ODYSSEY OF THE MIND
- THE STRUCTURE PROBLEM -

The intended audience for this paper is any Odyssey of the Mind (OM) structure coach, including Division I. In some portions of this paper, there are references to more advanced concepts of structural design than the general knowledge required for understanding and coaching basic structure building. It is hoped that the more experienced coach will be able to use the advanced concepts to go beyond the basics.

I do not attempt to answer all questions; in fact, I avoid some areas because of outside assistance rules. The purpose of OM competition is to compare different solutions, and it is up to each team of designers to find their own solution. I only attempt to address some of the basic design principles which might otherwise be obtained from reading or research.

I intend for coaches to use this paper as the basis of training for teams participating in the Odyssey of the Mind program. Is some cases, the vocabulary used may be unfamiliar to the beginner. Where possible, I have tried to limit this, but it is likely that the beginning coach will need to seek help from either someone else or a dictionary. I encourage the latter because in the world of engineering, vocabulary and its precise understanding are often quite crucial.

PART I

The balsa wood structure problem, as it is defined by the Odyssey of the Mind program, is a vertically loaded column. This is to say, *that the entire structure acts as a column and is weighted in a* downward direction. This differs significantly from a bridge problem which many science programs use. With the OM problem, a structure is closely defined with limits on how much wood can be used, how it can be constructed, and its size and general description. Some of these parameters change from year to year.

The first thing you need to do is read and re-read the problem rules, the program handbook, and any other required material. It is heartbreaking when a team is penalized and their hard work wasted because the team members, and especially the coach(es) haven't taken the time to know and understand all of the rules. There are often references made to other manuals or handbooks in the rules. These should be obtained and read carefully.

For the beginning builder, it might be beneficial to study various structures such as radio and electric towers, crane booms, and building frames. However, this can be somewhat misleading because the purpose of these structures is often different from that of the structure you want to build. For example, a radio tower often starts out wide at the bottom and gets smaller as it goes up. This is because the tower only has to hold itself up; at the bottom, it must support the whole tower, while at the top, it only has to hold up the little red light. An OM structure is required to hold up hundreds, even thousands of times its own weight. The top of you structure needs to be just as strong as the bottom. There are many things to be learned by studying structures, but you must keep asking, "What is the purpose of the structure I'm looking at?"

Before trying to decide on your design, it would be beneficial to know something about the strength of the materials. Let's first think about how a solid wooden post acts when you stand it on end, and lower a huge weight onto it. One of two things is going to happen if you put more weight on it than it can hold:

1. The post will simply smash downward and break into little pieces. This will happen if the post is either very short, or very fat, or both.

2. If the post is rather long and slender, it will begin to bend, *and soon it will snap, probably breaking near the middle.* If the post is thinner in one direction than the other, it will most likely bend in that direction.

If the post bent before breaking, it probably broke under a lot less weight than it would have if it had stayed straight and smashed downward. Making the post shorter makes it harder to bend, and therefore much stronger.

A good experiment to demonstrate this is to take a piece of uncooked spaghetti, stand it on end, and push downward slowly. As you do, pay attention to how much force it takes to make it bend and how much force it takes to break it. Next, take a piece of spaghetti which is half as long as the first piece and repeat the experiment. You should find that it takes a lot more force to start it bending. Continue shortening it and see what happens.

If your measurement of force is very scientific, you will find that each time you cut the length in half, it takes four times as much force to bend it. If you cut it into three parts, it takes nine times as much force. This is called the Law of Squares, more specifically, it comes from Euler's (pronounced oiler's) Formula. This formula gives us a mathematical way to predict how much force is necessary to start a column bending, which will ultimately lead to its collapse. If you are mathematically inclined, find a text book on static structural design and look that one up. The whole theory of structural design for this problem is wrapped up in it.

At this point, you may have noted that the OM problem description specifies a minimum height for the structure, so there will come a point at which you cannot make the structure stronger by making it shorter. Try this experiment.

1. Take a new piece of uncooked spaghetti and, standing it on end on a hard surface, have someone else put their thumb and forefinger from each hand against the middle of the spaghetti so that it can't bend sideways in any direction.

2. Now, press straight down (emphasis on 'straight down') on the end and see how much force it takes to cause the spaghetti to bend. If it bent into an 'S" shape just before it broke, you did it correctly.

How much force did it take to start the spaghetti bending? You might have to try this one a couple of times, but the answer is 'the same amount of force as for a half sized piece'. Does that suggest any solution to you?

