DESIGNING, ENGINEERING, AND TESTING WOOD STRUCTURES

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KEY WORDS: wood, design, factor of safety, engineering economy, duration of load, stress, tension, compression, bending, deflection

PREREQUISITE KNOWLEDGE: This material could be taught to a typical student of materials science, at the high school level or above.

OBJECTIVES: To introduce basic structural engineering concepts in a clear, simple manner while actively involving students. This project emphasizes the fact that a good design uses materials efficiently.

The test structure (Figure 1)* can be easily assembled, has various design options, and can be reused year after year. Even when the structure is loaded until it collapses, only one or two pieces usually break, leaving the remaining pieces intact and reusable.

Groups of students are asked to use their intuition to choose different pieces with various cross-sectional areas for the structure, which will span a distance of 0.9 m (3 ft). Their goal is to support at least 23 kg (50 lb) at a minimum cost.

EQUIPMENT AND SUPPLIES: This list includes materials for three demonstration models plus enough material for three student groups to complete any design that they choose.

Superstructure
About 5.5 m (18 ft) of Southern Pine or Douglas-fir nominal 2 x 4 (38 x 89 mm). If another type of wood is used, you may have to adjust the target load value. The ideal structure should comfortably support the target load. Cut wood to sizes and drill the holes as indicated in Figure 2. Make pieces as clear (free of knots) and straight grained (grain parallel to length of piece) as possible.

- 32 red pieces
- 32 blue pieces
- 32 green pieces
- 60 yellow pieces

Frame, supports and platform
- Nine 19 mm x 51 mm x 305 mm (3/4 in x 2 in x 12 in) pieces of wood with slots as shown in Figure 5a
- Six 6.4 mm x 25.4 mm x 254 mm (1/4 in x 1 in x 10 in) pieces of wood
- Two 216 mm (8-1/2 in) pieces of nominal 2 x 4s (38 mm x 89 mm) with a 3.2 mm (1/8 in) lengthwise groove.
- One 457 mm x 305 mm x 19 mm (18 in x 12 in x 3/4 in) piece of plywood with holes drilled in each corner

*** Figures 1--8 are grouped according to experimental sequence.**

Hardware

- 3.2 mm (1/8 in) diameter threaded rod--total of 9 m (30 ft) cut to 305 mm (12 in) lengths
- 60 wing nuts
- 120 hex nuts
- 120 washers
- Three nails, approximately 4 mm in diameter (10-penny)
- Approximately 6 m (20 ft) of 1.0 mm diameter (18-gauge) copper or bronze wire

Other

- Spray paint or marking pens (four colors for marking wood)
- Nylon cord (4.6 m to 5.5 m (15-18 ft) length, 3.1 mm (1/8 in) diameter)
- Carpet or pad to protect floor
- Weights (bricks or suitable dense objects of equal, known weight)
- Safety glasses for each student

PROCEDURE: The structures to be built have interchangeable pieces of varying size and cost. There are four types of pieces of equal length with varying cross-sectional dimensions, referred to in units. Each unit equals 1.6 mm (1/16 in). Thus, a 1/4 in x 1 in piece is 4 x 16 units. Fictitious dollar values are assigned to each piece based on the amount of wood used and are color coded for easy identification (Figure 3).

Before the actual classroom activity, prepare three models for demonstration, using the model in Figure 4. Make sure to place a washer between each wooden piece and the hex and wing nuts on the rods. Once the structure is assembled, attach wire supports diagonally to the wing nuts at each end of the rods as shown in Figure 4. These supports prevent the structure from collapsing sideways.

The loading frame is necessary to prevent lateral buckling, or twisting, of the top pieces. The frame is designed to rest on the top pieces of wood that have been spaced 229 mm (9 in) apart by the hex nuts on the threaded rods. Make sure that this measurement is accurate. Three frames are needed with slots of different widths to match the three possible widths of the top cross pieces (see Figures 5a and 5b). The loading heads are made from nine 19 mm x 51 mm x 305 mm (3/4 in x 2 in x 12 in) wood pieces with 1 inch slots cut as shown in Figure 5a. The braces are made from six 6.4 mm x 25.4 x 254 mm (1/4 in x 1 in x 10 in) wood pieces. Three nails--approximately 4 mm in diameter (10-penny)--serve as loading frame pins.

