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# PYRAMID BUILDING

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Recent articles in Natural History[1,2] indicate that there is disagreement as to how the huge stones, weighing in some cases many tons, were lifted into place to form the ancient pyramids.

I propose a simple method featuring one basic tool which one might use to build a pyramid. The tool, shown in Fig. 1, was copied from the lower left-hand corner of a 3900-year-old tomb painting tracing shown on page 12 of Ref. 2, being carried by three men. It is described as a wooden lever or pry bar. Several of these notched timbers, some rope and perhaps some additional smaller planks and triangular blocks are all that would be needed to assemble a reliable, simple, versatile and relatively safe low-friction pyramid erecting system. The dimensions of the tool are proportional to measurements taken from the picture in Ref. 2, and are shown in Fig. 2 in terms of an arbitrary cube edge length, $\ell$.

Figure 3 shows one possible basic portable crane. Figure 4 shows a possible setup and stone transfer technique.

Tests have been conducted with a scaled-down model of the proposed portable "step walking crane" system. The tests helped provide rapid solutions for some of the problems that one might anticipate.

One important problem is the damage that might occur when a large cube or parallelepiped is dropped from the inital crane to the "new" upper boom or booms. Several solutions are possible, and one that may work would be to use ropes from the mast or separately-held ropes wrapped around the stone as friction hold shock absorbers. Wear to the ropes might be minimized by stringing sleeves or bands over the rope. The smooth side of a timber might be used as a friction drag shock absorber, or reed mats as cushions.

A slightly modified and perhaps better basic method would be to deliver the stone to a second set of booms, as shown in Fig. 5, and then reset the initial set of booms up two steps and continue using them for delivery to the booms at the third step, etc. In this way, a gentle release of tension on one main rope would softly transfer the stone to the next set of booms. A second main rope on the second set of booms could then continue the upward progress. A few men would suffice to lift the fulcrum ends of the first booms up two steps each time while the rock is being lifted by the second set of booms. This method would greatly reduce the large shear forces at the notches which may occur in the first method. The model tests indicate that this method can be used to lift blocks up steps with a 75° slope.

Another problem would be wear and tear of the booms at the fulcrum. This may be reduced by placing a right triangular moveable fulcrum block at the inside corner of each step as the crane ascends.

Tandem operation of several cranes along a parallelepiped or long triangular stone may be considered as a technique for lifting much larger stones.

Eshbach[3] gives the maximum safe load for a simple beam with the load concentrated at the center as

$$W = \frac{1}{3} s \frac{S}{L} \text{ (lbs)} \quad ,$$

where s is the extreme fiber unit stress in lb/in$^2$, S is the section modulus in in.$^3$, and L is the length of the span in feet. If the booms were made of 8 in. × 12 in. × 10 1/2 ft pieces of dry cedar with s = 1000 lb/in.$^2$, each would weight about 190 lbs and could be expected to safely support a concentrated load of approximately $W = \frac{1}{3} \cdot 1000 \cdot \frac{192}{9} \approx 7200$ lbs or 3 1/2 tons for a nine-foot span. A maximum shear load parallel to the grain of a solid rectangular wood timber is given by the formula[3]

$$V = \frac{2}{3} s_s A \text{ (lbs)} \quad ,$$

where $s_s$ is the average unit shearing stress in lbs/in.$^2$ and A is the area of the section in in.$^2$. Thus, an allowable horizontal shear stress of 80 lbs/in.$^2$ for cedar would allow each 8 × 12 in. timber a maximum vertical shear of roughly 2 1/2 tons,

$$\frac{2}{3} \cdot 80 \text{ lb/in.}^2 \cdot 96 \text{ in.}^2 \quad .$$

If one assumes $1/24\ \ell = 1.5$ in., then A = 12 in.$^2$ and each notch would be limited to a shear stress of roughly 640 lb per timber,

$$\frac{2}{3} \cdot 80 \text{ lb/in.}^2 \cdot 12 \text{ in.}^2 ,$$

unless the notches were inlaid with blocks of copper or wood with the grain perpendicular to the force of the stone. Inlays might allow roughly a factor of three greater shear loads. Thus, the first-mentioned block lift method might be used with a larger timber thickness and inlays at the notches. The second method would be safely applicable with or without inlays since the shear forces are expected to be much less. Final block placement deliveries could be made to the smooth side of a boom. The block could then be slid off and levered into place.

