testing it. While not intended to be a highly competitive design, this is intended to teach some construction techniques to the students, and to give them a working model for load testing and observation. The hands-on nature of this activity will reinforce the physical concepts, enhance confidence of the students in their ability to build, and appeal to those students who learn best by doing rather than listening.

2.1. Problem Statement

**Objective:** Design and construct a Boomilever, a cantilevered wood structure with the highest possible structural efficiency, to support up to 15 Kg at a distance 40.0 cm horizontally from a vertical supporting wall.

**Design:** Any design for the Boomilever may be constructed which meets the specifications given below. The Boomilever must be a single structure without detachable parts. Students may use trusses, gussets, and unlimited lamination by the student. The Boomilever must be designed to support a 50 mm x 50 mm block and eyebolt, which will hold a bucket below the outward (distal) end of the Boomilever. The block may be supported at any height above the floor. The Boomilever must attach to a standard supporting wall.

**Materials:** The Boomilever is a single structure made of wood and glue only. Any type of wood may be used, but the individual pieces of wood may not be larger than ¼” x ¼” in cross section dimensions. Manufactured wood products, such as plywood or particleboard may not be used. Any type of glue may be used. The Boomilever may be constructed with an attachment base to bolt to the supporting wall. The attachment base may be made of any type of wood or wood product, including plywood, but may not be more than ½” thick. The attachment base must be glued to the Boomilever and is included in the mass of the Boomilever.

**Construction:** The Boomilever must be attached to the holes in the supporting wall. The holes shall fit ¼” bolts located 20.0 cm on centers horizontally, 5.0 cm below the top edge of the wall. A full-scale template matching the pattern is included in the kit. The Boomilever shall be attached to one or both of the holes with ¼” bolts, flat washers, and wing nuts. The center of the load block shall be a minimum of 40.0 cm from the face of the supporting wall, measured horizontally, and may be at any level above or below the center of the holes. The Boomilever may not touch the supporting wall below a horizontal line 20.0 cm below the center of the holes.

**Testing:** The students shall fasten the Boomilever to the supporting wall. The center of the load block shall be placed on the Boomilever at a minimum distance of 40.0 cm from the wall, and a bucket shall be suspended from the block with an eyebolt and chain or S-hooks. Students shall add sand to the bucket until a total mass of 15 Kg is applied, or until failure of the Boomilever, whichever is less.

**Scoring:** The structural efficiency of the Boomilever shall be determined by the following formula: Structural Efficiency = Mass Supported (grams) / Mass of Boomilever (grams). 15 Kg is the maximum supported mass allowed for scoring purposes. Boomilevers that meet all specifications will be ranked above any Boomilevers that do not, such as holding the load too close to the wall or touching the wall lower than 20.0 cm below the bolt holes, or any other rules violation.
2.2. Example Design and Construction

Photo 1
Unloaded Boomilever on supporting wall

Photo by Liz Monetza

Photo 2
Boomilever set up for testing

Photo by Liz Monetza

Photo 3
Boomilever with load block

Photo by Liz Monetza

This kit contains plans, instructions, and materials to construct the Boomilever shown in these pictures. This example Boomilever provides a starting point for understanding the construction techniques, testing, and evaluation of a Boomilever structure. Students will be challenged to create better, more efficient designs after practicing the construction of this Boomilever.
2.2.1 Materials and Tools

Each Example Boomilever will require:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Materials Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1/8” x 1/8” x 24” Balsa strips</td>
</tr>
<tr>
<td>2</td>
<td>3/16” x 1/8” x 24” Basswood strips</td>
</tr>
<tr>
<td>1</td>
<td>1/4” x 1/8” x 12” Basswood strip</td>
</tr>
<tr>
<td>1</td>
<td>Tacky glue (Midwest Tacky Formula Modeling Glue, #362, included in kit)</td>
</tr>
<tr>
<td>1</td>
<td>Full size pattern with two side views, bottom and top view, and attachment base detail</td>
</tr>
</tbody>
</table>

Paper towel, rags, or napkins

Tools recommended:

Tools are commonly available at hobby stores, or may be purchased from your Educational Products supplier. Tools are not included in the kit.

- Midwest’s Easy Miter Box Deluxe, #1136
- Midwest’s Grip Pins, #587
- Midwest’s Big Craft and Hobby Square, #1137
- Midwest’s Super Sander - Fine Grit, #1130
- Hobby knife with straight chisel blade (X-acto® #17, Excel® #17 small chisel or similar)
- Forceps or tweezers, self-closing clamping forceps
- Cutting Board - 24” x 18” (minimum): masonite, high density particle board, or plastic laminate (Formica)
- Assembly Board - 32” x 24”: soft wood or extruded blueboard styrofoam (NOT expanded styrofoam insulation, soft mineral fiber board, or cardboard)
- Masking tape
- Scissors
- Sanding sticks (Excel #55678 or similar, with replaceable sanding belt)

Additional items:

The plans and instructions included in this section describe the construction of an Example Boomilever on a flat table or workbench. Assembly may be aided by a Construction Jig, which will hold the subassemblies in place in the correct 3-D orientation while applying and drying the glue. While not necessary for this set of plans, a Construction Jig can be valuable for constructing innovative designs for the competitive or experimental problems described in Part 4. A drawing for a Construction Jig is included in Part 3.

For testing, a 50 cm x 50 cm x 20 cm load block will be needed, with a hole for a 1/4” eyebolt through the center of the square face. A 1/4” eyebolt, two or three S-hooks, and a 5 gallon plastic pail with a wire handle plus approximately 15 Kg. or more of clean, dry, free flowing sand will be needed. It may be helpful to make simple length gauges from straight pieces of wood or Plexiglas, for checking the minimum distance to the load block center and the height of the Boomilever. Alternatively, these can be measured with any meter stick. A short spirit level (9” torpedo level) is used during set up to level the load block.

A full size printed template for a Supporting Wall is included in the kit. Boomilevers must be tested by bolting the attachment base to holes accurately located in a vertical piece of plywood or similar material. The template may be used to locate the edges and holes for a Supporting Wall. Wall materials and drills are not included in this kit.
2.2.2 Step by Step Construction Instructions: An Example Boomilever

This kit contains plans and instructions to build this Example Boomilever.

Figure 2.1 - Example Boomilever Design
Tension Boomilever with one-hole attachment base

2.2.2.1 Select a clean workplace on a flat table, workbench, or desk. There should be enough room to lay out the materials, tools, and pattern. There should also be room to pre-cut pieces of wood and set them aside until needed. Keep the workspace organized and clear of trash or scraps. Keep some paper towel or napkin handy for wiping up excess glue. Keep food and beverages away from the work area. WASH YOUR HANDS. Balsa and Basswood will absorb water, grease, oil from skin, etc., and excess glue. These contaminants will inhibit the adhesion in the joints. Construction will be done over a period of two or three days, so leave the partially built Boomilevers and materials on the assembly board and put them away where they will stay clean and undisturbed.

2.2.2.2 These instructions assume that the Tacky Glue supplied with the kit will be used. If fast-drying solvent based glue such as cyanoacrylate (CA or super glue), fast setting epoxy, or isopropyl-acetate based glue (model cement) is used, the procedure is slightly different. Many schools will not allow these glues to be used in classrooms. In general, water-based tacky glue or carpenter’s (yellow) aliphatic glues require pressure on the joints and far more time to dry and harden than CA or similar glues. Care must be taken with tacky glue that the joints do not shift or slip while the glue sets. Further suggestions are included below to account for the differences.
2.2.2.3 It is a good practice to record information at each step of the construction. Any useful format may be used, a log sheet form is provided in Section 3.7. Begin the log sheet by recording the mass of each strip of wood used in the Boomilever. As described in Section 3.5.1, wood density is highly variable and the density has a huge impact on wood strength. As each truss is completed and removed from the pattern, record the weight of each one. Also record the weight of the attachment base parts and the completed Boomilever. Try to estimate the amount of weight added by glue. Testing of Boomilevers is often destructive and this information will be useful in duplicating a successful design. This information will also be useful in making improvements in the strength and weight of Boomilevers.

2.2.2.4 Place the full-scale pattern on a Cutting Board, and pre-cut pieces of wood directly on the pattern. The Cutting Board is a smooth, hard material so that the cuts may be precise; it also protects the worktable. Each piece must match the size and shape on the pattern. The pattern may be protected with clear waxed paper or clear plastic sheet. Cut balsa with a chisel-tip hobby knife blade. For Basswood or for thick pieces of balsa, a hobby saw will work better. Avoid damaging the pattern by first scoring the wood with the tool and then moving the wood off the pattern to finish the cut. Be careful to match the angle of the cut ends of strips to the angle on the pattern. Joints must fit tightly and without gaps. Where the pattern calls for wood to have excess length, the wood will be trimmed to final length after assembly.

Pre-cutting all pieces of wood is efficient when building with tacky glue or other slow-drying glues. If building with CA or similar glue, it may be faster to build with random length pieces and trim them after gluing, since the joint will be strong enough to allow cutting in a matter of seconds. This method may save time, but will use more wood.

Note: when using exposed blades such as chisel-tip hobby knife blades, use proper care to avoid injury. Change the blades as soon as they begin to get dull. Sharp blades require less pressure to cut and are safer to use than dull blades. Respect your tools.

2.2.2.5 The side trusses will be assembled directly on the pattern. Two patterns are provided. Both trusses may be built at the same time, or one of the patterns may be used for cutting pieces and the other as an assembly pattern. Tape or pin the pattern to the Assembly Board at the corners. If the pattern is to be re-used, protect it by covering it with clear waxed paper or clear plastic sheet. When water-based tacky glue is used for construction, it will be necessary to stick push pins through the pattern to hold wood in place and to apply pressure to joints while glue is drying. Alternatively, a board or small weights can be set on the trusses to apply pressure until the glue sets.

If using CA glue, assembly can be done without pins or weights because the joints will tack almost instantly. As a result, a separate Assembly Board capable on holding pins is not needed and the pattern can remain on the Cutting Board or be placed on any tabletop. Leaving the pattern on the Cutting Board during assembly makes it easier to trim random or uneven lengths of wood strips.

2.2.2.6 To construct the two side trusses, follow the steps shown in Figure 2.2 and Figure 2.3. It is very important to place the strips of wood directly over the lines on the pattern. Failure to follow the pattern precisely will cause the finished Boomilever to be uneven, with poorly-fitting joints. Stand up and look directly down on the pattern when gluing pieces, particularly when the wood stacks up away from the paper. Some of the wood strips are shown extending past the finished Boomilever truss. These extra long ends should be taped or glued down to the pattern to hold the Boomilever in place as it is being built, and the excess will be cut off when truss assembly is complete. Do not handle the truss or attempt to remove it from the pattern until the glue is set enough to prevent the joints from slipping or separating. See also Photos 4 through 9.

The two trusses must be identical for the Boomilever to be properly balanced. If the trusses are not equal in strength, or if they don’t line up when assembled together, the load from the load block will place unequal stress on them.
Step 1
Attach strips of Balsa for bottom chords and gussets directly to pattern. Truss will be built on these strips, then removed from paper pattern.

Step 2
Attach strips of Basswood for top chord and bracing to pattern. Carefully locate strips over pattern while gluing and trim off excess length of top chord and bracing pieces.

Step 3
Attach strips of Balsa for web chords over bottom chord strips. Carefully locate strips over pattern while gluing and trim off excess length of web chords.
Step 4
Glue bottom chord Balsa strips over web chords. Cut strips to length on pattern before gluing.

Step 5
Cut excess wood from truss and remove from pattern. No paper should be stuck to truss. Pattern may be re-used or discarded.

Quantities of Each Strip Required

<table>
<thead>
<tr>
<th>Strips of wood may be all cut before assembly or cut when used. If pre-cutting all strips, see quantity table at right.</th>
<th>1 x 1</th>
<th>7 x 2</th>
<th>13 x 2</th>
<th>19 x 2</th>
<th>25 x 1</th>
<th>31 x 1</th>
<th>37 x 1</th>
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<tbody>
<tr>
<td>2 x 1</td>
<td>8 x 2</td>
<td>14 x 2</td>
<td>20 x 2</td>
<td>26 x 1</td>
<td>32 x 1</td>
<td>38 x 1</td>
<td></td>
</tr>
<tr>
<td>3 x 2</td>
<td>9 x 2</td>
<td>15 x 2</td>
<td>21 x 2</td>
<td>27 x 1</td>
<td>33 x 1</td>
<td>39 x 2</td>
<td></td>
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<tr>
<td>4 x 2</td>
<td>10 x 2</td>
<td>16 x 2</td>
<td>22 x 4</td>
<td>28 x 1</td>
<td>34 x 1</td>
<td>40 x 6</td>
<td></td>
</tr>
<tr>
<td>5 x 4</td>
<td>11 x 2</td>
<td>17 x 2</td>
<td>23 x 2</td>
<td>29 x 1</td>
<td>35 x 1</td>
<td>41 x 1</td>
<td></td>
</tr>
<tr>
<td>6 x 2</td>
<td>12 x 2</td>
<td>18 x 2</td>
<td>24 x 8</td>
<td>30 x 1</td>
<td>36 x 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.3 - Step-by-Step Procedure for Side Truss Construction
2.2.2.7 When both trusses are completed and the glue is dry, trim off any excess wood ends and sand the surfaces lightly to prepare the wood for gluing on the cross bracing. Glue bonds best to clean wood surfaces. Follow the steps in Figure 2.4 to assemble the trusses together. Cross braces and diagonal braces will be glued to the two sets of bottom chords. Be careful that the trusses are vertical while gluing on the cross bracing, so that the finished Boomilever will be straight. The result will be a box truss at the lower part of the Boomilever formed by the horizontal compression chords and the cross bracing, with the upper tension chords projecting above this assembly. It may be necessary to place some small weights on the bracing while the glue is drying. [If using CA glue, the glue sets fast enough that simply pressing the joints together for 0-5 seconds will work.] See also Photos 10 through 15.
Step 6
Attach strips of Balsa for cross braces directly to pattern. Truss will be assembled to these strips, then removed from paper pattern.