The "super economy" model is made with all yellow pieces (the weakest ones, 2 x 6 units) for a total cost of $14. The second model is made with all red pieces (the strongest ones, 4 x 16 units); it looks very sturdy, but its cost is a formidable $116. The third model (combination of blue, green, and yellow) costs $32 and is the most efficient design. This "ideal" model is kept out of view until all the students' structures are tested. It would be a good idea to pretest your ideal model to make sure that it supports the 23 kg (50 lb) load. If it doesn't, you could adjust the target-load value.

Explain the challenge--to design and build an efficient structure capable of supporting 23 kg (50 lb) at a minimum cost. As an example, bring out the red structure (the strongest) and load it to

46 kg (100 lb). No visible signs of stress on the structure will be evident. The students are told that the structures could be built without red pieces and still support 23 kg (50 lb), but they can use the red pieces if they'd like. You might want to put an upper limit on the total dollar cost for each structure to prevent students from being overly conservative in their design.

The class is divided into groups, and each group receives a supply of lumber and materials. Students are encouraged to use their intuition and discuss their design within their group before proceeding to build it. They should take about 15 minutes to complete their design. After everyone has assembled their structures, begin testing (Figure 6). By adding loads in small, 4.5 kg (10 lb) increments, students can see problems developing before catastrophic failure.

Add weights one at a time; be prepared for a sudden collapse of the structure. Green pieces (5 x 6 units), when used as top members, will break well below the target load. Blue pieces (2 x 16 units), as side compression members, should break or show considerable buckling at the target load. Wear safety glasses. Make sure that the students also wear safety glasses and stay several feet away from the structure. Continue adding weight until the structure collapses or the optimal weight is reached. It will become obvious to the students that the way a piece performs depends on where the piece is placed in the structure. Students will mentally revise their designs as they watch their structures contort and buckle under the heavy load.

In some cases, the bowed structures actually hold the 23 kg (50 lb) load, but students will realize that they wouldn't want to be driving across a structure of that design! This illustrates the concept that maximum allowable deflection is sometimes the limiting factor in engineering design.

Sometimes the structure will hold the load initially, but suddenly will come crashing down before the next weight is added. This unexpected phenomenon shows that the length of time a structure is loaded affects how it behaves. This illustrates the concept of duration of load.

After each group's structure is tested, load the "super economy" yellow structure (2 x 6 unit pieces) which, when tested, doesn't support even a 4.5 kg (10 lb) load. Next, unveil the so-called "ideal" design and show that it will indeed support the 23 kg (50 lb) load, without showing too many signs of impending failure. As a grand finale, load the red structure (the strongest). You can keep adding weight until the structure shows signs of stress, or for a dramatic effect, continue adding weight until it crashes to the floor as the load exceeds 69 kg (150 lb).

On the blackboard, record the cost of each structure and the load it held before it collapsed. These test results give you the opportunity to compare the safety, cost, and design efficiency of each structure. The structures that support a higher load are the safest, while the ones that support at least 23 kg (50 lb) for the lowest cost are the most efficient. Occasionally, variability in wood performance shows up when similar designs perform differently.

Another concept that may be discussed during this demonstration is the factor of safety. You may explain that the factor of safety chosen for a given situation depends on many variables, including the duration and frequency of the applied load, the variability in performance of the structure, and the consequences of a failure (would it be life threatening?).

Both the size (cross-sectional area) and shape of a piece of wood affects its performance when it is subjected to stress. By designing wisely, you can use less wood and still have a strong, reliable structure.

SAMPLE DATA SHEET:

STRUCTURE NO.	COST	ULTIMATE LOAD
1	$14	< 4.5 kg
2	$32	23 kg
3	$116	69 kg
4	$40	12 kg
5	$32	< 4.5 kg
6	$40	23 kg

INSTRUCTOR NOTES: As a way to begin analyzing what happens to the structures, have the students pick up individual pieces and try to bend, compress, and pull them in tension with their hands. Because of their different dimensions, each piece responds differently to the forces. By comparing what happens to the individual pieces with the performance of the structures, the students can begin to identify forces causing the structures to deform. All pieces for this experiment are made from clear wood (free of knots or other defects) and are very strong in tension. A small cross-sectional area can withstand very high loads. Try to pull apart a yellow piece (2 x 6 units) by pulling the ends away from one another. Next, try pushing in on the ends of the same yellow piece. When a piece is loaded in compression, it tends to buckle. The load at which it begins to buckle is controlled by the narrowest cross-sectional dimension. Compare the effects of compression on the blue (2 x 16 units) and green (5 x 6 units) pieces, which have nearly identical cross-sectional areas. The blue piece buckles more easily than the green piece because it has the narrowest critical dimension. In compression, then, a square cross-sectional area makes the most efficient use of material.

