CONSTRUCTION OF THE TOP OF THE EGYPTIAN PYRAMIDS: AN EXPERIMENTAL TEST OF A LEVERING DEVICE

By

ROBERT SCOTT HUSSEY-PAILOS

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

UNIVERSITY OF FLORIDA

2005

To Carl Sagan, whose work helped me recognize fraudulent and fallacious arguments, gave me the means to construct and understand a reasoned argument, and serve as a model for good prose.

ACKNOWLEDGMENTS

I thank my parents, my family, girlfriend, friends, Rinker Inc., Dr. Properzio, Glenn Ketcham, Dr. Sassaman, Dr. Wagman, and Dr. Schmidt.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Arts

CONSTRUCTION OF THE TOP OF THE EGYPTIAN PYRAMIDS
AN EXPERIMENTAL TEST OF A LEVERING DEVICE

By

Robert Scott Hussey-Pailos

May 2005

Chair: Peter R. Schmidt
Major Department: Anthropology

A great deal is known about Egyptian pyramid quarry sites, tools used in their construction, transportation of stones from the quarries to the pyramids, and the leveling of stones. However, there is a dearth of information concerning the process of lifting of the blocks from the ground onto the pyramid's superstructure. While ramps are the most widely accepted method, it is an incomplete approach because ramping cannot lift the blocks at the top of the pyramid. Most Egyptologists suggest that a form of a levering device should accompany ramps to form an amalgamated method. Unfortunately, there are no experimental tests demonstrating that a levering device, composed of materials and technology available to the pyramid builders, can function to lift a block in the limited space available at the top of the superstructure.

My study involved a levering device designed to work with ramps to construct the top of the pyramid. My objective was to construct and build a working lever, by encasing its design within the framework of technologies and materials available to the ancient

Egyptian pyramid builders. Testing this lever entailed the fabrication of many models; tests with weights greater than 5560 pounds; and a large-scale experiment that raised a 2530-pound block up one tier in under a minute.

CHAPTER 1
INTRODUCTION

Methods of lifting the blocks up the Egyptian pyramids have attracted a substantial amount of research. Though there is good information concerning the location of the quarries, tools used to split and shape the stone, transportation of the stone from the quarries to the pyramid, and methods of leveling the foundation and rising superstructure tiers (Lepre 1990: 252), there is a dearth of information regarding the methods of moving the blocks up the superstructure. There are no direct historical or archaeological inferences available to resolve and answer this facet of pyramid construction.

Unfortunately, without strong inferences from archaeological or historical sources, we must select methods of moving blocks up the pyramid superstructure that are Technologically (capital intended) probable and historically possible. In other words, we must identify models that have the best historical and archaeological information; and then intersect this information with materials, culture and technology, and models of efficiency.

The models with the best historical, archaeological, material, and technological connections are ramps followed by levers. Ramps are discussed in Egyptian and Greek historical documents. Short ramps have been found, in situ, within various Egyptian pyramid complexes. The materials to construct these ramps are readily found within the pyramid complex.

While the evidence for ramps is strong, arguments of functionality preclude ramps from serving as a panacea to this facet of pyramid construction. Most ramping methods, while able move the blocks of approximately the bottom two thirds of the superstructure, fail in transporting the blocks at the top of the pyramid. Because of the geometric limitations of the pyramidal shape, each increase in vertical distance reduces available width and depth of the superstructure on which to place a ramp. These problems of reduced space encumber most ramp hypotheses. The ramping method that can complete the structure alone (the large straight ramp) is criticized for the tremendous amount of material needed for its construction. Academics who propose other ramping models augment their methods at these higher strata with scaffolding, staircase ramps, and in many cases, the use of a conceptual levering device.

The two major hypotheses, ramps and levers, are often posed in popular literature as two competing methods. Ramping methods generally prevail under this false dichotomy as the model with the most conclusive historical, archaeological, and experimental evidence. This is curious since many Egyptologists regard the leading technique (ramps) as an incomplete method to construct the pyramids, and they supplement the various proposed ramp models with the use of the second most accepted method: levers (Arnold 1991, Isler 1985, 1987 Lepre 1990, Lehner 1997).

The use of levering devices in the construction of the Egyptian pyramids has a deep pedigree within historical accounts. Herodotus's accounts of pyramid construction are the first to record the methods of moving the blocks up the superstructure. However, his vague description of such a device, coupled with a lack of any other direct inferences for levers used to lift large weights, has resulted in a large variety of proposed levering hypotheses. The lack of adequate and successful experimental tests of these levering hypotheses contributes greatly to arguments doubting their feasibility. Regardless of the many arguments concerning the practicability of levering hypotheses, for many leading authorities writing on the subject of Egyptian pyramid construction, levering remains the most plausible method to complete the top of the pyramid superstructure.

While the fields of materials and culture and technology are part of a strong archaeological analysis, examining models of efficiency (in this case) is not. Selecting technology based on functionality and efficiency should not be the sole method of determining technological selection. Doing so ignores culture by presupposing formalistic economic rationality, and assumes that a culture will strive to maximize profit and labor potential. While these may be good avenues to pursue for a type of technology with strong archaeological and historical inferences, it is a weak means of selecting the definitive levering device to move the blocks up the Egyptian pyramid. However, using this avenue to determine the validity of a new method from a pool of experimental models that are inadequate based on efficiency is an argument that bears merit. In other words, if one model stands out as the only design that can perform the task within the parameters of time and space, materials, and available technology; and it fits the historical and archaeological record, then it can be considered more plausible than the other levering methods.

In this regard, levering methods of moving pyramid blocks can benefit from an exploration of functionality to determine a viable method of moving the blocks up the superstructure. A number of levering hypotheses are simply discussed on paper and are untested. Levering methods that are experimentally tested inadequately demonstrate the principle to function in the appropriate time, such as Martin Isler's experiment that required one hour and a half to move a 2-ton block up one tier (Isler 2001: 252); or Julian

Keable's (Hodges 1989) experiment which lacked effective materials. If a levering model can be shown to safely and quickly function through an experiment in which the types of technology and materials used in the test rigorously follow models available to the ancient Egyptians, this levering model would stand apart from the other levering models as one that is functional, Technologically probable and historically possible.