By bracing the middle of the spaghetti, you effectively halved the distance that it was allowed to bend, so your column is four times as strong as before. That may not seem very significant, but take another look at that radio tower we talked about. Chances are, it has large, strong vertical members at the corners, and much smaller pieces connecting them. Most of the connecting pieces are positioned at an angle. Their primary purpose is not to hold any of the weight, but to keep the larger vertical members from bending. This is the most important point to remember: keep the vertical member from bending. If it doesn't bend, a single piece of normal balsa wood measuring one-eighth inch by one-eighth inch can hold more than seventy-five pounds before it crushes. The trick is to arrange your structure so that the weight bearing members cannot bend.

Back to the radio tower. Why are most of the braces positioned at an angle? What shape do they form? In some fashion they form one or more triangles. We all have heard that a triangle is stronger than a square. To understand why this is true, try the following experiment:

1. Take a 3" x 5" card, or something similar, and cut out four strips 1/2 inch wide and 4 to 5 inches long.

2. With each strip, poke a thumb tack through it in the center, about 1/4 inch from one end. Make a similar hole in the other end, but remove the thumb tack.

3. Connect the pieces together into a square by putting the hole in one through the thumb tack in the next piece.

By taking the form you have created and moving it around, you can see that it is easy to change its shape. To do so, all you have to do is change the angle at the corners. Notice that none of the sides change length, but you can still change the shape of the figure.

Now, for the triangle: remove one side completely and reconnect the pieces to form a triangle Can you change its shape without forcing anything? The key is that without changing the length of one of the members, you cannot change the shape of the triangle. With a specific set of three sides, there is only one triangle that you can make. You can turn it around and over, but there is still only one triangle that you can form. Now, if you have satisfied yourself that this last statement is true, put a fold in one side of the triangle so that you can bring two of the tacks closer together. Your whole figure seems much weaker.

Here is a two part question for you to ponder. If you built a radio tower and placed the braces so that they all laid flat (horizontal), 1) what figure would they form, and 2) could that figure change shape easily? If you answers are a 'rectangle' (or 'square') and 'yes', we're coming along together. If there are any doubts, go back to the last experiment and see how it relates to this type of construction.

That is the total extent of the theory of structure design. Of course, there are many more ways, some of them not so obvious. To use this theory to build a great structure, there are two important things to keep in mind:

1. Shorter is better. This refers to the portion of the member that is allowed to bend. If the member is braced in the middle against bending, the length to consider is from the middle to either end.

2. Bracing with three sided figures (triangles) is better than four sided figures because the figure cannot change shape by bending or stretching, without changing the length of one or more of its sides.

Taking these concepts and applying them is the interesting part. Let's talk about a piece of pine wood which is two inches by two inches (a 2x2) and several feet long. If we begin with a apiece about eight feet long, you can easily imagine that if I stand it on end and put enough weight on it, it will bend and break. If I take a piece of that same 2x2 that is four inches long and keep adding weight to it, it will probably crush before it bends. The weight that it takes to crush the 2x2 is absolutely the most weight that it can hold under the best of conditions, and it is much, much more than the weight needed to bend and break the eight foot length.

What does this tell us? It says that if I start out with a piece eight feet long and test shorter and shorter pieces, I will find that it takes more and more weight to make the piece bend until it finally won't bend at all. When you find the length where it just stops bending and starts to crush, you have found the magic length we call the 'critical length'. For the purposes of this paper, let us assume that for a pine 2x2, that length is eighteen inches and that it will support one-thousand pounds.

This means that if I use a 2x2 to form a vertical support member, the most that member will hold under the best of conditions is one thousand pounds and four such members will hold two tons (four thousand pounds). In order to get those vertical supports (which for this discussion shall be eight feet long) to hold a total of two tons, I have to shorten up the lengths that are allowed to bend to eighteen inches or shorter. Also, it tells me that there is no benefit to shortening the bending length below eighteen inches. The structure will not get any stronger because the wood will splinter before it bends. If you're still with me, you're well on your way to being the next generation of skyscraper engineers. At this point, you should go back over the material we have covered and make sure that you understand it. The discussion of 'critical length' is very important.

For the more advanced coach, Euler's Formula predicts the force necessary to cause a given column of a given length to start to bend. If you know what weight it takes to crush a short sample of a particular column, the formula will tell you at what length the force required to cause it to bend is equal to the crushing force. That is the 'critical length'.

Back to the discussion of the 2x2 structure which is eight feet tall. In order to make the structure hold two tons, I must somehow brace the 2x2s every eighteen inches so that they cannot bend. The next obvious question is 'How?' This paper will not answer all of your questions and will leave it up to the reader to transfer these ideas from pine 2x2s to balsa wood.