Step 7
Set Boomilever trusses over cross braces and line up with pattern. Make sure ends line up with end of pattern also. Glue bottom of trusses to each cross brace.

Step 8
While Boomilever is upright and bottom cross bracing is still stuck to pattern, glue in all cross bracing and diagonals on top of upper compression chord.

Step 9
Cut cross braces loose from pattern along edges of trusses.

Figure 2.4 - Step-by-Step Procedure for Boomilever Bottom Truss Assembly
2.2.2.8 Remove the Boomilever from the pattern, glue in the remaining diagonal braces on the bottom, and assemble the attachment base as shown in Figure 2.5. The attachment base design included with the pattern may be built in advance and glued to the Boomilever assembly, but it is easier to build it around the ends of the tension chords directly on the pattern as part of STEP 11. See Pictures 16 through 22.
Step 10
Flip Boomilever upside down and glue diagonal bracing between cross bracing chords. Trim to edges of trusses.

Line up six (6) 1/4" x 1/8" Basswood strips, standing on edge to line as shown. Cut off excess length after top strip is glued on.

Glue these strips to top chord of Boomilever (both chords)

Back Layer

Construct Attachment Base

Step 11
Final assembly. Boomilever bottom chords should be perpendicular to testing wall. Check with Big Hobby and Craft Square or similar tool

Place Boomilever upright on end on a flat surface to glue attachment base strips to top chords. A pattern is provided to properly locate base.

After attachment base glue has set, fill in remainder of space in top chord slots with wood wedges and/or glue.

Sand ends of Boomilever compression chords as needed to make contact with testing wall on all ends. Boomilever should not rock on wall.

Figure 2.5 - Step-by-Step Procedure for Boomilever Final Assembly
Photos by Liz Monetza

Photo 16 - Assembly Step 11
Boomilever in position on pattern

Photo 17 - Assembly Base first strip

Photo 18 - Attachment Base Construction

Photo 19 - Checking Boomilever with machinist’s square

Photo 20 - Attachment Base upper front strip

Photo 21 - Attachment Base with front strips glued in place

Photo 22 - Attachment Base trimmed
When assembling the attachment base, with the Boomilever standing on end on the Assembly Board (or Cutting Board), check that the Boomilever is perpendicular to the Board with a hobby square or machinist’s square, as seen in Photos 16 and 19. Allow plenty of time for the glue to dry before handling the finished Boomilever. Completely fill the spaces between the attachment base and the ends of the tension chords with glue or glued-in wood wedges. For other joints glue is used sparingly, but the attachment base is an exception. Use enough glue to fill the joints and form a shallow fillet (rounded surface) of glue between the pieces of the attachment base and the tension chords. Sand off any excess glue and trim or sand long ends of strips before testing. A completed Boomilever is shown in Photos 23 and 24.

Photo 23 - Completed Boomilever

Photo by Liz Monetza

Photo 24 - Completed Boomilever

Photo by Liz Monetza

2.3 Testing

Boomilevers are tested by attaching them to a standard Supporting Wall, placing a standard Load Block on the distal end, and adding sand to a bucket hung from the Load Block until a total load of 15 Kg is applied to the end of the Boomilever. Everyone should use the same supporting wall, bolts, and block to ensure fairness in the testing.

The supporting wall is described in Section 2.1, Problem Statement, and a full-scale template of a supporting wall is included in this kit. It will be necessary to make a wall. The wall can be made from 3/4” plywood, particle board, or any other smooth, stiff material. The template may be taped or glued to the plywood and holes drilled. The supporting wall must be securely fastened to a table, wall, or some sort of framework which will not shift or sag during repeated loading of Boomilevers, and it must be vertical. Check that the line between the bolt holes is level, and the wall is vertical, with a spirit level.

Record the mass of all Boomilevers at the beginning of any test or competition. Check the dimensions of the Boomilevers to determine whether they comply with the rules in the Problem Statement. Any Boomilever which does not meet ALL of the rules should be ranked below all Boomilevers which do meet the rules. It may be helpful to make some simple gauges from sticks of wood for checking dimensions.
Students should set up the test. Bolt the Boomilever to the supporting wall. Before tightening down the bolt(s) check that the Boomilever is hanging straight. If it is tilted, the load will not be even on the sides and an early failure may result. Check the Boomilever set up in two ways: the end of the Boomilever at the wall should be parallel to the lines on the template, and the load block should be level. If the Boomilever itself is crooked, it is more important to have the load block level. Place a small spirit level (a 9” torpedo level works well) on the top of the load block, level it, then tighten the bolt(s) and check the level again.

Students must follow all safety precautions which the teacher or the event supervisor may require. At a minimum, everyone within five feet of the test should wear safety glasses with side shields. Never put hands or fingers under the bucket during a test.

Put an eyebolt through the load block, hang a bucket from the eyebolt with two or three S-hooks or a short length of chain, and add sand until the total mass of block, bucket, eyebolt, S-hooks, and sand are at least 15 Kg, or until the Boomilever breaks. Add the sand as smoothly as possible to avoid “slugging” or impact loading, don’t allow the bucket to swing or rotate, and load it quickly if possible.

When the test is complete, remove the Boomilever and apparatus. Record the mass supported (not including the wall bolts) and the Boomilever mass so that the efficiency may be calculated. Sweep up any spilled sand.

2.4 Evaluation

Each Boomilever should be load tested and the Structural Efficiency of each Boomilever should be calculated. On the log sheets with the weights and densities, students should also record all observations of strain and deflection, and if the Boomilevers break, observations should be recorded summarizing the failure mode. Boomilevers that do not break at 15 Kg should be loaded with additional weight until they break, and the structural efficiency at ultimate load may be determined. Efficiency at ultimate load should be compared to efficiency at maximum scoreable load to illustrate the excess capacity of these Boomilevers. Log sheets and the finished Boomilever should also be evaluated for attention to detail and neatness. Students may suggest changes in the design and choice of materials to improve the efficiency of the Boomilever, but should be prepared to justify the suggestions based on observations.

There is far more to be learned from breaking the Boomilevers than from letting them survive the 15 Kg test. Building and testing Boomilevers, or any other model structure, is a research exercise intended to help us understand how structures respond to loads, and the limitations of structures. Real-world structures will be built with conservative safety factors to ensure that they don’t fail and endanger their users. The knowledge about ultimate strength of structures and appropriate safety factors comes from testing model structures and forcing them to fail.

Students must be careful and systematic in their observations. Try making a video recording of the tests and playing them back frame-by-frame. Structures will distort and sag as they are loaded. When they break, it happens so quickly that it is often difficult to see the initial break and the sequence of failures that follow. Have as many students as possible watch while testing and discuss their observations of strain and failure, from different angles. If a video recorder is not available, the observations of the students will be critical to identify the initial failed component.
When a Boomilever has broken, lay out the broken parts and look at the broken ends of the wood. Try to distinguish between tension failures, where wood fibers have pulled straight apart, and buckling failures in which the wood has broken midway between joints in a sideways direction. Joints may fail due to the glue shearing apart. Check to see if the wood has separated from the glue, this may indicate a poor bond or too little (or too much!) glue in the joint. Often, joint failures occur as secondary failures while the Boomilever is collapsing, and the joints get twisted out of their normal plane. Careful observation of the collapse will help determine the failure sequence and the weakest part of the Boomilever.

When all Boomilevers have been tested, compile data on their masses, loads supported, failure modes noted if Boomilevers are broken, and any other details which are of common interest. See Section 3.7 for a sample data collection form. From the compiled data, make a chart showing the minimum, maximum, and average capacities and efficiencies of tested Boomilevers. How many carried 15 Kg? How much scatter is in the test data? Scatter is a random distribution of data points due to unpredictable differences in wood, glue, quality of workmanship, etc. Are the load capacities a function of the Boomilever masses? That is, do heavy Boomilevers consistently carry more total load than do light ones? Are the maximum and minimum capacity Boomilevers exceptions due to poor construction or extremely high mass? Is there a correlation between efficiency and capacity?

**Safety Factor and Reliability** are important concepts for engineers. Structures are designed to carry certain loads, or combinations of loads, depending on the purpose of the structure. This is called the design load. In real-world structures, the exact loads are never known, and unusual circumstances may overload a structure, causing a catastrophe. For this reason, the structure is designed to carry more than the intended load. The design load is multiplied by a safety factor which will to allow for some unknown loads, and for repeated loads. Choosing a safety factor is based on tests similar to this Boomilever exercise.

What load can these Boomilevers safely carry? A real-world structure may have a safety factor ranging from 2 to 5 or more, depending on how critical the application is. The permitted load on the structure will then be one-half to one-fifth of the load expected to make the structure fail. For example, if most of the Boomilevers fail at 15 Kg, then a safety factor of 3 means the safe capacity of the Boomilever is 5 Kg. Conversely, if 15 Kg must be carried, then a safety factor of 3 means the Boomilevers should be built to break at 45 Kg. A high safety factor protects users against disastrous collapses, but the trade-off is that the masses of the structures will be greater and the structural efficiency will be lower.

Discuss the balance between how large a safety factor should be versus the cost (mass) of the structure.
3.1 Compression Boomilever Design

The main chords of a Boomilever are the top chord, loaded in tension, and the bottom chord, loaded in compression. In the example Boomilever, the bottom chord is actually a box truss built up from many smaller pieces of wood. Depending on the height of the loading block compared to the height of the mounting holes, the length of the tension or compression chord may be minimized. If the load block is supported at the same height as the mounting holes, the tension chord is minimized and the compression chord becomes longer and heavier, and carries a greater amount of force. For the purposes of this guide, this design is called a “Compression Boomilever” because the design is dominated by the requirements of the compression chord. See Figure 3.1.

Figure 3.1 - Profile of “Compression Boomilever”

The advantages of this design are: the top chords naturally provide a level platform to support the loading block, directly above the joint with the bottom chord; the joints at the attachment base and the loading block end are simpler and more reliable; and the overall sag of the Boomilever as it is loaded is less than in other designs.

The main disadvantage is that the longest and most heavily loaded chord is in compression. Strips of wood in compression will buckle and must be thicker and heavier, or have more lateral cross bracing, than strips in tension. See Section 6.5 for more on buckling. The greater length makes the buckling worse and makes the overall mass of the Boomilever greater. In addition, the Compression Boomilever design places a vertical reaction load at the unboltered bottom contact with the supporting wall, so that the Boomilever must have a chord to transfer the reaction back up to the attachment base. This is an inefficient design.
3.2 Tension Boomilever Design

If the load block is carried at the same level as the compression chords where they contact the supporting wall, the length of the compression chords are minimized and the compression chords are perpendicular to the supporting wall. The tension chord is the longest chord and carries a greater amount of force. For the purposes of this guide, this configuration is called a “Tension Boomilever” because the design is dominated by the requirements of the tension chord. The Example Boomilever is this design. See Figure 3.2.

![Figure 3.2 - Profile of “Tension Boomilever”](image)

This is the most efficient arrangement of main chords for a Boomilever. By minimizing the length of the compression chord, the tendency to buckle and the need for bracing are also minimized. The forces in the compression chord are also less in this arrangement. The long, more highly loaded tension chord takes better advantage of the structural qualities of wood. In addition, since the bottom chord is perpendicular to the supporting wall, there is no vertical reaction there and no need for a load-carrying strut back to the attachment block.

The disadvantages are: the sag of the Boomilever is greater as the tension chord stretches; shear stresses at the joints at the attachment block and at the load block end are greater and tend to bend or twist with the sag, so that the joints are more difficult to build; and the load block must be supported level by extending the bottom chord past the tension chord end or by building a platform between the chords.
3.3 Attachment Base

The Boomilever must be bolted to the Supporting Wall. The bolted connection resists the pull of the tension chords as the load presses down on the outermost end of the Boomilever. The compression chord presses inward against the wall and does not need to be attached to the wall. An attachment base is added to the end of the tension chords to hold them to the bolt(s). The attachment base may be made in one or two pieces, using one or two bolts in the supporting wall, see Figure 3.3.