I explored the various ramp and lever hypotheses for moving the blocks up the pyramid superstructure. I then developed my own levering method as a viable and functional model to complete the top portion of the pyramid left unreachable by many of the ramp hypotheses. I based the construction of my levering device on historical, archaeological, and experimental evidence, ending in an experimental test to assess the mechanical feasibility of this device. My objective was to construct and build a working lever, encasing its design within the framework of technologies and materials available to the ancient Egyptian pyramid builders.

This study of experimental methods began as a class assignment for Peter Schmidt, Professor of Anthropology at the University of Florida. Testing this lever entailed the construction of a three-course pyramid with 2500-lb blocks.

CHAPTER 2
OVERVIEW OF THE EGYPTIAN PYRAMID SUPERSTRUCTURES

For millennia the Ancient Egyptian pyramids have attracted scholarly research. The voluminous archaeological and historical information we have at our disposal has resulted in a thick description of Ancient Egyptian culture unlike that of any other civilization. Despite this tremendous volume of information, there is no direct evidence regarding the various methods used to move blocks up the pyramid superstructure, including its apex.

Further complicating the issue, the arrangement, size, and material comprising the pyramids changed through the long expanse of time in which they were constructed. In other words, there is no standard pyramid, nor was there a standard method of pyramid construction (Lehner 1997: 200).

The pyramids of the 4th dynasty, which contain pyramids with the largest interior blocks, exemplify some significant changes in the superstructure that were maintained throughout the remaining centuries of pyramid construction. The 4th dynasty reign of Sneferu, namely the pyramid at Meidum, marks a series of transitions on pyramid construction from mastabas to 'true pyramids'. Snefru's pyramid at Meidum contains the same inward-leaning accretions as the older 'step pyramids' for the inner core. External tiers of horizontally level layers of stone (Lehner 1997: 96) establish the smooth surface.

The Bent Pyramid represents a transition between the inward sloping stones and the horizontal layered pyramids. The bottom half of the Bent Pyramid was constructed with the older, sloping method; while the top half was constructed with horizontal tiers

(Lehner 1997:103). All Egyptian pyramids, built after the Bent Pyramid, externally are similar, except in size with small deviations with the angle of incline and the stones used for the lower stones of the outer casing (Edwards 1985: 254).

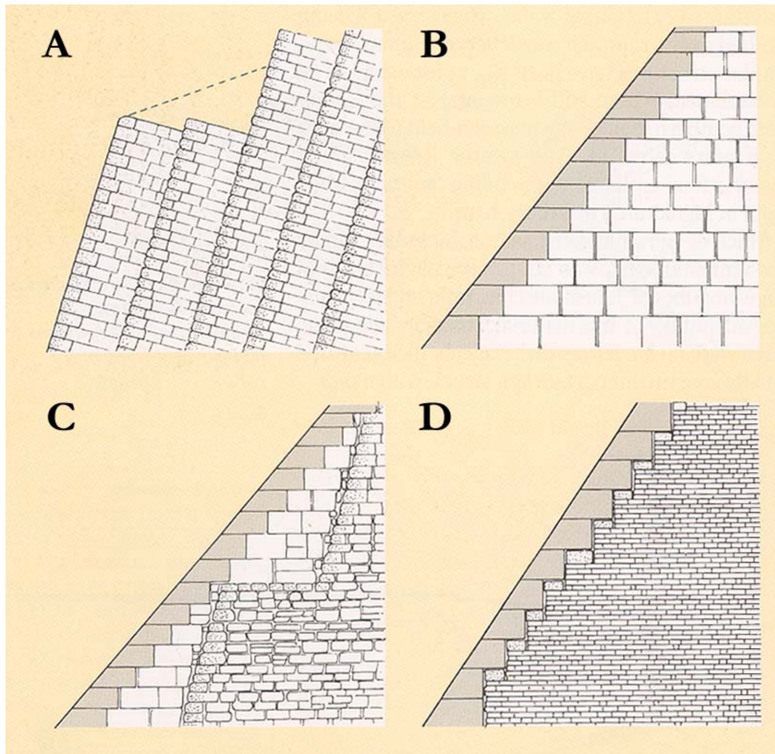


Figure 2-1. Overview of the pyramid superstructures. A) Construction techniques of the pyramids from the reign of Djoser (2630-2611 B.C.) to Sneferu (2575-2551 B.C.), which assemble the superstructure blocks in inward-leaning accretions. B) Changes in construction from Sneferu to the 4th dynasty (2575-2465 B.C.), using well-built horizontal layers with large interior blocks. C) Changes of later pyramids that employed rough masonry interiors within the fine limestone casing. D) Superstructures employed in the construction of Senwosret III's and later pyramids which utilized a mud brick core faced with fine casing stones. (Lehner 1997: 218)

The construction of the pyramid superstructure with level, horizontal tiers continued into the 4th dynasty and onward to the last of the Ancient Egyptian pyramids. Later pyramids replaced the smooth masonry cores of the 4th dynasty with rougher masonry cores. The pyramids of Senwosret III exchanged the masonry cores for mud brick cores, which were lighter, easier to transport, and not as structurally sound as the masonry cores of the 4th dynasty pyramids.

The 4th dynasty Giza pyramids seem to serve as the standard testing ground of pyramid construction hypotheses. The rationale behind this seems to lay with the sheer volume of these particular pyramids, as well as their large infrastructure block sizes. To test a lifting method by the standards of the Great Pyramids is to test the technique against variables that add blocks with the largest mass and monuments with the largest volume. Of course, when using the model of one Egyptian pyramid to serve as an analog to test a method, it is important to understand the differences in construction between the Egyptian pyramids.

It is also important to note that Pharaonic-era construction is highly repetitive. Ancient Egyptian architectural and technological techniques recur through long expanses of time (Clarke and Engelbach 1990: 1). With this in mind, it is important to consider the crystallization and continuity exhibited in Ancient Egyptian culture as a potential indicator that similar methods of lifting the pyramid blocks up the superstructure would show evidence of the same monotony.

However, there are strong deviations from this concept as well. The size and shape of the mortuary structures deviated within the Giza pyramids themselves, not to mention between dynasties and between Old, Middle, and New Kingdoms for that matter. However, during the centuries of Egyptian monument construction exist strong examples of continuity, there are differences as well. These differences are manifest within the pyramids themselves: within their internal chambers, and the within the entire mortuary complex. The 4th dynasty from which these monuments arise, encompasses the era of the earliest of the true pyramids. This dynasty is also only 150 years removed from Djoser's reign and the construction of the step pyramids.