The number of steps, n, which must be ascended by all of the cubes in a solid pyramid which has a base s blocks square, with each higher tier side length diminishing by one block, is given by the following expression:

$$n = \frac{s^2(s+1)(2s+1)}{6} - \frac{1}{12}(s-1)(s)(s+1)\left[3(s-1)+5\right] .$$

For a hypothetical pyramid with s = 190, the number of one-step block lifts necessary is roughly 111 million. The pyramid would contain roughly 2.4 million blocks and the "average" block would undergo about 46 one-step block lifts. Assuming three-foot cubes weighing 5000 lb and a 70-man team on one rope connected to cranes on two opposite faces, acting on the cranes alternately while slack in the rope is taken up, it is estimated that ten one-step block lifts per minute could easily be made if slack is taken up quickly and there are some additional assistants at the cranes to lift and place the masts the next step up, take up slack in the ropes, hold and move safety blocks or bars and set the next crane. At this rate, 600 block lifts per hour for a five-hour day, one might expect to make about 3000 block lifts per day. This corresponds to each man working at a rate comparable to about 1/15 horsepower, or each man pulling on a rope with a 36-lb force while moving one foot per second.

In the above manner one might accomplish the 111 million one-step block lifts necessary to build a pyramid which would contain about 2.4 million blocks with ten or twenty teams of 100 people (including safety people who would keep notched bars or blocks in the proper places to guard against mishaps) in about five to ten years.

There are variations to the two basic methods outlined above which should not be ruled out and which may add stability to the stone as it is lifted. One variation may involve a different sequence of moves, with the first booms on the outer portions of the bearing area always doing the majority of the lifting, while the central booms serve as a temporary resting place and the first booms are replaced only one step up each time.

Whether this method was actually used to build the ancient pyramids is still a matter for debate. A combination of the "portable crane" and the ramp and sledge methods may have provided the most effective means for erecting a pyramid. The ramp and sledge technique may have been used for the lower levels, with portable cranes taking over at a point where ramp construction became too time consuming.

ACKNOWLEDGEMENTS

I would like to thank George Shalimoff for providing me with an instant mini-library of books on pyramids when I first told him of the machine idea. I thank Herman Robinson for his help in deriving an expression for the number of block moves, and Elinor Potter for her help with the initial calculations. I thank Gardener G. Young and Hardy Wandesforde, who machined our first notched bars, and Gene Miner for his help in checking the engineering calculations and figures. I thank my lovely wife Marie for subscribing to the magazine Natural History, for typing the initial drafts, for helping with the illustrations and for calming my wild excitement about this idea with a sphinx-like serenity.

I am especially grateful to Professor Kenneth Street and Professor and Mrs. Luis W. Alvarez for their kind assistance and helpful advice.

REFERENCES

1. Olaf Tellefsen, "A New Theory of Pyramid Building," Natural History 59-9, 10 (1970).

2. Kent Weeks, I. E. S. Edwards, O. Tellefsen, "The Great Pyramid Debate," Natural History 59-10, 8 (1970).

3. O. W. Eshbach, Handbook of Engineering Fundamentals, (John Wiley and Sons, Inc., New York, 1936), Section 5, pp. 23-32.

## FIGURE CAPTIONS

Fig. 1. Notched wood timber. The circled notch is optional and has been added for versatility. A man's hand obscures this position in the tomb painting reproduced in Ref. 2.

Fig. 2. Notched timber showing approximate lengths taken from Ref. 2. If the figures in the original painting were about 5 1/2 feet tall, then $\ell$ would be about three feet.

Fig. 3. A basic portable crane. The use of a notched timber as a mast, the mast angle and its fulcrum point are all arbitrary and would be arranged for optimum coupling with the men pulling the rope. Each boom is roughly 10 1/2 feet long, and one foot high by eight inches thick in cross section.