![Diagram of Attachment Base for One or Two Bolts](image)

**Figure 3.3 - Attachment Base for One or Two Bolts**
Compression Style Boomilever shown for illustration only. Either attachment base style may be used with any Boomilever configuration.

The attachment base is allowed to be plywood or similar man-made wood products. It may also be thicker and wider than the sticks used for the rest of the Boomilever. This is because the attachment base must resist a high shear load perpendicular to the supporting wall, and a bending load between the head of the bolt and the end of the tension chord, since the tension chord usually is offset to one side of the bolt.

3.4 Joint Design

Joints must be carefully designed and the precise assembly of the joint is crucial to success. Joints should be tight and the ends of structural members should match without gaps. Enough glue should be used to form a thin, even film on the bonded surfaces, without gaps or dry spots. Avoid using excess glue; the extra glue adds weight, makes a mess, and in some cases actually makes the joint weaker. Form a shallow fillet (concave surface) of glue on the outside of the joint; this will help resist tearing of the joint when the joint is twisted or pried apart during loading. Wipe off or sand off any excess glue which may be squeezed out of the joint. Joints are often the most highly stressed part of a structure, and precise assembly of joints will get the maximum performance from them.
The basic types of joints are lap joints and butt joints, although there are a number of variations. Butt joints are simple joints in which the end of one piece of wood is glued directly to the side or end of another piece. This type of joint is strong in direct compression, but has little strength in tension, twisting, or shear. The end grain of the wood makes a poor surface for a glue joint, because the glue wicks into the wood, the end is often uneven, and the ends of the wood fibers do not provide a good bonding surface. The joint is all in one plane, and so any forces such as bending or twisting of the joint will easily peel the joint apart. Butt joints can be greatly strengthened by adding gussets, thin pieces of wood that span across the joining plane. Gussets provide additional glued surfaces perpendicular to the original joint. The addition of gussets to a butt joint makes a strong joint capable of resisting forces from all directions. See Figure 3.4.

Lap joints are simple joints in which the side of one piece of wood is glued to the side of another piece. The side grain is a better gluing surface than end grain and makes a stronger joint than a simple butt joint. Most of the joints in the example Boomilever are lap joints. A lap joint is usually loaded in shear, so that the force is directed in the same plane as the glue. The joint is also strong in compression, similar to a butt joint, but the side grain of the wood will crush more easily than end grain. Since the joint is all in one plane, the lap joint will also peel apart when subjected to twisting and bending forces. Lap joints can be strengthened by cutting notches in the wood to create additional gluing surfaces (half-lap or ship-lap joints), or by overlapping several pieces together to make a more complex joint. See Figure 3.5.
Also shown in Figure 3.5, the concept of a laminated joint can be extended to building up the thickness of the chords with thin layers of wood, overlapping with the layers in another chord, to build a joint which is fully integrated with the structural chords. In effect, the chords are woven together at the joint and the chords become a single built-up piece of wood.

Structures usually sag, bend, twist, and deform in unexpected ways when loaded. The effect of deforming any structure shows up in all three dimensions, and so the joints must resist forces in all directions, plus twisting and bending forces. Either the joints must have glued surfaces in two or three different planes, or several joints must be arranged to support each other. In the example Boomilever, most joints are simple lap joints, but they are arranged so that adjacent joints help each other to resist out-of-plane forces.
Joints may also be designed with pinned or pegged construction. If two pieces of wood are glued side to side in a simple lap joint, the stress on the joint is a shear stress through the glue. If the glue is brittle or not properly adhered to the wood the glue itself may break. If a hole is drilled through the joint, a peg of wood made from Basswood or spruce, such as a toothpick of small dowel, can be inserted through the joint. The cross section area of the wood peg will resist the shear forces in addition to the glue. This may be useful for a joint such as the attachment base or the distal end of the Boomilever where the stresses are concentrated. A pegged joint will resist the twisting and bending of the joint better than a plain glue connection. The disadvantages of this joint design are that it may be heavier and more complicated to build, and the peg may tear through the end of the chords.

3.5 Materials

3.5.1 Wood The rules of the Boomilever problem require that they must be built with wood and bonded with glue. Any kind of wood is allowed, and any kind of glue is allowed, although the glue must be used as an adhesive rather than as a coating. By far the most common wood for use in model structures is Balsa, and next most common is probably Basswood. Other types of wood, such as Spruce, Poplar, Maple, Oak, etc., are so dense that it will be difficult to achieve a high efficiency with these.

One key to the best choice of wood for Boomilever, or any high-efficiency model structure, is the strength-to-weight (S/W) ratio of the wood. Wood has the capacity to carry weight in compression, tension, bending, etc., and every variety of wood has limitations. If more force is imposed on the wood than the wood fibers can withstand, the wood will crush in compression or tear apart in tension or shear. Denser woods usually have more strength, but that strength comes at a price: the Boomilever will be heavier and the efficiency could be lower, depending on the actual load the Boomilever can carry. Building for high structural efficiency means that a compromise must be found between the strength of the materials and the overall weight of the Boomilever.

Another key quality of the wood is stiffness, or elasticity. Wood bends, stretches and compresses and changes dimension under loads. This is called elastic strain; it causes the Boomilever to bend, sag, or twist, and when the load is removed, the Boomilever will return to its original size and shape. Long slender chords will buckle (see Section 6.5) when an axial compression load is placed on its ends. The stiffness of the wood is a key quality in resisting buckling. The stiffness of a strip of wood may be estimated by securing one end of a standard length (24” or 36”) strip of wood to a tabletop and letting most of the length of the strip cantilever out. The wood will sag under its own weight or a small weight may be attached to the free end. By comparing the sag of different strips and different densities of wood, a comparative estimate may be made of the elasticity of the wood. This will give students an intuitive measure of the quality of the wood. Stiffness is often measured as the modulus of elasticity of the material, in units of pressure (psi or pascals). It is different for different materials, and in the case of wood, it changes with the density. Like a spring constant, a higher modulus of elasticity indicates greater stiffness.
Balsa is a fast growing tree commonly from Central and South America. The wood is light, varies greatly in density, and has a reasonably high strength-to-weight ratio. The strength-to-weight ratio of Balsa varies with the density, and increases at higher densities. Here are some properties for different densities of Balsa, at the point of material failure.

<p>| Strength of Balsa Wood at Different Densities (12% moisture content) |
|---------------------------------|----------------|---------------|---------------|----------------|---------------|---------------|----------------|</p>
<table>
<thead>
<tr>
<th>Density (pcf)</th>
<th>Compression (psi)</th>
<th>S/W ratio</th>
<th>Tension (psi)</th>
<th>S/W ratio</th>
<th>Bending (psi)</th>
<th>S/W ratio</th>
<th>Modules of Elasticity (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>750</td>
<td>125</td>
<td>1375</td>
<td>229</td>
<td>1375</td>
<td>229</td>
<td>280,000</td>
</tr>
<tr>
<td>8</td>
<td>1380</td>
<td>172</td>
<td>1850</td>
<td>231</td>
<td>2200</td>
<td>275</td>
<td>425,000</td>
</tr>
<tr>
<td>11</td>
<td>1910</td>
<td>174</td>
<td>3050</td>
<td>277</td>
<td>3050</td>
<td>277</td>
<td>625,000</td>
</tr>
<tr>
<td>15.5</td>
<td>2950</td>
<td>190</td>
<td>4525</td>
<td>292</td>
<td>4525</td>
<td>292</td>
<td>925,000</td>
</tr>
</tbody>
</table>

Test results vary for balsa strength, and moisture and the grain size and direction in the wood also affect the strength values, and so the actual strength of any piece of Balsa may not match the values presented here. The important point to note is that Balsa density can vary by a factor of more than two, and that the strength-to-weight ratio increases as the density increases. This means that more strength can be obtained with less total weight of wood at high densities than at low densities. The problem with using high density Balsa is that the chords must be smaller cross sections to reduce the total weight. Smaller sections reduce the surface area available for glue joints, and in compression, smaller sections are more likely to buckle. The grain of Balsa is an open, coarse grain, often not straight, and so strips of Balsa usually are cut across some of the wood fibers along the length of the strip. This further weakens the wood, and this problem is worse with very small sections. For model structures such as Boomilevers, an average density Balsa, or a mixture of densities, is usually the best choice.

Balsa has additional advantages that it is porous and is easily glued together, and it is relatively soft and easy to cut, strip, or carve. The greatest disadvantage is the variability of the wood. Students must learn to be very selective when choosing individual pieces of wood; much will be rejected when building competitively. Students should measure the mass of each piece of wood, determine the density (in pounds/cubic foot (pcf) or kilograms/cubic meter (Kg/m^3)), and estimate the stiffness of the strips of wood compared to other strips.

Basswood is a good alternate choice of wood. It has a similar strength-to-weight ratio to high density Balsa. Basswood also is much more consistent in density, so that there will be less rejected wood. Basswood has a much finer, straighter grain and is generally tougher, so that it can be bent more sharply without breaking. Basswood has the disadvantage that its density is twice as great as high density Balsa. For a chord made of Basswood to be of equal weight and equal strength as a chord made of Balsa, the cross section area will be approximately half that of the Balsa. Structures made of Basswood will be made from extremely thin strips of wood. Very thin strips of wood may work well in tension, but they work poorly in compression, because a chord needs a large cross section to resist buckling even for a stronger wood.
In the example Boomilever, the main tension chord is made from Basswood and the rest of the structure is made from Balsa. This design attempts to use the best qualities of each type of wood: the high tensile strength and high modulus elasticity of the Basswood in the top chord, and the lower density, larger cross section of Balsa pieces in compression. The example design has not been optimized to find the smallest sections. It may be found by experiment that smaller sections are adequate, or that the Basswood can be replaced by Balsa, or that the stiffer Basswood can be used in compression with less cross bracing than the Balsa. The different qualities of the woods should be used to their best advantage.

Other wood species offer little advantage. The strength-to-weight ratios for spruce, pine, oak, etc., are lower than Basswood, but the densities of these woods are equal to or more than Basswood. Harder woods are more difficult to cut into strips.

More information on Balsa and Basswood can be found at:
www.fpl.fs.fed.us/documents/fplgtr/fplgtr113/ch04.pdf (very technical)
www.zimsweb.com/balsa/information/info.htm
en.wikipedia.org/wiki/Balsa, and en.wikipedia.org/wiki/Tilia

3.5.2 Glue Glues used in Boomilever construction fall generally into two categories: water-based glue and solvent-based glue.

Water-based glues have high shear and tensile strength, and tend to be resilient, that is, they can stretch a little before breaking. These glues are also heavy by comparison to solvent glue, and they take a long time to dry. Glue joints often must be clamped or weighted during drying to ensure that the joint adheres properly. The tacky glue included in the kit is a water-based polyvinyl acetate glue; commonly available carpenter’s (yellow) glue is also water-based. These glues are usually used in classrooms because they are less toxic than solvents.

The most commonly used solvent-based glue is probably cyanoacrylate (CA) glue, also known as super glue. CA glue tacks quickly and weighs less than water-based glue. It has high strength, but it is generally more brittle in shear or tension than tacky glue. CA is a short-chain polymer suspended in solvent. When it is applied to a surface, the suspending solvent evaporates and the molecules polymerize into long chains that mechanically bind to the surfaces. The polymerization reaction is accelerated by moisture on the surface (it sticks to skin better than it sticks to wood). CA glue cures very fast, depending on the viscosity of the glue, usually in 5 to 15 seconds. When building a structure with CA glue, construction can continue without waiting for glue to dry because the joints will have enough strength to be handled almost as fast as the parts can be joined. The curing process may take two hours or so to fully cure. An accelerator spray is available to speed up the curing process even more, but it tends to short-circuit the polymerization and results in a weaker joint. CA glue is more toxic than tacky glue; the solvent fumes from curing CA glue can trigger respiratory problems in some people. CA glue is usually a better choice for competitive structure building.

More information on CA glue is available at:
en.wikipedia.org/wiki/Cyanoacrylate and at
Other glues sometimes used in Boomilever building include isopropyl acetate/acetone solvent cement, Duco, Ambroid, and Gorilla brand glues; and two-part reactive glues like epoxy, each of which have different advantages and disadvantages. Determining the best glue could be done with extensive comparison experimentation.

For structural joints, the gap between pieces of wood must be as small or tight as possible, and the entire area of contact must be glued. It is easy to use too much, and excess glue not only adds weight, but also can weaken the joint. A thick film of glue acts like a bridge between pieces of wood and the glue is often more brittle than the wood. There should be enough glue in the joint to form a shallow fillet on the outside of the joint. The fillet will help keep the joint from tearing at the outer edges of the joint when out-of-plane forces tend to twist or pry the joint open.

### 3.6 Craftsmanship

An optimized design and ideal materials will be wasted if the structure is poorly built. The structure must be of the correct proportions and dimensions to balance the internal strains. The joints must be assembled properly to avoid stress concentrations at weak points. Glue must be applied evenly and thoroughly to develop the strength required to hold together joints and laminations.

