Trusses – Theory and in LEGO

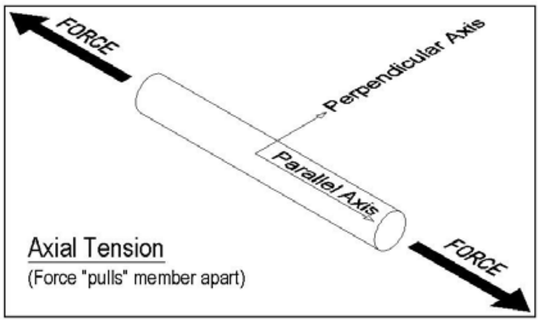
TJ Avery, c. 2001 (updated May 2009)

This article explains what a truss is and how it functions structurally. Also presented are examples of how to build a truss structure using LEGO parts.

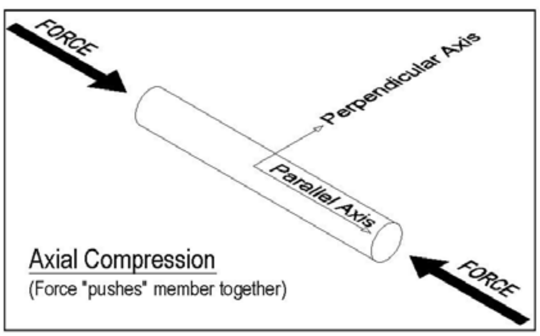
1. A Quick Primer

Several types of loads can be applied to structural members: axial (tension and compression), bending, torsion, and shear.

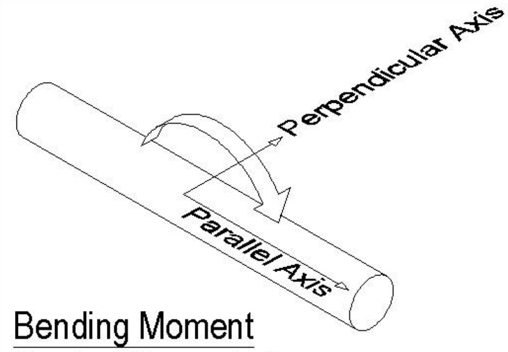
Tension is a force pulling a structural member apart, roughly speaking. The loads are perfectly in-line with the member's axis, like this:



Compression is a force squeezing a structural member together, roughly speaking. The loads are perfectly in-line with the member's axis, like this:

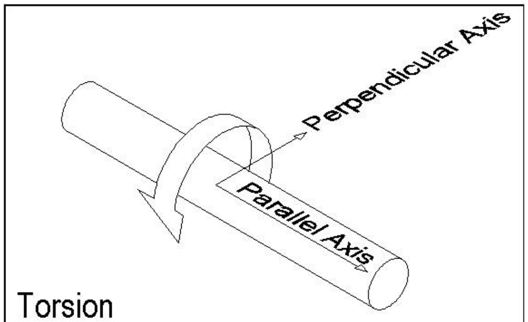


Bending (or "bending moment", or sometimes just "moment") is a curving of a structural member. Imagine grabbing a long bar with two hands, and then rotating your wrists to make the bar into a curved shape. This is a complex loading situation where the top fibers of the bar (i.e. the "outside" fibers of the curved member) experience tension, and the inside fibers of the bar experience compression.



Bending Moment
(Bending of the member)
(Bending moment acts about the perpendicular axis of the member)

Torsion is a twisting of a structural member. Again, imagine grabbing a long bar with two hands and then trying to wring it as if you were twisting a damp washcloth and trying to squeeze moisture out of it.



Torsion
(Twisting of the member)
(Torsion acts about the parallel axis of the member)

Shear (no picture) is a force that attempts to slice apart a structural member. Again, with two hands on the imaginary bar, imagine pulling one hand towards you and pushing the other hand away from you. The force acting on the bar wants to slice it in half.

In real life, pure loads do not exist by themselves. Loading on a structural member is usually a combination of two or more load types. For example, the frame rails in your vehicle will probably experience tension, bending, shear, and torsion as you drive along. A column in a building frame will likely experience compression, bending, and shear at the same time.

2. Definition of a Truss

A truss is a structural system where, theoretically, all members are either in pure tension or compression. The advantage of this system is that, in layman's terms, structural members (e.g. tubes, I-beams, etc.) perform more efficiently if they are put into pure tension or compression instead of a combination loading system where they experience several loads at once.