Overall, while the Egyptian pyramids seem monotonous in their architecture, it is important to understand the differences between the monuments to avoid drawing false conclusions in an experimental test of a technique of moving blocks up a pyramid superstructure. The Giza pyramids remain the most often used model from which to test a lifting device. The casing and internal stones found in the Giza pyramids, particularly Khufu's are among the heaviest, their dimensions are the biggest, and they are the subject of a large amount of academic writing. For these reasons, Khufu's pyramid is selected as a good model to test a lifting device.

CHAPTER 3
HISTORICAL ACCOUNTS OF LIFTING THE PYRAMID BLOCKS

The first historical documents describing the construction methods employed by the ancient Egyptians to lift the blocks up the pyramid superstructure come centuries after the era of pyramid construction from the Greek Historians Herodotus and Diodorus Siculus. Herodotus provided the first accounts, written in the 5th century B.C., that vaguely describes a portable levering device made from short pieces of wood:

> This pyramid was made like stairs, which some call steps and others, tiers. When this, its first form, was completed, the workmen used short wooden logs as levers to raise the rest of the stones; they heaved up the blocks from the ground onto the first tier of steps; when the stone had been raised, it was set on another lever that stood on the first tier, and the lever again used to lift it from this tier to the next. It may be that there was a new lever on each tier of steps, or perhaps there was only one lever, quite portable, which they carried up to each tier in turn; I leave this uncertain, as both possibilities were mentioned. But this is certain, that the upper part of the pyramid was finished off first, then the next below it, and last of all the base and the lowest part (Godley 1920: Book2 Chapter 125).

Diodorus Siculus wrote the following 1st century B.C. account of pyramid construction describing ramps as the method of moving blocks up the superstructure:

> And 'tis said the stone was transported a great distance from Arabia, and that the edifices were raised by means of earthen ramps, since machines for lifting had not yet been invented in those days; and most surprising it is, that although such large structures were raised in an area surrounded by sand, no trace remains of either ramps or the dressing of the stones, so that it seems not the result of the patient labor of men, but rather as if the whole complex were set down entire upon the surrounding sand by some god. Now Egyptians try to make a marvel of these things, alleging that the ramps were made of salt and natron and that, when the river was turned against them, it melted them clean away and obliterated their every trace without the use of human labor. But in truth, it most certainly was not done this way! Rather, the same multitude of workmen who raised the mounds returned the entire mass again to its original place; for they say that three hundred and sixty thousand men were constantly employed in the prosecution of their work, yet the entire edifice was hardly finished at the end of twenty years (Murphy 1990: 79-80).

Both of these Greek historical accounts are difficult to interpret as their writings contain gross errors. Despite recurrent critiques of the inaccuracies within their works, however, these accounts are also known to contain historical fact (Lepre 1990: 255, Murphy 1990: ix). One of the standard criticisms aimed at Diodorus Siculus is that he borrowed from Herodotus's accounts. Both share gross inaccuracies. One glaring error being dating of the 4th dynasty pyramid builders after Ramesses II of the 19th dynasty (1279-1213 B.C.) (Burton 1972: 187). Both historians also state similarities in the method of construction in a series of steps, although it is commonly thought that Siculus was borrowing or misunderstanding Herodotus (Burton 1972: 188).

Both historians present erroneous information individually. Herodotus' description of the use of slave labor for the construction of the Great Pyramid is one of the most persistent and infamous myths associated with pyramid construction. On the other hand, Diodorus Siculus erroneously describes the shipment of stones from Arabia.

Since both Herodotus' and Diodorus Siculus' historical accounts of moving blocks up the pyramid superstructure are difficult to qualify, a single method –ramps or levers– cannot be selected from the texts. Basing an argument on simply one account does not provide for a good argument. Instead, these historical accounts give credit for both methods. Both writings contain contradictory observations, warning us that multiple methods, each appropriate in its circumstance, may have been employed.

CHAPTER 4
RAMP METHODS

Ramping techniques are, by far, the most widely supported method of moving the blocks up Egyptian pyramid superstructures, due to archaeological inferences that suggest that ramps were used during pyramid construction. Some ramps have been found in situ of pyramid complexes, which leave little doubt that they were used as a method to move blocks up the superstructure (Lehner 1997: 217).

There is a considerable amount of discrepancy regarding what type of ramp was used to build the pyramids. The archaeological record gives evidence of only small ramps and inclined causeways, not something that could have been used to construct even a majority of the monument. To add to this uncertainty, there is considerable evidence demonstrating that non standardized or ad hoc construction methods were used in pyramid construction (Arnold 1991: 98, Lehner 1997: 223). These factors in combination with the variable distance and location of the quarries in relation to the pyramids have lent themselves to an array of ramp hypotheses, that can be readily classified into straight ramps, spiraling ramps, and methods employing the use of the smooth pyramid face as a ramp.

Straight Ramp Methods

The Large, Straight Ramp

The earliest and most widely refuted ramp is the single, large, straight ramp (Arnold 1991: 99). The construction of such a ramp would have been an enormous construction project in its own right. Each time the ramp needed to be modified for more height, the ramp would have to be lengthened and extended on the sides to support the weight. The large straight ramp presents other problems as well. To use the familiar example of Khufu's pyramid, a straight-on ramp with a ten to one incline would extend past the quarry site.

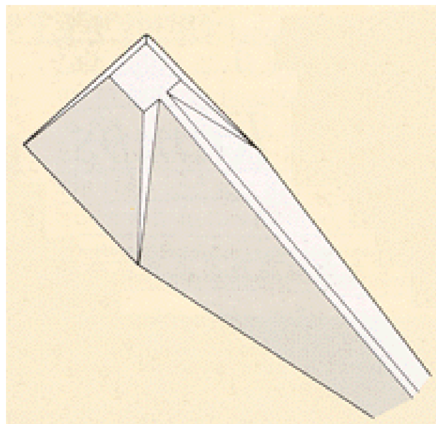


Figure 4-1. Large, straight ramp. (Lehner 1997: 216)

The construction material used on such a ramp would present its own limitations. Sand has a more acute angle of repose than that of the pyramids; therefore, the ramp would have to be very wide. A wide ramp would have covered up two of the pyramid's corners, eliminating the use of those corners for backsighting[1], or, sighting up the pyramid to ensure accurate construction (Lehner 1997: 215). A large, straight, sand ramp would dwarf the pyramid, and cover much of the Giza plateau (Isler 2001: 213).