Every structural element should be carefully measured and cut, to the precise size and shape required by the design. If each piece is correct, it will be much easier to assemble the complete structure symmetrically. If the structure ends up uneven, because of mismatched struts and chords, then it will not distribute the forces of the load efficiently and could fail.

### 3.7 Data Collection

As suggested in Section 2.2.2.3, students should record information about the materials, design, subassemblies, and finished Boomilevers, including observations, test results, and comparative information. This section includes an example of a construction data sheet for a Boomilever, a judging and testing form to be used during tests or competitions, and a comparative data summary form to compare and analyze the results of several Boomilever tests. The comparative form may be used to compare Boomilevers of identical design, or to chart the progress of a succession of Boomilever designs based on iterative testing and improvement.
# Boomilever Construction Log

**Names:** ____________________________________________  **Date:** ______________________

| Information Collected During Construction |  
|-------------------------------------------|---|
| A sketch of the Boomilever with emphasis on the pattern of assembly of the chords and exact measurements of wood used to create the Boomilever |  
| Make labels and notes on important parts of the Boomilever |  
| Sizes and types of wood used, mass and density of each whole strip of wood, estimated stiffness |  
| Mass of the sub-assemblies (side trusses, main chords, etc.) |  
| Mass of Boomilever without Attachment Base and mass of Attachment Base |  
| Total mass of the Boomilever and total load supported. Did the Boomilever break? |  
| Observations of sag, strain, and stability. May include digital pictures of Boomilever with load applied. |  
| Observations about **how** Boomilever failed |  
| Observations about **where** the Boomilever failed |  
|  
|  

**Wall**  
**Load**
Boomilever Testing Checklist

Student Names: ____________________________________________  Test Date:  _______________

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pieces of wood are more than 1/4” x 1/4” (6 mm x 6 mm) in cross section dimensions. Dowels are not more than 1/4” diameter.</td>
<td></td>
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</tr>
<tr>
<td>Commercially laminated wood, particleboard, or other materials are used only for the Attachment Base, and may not extend more than 1/2” from the Supporting Wall.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boomilever Attachment Base is made from wood, plywood, or other manufactured wood products, plus glue, and nothing else.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boomilever Attachment Base is one or two pieces and no larger than 30.0 cm x 20.0 cm x 1/2”.</td>
<td></td>
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<tr>
<td>Boomilever Attachment Base will bolt to holes in Supporting Wall. No other attachment means is used.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No part of the Boomilever touches the Supporting Wall lower than 20.0 cm below the centerline of the bolt holes.</td>
<td></td>
<td></td>
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<tr>
<td>An opening with clearance exists for the eyebolt on the Loading Block.</td>
<td></td>
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<tr>
<td>The center of the Loading Block is 40.0 cm or more from the Supporting Wall measured horizontally.</td>
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</tbody>
</table>

1. Mass of Boomilever in grams  ______ g
2. Mass of Load supported in grams  ______ g
3. Efficiency: Load supported/Mass of Boomilever  ______
4. Boomilever Rank Scoring  ______
   1. Boomilever meets all specifications
   2. Boomilever does not meet specifications
   3. Boomilever could not be loaded
### Comparative Boomilever Trial Summary Table (Example)

<table>
<thead>
<tr>
<th>Boomilever Trial</th>
<th>Mass (g)</th>
<th>Total Load supported (g)</th>
<th>Efficiency using 15 Kg. max load</th>
<th>15 Kg Load Efficiency Rank</th>
<th>Ultimate Efficiency (Efficiency at Failure)</th>
<th>Ultimate Efficiency Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td>31.5</td>
<td>19500</td>
<td>476</td>
<td>2</td>
<td>619</td>
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<tr>
<td>Example 2</td>
<td>29.2</td>
<td>14800</td>
<td>507</td>
<td>1</td>
<td>507</td>
<td>3</td>
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<tr>
<td>Example 3</td>
<td>34.8</td>
<td>20200</td>
<td>431</td>
<td>3</td>
<td>580</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Maximum Capacity** = 20200 g
- **Average Capacity** = 18167 g
- **Minimum Capacity** = 14800 g

- **Maximum Scored Efficiency** = 507 g
- **Average Scored Efficiency** = 471 g
- **Minimum Scored Efficiency** = 431 g

- **Maximum Ultimate Efficiency** = 619 g
- **Average Ultimate Efficiency** = 569 g
- **Minimum Ultimate Efficiency** = 507 g

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### Comparative Boomilever Trial Summary Table

<table>
<thead>
<tr>
<th>Boomilever Trial</th>
<th>Mass (g)</th>
<th>Total Load supported (g)</th>
<th>Efficiency using 15 Kg. max load</th>
<th>15 Kg Load Efficiency Rank</th>
<th>Ultimate Efficiency (Efficiency at Failure)</th>
<th>Ultimate Efficiency Rank</th>
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- **Maximum Capacity** =
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- **Maximum Ultimate Efficiency** =
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- **Minimum Ultimate Efficiency** =
3.8 Construction Jig

The example Boomilever is easily assembled on a flat table by working directly on the full-scale patterns. Assembling the Boomilever halves into a three dimensional structure is done on the plans with the use of a hobby or machinist's square to make sure the Boomilever will hang properly on the supporting wall. This technique is possible because the Boomilever sides are complete trusses and hold their shape precisely during assembly.

It is critical to have the geometric relationship of the supporting wall, attachment base, load block, and Boomilever chords straight and accurate. A construction jig may be made from plywood, MDF board, or other common building materials as shown in Figure 3.6. Use rigid, warp-resistant materials and be very precise about assembling the parts. The load block should be set on a long bolt or threaded rod at an appropriate height for whatever design is being built. In Part 4, some alternative problem conditions are suggested, and the creative designs which students may choose to build will be easier to assemble with a 3-D jig to hold everything in the correct place when the parts are glued together and while the glue dries.

Figure 3.6 - Construction Jig

-33-
Part 4 - Boomilever Design Challenges

The common design that everyone constructed in the previous section was intended to teach construction techniques and to facilitate observations. As a follow up to this, experimental problems may be posed to the students. Engineering and technology experiments are similar to scientific experiments that follow the scientific method. They are set up with a problem statement, or a problem to be solved; a proposed solution or hypothesis; a design procedure; a series of construction, testing, and refinement steps, including intermediate data; testing of the final constructed device; and conclusions drawn regarding the device as a solution to the original problem statement. Students should prepare a notebook recording their procedures and results. The final testing of the Boomilevers may be staged as an in-class or intramural competition, with recognition given to the winning Boomilever efficiency.

Competitive design problems should be variations on the original Boomilever problem statement given above. Problem variations should be different enough that the basic design cannot be used without substantial changes. This will force the students to develop new designs by applying the concepts and techniques previously learned to a new situation. The following are proposed competitive problems. The teacher and/or class may develop another problem statement as they prefer. These problems will use similar quantities of materials as the original basic Boomilever problem. Designs should be drawn full size of graph paper or drafting paper, not included in this kit.

4.1 Challenge 1: Repeat the original problem, with a new requirement that a maximum given Boomilever mass must not be exceeded. Choose a maximum mass at least 25% less than the lightest mass of the initial set of Boomilevers.

Questions

1. What changes must be made to satisfy the new constraint? How does this change the Boomilever? When the design is changed to satisfy the new requirement, what new capabilities or improvement in performance do you expect?

2. How much extra strength does the Boomilever have? It is required to carry up to 15 Kg, but not more. How much can the example Boomilever actually carry?

3. Which structural members (wood chords) are most heavily stressed when carrying the 15 Kg load? Which carry little or no load?

4. If the example Boomilever is loaded until it breaks, which part breaks, and how does it break? Is it broken at a joint? Or is it broken in a main chord between joints? Did the broken part fail in tension, compression, shear, or buckling?

5. If the example Boomilever has excess strength, how much can the wood chords be reduced to save weight and still have enough strength to carry 15 Kg? Can you eliminate any of the chords completely?

6. Is there a more efficient design?
4.2 Challenge 2 - Decrease the maximum vertical distance from the center of the mounting holes to the lowest point that the Boomilever may touch the wall to 15.0 cm, while leaving all other parameters the same.

Questions
1. What changes must be made to satisfy the new constraint? How does this change the Boomilever? When the design is changed to satisfy the new requirement, what new capabilities or improvement in performance do you expect?
2. When the vertical distance between the bolted connection and the point of contact for compression is reduced, how do the stresses in the main chords change? Why?
3. If the stresses increase, will stronger main chords be required? How do you make them stronger?
4. What happens to the stresses in the cross bracing or in diagonal bracing? What purpose do these pieces serve, and how does an increase in stress in the main chords affect them?
5. Is there a more efficient design?

4.3 Challenge 3 - Increase the distance between the load and the supporting wall to 50.0 cm., while leaving all other parameters the same.

Questions
1. What changes must be made to satisfy the new constraint? How does this change the Boomilever? When the design is changed to satisfy the new requirement, what new capabilities or improvement in performance do you expect?
2. When the distance from the supporting wall to the load is increased, how do the stresses in the main chords change? Why?
3. If the stresses increase, will stronger main chords be required? How do you make them stronger?
4. What happens to the stresses in the cross bracing or in diagonal bracing? What purpose do these pieces serve, and how does an increase in stress in the main chords affect them?
5. Is the stability of the Boomilever affected by increased span (length to load)? That is, does the Boomilever tend to swing side to side more, or sag more, or buckle in the compression chords?
6. Is there a more efficient design?

4.4 Challenge 4 - Specify that the level of the load block shall be 0.0 cm higher than the holes in the supporting wall, while leaving all other parameters the same. (Any level may be chosen with respect to the mounting holes. The original problem does not specify a dimension, and the example Boomilever places the load 17.7 cm below the mounting hole level.)

Questions
1. What changes must be made to satisfy the new constraint? How does this change the Boomilever? When the design is changed to satisfy the new requirement, what new capabilities or improvement in performance do you expect?
2. How does this configuration change the stresses in the main chords? How does it change the reactions (resisting forces) at the supporting wall? This is similar to a “Compression Boomilever” (see Section 3.1), except that the tension chord is not perpendicular to the supporting wall.
3. If the stresses increase, will stronger main chords be required? How do you make them stronger?
4. Can you find examples of similar real-world structures? How do they handle the load and transfer forces back to their supports?
5. Is the stability of the Boomilever affected by increased angle of the chords? That is, does the Boomilever tend to swing side to side more, or sag more, or buckle in the compression chords?
4.5 Challenge 5 - Specify that any portion of the Boomilever 20.0 cm or more from the supporting wall must fit through a 80.0 mm diameter circle, while leaving all other parameters the same.

Questions

1. What changes must be made to satisfy the new constraint? How does this change the Boomilever? When the design is changed to satisfy the new requirement, what new capabilities or improvement in performance do you expect?

2. What will the geometric profile of this Boomilever look like to satisfy this requirement? How will this affect the main tension and compression chords? Can the main tension and compression chord be built in straight lines?

3. In most types of Boomilevers, the stresses in the main tension and compression chords are constant from the load end to the supported end. Is that also the case in this configuration?

4. Is the stability of the Boomilever affected by uneven angle between the chords and narrow profile of the Boomilever? That is, does the Boomilever tend to swing side to side more, or sag more, bend or buckle in the compression chords?

Many other variations on the Boomilever problem are possible and may be defined by the teacher or the students. It could be a fun brainstorming activity. Alternatively, a specific performance-based problem may be posed with a Boomilever solution, but without a list of constraints. The following would be an example:

4.6 Challenge 6 - Design a bracket to hold an average-to-heavy backpack full of books in a bathroom or shower room. Backpacks should never touch the wall or the floor. The bracket must be made of cheap, readily available materials, such as wood and glue, and be made using simple tools. You will need lots of brackets, so they must be cheap and easy to make.

Questions

1. How much does an average-to-heavy backpack weigh? Is it similar to the 15 Kg Boomilever load?

2. How far from the wall should a backpack be held from the wall and floor to ensure that none will touch? What are the largest common dimensions of a backpack? How will you fasten the bracket to the wall?

3. What makes a bracket cheap and easy to make? The bracket must also be reliable, so that backpacks never touch the wall or floor. This is a question about the efficiency and effectiveness of design, a central question in engineering solutions.

4. This problem may be modeled as a Boomilever by determining the best dimensions, mounting method, and maximum expected load, and least amount of material required for economy and efficiency. Students may be asked to go beyond effective structural design and estimate the cost in time and materials to build and install the backpack brackets.
Part 5 - Basic Structural Concepts - Entry Level

5.1 Forces, Resistance, and Stress

**Forces** are understood as a push or pull on an object, and may be from gravity, contact with moving objects, pressure from heat expansion, or other sources. Forces act in a straight line; they are **vectors**. In physical terms, a force causes a given amount of mass to accelerate, or start moving, and the magnitude of the force is directly proportional to the acceleration of the mass. Force is measured in Newtons or pounds. Loads are often stated in grams or kilograms, a measure of mass, but the force is actually the pull of gravity on that amount of mass.