It would be necessary for the designer of this pine structure to formulate a design that will brace one 2x2 against another effectively. In order to visualize what this means, consider the triangle you constructed out of cardboard. If you try to distort the figure, you will be trying to either shorten or lengthen one or more of the members. Shortening puts the member in 'compression' and lengthening it puts the member in 'tension'. I will talk more about compression and tension in Part II. When evaluating your structures, you would do well to consider the types of stress the various members are subjected to.

PART II

When evaluating a design, the builder must also consider the joints to be used. In the case of the radio tower, the joints are sometimes welded, but most often are bolted together. These joints hold well in tension and in compression. In wood construction where glue is used, there are several basic types of joints, just as there are also several types of forces which work to take the joints apart. A force which pushed the joint together is a 'compression' force and the joint is said to be 'in compression'. The force which tries to pull the joint apart by pulling one piece of wood straight away from the other is a 'tensile force' and the joint is said to be 'in tension'. A third force, and maybe a little more difficult to understand, is 'shear force'. This occurs when a force tries to move one member sideways, with respect to the joint.

To demonstrate the three kinds of force, consider a box glued to a table top. Following is a summary of the three primary forces acting upon that glue joint:

Tension:	If I try to lift the box, that is tension
Compression:	If I push downward on the box into the table, it would be compression
Shear:	If I try to slide the box sideways, it is said to be putting the joint 'in shear stress'

When two pieces of wood are glued together properly with the right type of glue, the glue in the joint is almost always stronger than the wood itself. When a good glue joint is stressed until it breaks, what usually breaks is the wood at the edge of the joint. This is hard to demonstrate with pine because of the high wood strength involved, but with balsa it is relatively easy. In such cases, when you examine the broken joint, there will be a significant amount of wood still attached to the glue on the failed side. How well the glue attaches itself to the member becomes the determining factor in the strength of the joint.

The most commonly seen join is the 'butt joint'. With this joint, one piece is simply 'butted up' against the other and glued. Other types of joints which might readily be used are 'lap joints' and 'log cabin joints'. A lap joint is one where one piece of wood is laid against the other, usually so that the primary type of force acting upon it is shear stress. The 'log cabin joint' is a combination of a butt joint and a lap joint. This joint is usually positioned so that the primary force puts the majority of the joining surfaces in shear stress and the ends of the notches are either in compression or tension.

Whatever type(s) of joint you use, and you should consider as many as you can think of, you should repeatedly ask 'What type of force will be acting upon this joint when the structure is tested?' and 'How will it be likely to fail?' If you can accurately answer these questions, you will know where to concentrate your efforts.

There are many types of glue that can be used and OM rules on this subject change occasionally, so I'll leave it up to you to know the rules and select the glue.

The selection of wood is also an important issue. The exact specifications may vary from year to year, and it is important for the designer to be very familiar with the current set of rules. The changes may affect the size of wood allowed as well as type. Balsa wood is commonly available at hobby outlets and through mail order. The quality of wood varies tremendously and it is important for the structure builder to ensure that the type of wood used is matched to the job.

The grain of the wood is the most apparent variable. Wood cut from smaller trees will often have crooked grain and when you load the wood during the structure testing, it will apply a shear stress to the grain of the wood that is not straight. The wood can separate or split along the grain and cause an early failure. It is important to select straight grained wood, if possible.

The two major components of wood are pith and xylem. The xylem are the tubes seen as the grain, which once carried liquids up the tree when that part of the wood was in the live or cambium layer. The pith is the material surrounding the xylem that 'glues' it together. The composition of these two elements varies widely from sample to sample. It is the xylem which supports most of the weight and is generally the yellowish brown color while the pith is a whiter color. The closer packed with xylem, the greater the density.

The density of wood available at hobby stores can vary by a factor of four. For example, a piece of one-eighth inch by one-eighth inch balsa thirty six inches long can weigh anywhere from a little less than one gram to a little over four grams. As a designer, you need to be aware of what you are buying. You will have to decide what weight is best for a specific task.

Moisture is another factor which can be important to a structure builder. One gram of balsa wood can absorb more than one tenth of a gram of moisture from the air. If you build and weigh your structure on a dry day and test it on a rainy day, you may be alarmed to find that your structure has gained a serious amount of weight. For structure builders who live in a dry climate, and go to a damp region for competition, this can be a nasty surprise. There are several strategies to either control the moisture in the structure or to account for it. Whatever you decide, you need to be aware of this complication.