A truss is basically a series of triangles connected together. A theoretical truss will have frictionless pinned joints at the intersection of the members. Only in this situation will you have pure tension or compression in all the members of the truss structure.

In real life, no such pure structural system exists. However, the loads in the members of a truss are dominated by tension or compression. They will still see a very small amount of bending, shear, and torsion (depending on the set-up), but the dominating loads will be tension or compression.

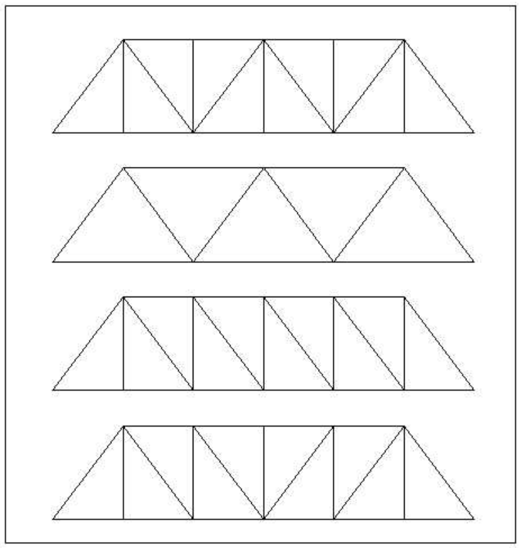


Figure 1: Examples of Trusses

If a structure does not contain connected triangles, then the structure becomes a frame or some sort of hybrid truss/frame structure.

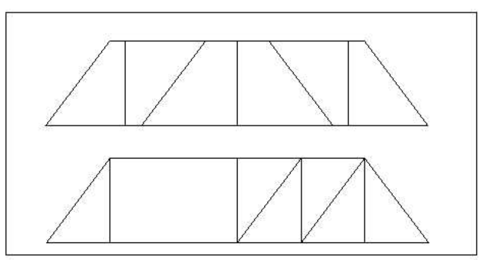


Figure 2: NOT A TRUSS Examples

A frame structure will primarily resist bending moment and also a combination of loads (e.g. moment and compression).

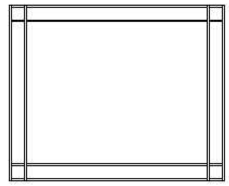


Figure 3: Moment-Resistant Frame

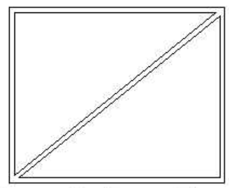


Figure 4: Truss Frame

In the figures above, either the frame or the truss will make a feasible structural system, but there are advantages and disadvantages to both.

Category	**System**	**Advantage / Disadvantage**
Weight and Materials Used	Truss	Advantage – truss is more efficient and will therefore be lighter.
	Frame	Disadvantage – frame members are thicker to resist bending moments and combination loading and will therefore be heavier than the truss.
Clear Space	Truss	Disadvantage – truss requires diagonal members to make triangles, and will block clear space through the structure.
	Frame	Advantage – frame can have large open space through the inside (good for buildings).
Construction	Truss	Disadvantage – joining members at odd angles can sometimes be difficult.
	Frame	Advantage – members are all joined and right angles.
Rigidity	Truss	Depends on Application – trusses will be much stiffer than frames, i.e. they will not flex as much as a frame when under similar loads.
	Frame	Depends on Application – frames will be more flexible than trusses, i.e. they will flex more than a truss when under similar loads (frames are good for vehicle frames).
Failure	Truss	Disadvantage – failure of a single member usually results in catastrophic failure of the whole truss system (unless the system has been designed with redundant members).
	Frame	Advantage – failure of a single member does not necessarily result in catastrophic failure of the whole frame system, adjacent members can take some of the extra loading after one member has failed (depending on the design and loads applied).
Fire Resistance	Truss	Disadvantage – members are relatively thin and more susceptible to weakening from the heat of a fire.
	Frame	Advantage - members are relatively thick and less susceptible to weakening from the heat of a fire.

Adding up the disadvantages for a truss shows that it's clearly outnumbered compared to a frame. However, in many applications, weight and cost are the most important factors and a truss wins there.

One example to show the loads within a truss system is to look at a simple frame being loaded from the side. Depending on the direction of the load applied to the truss, the diagonal member will either be in compression or tension.