Now compare bending the blue piece (2 x 16 units) in the two ways shown in Figure 7. The most important dimension of bending is depth. The deeper the piece, the stiffer it is and harder it is to bend. This is because stiffness is directly proportional to the cube of the depth and only linearly proportional to the width.

When a student-built structure is supporting a load, the forces distributed to each piece depend on its location within the structure (Figure 8). As discussed at the beginning of the demonstration, red pieces are more than adequate (but not necessary) to support the maximum predetermined load. A discussion of engineering principles applied to wood design provides the clues students need to choose pieces adequate for building a structure that meets its design criteria with a minimum amount of wood (or cost).

FOR FURTHER READING: Hoadley, R. B. 1980. *Understanding Wood*. The Taunton Press, Newtown, CT.

McCarthy, M., and T. Gorman. 1990. Building excitement in the classroom. *The Science Teacher* 57(5):43-49.

USDA Forest Service. 1987. *Wood Handbook*. USDA Agri. Handbk. 72 (rev.) Madison, WI.

SOURCES OF SUPPLIES: All materials for this demonstration are commonly available in home centers, hardware stores, and/or building supply outlets.

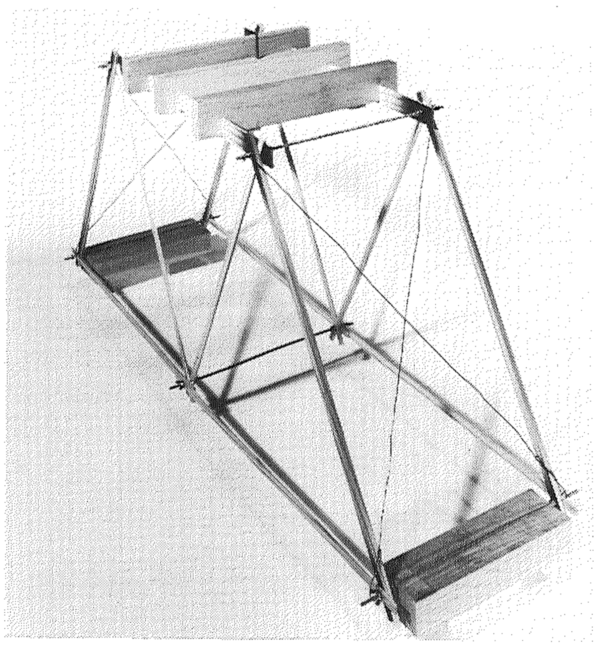


Figure 1. Assembled structure, resting on support blocks, with loading frame and wire cross bracing in place. *(Photo courtesy of USDA Forest Products Laboratory)*

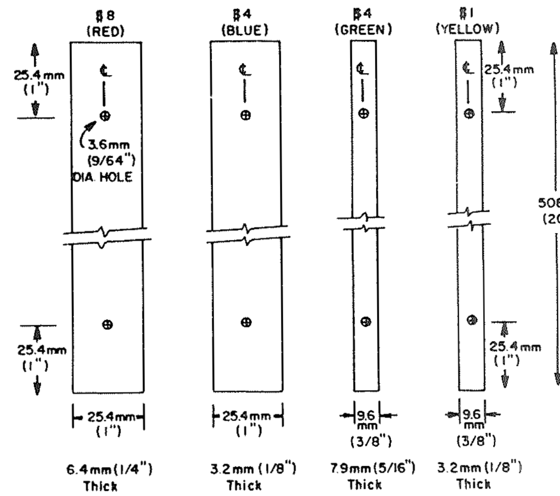
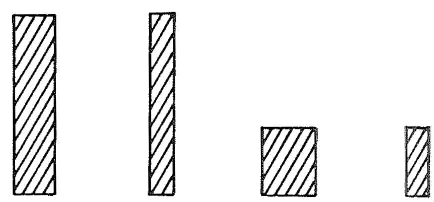


Figure 2. The dimensions of the red, blue, green, and yellow sections of wood. *(Drawing courtesy of USDA Forest Products Laboratory)*



	RED	BLUE	GREEN	YELLOW
price/ piece	$8	$4	$4	$1
UNITS	4x16	2x16	5x6	2x6
mm	6.4 x 25.4	3.2 x 25.4	7.9x9.6	3.2 x 9.6
in	1/4 x 1	1/8 x 1	5/16 x 3/8	1/8 x 3/8