**Structures** function by reacting to forces applied from the environment. These external forces are loads, and the structure provides an opposing force, or resistance, to the load and transfers the force of the load to a foundation. If the structure is strong enough and anchored securely enough to resist the forces without moving or collapsing, then the structure is in **equilibrium**. If the structure reacts to a load by moving, as in a pinwheel vane or a baseball, then the system is dynamic and is not in equilibrium. Structures that are in equilibrium are analyzed by a set of rules known as **Statics** (see Section 6.1). Structures that are set in motion by the applied forces are analyzed by the rules of Dynamics. In the case of beams or brackets carrying a load, motion only occurs when the structure fails and collapses.

**Stresses** are a reaction to external forces, and are a measure of the intensity of the internal forces within a structure. When a load pushes on a structure, the components of the structure push back to provide resistance. The amount of resisting force in each individual part will depend on the design of the structure. The stress in each part is the force divided by the cross section area through which the force is acting, and is measured in Newtons/square meter or pounds/square inch. The strength of the part is limited by the amount of stress that will cause the material to crush or tear apart.

There are five basic forms stress in structures: tension, compression, shear, bending, and torsion, or twisting. If a component of a structure could be examined on a microscopic level, it could be seen that all stresses are either tension or compression, and the other stresses are combinations of these.

5.1.1 **Tension** is a stress that pulls a structure apart. See Figure 5.1. It is seen in the pull of a string or a rubber band. When a structure resists a tension load, it pulls against its supports, and must be fastened to its foundation or supporting wall to avoid pulling away from it.

5.1.2 **Compression** is a stress that crushes a structure together. An example is the weight of a load pushing down on the leg of a tower. See Figure 5.1. Many building materials, such as wood and steel, are much stronger when resisting tension than compression. Thus, tension members of a structure can be smaller and still be as strong as compression members. Other materials, such as concrete, chalk, or ice, are strong in compression but brittle when loaded in tension, so that they break easily. As a result, stone bridges are usually low and massive, supporting their loads from underneath, but steel or wood bridges can be light, with longer spans, and carry loads more indirectly.

![Figure 5.1 - Tension and Compression](image-url)
5.1.3 Shear occurs when parts of a structure tend to slide past each other. If two pieces of wood are laid across each other and glued, and then the pieces are pulled apart along the plane of the joint, in a sliding motion, the joint is stressed in shear. This is basically the same as tension, except that a tension load would be perpendicular to the plane of the glue, pulling the sticks away from each other, and shear is in the same plane as the glue. On a microscopic level, the glue is being pulled apart by the stress.

![Shear in a Lap Joint](image1)

![Shear in a Chord](image2)

**Figure 5.2 - Shear Stresses**

Shear is also seen in the action of scissors, where two opposing, slightly offset forces act across the thickness of an object and tear or cut the object.

5.1.4 Bending uses the stiffness of a beam to resist a force which is perpendicular to the length of the beam. This called transverse loading. Bending works as a combination of tension stresses and compression stresses acting against each other, within the same structure at the same time. Suppose a simple beam spans across the space between two tabletops, and a weight is placed at the center of the beam. See Figure 5.3. The beam will bend downward under the load. If the top of the beam could be carefully measured, it would be found to have become shorter; the bottom of the beam would be longer. The beam resists the load from the weight by compressing the material at the top of the beam and stretching the material at the bottom. These tension and compression stresses are balanced, and proportional to the weight of the load. If the load is too great, the beam will break because the material in the beam will fail at the top or bottom surface.

![Simple Beam](image3)

![Cantilever Beam](image4)

**Figure 5.3 - Bending in Beams**
5.1.5 Torsion, or Twisting of a structure occurs when a load is applied off center to the structure. A freely floated object, called a free body, will rotate if pushed by an off-center force. A crank or a knob with a force applied to the end of the crank forces a shaft to rotate. Structures such as towers may have a twisting load if they are not symmetrical or not properly braced. The downward load makes the tower rotate as the legs and joints bend; the direction of rotation will be whichever way the tower is weaker. Twisting of a tower or boom affects the stability of a structure, and it is one of the hardest problems to solve in a structure.

![Diagram of torsion and tension on objects](image)

**Figure 5.4 - Twisting or Tension (Torque) on Objects**

When a force is applied which causes rotation, the force multiplied by the perpendicular distance to the resisting force or attachment point of an object is called a moment or a couple. This is the measure of how much torsion or torque an object must resist to remain in equilibrium. This is discussed in Section 6.1.

5.2 Rigid Structures, or Frames

Individual components like beams, columns, chords within trusses, resist external forces without changing shape, or by bending or twisting elastically, like a spring, then returning to their original shape when the load is removed. When components of a structure resist a load, they also transfer the load through the joints between components and finally to a foundation or supporting wall or similar anchor. If the joints are rigid, that is, the joints don’t allow the angle or the spacing of the components to change, then the structure is called a rigid frame, or simply a frame. The joints must be stiff enough to prevent the ends of beams from rotating when the beams sag, and to prevent the structure from folding like a cardboard box. In rigid frames, the bending effect on a beam is transferred through the joints and every component attached to the joint will be subjected to bending forces as well. See Figure 5.5. In rigid frames, the joints must be heavy or gusseted, and the beams or chords must be massive and stiff to resist bending forces from all parts of the structure. This type of framing was once common in barns and timber-framed houses. Rigid frames are relatively heavy, inefficient structures.
Classroom Activity

Cut out a square approximately 8” each side from cardboard (non-corrugated, like a cereal box or the back of a notepad), and cut out the inside of the square so that the sides are about ¼” wide. Cut the corners wider to simulate the gussets in Figure 5.5. Lay the cut-out square on the table and press two opposite corners toward each other. How do the sides bend? Do they stay flat on the table? Weight down the corners and try again. How do the sides bend?

Cut out five more squares and tape them together edge-to-edge to form a cube. Is the cube stable, that is, does it hold its shape without any bracing? When weight is placed on the cube, how do the sides distort?

Make an “X” over each side of the cube with masking tape, from corner to corner. Does this change the strength and stability of the cube?

5.3 Trusses

As an alternative to rigid joints and heavy framework, a structure can be designed with bracing arranged in triangular patterns. Triangles are the only geometrically stable shape, and the joints don’t require any stiffness. Joints may be pinned, or hinged, and free to rotate as in Figure 5.6. Chords with pinned joints have an advantage over the rigid joints in frames because bending moments are not transferred through the joints. Forces applied to any chord are transferred through the joints as simple tension and compression forces to the next chords. The chords do not need to be thick or stiff to resist bending. Structures built with pinned joints and with a triangulated arrangement of chords are trusses.
Trusses are often used to replace beams, but they do not bend like beams. In a truss, the individual struts, or chords, of the truss are either in tension or compression. For a given load, each strut will have for a specific force of tension or compression. See Figure 5.7. In some ways, the truss acts like a beam: stresses are greatest in the center of a span, and the top of truss is being compressed while the bottom is being stretched. Trusses are usually deeper and stiffer than beams, but they can also be much lighter. The key to the performance of a truss is its depth. By making the truss deeper, the stresses in the top and bottom chords become smaller, and the chords may be built lighter.

![Figure 5.7 - Forces in a Truss](image)

Truss structures constructed with glued joints have rigid joints, like a frame, but if the wood chords are thin and flexible there will be some “give” in the wood at the joint. These joints are semi-rigid and a truss with semi-rigid joints and a triangulated structure will work like a truss with pinned joints.

**Classroom Activity**

Cut out strips of heavy paper or card stock, all the same length. If necessary, roll the strips into tubes to stiffen them. The strips may be any convenient length provided they are stiff enough to build a truss. Punch holes in the ends of the strips and connect them together with brass paper brads or something similar, so that the strips can rotate freely at the end connections. Use these as truss chords and build a flat truss similar to Figure 5.7. Build two identical trusses and attach them to each other side by side with short connecting chords to make a bridge-like structure in three dimensions (See Section 5.4 on 3-D structures). Simulate a load on the trusses by supporting the ends on books or on the edges of tables, while pressing down on different nodes. Which nodes are in tension? Which are in compression? How does the truss deform? How do the tension and compression forces change when the load is moved to another node? Try removing tension chords and replacing them with string or thread. The truss will still work, but if the load is moved or if the truss is flipped upside down, the truss will collapse. This paper truss demonstrates how forces flow through a truss from the load point to the supports.

**5.4 Three Dimensional Structures**

The trusses and frames shown in Sections 5.2 and 5.3 are two dimensional structures. They are presented this way mainly to simplify the illustration, but often the design of Boomilevers and other structures begin as flat subassemblies which are later tied together by cross bracing in the plane perpendicular to the page.
For example, roof trusses intended for house construction are manufactured as flat trusses, lifted onto the walls of a house and placed upright at appropriate spacing. They are then tied together by the plywood sheathing that forms the surface of the roof. Until the sheeting is installed, the trusses are very weak and easily bend in the direction perpendicular to the plane of the truss. The sheeting restrains the trusses in this third dimension and prevents the out-of-plane bending.

Forces are one-dimensional. They have direction and magnitude only. However, forces operate in all three dimensions of space. Structural chords will resist a force in the opposite direction to the force, provided they are stiff enough and anchored well enough that they do not become distorted or rotated. Structures which are subject to compression loads tend to buckle, or bend sideways at a fraction of the crushing strength of the chord (see Section 6.5). Forces which are not perfectly aligned with the plane of the truss tend to push the truss over or force it to rotate and twist. Flat, two-dimensional trusses and frames have no way to resist forces directed out from their plane. In theory, the directions and magnitudes of forces can be determined in flat structures, but they can't actually be tested without support in three dimensions.

Just as a roof truss must be supported perpendicular to the plane of the truss, so do the flat sub-assemblies of Boomilevers, bridges, or any other model structure. In the example Boomilever, the cross bracings which are used to connect the two side trusses together have no theoretical load, they are indeterminate. When load is applied to the load block, all of the force should be transferred directly to the supporting wall. If the two side trusses are hung independently and the load block placed at their distal ends, the trusses will sway or buckle sideways. The cross bracing allows the trusses to stabilize each other, and the diagonal chords of cross bracing resist the buckling effect. Since the bracing between trusses does not directly carry a load, it is extra mass that makes the Boomilever less efficient. However, when a load is imposed, these additional loads will always appear and the design of the structure must account for them.

Trusses can be built as three-dimensional space trusses or frames. Three dimensional space trusses are not illustrated in this guide. They are often based on fundamental 3D shapes like the tetrahedron (a four-sided triangular pyramid) and octahedron (with eight triangular sides). A carefully designed 3D truss does not have two separate sides tied together with cross bracing. This could be more efficient, but it will be more complicated to build. Such an approach may be useful in the challenge problems of Part 4.

Activity Follow-up

5.2 Classroom Activity

A cardboard square with rigid corners will warp up away from the table when opposite corners are pushed toward or away from each other. The sides warp into long S-shaped three-dimensional curves and the other two corners lift up. If the corners are held down by some weights, like a stack of coins or washers, the sides will pucker up in the middle. However, the corners themselves remain 90 degree angle – all of the bending strain is forced into the length of the sides and transferred around the corners. All four sides are affected.

A cube made from flat square rigid frames will warp in the middle of the sides, with the corners remaining square and the angle at which the sides meet flatten out from the original right-angle joint. The cube does hold its shape without bracing with no load or low load at the corners; the stiffness of the corners provides resistance to collapse. Again, the effect propagates throughout the structure as the bending moment from one side transfer to adjacent sides.

Placing diagonal tension bracing across the faces of the square will help to support the edges. The warping effect should be noticeably less as the tape prevents the opposite corners from moving away from each other. The strength of the cube depends on the strength of the edges. The diagonal bracing does not add strength to the edges, but it helps the edges to remain straight at a higher load.
5.3 Classroom Activity

A square made from strips of cardboard pinned at the corners will easily pivot into a rhombus or diamond shape when opposite corners are pushed or pulled, with no noticeable warping of the strips. The pinned corners offer no resistance to the force, and transfer no bending moments. A triangle made with pinned strips has a stable shape simply because it has no degrees of freedom to rotate. If the holes in the ends of the strips are larger than the brads, the strips may slip a little. The truss is made up of triangles. When the truss is loaded, the strips slip at their ends and allow the truss to sag, but the strips don’t transfer warping the way that the rigid frame does. It works best to make two trusses and connect them with strips of cardboard so that the truss can be set up like a short bridge. It should be easy to see which strips are being stretched and which are being compressed. Changing the tension strips to strings may help make this point.

Part 6 - Additional Structural Concepts - Advanced Level

6.1 Static Analysis

The basic analytical method for evaluating the forces imposed on structures in equilibrium is called Statics. If a structural system is in equilibrium, then it does not move. If the forces or moments imposed on a structure are not in equilibrium, the structure will be accelerated by the forces and the system becomes dynamic. In general, the structures of interest in this guide do not move unless they collapse under an excessive load. Statics provides simple rules for balancing forces and moments. Statics does not determine a choice of materials, or sizes for chords or joints, it only describes the amount of force to be resisted.