PART III

Once the structure is designed, you have to construct it. At this point, all of your careful study and analysis can either come together or it can go out the window. The analogy of a weak link in a chain is very accurate here. The weakest point of a structure will fail early and take the rest of the structure with it. For example, suppose that you have the best designed structure but it has a flaw near one end. That flaw can be a weak glue joint, a poorly selected piece of wood, or a nick in one of the support members. The stress will reach the breaking point for that member earlier than for others and when it does, the load it was carrying will be put onto other members. That may not cause an immediate failure, but it will, at the least, hasten it.

Quality cannot be inspected into a product; it has to be built in from the start. This is a truism in many aspects of engineering and is particularly applicable with glued wooden structures. It is impossible, except in cases of extreme omission, to tell after a joint is assembled whether or not it had enough glue and if the glue was applied correctly. An inspector cannot take a structure which has been built with questionable technique and identify all of its flaws. The builder must be aware of what constitutes good construction and must be sincere in the desire to do the best job possible. To quote Gates Rubber Company's quality philosophy, 'Good enough isn't'.

A point that is often missed in construction is how straight and square the structure stands on the test stand. All contact points must be touching the bottom as well as the top. If there is any gap between what is supposed to be a contact point and the stand or crusher board, that member is not going to contribute to the support of the weight until the structure either distorts or compresses significantly. Sometimes that distortion means that glue joints pop and the structure shifts, causing the loss of bracing. Just like carpenters and machinists, many structure builders use jigs to ensure accurate placement of parts and to hold the parts correctly while the glue sets. It is imperative that these jigs be straight and square.

Now, suppose that the structure is assembled and everyone is admiring its intricacy. There is still one final point to consider. 'How flat are the bottom and top?' Even the best of jigs will often not bring the structure into close enough alignment. If the builder has left enough of a margin on the minimum length, he or she can sand it into flatness. A word of caution: be careful and measure often. It can be a nasty surprise to find that the wood sanded down a lot faster than expected. Also, it is often difficult to sand it evenly. The use of four hundred to six hundred grit sand paper and a lot of patience is advised at this point. Placing the structure on a sheet of glass and looking at the surface reflection from a very low angle is a good way to see if all points tough. It is possible to get obsessive at this point. The thickness of a thin sheet of paper is probably close enough. The amount of shifting and compression caused by a few thousandths of an inch is not likely to cause significant damage. Besides, this is probably flatter than the test stand or crusher board anyway.

There is a lot more to be learned than what has been covered in this paper, and much of it must be learned through trial-and-error. To speed up this process, a serious-minded coach can build one or more of several types of test stands for use by students. If the structure builder wants to construct a complete structure before testing, a stand similar to that used at competitions is useful. The difficulty or expense comes in obtaining weights. Olympic style weights can be expensive. Eight hundred pounds of lead costs nearly that many dollars and the equivalent in water will be nearly one hundred gallons. Sand weighs about one hundred and fifty pounds per cubic foot, and five or six cubic feet can become difficult to handle safely. Bricks weigh from four to five pounds each, but a stack of one to two hundred bricks can be dangerous when the structure gives and lets them drop.

To save the time and effort of building a complete structure, the designer may choose to build and test a portion of a structure. If this is the case, a scaled down stand may be desirable. If the structure being tested is smaller around than the final design, balancing the crusher board can be a problem. A stand with a 'guided' crusher board might be useful.

Something that the test stand designer must always keep in mind is the safety of the students. That is the purpose of the vertical pipe and the 4x4 blocks at competition. A loose stack of weights can easily tip, especially considering that the structure may collapse in any direction. The lives and health of the team members should always be the first consideration at any OM activity.

Odyssey of the Mind is a program that can benefit students in many ways. Even if a participant never builds a structure that posts a weight-held score approaching a four digit number, there is a lot to be gained. Structure building seems to catch the imagination of many people, often to the point of obsession. Maybe that's what the 'O' on OM really stands for. It attracts a following in students and coaches who perfect their techniques over a period of many years.

I hope that readers of this paper will take the information which I have attempted to impart and have the team members build upon it. You must always remember, it is the process which is important.

Every coaching adventure has its moments when you will question the value of it all, but there are also the little points that make it worthwhile. When a student tells you they have found talents that even they didn't know they had, you will know you have done something right. If you ever get the chance to listen to a third grade student explain Euler's Formula and its use to a professor acting as judge, you will know that something you said got soaked up by an active, young mind. As a parting word, remember that to harvest a crop, you must first sow a seed.

This paper was written by Arlyn Whitchurch, Colorado Odyssey of the Mind, 1992.

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