Fig. 4. Possible setups for block lifts. Sets of ropes and masts for the second set of booms are omitted to simplify the diagram. The booms are used in pairs, with the second set fitting inside the first set. The idea of using rope or reed cushions was proposed by Bob Harney of our transportation department who had previously worked in the ship yards. He happened to notice the figure and suggested the use of some straw or mats to ease the shock as weight is transferred to the second booms.

Fig. 5. A method for lifting arbitrarily-shaped stones up the side of a pyramid. The obttom of the stone always contacts the bearing area of the booms. Masts would be placed to allow optimum coupling with the men pulling the ropes.

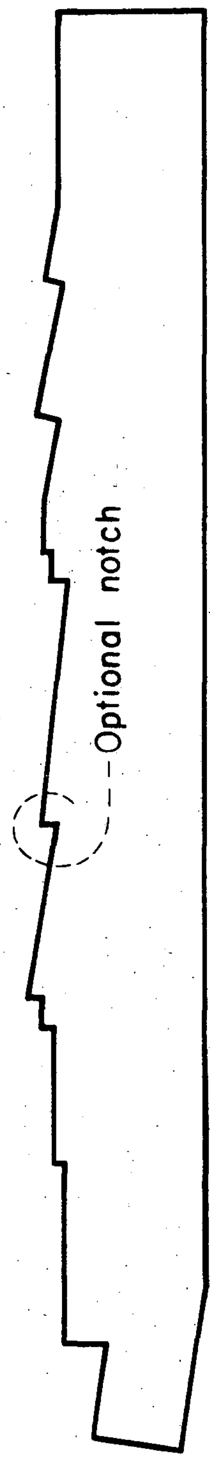


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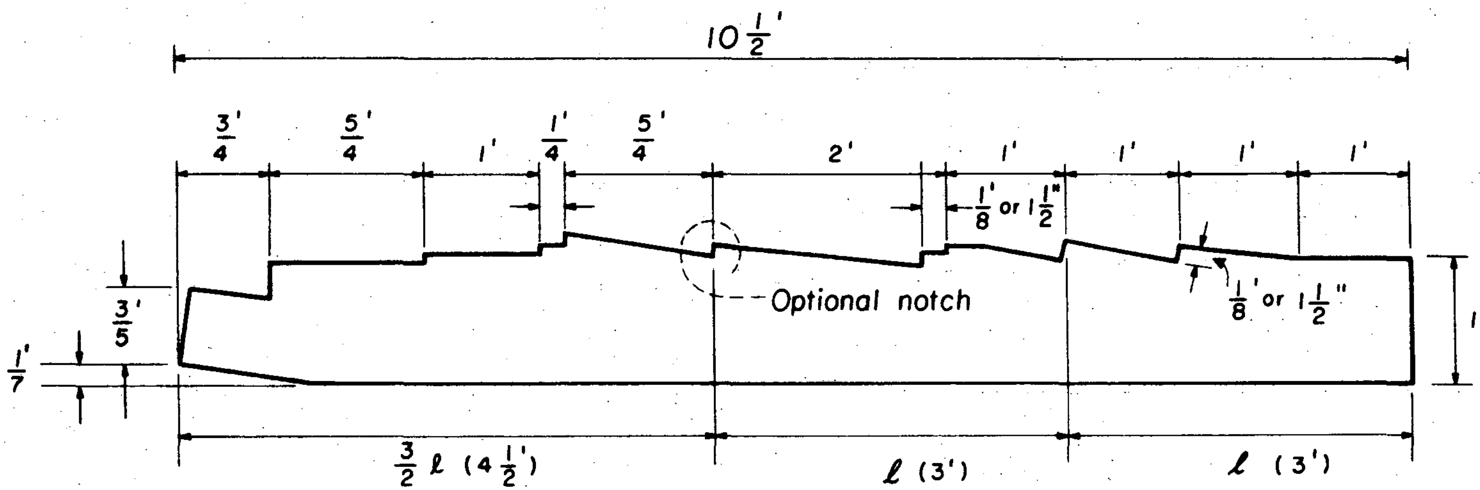
Fig. 1