Of course, the structure could be much narrower if walls were used to contain the sand, or if the entire ramp was made from another material. The Egyptians did not employ burnt brick until the Roman times (Isler 2001: 213), instead using mud bricks for earlier projects. However, mud brick has a number of problems that eliminate its use in the construction of a large straight ramp. The maximum height a mud brick ramp under

[1] Backsighting is the act of visually measuring that the superstructure's slope is correct and that the faces are straight. An indication to the importance of backsighting is the slight twist at the top of Khafre's pyramid.

no load could attain before crushing under its own weight is approximately 380 feet (Isler 2001:213). Additionally, the weight of the stone transported on the ramp adds to this problem (Isler 2001: 213). If the construction material were waste limestone chips, water, and tafla, a claylike desert substance that forms a hard concretion when mixed with water, each limestone block would have to produce about eight times its volume in waste chips (Isler 2001: 213). This point of waste material is important in Isler's critiques' because he feels that there was not sufficient waste material available from quarrying and shaping the pyramid stones to construct such ramps.

While such a thin ramp would have other benefits, such as allowing the exposed corners to be used for backsighting, ensuring against a crooked or twisted superstructure, it is uncertain whether a narrow ramp would be able provide access to the highest portions of the pyramid. These problems have led to the creation of other hypotheses that serve to alleviate the previously mentioned problems of the large straight ramp.

Straight, Zigzagging Ramps

One of the alternate hypotheses to the large, straight ramp method has the ramp moving up on one face of the pyramid in a zigzag motion from one corner to the other. In other words, it rests along the side of the pyramid as an accretion, much like the internal infrastructure of the step pyramids and the earliest true pyramids. While the ramp serves to reduce the construction material presented in the large straight ramp technique, it shares some of its flaws. Miroslav Verner and Martin Isler argue that such a ramp would be unable to complete the entire structure (Isler 2001: 213). With every increase in height, the entire ramp needs to be amended to meet the new elevation (Isler 2001: 200). Since one entire side is enveloped by a large ramp accretion, not all four corners are accessible for backsighting.

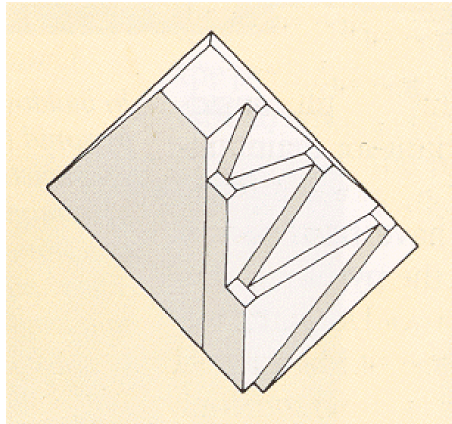


Figure 4-2. Straight, zigzagging ramp (Lehner 1997: 216).

Moreover, the zigzagging ramp cannot reach the apex of the pyramid without modification. If the angle of ascent of each zigzagging, or reversing, slope is maintained, then each ramp will progressively reach lower vertical distances due to the decreased distance allowed by the reduced horizontal space of the triangular shaped pyramid face. In other words, if the angles of the zigzagging ramp remain the same, then the decreasing horizontal space offered by the face the pyramid reduce the upward distance of the ramp. To make such a model work would require ramps of increasing angles of ascent and staircase ramps (Arnold: 1991: 100) at the top of the superstructure.

Archaeological evidence in some pyramids seems to point away straight, zigzagging ramps. Some monuments, such as the early stepped pyramids, seem ideal for ramps of this sort: there are three archaeological examples – at Saqqara, Sinki, and Medium – where stepped pyramids show remains of linear and not zigzagging ramps (Arnold 1991: 101). When making this point, it is important to recall evidence of ad-hoc construction techniques in the construction of the pyramids. Nonetheless, ramps of this variety are unable to complete the top of the pyramid, thus requiring an alternate method.

Straight Ramp Utilizing Part of the Incomplete Superstructure.

Dieter Arnold proposes a method very similar to the large straight ramp, which utilizes part of the growing superstructure as part of the ramp itself. In other words, the ramp, while straight, cuts into the monument and continues through the interior of the pyramid. Dieter Arnold admittedly points out the flaws with this system. The large amount of material left uncompleted trenches in the superstructure. These trenches would have disturbed the proper building of the pyramid interior (Arnold 1991: 101). Arnold does buttress his argument by pointing out possible construction gaps, which possibly could originate from interior ramps, in the core masonry of Sahura, Niuserra, Neferikara, and Pepy II (Arnold 1991: 101). This model, while efficient, is an incomplete technique due to its inability to complete the superstructure. Arnold makes clear that there would be only a minor amount of material left unreachable with this method and points out that the remainder could be constructed with exterior ramps and levers on staircase ramps (Arnold 1991: 100-101).

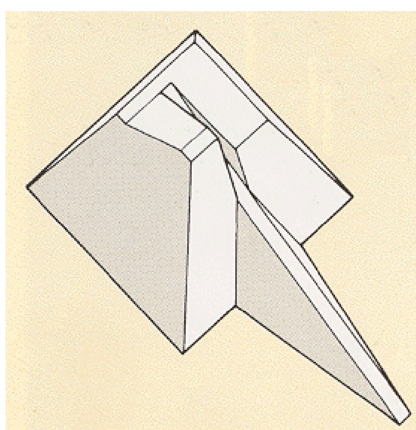


Figure 4-3. Straight ramp utilizing the incomplete superstructure (Lehner 1997: 216).

Spiraling Ramp Methods

Spiraling Ramps Fully Supported by the Superstructure.

The spiraling ramp hypotheses arose out of a need to address the problems found in the large, straight ramping method. Dows Dunham and W. Vose, both American researchers, devised an idea involving a ramp that spirals up at a 10 percent grade around the entire superstructure (Isler 2001: 215, Lehner 1997: 215). They can consist of one or as many as four individual ramps spiraling up the pyramid, and the design presents certain benefits. It can be constructed with less material than the large straight ramp. It would leave corners visible to back sight and would allow control over the slope of the superstructure (Lehner 1997: 215).