UNIT = 1.6mm (1/16 in)

Figure 3. Cross-sectional view of the four types of pieces to be used in the structure. All are 508 mm (20 in) long. *(Drawing courtesy of USDA Forest Products Laboratory)*

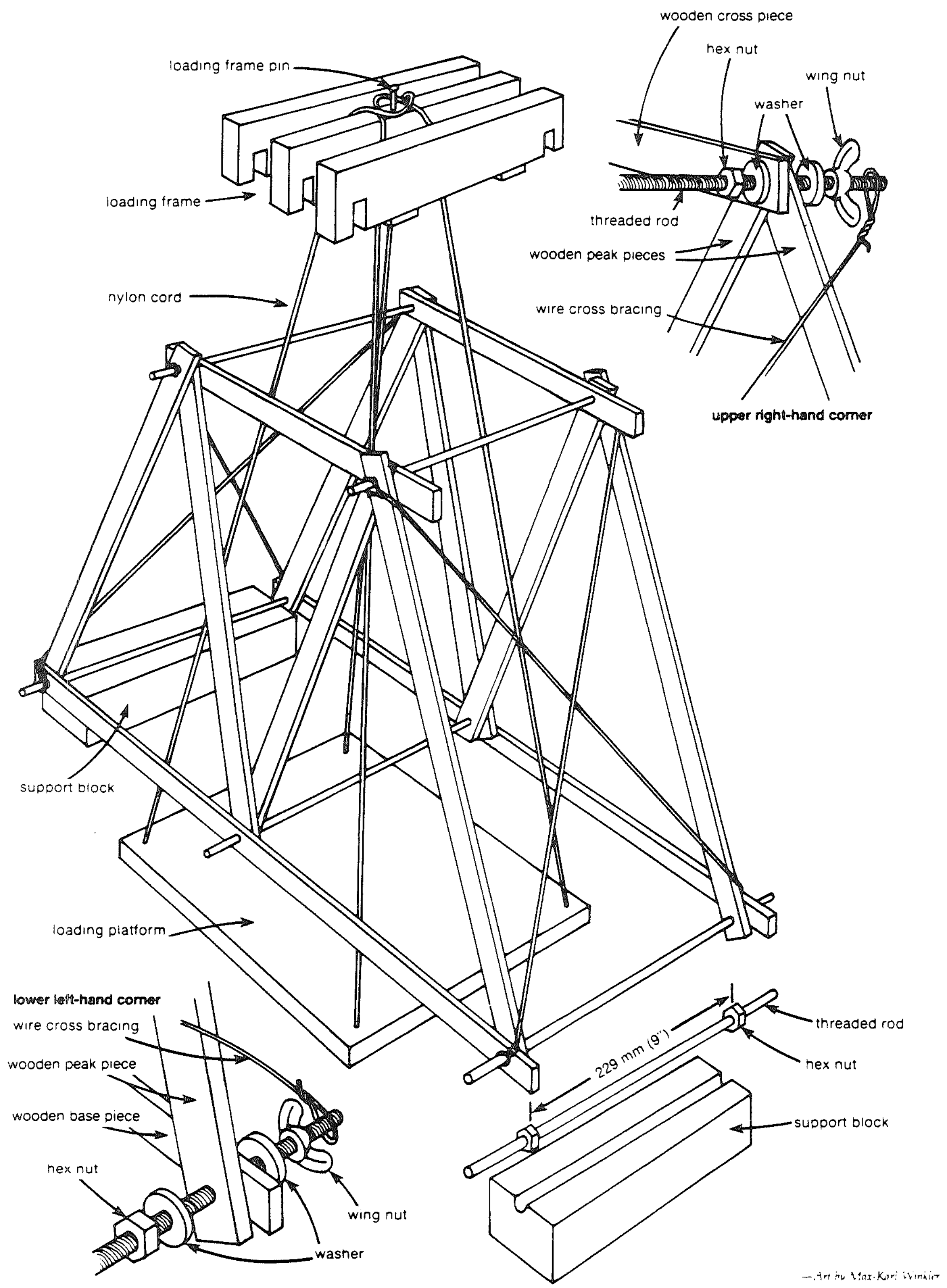
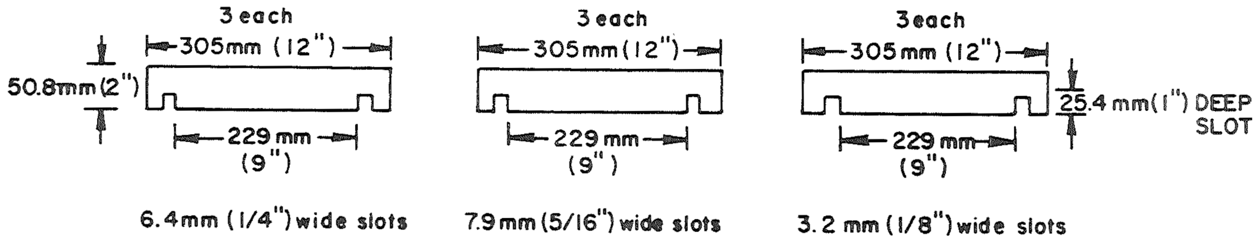
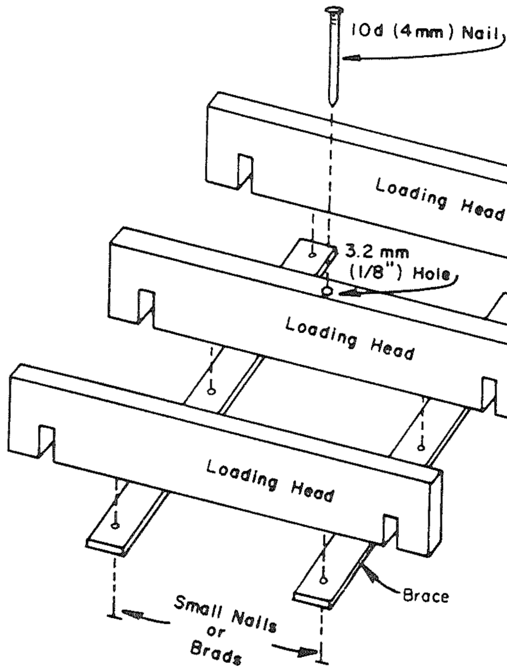