Statics has one basic rule: all forces must add up to zero, and all moments must add up to zero. Forces and moments have direction as well as magnitude, so two forces pointed in opposite directions with the same magnitude add up to zero. A combination of forces with different magnitudes and directions can add up to zero also. This is vector addition. Vector addition can be done graphically but it usually done by resolving the vectors into x, y, and z component vectors. Figure 6.1 shows vector addition of three vectors in two dimensions by resolving the vectors into coordinate components. Vector components pointed in opposite directions are subtracted. For convenience, assume that forces directed up or to the right are positive, and forces directed down or to the left are negative, and be consistent. (If a negative value is calculated for a force, it just means that the direction was assumed wrong. Change the assumed direction of the force.) The component vectors in each direction must add up to zero for the system to be in equilibrium. Basic trigonometric functions are used to resolve component vectors with respect to a common coordinate system. In Section 6.1.1 and 6.1.2 this technique is used to determine the internal forces in two-dimensional trusses. When the internal forces are known, the chord size can be estimated based on the strength of the material used.

Figure 6.1 - Force Vector Addition

For equilibrium at Node D:

\[ AD \cdot \cos(45) + BD \cdot \cos(30) + CD = 0 \]

\[ AD \cdot \sin(45) + BD \cdot \cos(30) = 0 \]
In a similar manner, the moments (the torsion or torque on a system) can be added. In a two dimensional system like the trusses in the next sections, moments are either clockwise or counterclockwise. Moments must add to zero to be in equilibrium, and they can be calculated at any point on the structure. All forces on the structure are multiplied by the perpendicular distance from each force to the point where moments are being calculated. Forces acting directly on the point will have a moment of zero at that point. In Figure 6.2, the moment from the cross-bracing chord must equal the moment from the load. The force of resistance from the cross-bracing chord will be larger than the load force. The magnitude of the force in the chord is an inverse ratio to the distances of each force to the joint.

**Figure 6.2 - Moments and Torision**

**Questions**

1. In Figure 6.1, two equations with two unknowns may be written by converting the vectors into x and y coordinate vectors. These equations must be solved simultaneously. If the horizontal force CD is 100 lb, what are AD and BD? If CD is rotated counterclockwise 15 degrees so that the force is directed down to the left, what are AD and BD?

2. In Figure 6.2, the force at the cross bracing chord is found by the ratio of L1/L2. What is the vertical force at the pinned joint? Is the sum of these vertical forces zero, for equilibrium?

### 6.1.1 Static Analysis of a Bridge Truss

The two dimensional bridge truss in Figure 6.3 is shown with a single load force at the center of the top chord, at node D. It is resting on bearing points at nodes A and G. The truss spans an opening of 40.0 cm and the bearing points are 42.0 cm apart. The geometry of the bridge is determined by the chosen height of the truss and spacing of the nodes. Many design variations are possible, and the design may be iterative, that is, calculated as shown, revised and calculated again, until a final design is chosen which optimizes the mass of the truss for the materials used. Note that there is no information in the static analysis about the strength of the chords. Statics only determines the forces needed to balance the forces that are known. The truss designer must provide enough wood, with enough strength, to resist the calculated forces.
The reaction forces at A and G are equal to each other and directed up, each of them half of the load force, because of the symmetry of the truss. If the load were not centered or if the truss were not symmetrical, the reaction force at each end would be determined by balancing the moments on the truss. In this example, calculating the moments of external forces around node G:

\[ Ra \times 42.0 \text{ cm (clockwise)} = 147.1 \text{ N} \times 21.0 \text{ cm (counter-clockwise)}; \]

\[ Ra = 147.1 \times 21.0 / 42.0 = 73.5 \text{ N} \]

Similarly, the moments of external forces around node A are:

\[ Rg \times 42.0 \text{ cm (CCW)} = 147.1 \text{ N} \times 21.0 \text{ cm (CW)}; \]

\[ Rg = 147.1 \times 21.0 / 42.0 = 73.5 \text{ N} \]

For equilibrium, all vertical forces must add up to zero:

\[ Ra + Rg - 147.1 \text{ N (downward force)} = 73.5+73.5-147.0 = 0 \]

Horizontal reactions at nodes A and G are ignored here. Once the reactions are known, the external forces are all determined. Now the internal forces in each chord may be calculated. At each node, the forces must add up to zero, so all vertical force components must balance out and all horizontal force components must balance out. The directions of the forces are shown in the diagram and are determined by balancing the unknown forces against the known forces.

In this truss, it is easier to start at an end node. Because the vertical component of AB is only balanced by the known force Ra, an equation may be written with one unknown quantity. Starting at node A and working toward the center node D:

\[ Ra = AB \times \sin(45), \quad AB = 73.5/\sin(45) = 103.9 \text{ N compression (C)} \]

\[ AC = AB \times \cos(45), \quad AC = 103.9 \times \sin(45) = 73.5 \text{ N tension (T)} \]

\[ BC \times \sin(60.9) = AB \times \sin(45), \quad BC = 103.9 \times \sin(45) / \sin(60.9) = 84.1 \text{ N (T)} \]

\[ BD = AB \times \cos(45)+BC \times \cos(60.9) = 103.9 \times \cos(45)+84.1 \times \cos(60.9) = 114.3 \text{ N (C)} \]

\[ CD \times \sin(52.1) = BC \times \sin(60.9), \quad CD = 84.1 \times \sin(60.9) / \sin(52.1) = 93.1 \text{ N (C)} \]

\[ CE = AC+BC \times \cos(60.9)+CD \times \cos(52.1) = 73.5+84.1 \times \cos(60.9)+93.1 \times \cos(52.1) = 171.6 \text{ N (T)} \]
Since the truss is symmetrical, it is not necessary to calculate the remaining chords. If the truss were unsymmetrical or if the load were not in the center, the calculations would continue in the same pattern. If the calculations are done from end to end, the internal forces at node G would have to add up to equal Rg, and that can be used as a check. When the forces required for equilibrium are calculated, the size and material for each chord may be estimated so that each will have enough strength to withstand the forces, so the truss does not collapse. Also, knowing the forces allows the designer to use only as much material as needed so that the mass of the truss is minimized.

Questions

1. In the truss in Figure 6.3, if the load force is moved to node B, how do the reactions at A and G change?

2. With the load force off center, are the maximum forces in the top and bottom chords larger or smaller than with the load at D?

3. Do any of the web chords change in tension or compression? How do you know which way the forces are going?

4. If the load force is applied to the bottom chord at node C, how do the forces in the truss change?

6.1.2 Analysis of Basic Boomilever Designs

The profiles of the two basic Boomilever designs from Part 3 are shown in Figure 6.4. These force diagrams are simpler than the bridge truss of Figure 6.3 because intermediate chords, if used, will have zero force from the static analysis and are omitted here. Intermediate chords are useful to resist buckling of the compression chord and they help control distortion of the truss when it sags under a load. Static analysis will not yield any information about the amount of force in these chords.

Figure 6.4 - Boomilever Static Analysis
For the “Tension Boomilever” (left diagram), the external forces are found from the known loads and the balance of the moments at each node which has an external force. Moments at nodes B, A, and C, respectively, must balance as follows. $P = 147.1$ N is the vertical load force, directed downward. $R_{Ax}$ and $R_{Bx}$ are horizontal reaction forces (x component of reaction vectors). $R_{Ay}$ is the vertical reaction force (y component) at node A.

For the moments about node B:
$\text{R}_{Ax} \times 19.6 \text{ cm} (\text{CCW}) = P \times 40.0 \text{ cm} (\text{CW});$
$\text{R}_{Ax} = 147.1 \times 40.0 / 19.6 = 300.2 \text{ N} \text{ directed to left}$

For the moments about node A:
$\text{R}_{Bx} \times 19.6 \text{ cm} (\text{CCW}) = P \times 40.0 \text{ cm} (\text{CW})$
$\text{R}_{Bx} = 147.1 \times 40.0 / 19.6 = 300.2 \text{ N} \text{ directed to right}$
$\text{R}_{Ax} + \text{R}_{Bx} = 0$; therefore horizontal forces are balanced.

For the moments about node C:
$\text{R}_{Ay} \times 400 \text{ cm} (\text{CW}) = \text{R}_{Ax} \times 19.6 \text{ cm} (\text{CCW})$
$\text{R}_{Ay} = 300.2 \times 19.6 / 40.0 = 147.1 \text{ N} \text{ directed upward}$
$\text{R}_{Ax} + P = 0$; therefore the vertical forces are balanced.

Calculating the internal forces, starting at node A:
$\text{R}_{Ax} = AC \times \cos(26.1); \quad AC = 300.2 / \cos(26.1) = 334.4 \text{ N}$
$\text{BC} = AC \times \cos(26.1) = 334.4 \times \cos(26.1) = 300.3 \text{ N}$

Vertical force at $A = AC \times \sin(26.1) = 334.4 \times \sin(26.1) = 147.1 \text{ N}$. This matches the vertical reaction calculated from the balance of moments.

It should be noted that $BC = \text{R}_{Bx}$ and is opposite in direction, and that the vertical force at $A$ equals the load at $C$ and is opposite, so the Boomilever is in equilibrium. The vertical force at $A$ is exerted against the bolt through the attachment base, not through a chord at $AB$.

In the “Compression” design, the vertical force at the wall must be carried up to the attachment base from node B with a structural chord, since the node at B is not fastened and will slide. Assuming no friction at B, the chord at AB will have a tension force of 147.1 N.

Questions

1. Suppose that node C is raised straight up in the right diagram (the “Compression Boomilever”) by 10.0 cm. What is the new the angle between AC and BC?

2. How do the forces in these chords change?

3. Do the horizontal reactions at A and B change?

4. Remember that the moment of the load force is the perpendicular distance from the wall multiplied by the vertical force. Do the vertical reactions at A and B change?

Notice the difference in the magnitude of the forces in the Boomilever chords compared to the bridge truss chords. For the same span and load, a cantilevered structure will have much higher internal stresses. If the heights of the trusses were the same, the Boomilever stresses would be approximately four times greater.
6.2 Beams and Bending

Beams are solid structural members, with transverse loads which cause the beam to bend sideways with respect to its supports. Transverse loads are loads perpendicular to the length of the beam. They can be a single concentrated load, multiple smaller loads spread out on the beam, or continuously distributed loads. The beam reacts to the load by elastically bending slightly, like a spring. This elastic bending tends to restore the beam to its original shape when the load is removed. Bending is a complex subject, and the specific bending behavior of a beam depends on the locations of the loads, the moment of inertia of the beam, the end conditions of the beam, and the materials used to make it. Beams may be shaped like I-beams for efficiency, or hollow box shapes for stability, or solid rectangular pieces for simplicity.

When a solid square or rectangular beam bends, the outermost surfaces of the beam are stressed in tension or compression. See Figure 6.5. The side near to the load will become concave, slightly shortened, and loaded in compression in the direction of the beam supports. The side away from the beam will be convex, slightly stretched, and loaded in tension in the direction of the beam supports. At the centroid of the beam, there is a neutral surface, parallel to the stressed sides, where there is no bending stress. If the beam bends elastically, the length along the neutral surface does not change. The intensity of the tension and compression stresses is greatest at the outer surfaces. This is called the “extreme fiber stress”, and is the limiting factor in the ability of a beam to resist a load without breaking. The intensity of the stresses decreases near the neutral surface, so the material inside a rectangular, solid beam is not resisting load anywhere near its capacity. That's why I-beams are more efficient than solid rectangles.

When a beam is stressed in bending, the fibers in the beam are forced to slide past each other in the direction of the supports. This is the same effect as rolling up a phone book starting at the binding, the pages slide past each other and spread out. If a phone book is rolled up, starting at the open edge, it will bulge because the edges of the pages are restrained by the binding. With wood beams, the wood fibers are being pushed against each other in the same manner. This “horizontal shear” is another internal stress that the wood must resist. The bending stress is zero at the supports and greatest at the center of the span of the beam. The horizontal shear is greatest at the supports.
The loading of a beam is similar to a truss in the sense that the top and bottom chords of a truss are stressed like the extreme fiber surface of a beam. A truss has intermediate web chords which maintain the separation distance between top and bottom, but a beam has continuous material which also takes some of the bending stress. Beams sometimes have holes cut into their sides to reduce weight or allow pipes and wires to pass through them. This is possible so long as the outer surfaces are not cut.

Truss chords are usually assumed to be loaded in axial tension and compression only. When a load is applied to a truss on the side of a chord, between two joints, individual chords are loaded with transverse loads and work like beams.

6.3 Section Properties

Once the forces within a structure are known, the components of the Boomilever must be designed to resist them. Some information was presented in Section 3.5 about the strength of Balsa and Basswood. The maximum stress values shown there are the intensity of force which will cause the wood fibers the break. If the amount of force which must be resisted is known, then the wood chords must be large enough to spread the force over the wood fibers without overloading them. In choosing the size and shape of a structural chord, it is important that the stress levels from Section 3.5 must not be exceeded for the forces required. Since stress is force per unit area, the cross section properties of the chord become important.