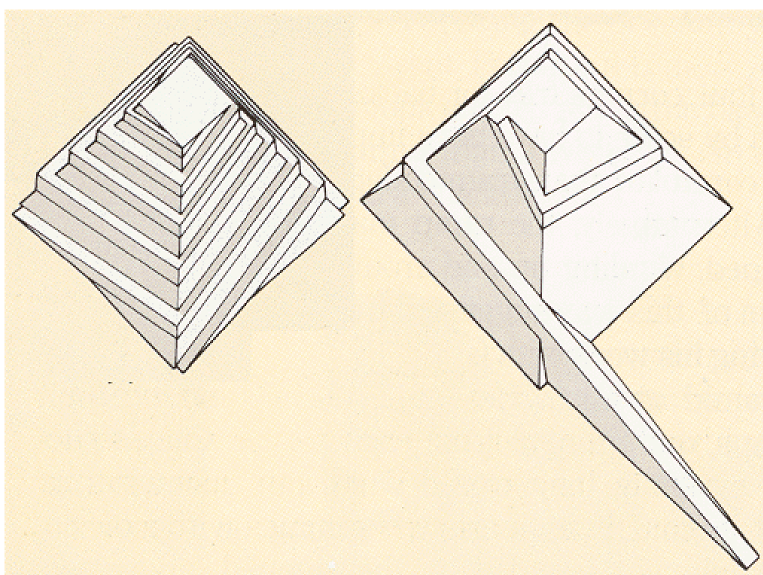


Figure 4-4. Spralling ramp fully supported by the superstructure (Lehner 1997: 216).

However, there are problems with this technique. This ramp, like the large straight ramp, is also unable to complete the critical top portion of the pyramid. It runs out of space at the top for reasons of converging pyramid faces and overlapping ramps (Isler 2001: 215-216). Dunham's spiraling ramp works under the supposition that the ramps would sit on unfinished casing stones, which would resemble steps (Isler 1985: 131).

Ramps of this nature require a stepped surface to allow the spiraling ramp to cling to the surface. Evidence at Menkaure's pyramid shows that the unfinished casing stones, with their handling bosses[2] intact, were not step-like, and could not have supported such a ramp (Lehner 1997: 215).

Spiraling Ramp Leaning on the Superstructure as a Large Accretion

Another spiraling ramp technique serves to solve the problems of a lack of a stepped surface for support. This ramp design, which is supported by Mark Lehner, would lean upon the pyramid superstructure as a large accretion. This accretion does not require the pyramid surface to be stepped, instead only requiring some of the casing blocks to provide support. A ramp of similar dimensions is described in the papyrus Anastasi of the late New Kingdom (Lehner 1997: 216).

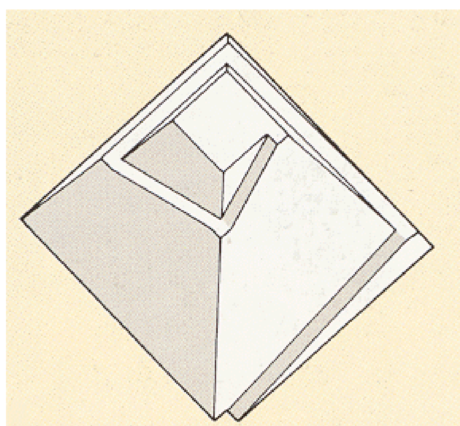


Figure 4-5. Spiraling ramp leaning on the pyramid superstructure as a large accretion (Lehner 1997: 216).

One of the more glaring issues criticizing this technique is the often repeated issue of the ramp cloaking the pyramid face, making the growing superstructure unavailable for backsighting. Mark Lehner challenges this notion by determining that the Egyptians

[2] Handling bosses are small, bulging faces or bulky knobs, protruding from the dressed or undressed surface. In some instances, bosses are thought of as unfinished or undressed. In instances where the handling bosses are still visible on a dressed surface indicates that the bosses remained there to be used for lifting the block (Arnold 1991: 135). For more information, read Arnold 1991 – pp. 131-141.

were “already, in effect, cloaking the pyramid by leaving an extra sock of material on every casing stone they set” and then determines that “sighting back to already laid masonry cannot have been a significant way of controlling the rising pyramid” (Lehner 1997: 216). However, there is a considerable difference between the cloaking effect of handling bosses and extra material on casing stones and an enormous spiraling accretion completely enveloping the superstructure.

General Critiques of Ramp Methods

While there are problems specific to various ramping hypotheses, there are also shared limitations. These common problems involve issues of pyramid cloaking, the archaeological record, and the ability of the temporary ramp structure to endure the elements. The authors claiming that the superstructure was constructed through outward and upward in layers, starting with the core and ending with the facing stones poses an interesting and, yet, damaging circumstance regarding the construction and efficiency of ramps.

More often than not, problems with back sighting and cloaking are used to question the feasibility of a ramping technique. It is difficult to establish a good critique using this form of argument and its foundations are often conjectural due to the problems inherent in quantifying what type of backsighting was needed, if any, by the ancient Egyptian pyramid builders.

Like the Greek historical accounts from Herodotus and Diodorus Siculus, the archaeological record also is a source of ambiguity. The remains of the ramps found within the pyramid complexes are small. The roads vary in size and distance from the monuments. Yet academics use the same remains to support opposing hypotheses. For example, while the remains at Medium, Lisht, and Senwosret have been used by ramp theorists to illustrate in situ roads and shallow ramps leading directly to the pyramid superstructure, Isler (1987: 96, 2001: 215) uses the same information, from Maragioglio and Rinaldi, to illustrate the use of short ramps and inclined roads.

Martin Isler, a proponent of several levering hypotheses, brings up another very significant point regarding the effect of rain on temporary ramps. Rain, though infrequent, does occur in sporadic torrential downpours, which could cause significant damage to a ramp made from mud-brick (Isler 1985: 130). Architects of Middle Kingdom pyramids took precautions from these periodic deluges in the construction of the broad, flat roofs on the pyramid temples (Bell 1975: 247-248).