Figure 4. A schematic of the completed structure. The upper and lower corners have been enlarged to show their construction. (*Drawing courtesy of The Science Teacher/May 1990*)





Figures 5a and 5b. The dimension of the loading heads for the loading frame are shown on the top. The assembly of the loading frame is shown below. *(Drawing courtesy of USDA Forest Products Laboratory)*

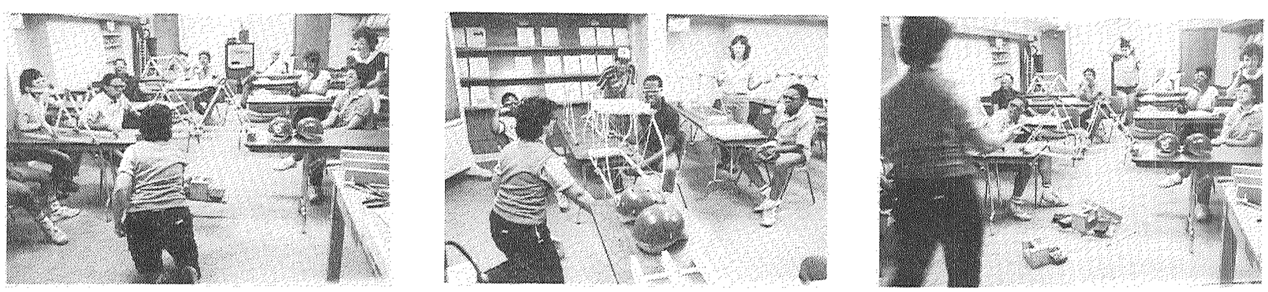


Figure 6. Testing the structure. In the first photo, one group's structure is loaded as the rest of the class looks on. (Note that everyone is wearing safety glasses) Next, side sections begin to buckle just before structural collapse. The structure supported 32 kg (70 lb) before it gave way. *(Photos courtesy of USDA Forest Products Laboratory)*