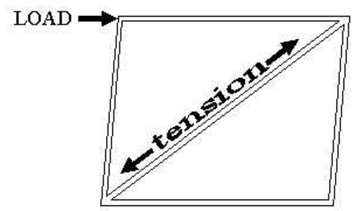


Figure 5: Sided Loaded Truss (1)

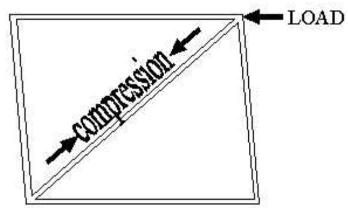


Figure 6: Side Loaded Truss (2)

A compromise to having a rigid diagonal member is to replace it with a X-pattern of cables. Cables cannot take compression, so using two will ensure that at any given time, one cable is in tension.

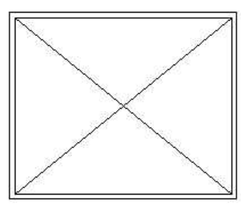


Figure 7: Truss with Cable Diagonal

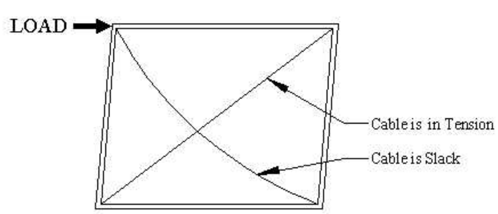
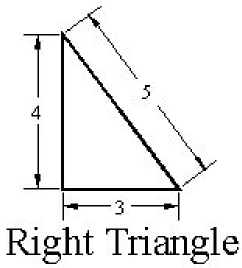
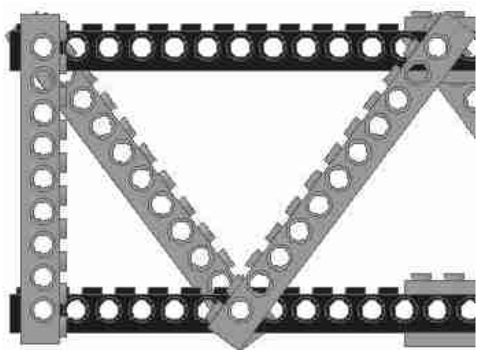


Figure 8: Truss w/ Cable Side Loaded

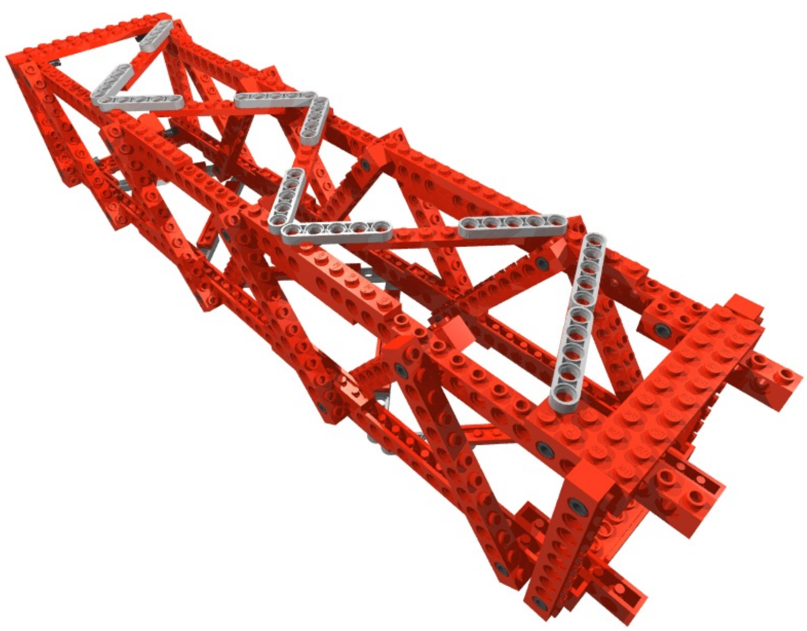
3. Building Trusses with LEGO Parts

LEGO Technic beams are well suited for constructing truss systems. A 3-4-5 right triangle is particularly well suited because the vertical and horizontal members will be at right angles relative to each other and also be able to easily integrate with adjacent LEGO parts in the whole structural system.





Below is an example of a boom section from a crane I built some time ago. The Technic beams allow connection of the diagonals in two planes.