What is the effect of rain on these ramps, which may be easily broken apart? Lehner discusses the construction of ramps with materials that can easily break up into its constituent parts. What is the effect of these sporadic deluges on limestone chip, tafla, and gypsum ramps, since, as Lehner describes, these structures could be easily disintegrated into its constituent parts when struck by a pick (Lehner 1997: 217)?

This easy disintegration could account for the diminutive archaeological examples and the complete absence of a ramp at the unfinished pyramid of Zedefra. Since in many ramp hypotheses, the ramps would be built in layers, it can be inferred that the archaeological evidence of some short ramps could be remnants of these shorter layers. In other words, some of the archaeological examples of roadways are very close to the pyramid superstructure. Surely, these roads would have been built close while the pyramid was in its earliest phases of construction, and then raised and lengthened with each successive tier. Using these examples to disprove ramp hypotheses can lead to ambiguous conclusions.

Isler and Pierre Crozet make the argument that the pyramid was constructed through successive stages of constructing an interior and building outward and upward. Isler presents the concept that the inner step pyramid was first completed, and then the external blocks and casing stones were added in succeeding stages, which would enable the pyramid builders to accurately control the angles of the superstructure (Isler 1987, 2001). Crozat introduces an idea that a complex algorithm was employed with the construction of the pyramid superstructure, which supports both Herodotus' account of pyramid building and the idea that the construction of the superstructure's interior preceded the construction of the exterior (Crozat 1997, 2002). These ideas of pyramid construction add tremendous amounts of labor to the construction of ramps. Under this type of construction, a ramp or ramps would have to be built to construct each stage, adding much more labor to the construction effort. Both of these authors present separate levering hypotheses as more efficient methods for this type of pyramid construction.

Techniques Utilizing the Finished Pyramid Face as a Ramp

There are those who dismiss the hypotheses that involve the construction of a ramp and levering hypotheses outright on models of efficiency, and propose that the smooth, angled surface of the pyramid was used as a working surface on which the blocks could slide up the superstructure. While ramping theorists claim that a gradient of 10-to-1 was necessary to safely and efficiently slide the blocks up the superstructure, the authors presenting methods of sliding up the superstructure claim that it is possible to both efficiently lift and safely control blocks when pulled up the steep gradient of the pyramid face.

Olaf Tellefson

Olaf Tellefson's method of lifting the blocks came with observing a modern *shadoof*[3]. During one of his visits to Egypt, Tellefson viewed a *shadoof,* or a counterweighted lever used in agriculture to lift water from low sources to high irrigation canals, and surmised that one of these lifting devices could be used in combination with a method of sliding the blocks up the angled face of the pyramid. With the ethnographic observation of a present day weighted lever used to put the weight on rollers, Tellefson concluded, "with the weight arm, greased skids (up the pyramid) suggest themselves" (Tellefson 1970: 16). In other words, the lever is used to move the block onto rollers. The block is then transported up the pyramid superstructure by way of a lubricated wooden track. At the top of the uncompleted structure, the block would then be moved off the tracks by another counterweighted lever onto rollers. Tellefson also provides a separate device, a double weight arm, for use in tight places unreachable by the sliding method. One arm is used for vertical movement and one for lateral movement.

His article is unabashedly limited in its exploration of Egyptian materials, culture, and technology. Admittedly, Tellefson is providing an article to stimulate debate rather than to provide experimental data. The sand that is blowing around the desert can easily stick to the greased surfaces, dramatically increasing the friction produced by these lubricated surfaces. Furthermore, as stated above (pp 17), there is significant evidence that the external casing stones remained unfinished. Though this last piece of evidence is not damning, it is possible that a track or section of the pyramid face was smoothed for this operation; the design could be best served by an experimental test.

---

[3] Alternate spellings are shaduf, shadouf, and chaduf.

James Frederick Edwards

Three decades later, James Frederick Edwards proposed a modified version of this design. His method has the blocks moving up the inclined face of the pyramid via sleds pulled by ropes (Edwards 2003: 347-348). The sleds would be lubricated by water and may or may not ride on a lattice like track up the superstructure (Edwards 2003: 348-349). While he does not test his method through experiment, he attempts to bolster his argument by briefly addressing issues of the force and the friction exerted when moving a sledge mounted 2.5-ton stone block up a 52-degree incline of the pyramid face.

To provide a justification for the sliding method, he briefly mentions the recurring functional and limited archaeological critiques of the ramp techniques, and he provides some functional critiques of the levering method. His criticisms of the levering techniques are based on both limited examples from known experiments and speculative critiques of Richard Koslow's levering design. The first critique describes Isler's and Peter Hodges, both proponents of an incremental levering technique of utilizing levers to jack up the block with levers, while wooden boards slid under the raised side of the block eventually elevate the block to the next tier. The criticisms regarding safety and time partly corroborates with the experiment conducted by Isler in the video, *This Old Pyramid,* by Nova. However, when Edwards criticized this technique on the issue of time, he does not account for Isler's mention that multiple jacking teams could operate on each tier.

Edwards' critiques of the Shadoof method are not based on experimental data. Instead, he cites Richard Koslow's web site, "How the Egyptians Built the Pyramids[4]." He criticizes this method as requiring "the construction of substantial wooden towers in

---

[4] www.egyptspyramids.com/html/article.html. Last visited on 12/05/04

order to withstand the forces involved" (Edwards 2003: 342). Koslow's method does involve the construction of a very large wooden device, and there is no mention in either Edwards' or Koslow's article regarding actual experiments testing the loads and stresses on such a device. There are other shadoof-based hypotheses of pyramid construction, and it is curious why Edwards does not discuss these methods. By not mentioning these other hypotheses, he arrives at the fallacious conclusion that a large wooden structure is required for any method utilizing the shadoof as a model.

Edwards also fails to address some issues concerning the finished face of the pyramid superstructure. Edwards, like Tellefson, does not mention the evidence that an extra sock material was left on the casing stones, thereby leaving the work of dressing these stones as the last portion of pyramid construction. Moreover, there is no effort to support this method through wear analysis at the pyramids. If all the material were dragged up the finished angled exterior blocks, there may be some wear from dragging the blocks. An occasional mishap where some of the blocks on just one pyramid, from the approximately 90 Egyptian pyramids, could slide off the lubricated wooden track and scar the surface of the casing blocks. Though many of the Egyptian pyramids are currently in no condition for an examination of the casing stones, there are still some that are intact. In the Great Pyramid alone, there are approximately 2,300,000 blocks of stone (Lehner 1997: 108), and therefore, millions of chances for a mistake on just 1 pyramid. Khafre's pyramid, which is slightly smaller than Khufu's, has many more casing stones left on the structure and might be a good place to examine for such wear.