Dimensions are approximate (shown in feet)




XBL 712-2780

Fig. 2

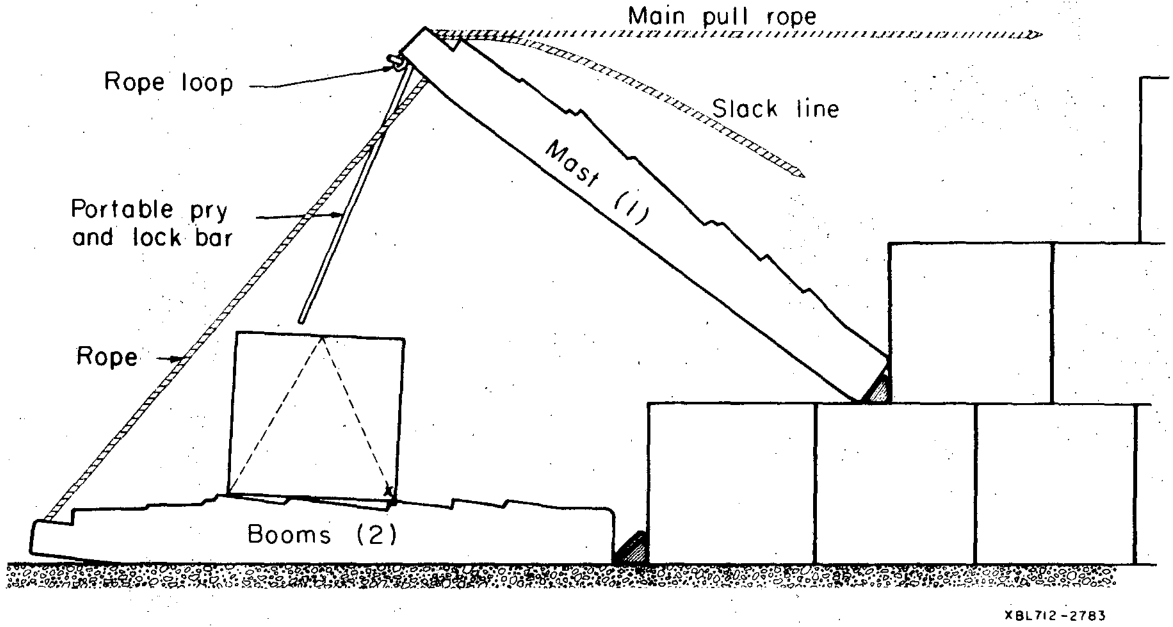
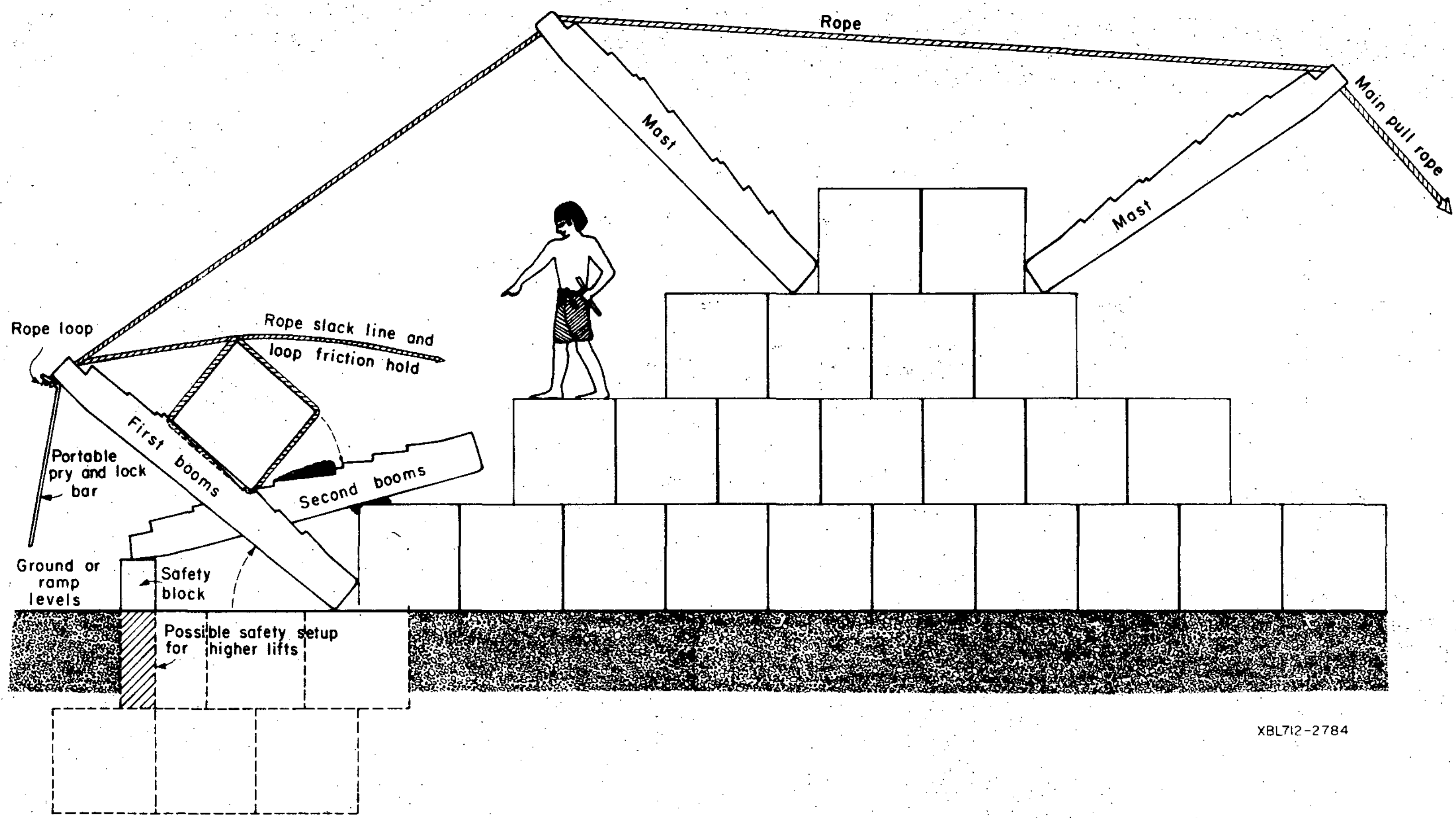