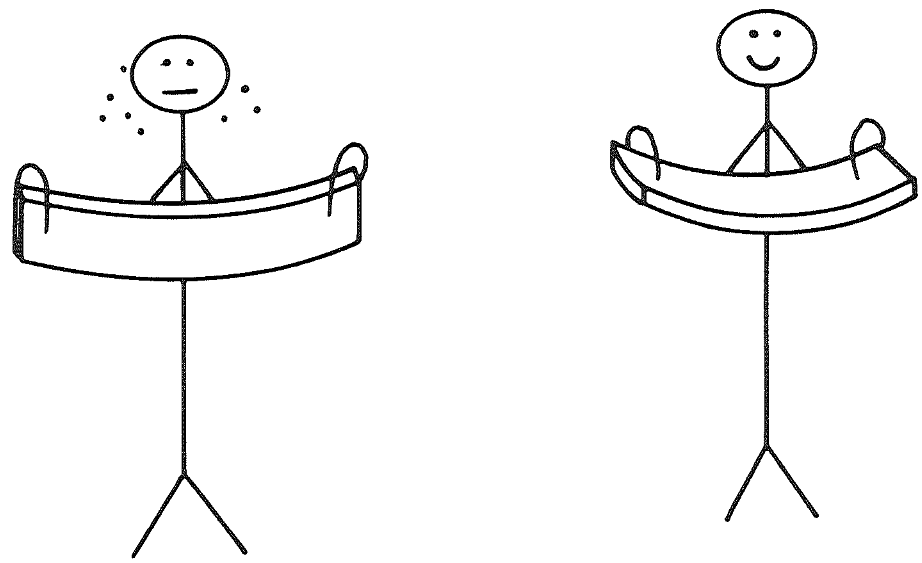


Figure 7. Bending a member in two different ways. The orientation with narrower depth is easier to bend. (*Drawing courtesy of USDA Forest Products Laboratory*)

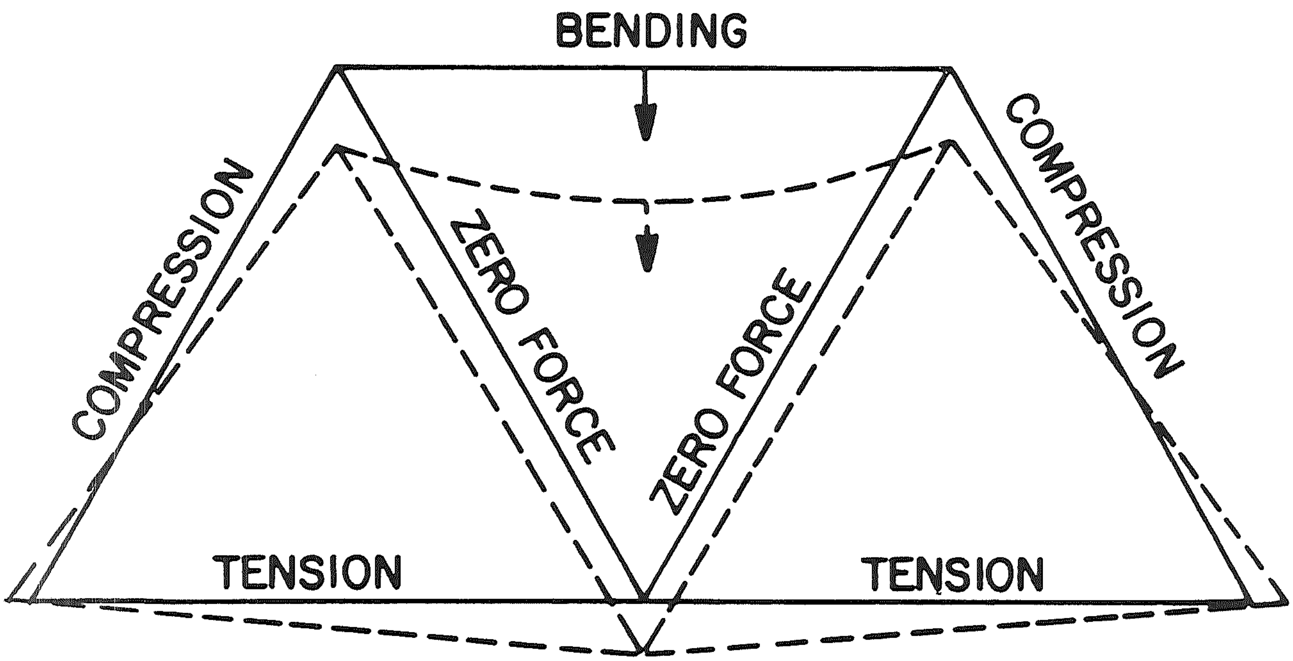


Figure 8. An exaggerated illustration of the structure shows how different members are subjected to different types of forces. The compression sections become shorter, the tension sections become longer, and the zero force sections remain essentially the same. (*Drawing courtesy of USDA Forest Products Laboratory*)