In a chord loaded in tension, as in Figure 5.1, the stress is simply the force divided by the area (A). Compressive stress in short, thick compression chords and stubby columns can also be calculated as force divided by area. Area is determined by multiplying the width times the thickness of the chord. This is accurate if the force is centered on the cross section. If the force is off center and the section is wide, the stresses will be uneven, so that the average stress may be acceptable but stress along one side could be too high. Shear stresses are usually also force divided by area, but the area used is the area of cross section in line with the force. In the lap joint shown in Figure 5.2, the area of shear is the contact area between the two strips of wood.

The center of area is called the centroid of the section; for uniform materials it may also be called the center of mass. For a square or round piece of wood, the centroid is in the geometric center of the section. For symmetrical shapes the centroid is easily found at the center dimension of the section. For an irregular compound sections such as a “T” or “L” shape, as in a compound chord made of laminated strips of wood, the centroid will be in the location where the areas (or masses) of all separate pieces are balanced. The location of the centroid is important in beam bending, as the neutral surface passes through the centroid. Section properties for some basic shapes are shown in Figure 6.6, all with the same area (and mass).

![Figure 6.6 - Section Properties of some sections with equal area](image-url)
The centroid of a compound shape is found by a process similar to the balance of moments employed to find the reactions of a truss. See Figure 6.7. Divide the section into separate, simple square or rectangular areas and determine the distance of the center of each of these areas to an edge. Multiply the area of each section by its distance to the edge, and then divide by the total section area. The result is the distance from that edge to the centroid. If the section is completely unsymmetrical, it may be necessary to calculate the centroid distance from two edges.

**Figure 6.7 - Calculation of centroid of compound shape**

**Classroom Activity**

Cut out some compound shapes from heavy cardboard made up of basic rectangular and triangular areas. Calculate the location of the centroid for each compound shape and mark it on the cardboard. Try to balance the cut-out on a tack to verify that the shape is balanced at the centroid.

**Figure 6.8 - Section properties of some hollow symmetrical shapes**

**Pipe**
- Area = 42.90 cm\(^2\)
- Inner Diameter = 11.00
- Outer Diameter = 13.25
- Moment of Inertia = 794.00 cm\(^4\)

**Hollow Square Tube**
- Area = 41.60 cm\(^2\)
- Inner Dimension = 10.00
- Outer Dimension = 11.90
- Moment of Inertia = 838.00 cm\(^4\)

**Four Cross-Braced Chords**
- Area of Four Chords = 16.0 cm\(^2\)
- Side of Each Chord = 2.0 cm
- Distance Center-to-Center = 14.4 cm
- Moment of Inertia = 835.0 cm\(^4\)

**Moment of Inertia** (I) is useful for calculating bending stresses. It gives us important information about the stiffness of a section when resisting a transverse force as in Section 6.2, or an off-center force which may cause bending or buckling.
Moment of Inertia can be thought of as the way area (or mass) is arranged around the centroid of a section. The farther that most of the area is from the centroid, the higher the moment of inertia. In Figure 6.8, the hollow pipe has a larger I value than a solid round section, even though it has less area (mass). The same is true for the hollow square tube and the solid square. Four separate posts, if tied together with cross bracing so that they fully support each other, will act like a single post with a very high I value, for a very small amount of area. The most compact shape is a circle, and for a given area a circle has the smallest moment of inertia of any shape.

The importance of this is that when the area (or mass) of a section is farther from the centroid, the section can resist bending better. In Figure 6.5 the bending forces in a beam are largest near the edge farthest from the center. A section which has more area out near the edge does a more efficient job of resisting the large forces. An “I” beam is more efficient, and has a higher moment of inertia, than a solid rectangle with the same area. A high I value is also best for resisting column buckling (Section 6.5), and a pipe or hollow tube makes a more efficient column than does a solid piece of wood.

Calculating moment of inertia is beyond the scope of this guide; moment of inertia is presented here as an intuitive concept. There are standard formulas for the more common shaped sections. Mathematically, the centroid is determined by finding the moments of simple partial areas (area times distance to a baseline) and dividing by the total area of the section. This gives the distance from the baseline to the centroid. The moment of inertia is determined by finding the moments of the moments (moments of simple partial areas times distances to a baseline). Moment of inertia is stated in units of cm^4 (or in^4, m^4, etc.). For example, the moment of inertia of a square section referenced to a line through its centroid is \( I = \frac{s^4}{12} \), and for a circle it is \( I = \frac{\pi d^4}{64} \), where \( s \) is a side of the square and \( d \) is the diameter of the circle.

### 6.4 Deflection

When any material is subjected to a load force, it will stretch or compress slightly. Some materials are highly elastic and can stretch out or squash down by a large factor without breaking. Rubber, nylon, natural fibers do this. Some materials are very brittle and fracture under low tension or shear stresses, such as ice and chalk. Wood is elastic and can change dimensions substantially before breaking. When a Boomilever is loaded, the tension chord stretches and allows the distal end to sag down. The compression end squashes toward the supporting wall. Usually, the compression chord is a heavy wood beam or a box truss while the tension chord is a very slender piece of wood, so the compression change is not obvious. See Figure 6.9 for the way a “tension” Boomilever sags. The amount of sag can be calculated if the modulus of elasticity of the wood and the cross section area of the tension chords are known.

![Deflection Profile and Force Diagram](image-url)

*Figure 6.9 - Deflection of “Tension” Boomilever*
For model wood structures, it is usually not important to know how much a truss or beam sags. In the case of a Boomilever, the joints at the attachment base and the distal end joint are solid, rigid joints. As the Boomilever sags, the angle of the tension chord changes. Since the angle at the joints can’t change, the tension chord will develop a bend which may cause the chord to snap at either end. This works like the distortion in a rigid frame in Figure 5.5. The bend in the tension chord may also put an excessive shear stress on the glue joint at either end, which may tear the joint apart. Also, as the angle of the Boomilever changes, the intermediate chords will begin to be loaded and will resist the sagging of the structure. These chords have no theoretical load from statics, but will have loads which are difficult to predict as the structure sags.

**Question**

1. **Figure 6.9** shows a sagging Boomilever with rigid joints and bent chords. What shape will the Boomilever and its main chords have if the joints are pinned and free to rotate? What advantages or disadvantages would result from this?

**6.5 Buckling of Columns and Compression Chords**

A characteristic of compression loading of long, slender pieces of wood is buckling. Buckling is an unstable reaction to an axial compression force on a long, slender column or chord. When a column buckles, it suddenly bends sideways and collapses. This is an elastic effect: if the load causes slight buckling and is removed, the wood will return to its original shape, but a small amount of additional load will break the wood. The amount of force that is just enough to cause buckling is the critical load for that column and is the maximum load that the column can safely support.

For example, a short dowel may support a large load on its end. The amount of load is limited by the crushing strength of the wood fibers. If the short dowel is replaced by a long dowel, it will buckle at a much lower load than the crushing strength of the wood. The long dowel does not have as much capacity, even with the same area, and if the dowel is made longer still, the capacity gets significantly lower. Buckling depends on the moment of inertia and the effective length of the column. In the example of a dowel pressed against the floor, the length of the dowel from floor to top is the effective length. The cross section is symmetrical in all directions and the moment of inertia is calculated from the standard formula for a circular section. See Section 6.3.

The critical load capacity of a long column can be increased by increasing moment of inertia; this generally increases the mass of the column substantially. Alternatively, the critical load can be increased by shortening the effective length of the column by restraining the column at points along its length with bracing. The new effective length is the distance between the nodes of the bracing. **Figure 6.10** shows how a column deflects in buckling when it is unrestrained and when it is braced at regular intervals. The diagram assumes that the braced points are stiff enough to stay on the original line of the column. If the effective length can be made short enough, no buckling will occur and the wood capacity is limited by crushing strength. The strength and stiffness of wood varies greatly and so the effective length, bracing pattern, and cross section will always be estimates, to be confirmed by experiment.
Classroom Activity

Use a 48” long dowel, 1/8” diameter as a column. Mark the dowel at 12”, 16”, 24”, 32”, and 36” from one end. Place a scale on the floor and press down on the scale from the top of the dowel. Record the reading on the scale as the dowel begins to buckle; this is the critical load at 48” effective length. Now have a student hold the dowel at the 24” mark so that it can’t move sideways. Place a straightedge (like a meter stick) behind the dowel for a visual reference, if needed. Press the end of the dowel until it buckles and record the reading on the scale. Repeat this while holding the dowel at both the 16” and 32” marks, then again at the 12”, 24”, and 36” marks (use as many students as needed to hold the dowel). With the effective length at 12”, it may not be possible to make the dowel buckle. How much more force can the dowel support as the effective length is reduced? What would be the effect of using a thicker dowel? How much load can a very short (4”) dowel support without breaking the wood?
Figure 6.11 shows how slender chords in compression buckle separately, and how they can be made to support each other with cross bracing. With no bracing, the chords buckle unevenly and support a low load. When the chords buckle together in a large overall curve, the buckling is global, that is, the whole structure buckles. In this case the chords provide some support for each other but the strength is not much improved. The addition of diagonal bracing has an effect similar to restraining the chords at intermediate node. This reduces the effective length. The buckling is localized to segments of the chords. The actual buckled shape of the structure will be a combination of local and global buckling. By combining chords with cross bracing, the resulting truss acts like a column with a much larger moment of inertia for relatively less additional material weight. In the example Boomilever of Part 2, the compression portion of the Boomilever is a box truss with eight long slender chords tied together by cross bracing.

Figure 6.11 - Global vs. local buckling on boom chords and column legs
Comments on Classroom Activities and Questions

Section 6.1 Question

Assume, from Figure 6.1, that forces directed upward or to the right have a positive sign, and forces directed downward or to the left have a negative sign. Write equations showing that the horizontal and vertical forces must add to zero:

\[
AD \cos(45) + BD \cos(30) + CD \cos(0) = 0
\]

\[
AD \sin(45) + BD \sin(30) + CD \sin(0) = 0
\]

Since \( CD = 100 \text{ lb} \) and is directed left, consider it to equal \(-100 \text{ lb} \). Since the vertical component of \( AD \) is down, write it as \((-AD)\sin(45)\). (If the directions turn out to be opposite from the assumed direction, then the answer will be negative.)

\[
AD \cos(45) + BD \cos(30) - 100 = 0; \quad AD \cos(45) + BD \cos(30) = 100
\]

\[
(-AD) \sin(45) + BD \sin(30) - 0 = 0; \quad BD \sin(30) - AD \sin(45) = 0
\]

Solving these equations simultaneously,

\( AD = 51.8 \text{ lb.} \) and \( BD = 73.2 \text{ lb.} \)

If \( CD \) is rotated CCW 15 degrees, directed down and to the left, both the x and y components will be negative:

\[
AD \cos(45) + BD \cos(30) - 100 \cos(15) = 0; \quad AD \cos(45) + BD \cos(30) = 96.6
\]

\[
(-AD) \sin(45) + BD \sin(30) - 100 \sin(15) = 0; \quad BD \sin(30) - AD \sin(45) = 25.6
\]

Solving these equation simultaneously,

\( AD = 26.8 \text{ lb.} \) and \( BD = 89.7 \text{ lb.} \)

In Figure 6.2, if \( Pb \) is the downward vertical force in the brace, then \( Pb = P \cdot L1/L2 \). This is greater than \( P \) unless the brace is located at the end of the chord. In order for the chord to be in equilibrium, there must be another vertical force applied equal to \( Pb - P \). The connection at the base of the chord must have a vertical upward reaction \( Ry \):

\[
Ry + P = P
\]

If \( P = 100 \text{ lb.} \), \( L1 = 48” \), and \( L2 = 12” \), then \( Pb = 400 \text{ lb.} \) and \( Ry = 300 \text{ lb.} \). The forces are set to add to zero to preserve equilibrium.

Section 6.1.1 Question

If the load force \( P \) is moved to node \( B \), then the reaction at \( A \) will be greater than the reaction at \( G \). Taking the balance of moments about \( G \):

\[
Ra \times 42.0 \text{ cm} \ (\text{clockwise}) = 147.1 \text{ N} \times 33.0 \text{ cm} \ (\text{counter-clockwise});
\]

\[
Ra = 147.1 \times 33.0 / 42.0 = 115.6 \text{ N}
\]

Similarly, \( Rg = 31.5 \text{ N} \). By following the same pattern of analysis as shown in Section 6.2:

\[ AB = 163.5 \text{ (C)}; AC = 115.6 \text{ N (T)}; BC = 36.0 \text{ N (C)}; BD = 98.1 \text{ N (C)}; CD = 39.9 \text{ N (T)}; CE = 73.6 \text{ N (T)}; DE = 39.9 \text{ N (C)}; DF = 49.1 \text{ N (C)}; EF = 36.0 \text{ N (T)}; EG = 31.5 \text{ N (T)}; FG = 44.6 \text{ N (C)} \]

As a check, \( FG \cdot \sin(45) = 31.5 \text{ N} = Rg \)

The forces in the top and bottom chords are lower, but the force in chord \( AB \) is greater. Chords \( BC \) and \( CD \) have stress reversals, with \( BC \) changing from tension to compression. \( BC \) may be subject to buckling if the load is moved to \( B \). The direction of force in the chords must be determined by the balance of vertical and horizontal forces at each node. It is easiest to start at one end and work across the truss, balancing each node in succession. If the \( P \) is applied to node \( C \), then chords \( BC \) and \( CD \) will both be in tension.
Section 6.1.2 Question

This is the problem posed in Part 4, Design Challenge #3. The angle between the horizontal line through node $C$ and $AC$ is $\arctan(10.0/40.0) = 14.0$ degrees. The angle between the horizontal line through node $C$ and $BC$ is $\arctan((10.0+19.6)/40.0) = 36.5$ degrees. The new angle between $AC$ and $BC$ is $36.5 - 14 = 22.5$ degrees.