Main pull rope
Rope loop
Slack line
Mast (1)
Portable pry
and lock bar
Rope
Booms (2)
XBL712-2783

Fig. 3




XBL712-2784

Fig. 4

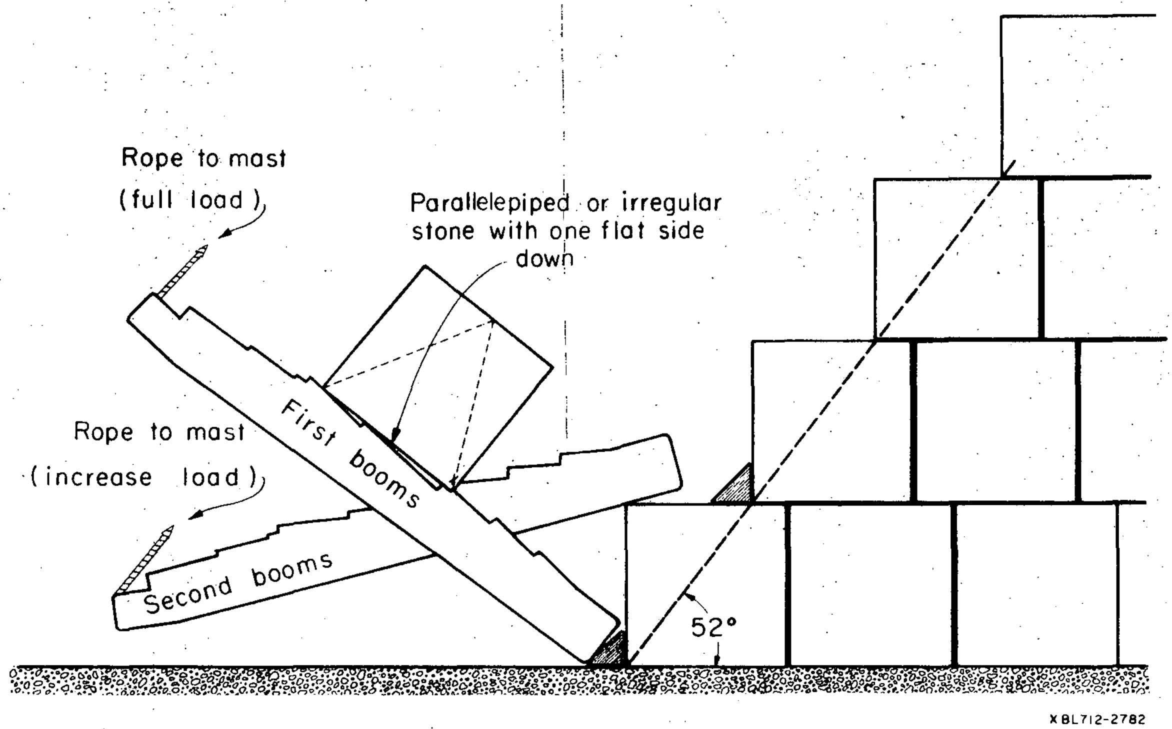

Rope to mast
(full load)
Parallelepiped or irregular
stone with one flat side
down
Rope to mast
(increase load)
First booms
Second booms
52°
XBL712-2782