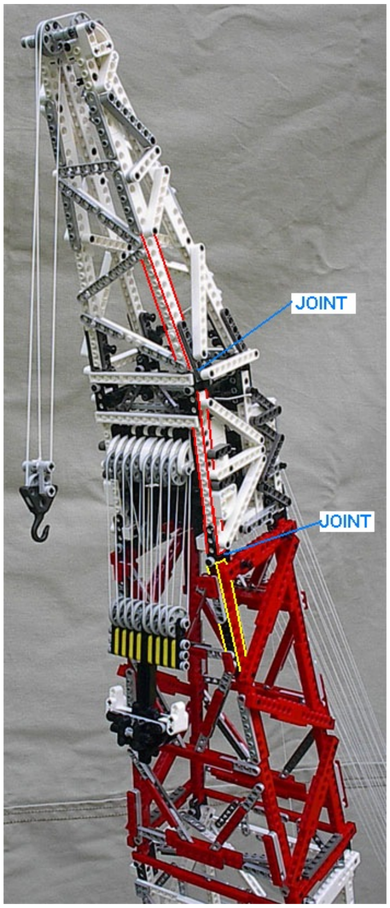


Note that the diagonals do not pin together with the vertical members on the same axis. The connections of the diagonals and the verticals to the horizontal members of the truss are separated by 2 studs. Therefore the end sections of this little boom section are not truly a truss structure (remember, the members a real truss connect at one point). However, the connection points come close, and the resulting structure is very strong and still makes efficient use of the pieces.

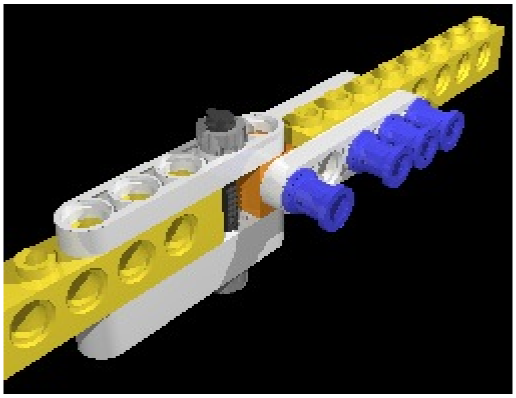
Also, the diagonals pin to the horizontal members from either side, and are separated by a width of two studs (measuring center to center of the diagonals). This also isn't a "pure" truss as the members do not meet up at the same point. In reality, truss members like this cannot physically meet at the same point. It's just not possible. But again, the connection points come close, and the resulting structure is very strong and still makes efficient use of the pieces.

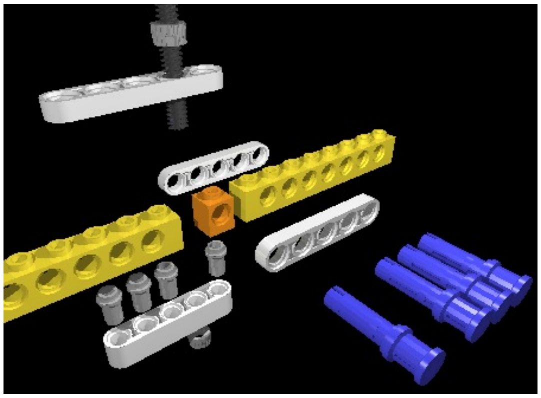
This crane also used a truss system for the boom:

The truss shape of the boom was complex. The boom design incorporated tapered sections to make it narrower towards the tip:



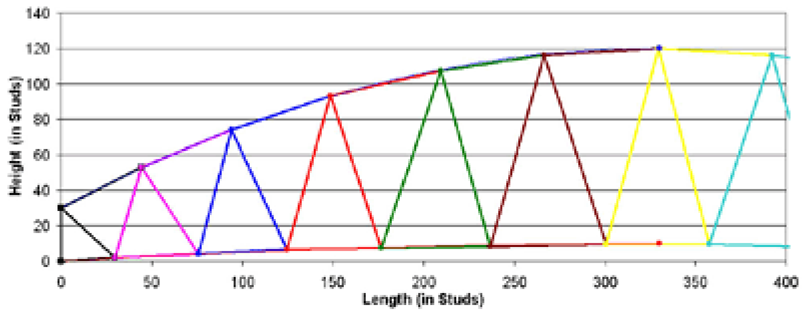
This required a dual-hinged connection (between two Technic beams placed in-line with each other) along the main truss members (chords). Below is the design of the hinges. They made use of a rare LEGO part – a 4-stud long threaded axle.