These sliding hypotheses share a major critical flaw found frequently within ideas about moving the blocks up the pyramid superstructure: the lack of experimental testing.

The literature is, unfortunately, full of untested assumptions that appeal to "common sense" or have impressive diagrams and mathematical figures to give weight to a certain method. Sometimes these diagrams are just incorrect, such as J.P. Lepre's demonstration of mechanical advantage showing incorrect weights (Lepre 1990: 256). Sometimes these drawings create compelling arguments on paper that fail during an experimental test due to the occurrence of unforeseen variables and conditions, such as Isler's application of his levering model[5] on the Nova experiment.

The importance on a carefully designed experiment to support a method cannot be overstressed. Without a proper experimental test, it is easy to make the very common scientific mistake of assuming inferences due to the complexities of the natural world vis-à-vis argumentation on paper. In other words, it is easy for a model to look good on paper, and easier still for that model to run into unforeseen problems once it is tested experimentally.

Indeed, the problems of experimental testing are not localized to Edwards' and Tellefson's models, but to all discussed within this thesis. More importantly, obvious difficulties arise when attempting to even model a combined ramp and lever method of moving blocks up the pyramid when there are no viable levering designs to choose from. The demonstration of a practical and functional levering device, which is comprised of culturally and temporally concomitant technologies and materials can advance the amalgamated ramp and levering concept.

---

[5] Pp. 40-42 of this thesis.

CHAPTER 5
EVIDENCE FOR THE USE OF LEVERS

Unlike ramp hypotheses, levering hypotheses for moving the Egyptian pyramid blocks up the superstructure do not have in situ examples. Moreover, there are no Old or Middle Kingdom Egyptian documents describing the use of levering. Therefore, much of the evidence shared by proponents of the levering devices are weak inferences suggesting the use of these tools. The earliest historical accounts of a lifting device come from Herodotus's vague description of a lifting machine used for the construction of the Great Pyramid. There are no direct archaeological examples, and the closest ethnographic device comes from the shadoof. The design of a levering method for the construction of the Egyptian pyramids, then, utilize a broad scope of loose inferences for the use of levers as well as the exploration of related concomitant materials and technologies. These loose inferences contribute to the wide variety of levering hypotheses.

Figure 5-1. Timber conversion from the 5th dynasty (Clarke and Engelbach 1990: 37).

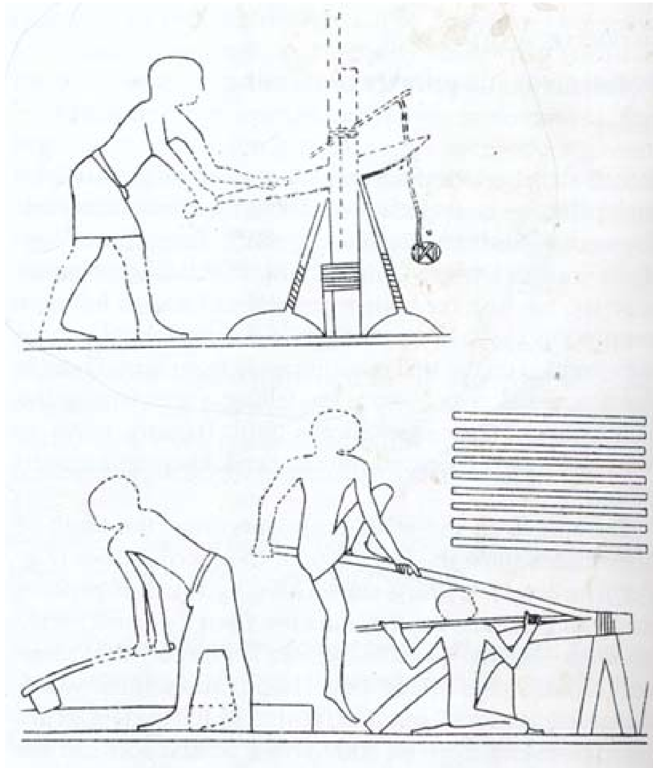


Figure 5-2. Scene in the Sixth-Dynasty tomb of Iteti at Deshasha showing craftsmen cleaving a tree trunk and other conversion processes (Gale et al. 2000. pp. 354).

The use of levers to pry, move horizontally, shift, and turn over stones was quite common in ancient Egypt (Arnold 1991: 287). Old Kingdom depictions of wood processing shows a lever operating to convert rough timber into lumber. Though wooden examples are scarce and difficult to determine, there are a few metallic examples found (Arnold 1991: 270).

Difficulties Locating Wooden Levers in the Archaeological Record

Wooden levers are difficult to locate archaeologically. Though Egypt is unique in its environmental preservation of wood (Meiggs 1982: 59), there are other problems associated with the location and preservation of such pieces of wood. It can be difficult to determine the function of these levers, when discovered within an archaeological context, as they could be confused for beams (Arnold 1991: 270). These levers can be, relative to large ramps, much easier to move from their positions near monuments.

Moreover, workers could have easily reused these timbers. There is documentation pointing to the value placed on such large timbers. For instance, the elite distributed large pieces of imported timbers to laborers working on these monuments. A papyrus records Thutmosis III issuing 'ash' and 'meru'[1], wood imported from Lebanon, to laborers for personal use (Meyers 1997: 347-349).

In addition to the value placed on large beams by the ancient Egyptians, there is evidence of the recycling of wood, which would also impede our location of such lifting devices. In one instance, the practice of recycling wood accelerated during Egypt's political and military weakness at the end of the 20th dynasty, when Egypt was unable to secure shipments of timber from Lebanon.