Fig. 5A

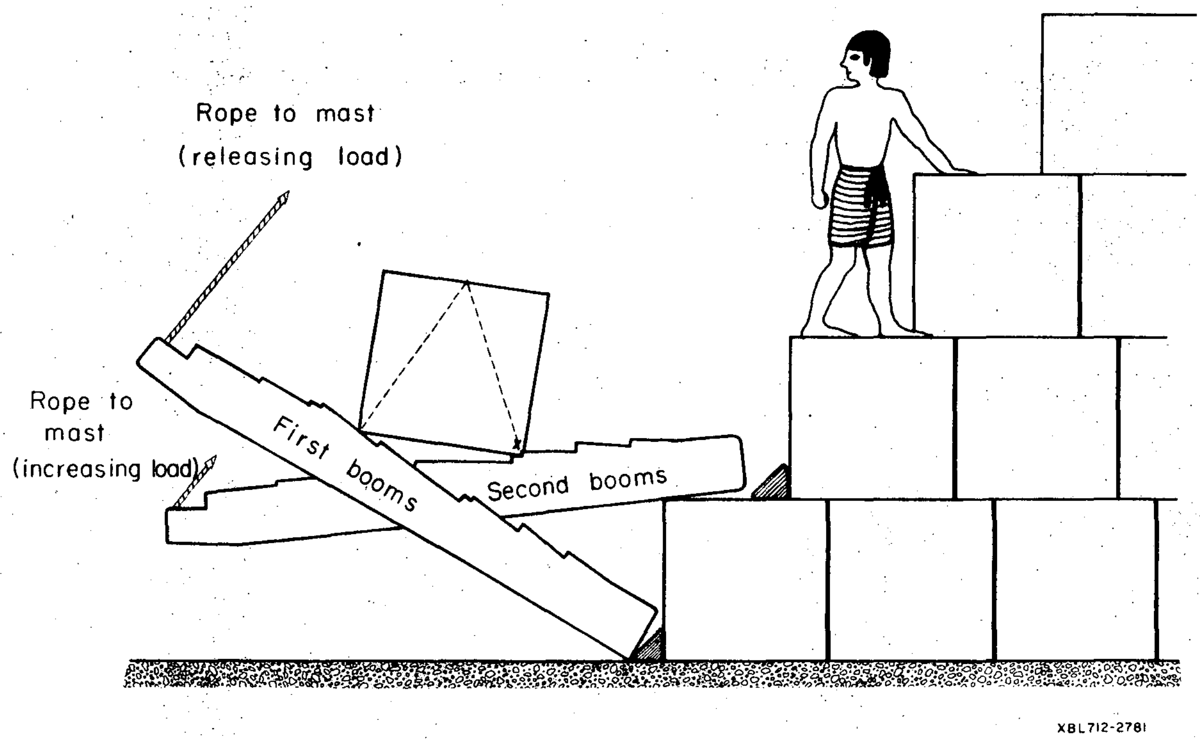

Rope to mast
(releasing load)
Rope to
mast
(increasing load)
First booms
Second booms
XBL712-2781

Fig. 5B

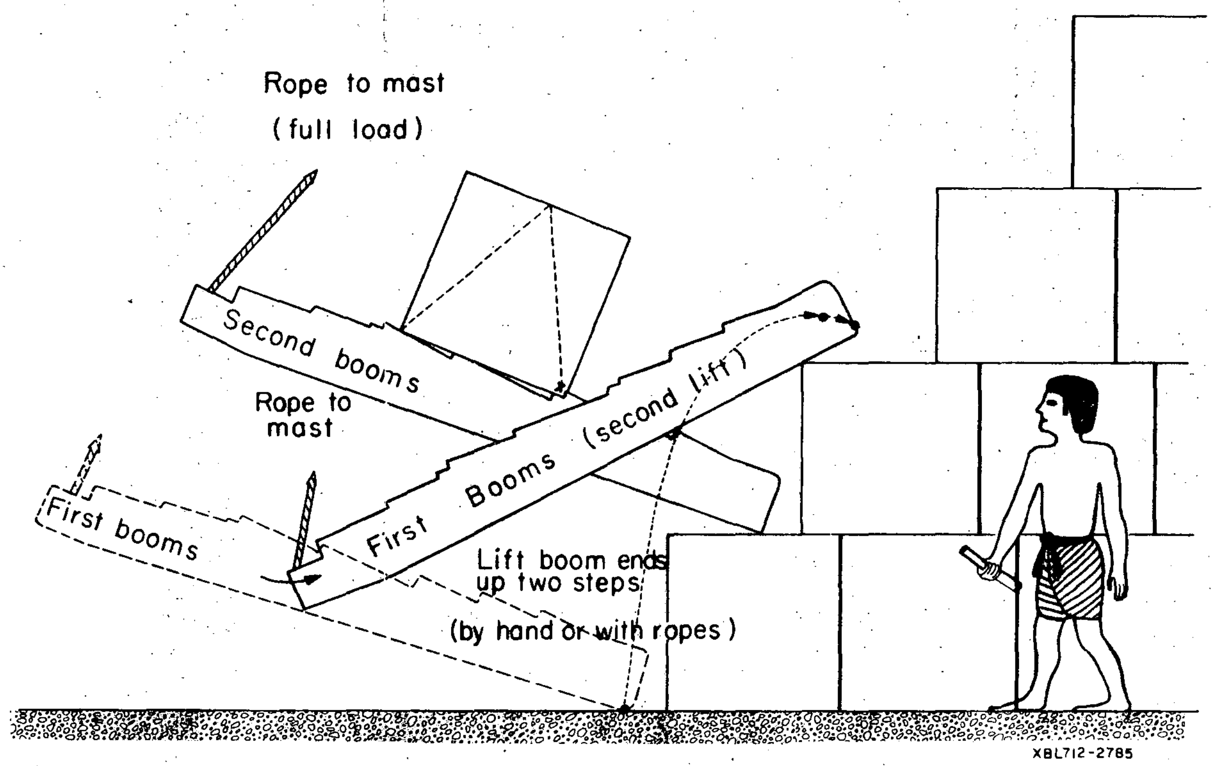

Rope to mast
(full load)
Second booms
Rope to mast
First booms
First Booms (second lift)
Lift boom ends up two steps
(by hand or with ropes)
XBL712-2785

Fig. 5C