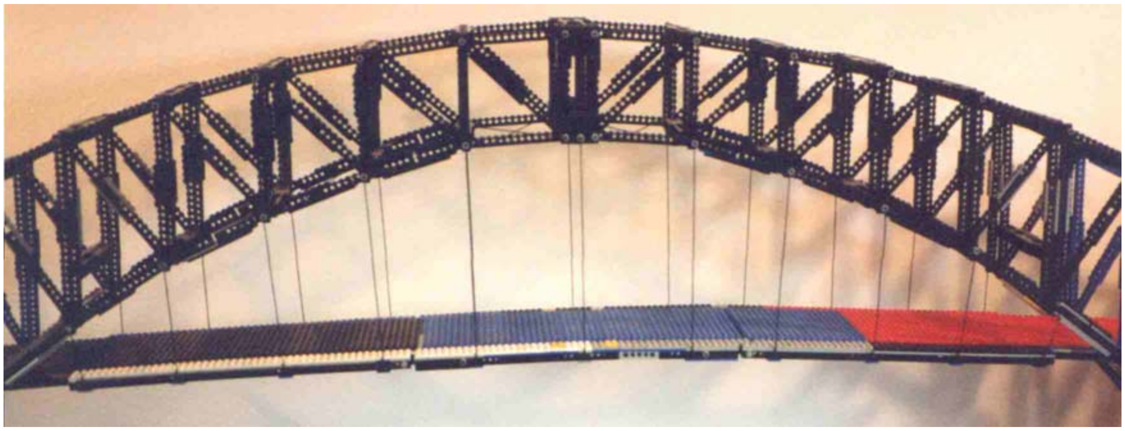
Figuring out the member lengths of the truss and the truss pattern can be a challenge. Trial and error works but is time consuming. Using CAD software to make plans before you start physically putting pieces together is an efficient way of doing it.

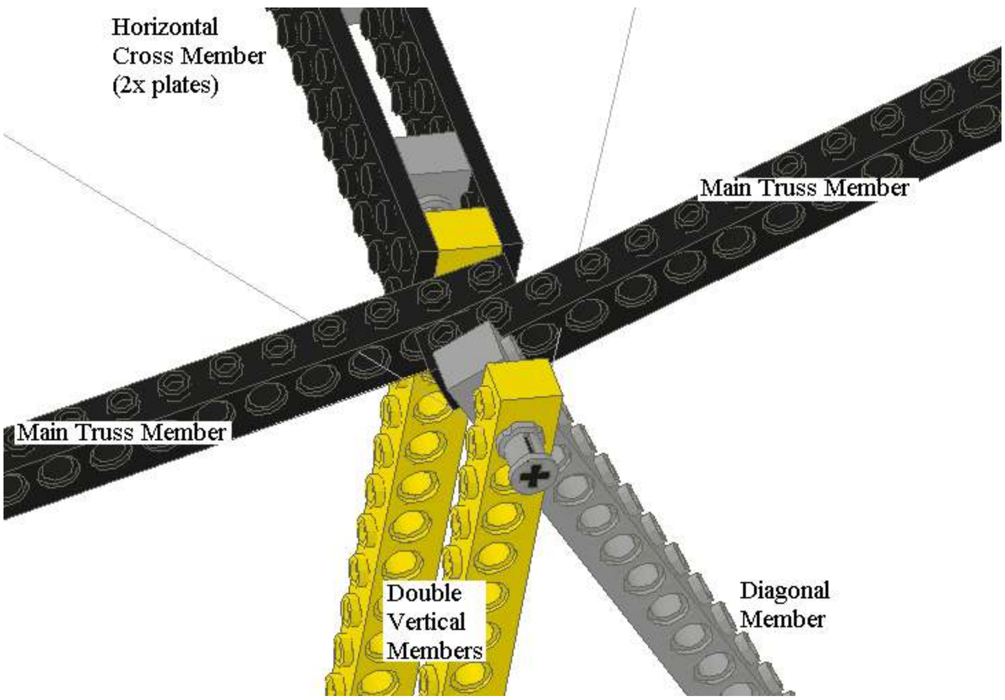
For my 17-foot bridge, I first designed the truss pattern using a spreadsheet I developed.



This method was still trial and error, but it was done quickly on the computer before I started piecing together the hard parts. Once I established the truss pattern and lengths of all the members, building it was quick and easy.

My very first truss structure was a 5-foot long bridge. In this design, I used string (in an X-pattern) for the cross bracing.





This idea seemed to work pretty well for that particular bridge, but I would advise against using string for cross bracing. String has a lot more give than plastic Technic beams. Using this design for a crane boom, for example, will result in a boom structure that is laterally unstable when loaded. The boom will slide over sideways because the string flexes too much and cannot hold the truss in a rigid shape.

For more LEGO truss building guidelines and examples, please also see my article titled, "Building Big".

I hope these examples spark some imagination and creativity in your building! Good luck!