The forces in chords $AC$ and $BC$ are larger in this configuration, even though the horizontal reactions at the supporting wall are the same. Taking moments about $A$:

\[ R_{bx} = 147.1 \text{ N} \times 40.0 \text{ cm} / 19.6 \text{ cm} = 300.2 \text{ N directed right} \]

Taking moments about $B$:

\[ R_{ax} = 147.1 \text{ N} \times 40.0 \text{ cm} / 19.6 \text{ cm} = 300.2 \text{ N directed left} \]

Calculating the forces at each node, by balancing the vertical and horizontal components:

\[ AC = \frac{R_{ax}}{\cos(14.0)} = 309.4 \text{ N, directed right and up (tension)} \]

\[ Ray = AC \times \sin(14.0) = 75.0 \text{ N directed down} \]

\[ BC = \frac{R_{bx}}{\cos(36.5)} = 373.4 \text{ N directed down and right (compression)} \]

\[ R_{by} = BC \times \sin(36.5) = 222.1 \text{ N directed up} \]

At node $C$, the forces must balance:

\[ BC \times \sin(36.5) - (AC \times \sin(14.0) + P) = 222.14 - (75.02 + 147.1) = 0 \text{ (vertical)} \]

\[ BC \times \cos(36.5) - AC \times \cos(14.0) = 300.2 - 300.2 = 0 \text{ (horizontal)} \]

The vertical reactions at the supporting wall are greater at both $A$ and $B$, and their sum equals the load, and so the Boomilever is in equilibrium:

\[ R_{by} - Ray = 222.1 - 75.0 = 147.1 \text{ N = P} \]

Section 6.3 Classroom Activity

Choose simple basic geometric shapes like squares, rectangles, triangles, and circles for which it is easy to determine the area and center, or centroid, of the shape. The shape shown in Figure 6.7 is a good starting shape. For triangles, the centers can be found by bisecting the corner angles: the center is located where the bisecting lines intersect. Draw a compound shape made up of basic shapes connected at their edges on a piece of cardboard and cut out the shape. For the compound shape, choose two adjacent sides to use as baselines. Measure the distance from the center of each basic shape perpendicular to a baseline. For each of these distances, multiply by the area of the corresponding basic shape. Add these products together, then divide by the total area of the compound shape. This gives the distance of the compound centroid to the baseline. Draw a line at this distance parallel to the baseline, then repeat for the adjacent edge. The centroid of the compound shape is located where these lines intersect. If this is done carefully, the piece of cardboard should balance on a tack at this point. If a compound shape with an open center is chosen, as in Figure 6.8, the centroid may be located where there is no material.
Section 6.4 Question

The curvature in the main chords in Figure 6.9 is the result of the transfer of bending moments through the joints at the attachment base and the distal end of the Boomilever. Basically, as the Boomilever sags and bends, the angles at the joints can’t change. This is the condition shown in Figure 5.5 for a rigid frame. If the joints could be replaced with freely pivoting joints, as in a truss, then the main chords would remain straight even as the Boomilever sags. The advantages of this are that the chords do not need to withstand the bending stress and can theoretically be more slender. Also, the bending of the chords is generally more severe next to the joints, so that the wood must be tougher (more ductile) in addition to the overall bending. Basswood often is better suited to withstand such stress than Balsa. However, using Basswood will add to the mass of the Boomilever. Freely pivoting joints could allow the use of the lighter, more brittle Balsa wood. The disadvantages of building pinned joints are that they are more complex to build, and a thick enough piece of wood, such as a toothpick or a dowel, must be used to resist all of the shear force imposed on the joint by the load. Sometimes, the dowel will not break, but it may rip through the wood fibers in the end of the chords. To make the pinned joints work, the chords must be flared out into wide, rounded ends to prevent the dowels from pulling through.

Section 6.5 Classroom Activity

The forces measured on the scale when pressing on the dowel will depend on the stiffness of the dowel. Try using more than one dowel and comparing the results. It may be difficult to get the students to hold the points on the dowel precisely in line; if possible, make a frame with adjustable clamps to hold the dowel at different points. Make sure that the dowel can slide freely vertically in the clamps. When the effective length of the dowel is short enough, the strength of the dowel in axial loading is governed by the crushing strength of the wood fibers rather than by buckling. This is an important spacing when establishing the distance between cross bracing joints in a tower column or a Boomilever compression chord. A spacing which is just close enough to allow the chord to function as a short, non-buckling column, will allow the chord to use the maximum strength of the wood with the least amount of bracing.
Part 7 - Glossary of Boomilever Terms

Assembly Board  A smooth surface on which the Boomilever may be glued together. The assembly board should be rigid enough that the parts of the Boomilever do not shift or press into the board when handled, but soft enough that pins may be used to hold down the parts while the glue dries. Softwood boards and high-density extruded polystyrene (blueboard) insulation work well, but cardboard, expanded Styrofoam and mineral-fiber ceiling tile are too soft.

Attachment Base  A part of the Boomilever used to attach the Boomilever to the Supporting Wall by means of the mounting bolts. The Attachment Base is an interface between the bolts and the rest of the Boomilever structure; it resists the outward pull of the tension chord. It is a permanent part of the Boomilever and is included in the Boomilever mass.

Bending  The manner in which a beam resists a lateral force imposed between the end supports. A beam resists the force by bending, or curving sideways. The stiffness of the beam provides the resisting force to the load force.

Boomilever  A wood and glue structure, which cantilevers horizontally out from a Supporting Wall, designed to carry a load as specified in the Problem Statement.

Boomilever Distal End  The end of the Boomilever farthest from the Supporting Wall.

Boomilever Height  The height, measured vertically, from the highest part of the Boomilever to the lowest. There is no limit on the Boomilever height, but no part of the Boomilever may touch the Supporting Wall below a line 20.0 cm from the center of the attaching bolts.

Boomilever Width  The largest outside width of the Boomilever at any point along its length.

Bottom chord  The bottom member of a truss, which may be continuous or made from short pieces fastened end-to-end. When a cantilevered truss is loaded with a weight, the bottom chord will be subjected to a compressive force.

Buckling  The tendency of a chord or column to bow out sideways when a compression load is applied to its ends. Buckling is an unstable reaction to a compression load.

Cantilever, cantilevered beam  A structure that holds a weight or resists a force at some distance beyond its support or foundation. A cantilevered beam may be rigidly attached to a wall, like a Boomilever, with a weight at its distal end, or it may be a balanced beam like a first class lever.

Centroid  The center of area of the cross section of a structural chord. It is the point around which the areas are balanced.
Chords  Structural members that are long compared to their thickness. Usually chords are loaded at their ends and transfer forces imposed on one end along their length to a joint at the opposite end. In trusses, chords are used as top chords, bottom chords, and intermediate (web) chords.

Compression  A force that pushes against an object and tends to crush the object. A chord subjected to a compression force is shortened by the force, pushes against its supports, and may buckle sideways if the chord is very long compared to its thickness.

Construction Jig  A construction aid, which holds the parts of the Boomilever in their correct geometric position. A construction jig simplifies the process determining complicated three dimensional angles or chord lengths.

Cutting Board  A hard, smooth board suitable for cutting out wood pieces with a knife or saw. If the assembly technique does not require use of pins to hold the subassemblies together, the cutting board may be used as the assembly board. Masonite, finished hardwood boards, and high-pressure plastic laminate (Formica) covered surfaces are ideal cutting boards.

Deformation  Also known as strain, the change of shape or dimension of a structure in reaction to external forces. Deformation may be show up as sag, stretching, buckling, or twisting of the structure. Usually, deformation is refers to overall effects on a structure, and strain refers to individual parts or chords of the structure.

Dynamics  A field of engineering analysis that describes how objects accelerate and move when forces are applied to them.

Equilibrium  A condition in which all the forces and moments acting on an object are balanced, so that the combination of forces does not cause the object to move.

Free Body Diagram  A diagram of a structure, structural component, or any object showing all external forces and moments acting on the body.

Glue  Any adhesive material designed for the purpose of bonding two pieces of wood together. Wood is sometimes coated with glue in an attempt to artificially strengthen the wood fibers, but for the purposes of this guide, it is considered to be glue only if used at a joint.

Gussets  Cover plates for joints, which help to hold joints together, usually made of thin strips of wood glued across the joint.

Joints  Connections between structural members. Boomilever joints are usually glued joints, but may be pegged or made with interlocking end shapes.

Laminations  Thin strips of wood glued together continuously along the length of the strips in layers to build up a thicker structural member.

Load block  A metal or wood block, 50.mm x 50.mm x 20.mm high, with a hole in the center of the square face for a $\frac{1}{4}^\text{\prime\prime}$ bolt, which is set onto the Boomilever during testing and used to suspend the bucket and sand from the Boomilever.
Load Distance (Cantilevered Span)  
The distance from the face of the Supporting Wall to the center of the Load Block, measured horizontally.

Load Height  
The distance of the load block above or below the mounting bolts, or the distance of the bucket from the floor.

Load  
The force or forces imposed on the Boomilever. The load described in the Problem Statement is the total mass (or weight), of the bucket, sand, S-hook, load block, chain, etc. resting on the distal end of the Boomilever.

Log Sheet  
A record of the process for building and improving Boomilevers. A log sheet should contain masses of wood pieces used and subassemblies, sketches of Boomilever designs, and information of tests, plus any other useful information or observations.

Moment, or couple  
When a force acts against an object, but does not line up with the center of mass of the object or with the anchor point of the object (if it is fastened to a rigid base), the force causes the object to twist or rotate. The size of the force, multiplied by the distance the force is off-center from the object or its anchor, is the moment or couple. Similar to Torsion.

Nodes  
Connections (joints) between truss members, internal to the truss. Nodes are generally considered to be the load points or bearing points of a truss.

Peg  
A narrow piece of wood inserted through a joint to improve the shear strength of the joint. The peg may resemble a pin or nail.

Sag  
The distance that the Boomilever deflects downward as the Load is applied.

Shear  
A force that acts across the width or cross section of a structural member or a joint to separate or tear it apart. Scissors and knives cut with a shearing force.

Statics  
A field of engineering analysis that describes objects in which forces are in equilibrium, so that the objects are not put into motion by the forces.

Strain  
The change in shape and dimension, from stretching, compressing, shearing, or twisting caused by a force on an object.

Stress  
The intensity of forces within structural components such as chords or connectors. The magnitude of stress is determined by dividing the sum of the forces imposed on a chord by that part of the cross section area of the chord that is resisting the force.

Structural Efficiency  
The ratio of the mass supported (gravity loading) to the mass of the Boomilever.
| **Structures** | Objects designed and constructed to resist specific forces and to transfer forces to a foundation or a supporting wall. Structures are assemblies of many components, joined together as needed by the design. The design of the structure will be different for different load conditions, and to satisfy the specific rules, or constraints, in the problem statement. |
| **Supporting Wall** | The wall to which the Boomilever is attached for support during testing. The Supporting Wall is part of the testing apparatus, with mounting hole and a flat, vertical surface as specified in the Problem Statement. |
| **Tension** | A force that tends to pull an object apart. A chord subjected to a tension force stretches, and pulls against its joints. |
| **Top chord** | The top member of a truss, which may be continuous or made from short pieces fastened end-to-end. When a cantilevered truss is loaded with a weight, the top chord will be subjected to a tensile force. |
| **Torsion, or torque** | A force which causes an object to rotate or twist. Similar to a Moment. |
| **Trusses** | Frameworks of wood, commonly made up of triangular patterns, which may be used as the main supporting part of the Boomilever. Trusses act like large, deep beams, assembled from many small pieces, called chords or members, connected at their ends at nodes. |
| **Vector** | Any quantity that has both a magnitude and a specific direction. Force and velocity are vectors. Mass and speed have magnitudes, but not direction, so they are not vectors. |
| **Web chords, struts, or intermediate truss members** | Pieces of wood connecting the main chords of a truss together. Web chords serve to hold the main chords apart, distribute load between the main chords, and lock in the shape of the truss. |
| **Wood Products** | Wood which has been processed and manufactured into other forms such as plywood, particleboard, masonite, cardboard, paper, etc. Wood products manufactured by industrial processes and purchased may only be used in the attachment block. |
| **Wood** | Generally, naturally produced cellulose fiber material from trees, cut and dried but otherwise not processed or modified. Students may modify the wood by shaping and laminating, but not by artificially strengthening with coatings or resins. Grasses such as bamboo are not considered to be wood. |