Evidence for Levers within Monument Stones

The large number of projecting bosses left on Egyptian monument stones indicates the use of levers. Projecting bosses used presumably for the lifting of blocks as well as levering sockets, adorn many of the stones in the pyramids and other monuments were most likely used for prying and for side adjustments in moving blocks into their final position on a monument (Arnold 1991: 135, 202-203, 270-271, Clarke and Engelbach 1990: 86, Lepre 1990: 248, 250, Isler 2001: 216-218). Quite a few sockets and notches can be seen on the sides, bottom, and top of a number pyramid casing stones and within other monuments, such as Mycerinus, Chephren's valley temple, Karnak-Nord III, Winlock, Hibis, Karnak Nord IV, (Arnold 1991: 270-271, Lehner 1997: 206, 209, Isler

---

[1] The exact types of wood described by the terms *ash* and *meru* are under dispute. For more information regarding these terms, please read Meiggs 1982 – appendix 2.

2001: 289). In the 90-ton pedestal of the colossus of Amenhotep III, large sockets point to the use of 20 x 30-cm thick levers to move the massive stone (Arnold 1991: 270).

The Shadoof

Some authors regard the shadoof as a plausible link to the use of such levering devices. The shadoof (Fig 9[2]), a counterweighted lever used to lift water to elevated irrigation systems was first depicted in Egypt within the context of an 18th dynasty tomb (Arnold 1991: 71, Lepre 1990: 255, Murray 2000: 515). Ethnographic observations of this device at work in modern Egypt led some authors to speculate that this levering device could serve as a historical and ethnographic example of a levering device connected to the erection of Ancient Egyptian monuments (Arnold: 1991: 71, Lepre 1991: 255-256, Tellefson 1970). Indeed, the first depiction of artificial irrigation comes from the 'Scorpion Macehead' (3200 BC) which depicts the ceremonial digging of a canal (Murray 2000: 515). The large separation of time between the onset of artificial irrigation in Egypt and the first Egyptian depiction of the shadoof, a simple and easily constructed tool used to facilitate filling irrigation canals, is peculiar. Could it be possible that such a tool that could be easily constructed by a few people for, and would magnify the labor potential of, the seasonal farmer, could have escaped the bureaucracy, writings, and depictions constructed by the elite and have been present during the Old Kingdom?

There are no strong arguments to place the shadoof within the Old Kingdom. While there are Middle Kingdom terms directly related to two types of land in relation to irrigation, low-lying and high-lying, there is no mention of canals for irrigation purposes within the various textual sources from the Old Kingdom; nor is there evidence directly

[2] This illustration of the shadoof and its operation in tiers comes from Lepre 1990: 255.

related to the bureaucracy of irrigation in the more than 2,000 administrative titles known from the period (Murray 2000: 515).

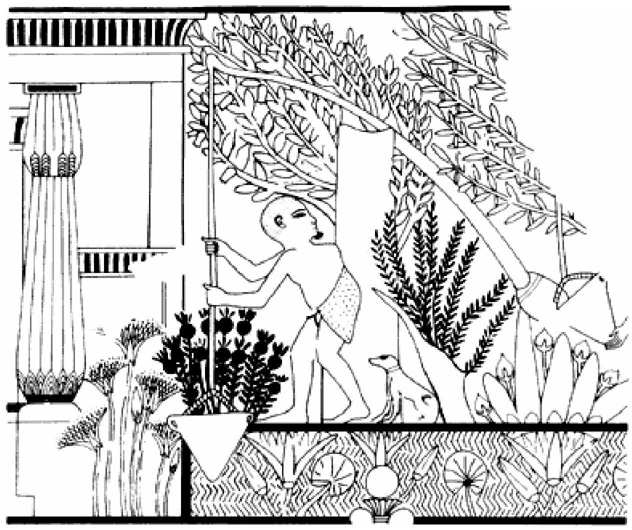


Figure 5-3. Shadoof found within the Theban tomb 18th dynasty tomb of Ipui (Arnold 1991: 71).

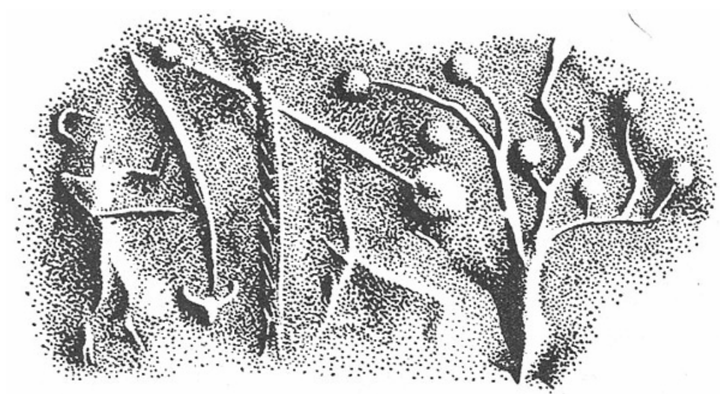


Figure 5-4. Mesopotamian Shadoof cylinder seal dating to the 3rd millennium B.C (Janick: 2002 and in Delaporte 1920: Vol. II, Pl. 72, A 156)

However, evidence from cylinder seals that place the shadoof in Mesopotamia circa the 3rd millennium B.C. (Salonen 1968, Postgate 1992: 177) establish the lifting device inside a time and culture with known connections that predate Old Kingdom Ancient Egypt. Similarly, the Harappan civilization, a trading partner with Sumer, also have third millennium BCE depictions of the shadoof (Leshnik 1968: 917).

Admittedly, there is no evidence to place the shadoof in the Egypt during the Old Kingdom. Nevertheless, there is evidence of this levering device within a culture with significant contact with Old Kingdom Egypt. Mesopotamian influence in Pre- and Protodynastic Egypt are found within Mesopotamian cylinder seals of the Jemdet Nasr period, recessed brick-building, Mesopotamian objects depicted on Egyptian monuments, and Mesopotamian motifs depicted in Egyptian art and tools (Frankfort 1941: 334-358).

Drawing parallels between Egypt and Mesopotamian shadoofs may help serve to illuminate the possible lack of representation within administrative titles. Mesopotamian shadoofs are underrepresented in the administrative texts because the operation of such devices requires no communal organization (Postgate 1992: 318). The lack of Egyptian bureaucratic and pictorial evidence for the shadoof could possibly reflect Mesopotamia's scant representation in administrative texts due to the small amount of labor needed to employ this device.

Of course, since there is no strong evidence placing the shadoof within the Old or Middle Kingdom in Egypt, the discussion of whether this levering device could serve as a model for a method of pyramid construction becomes disputable. Nonetheless, many people proposing hypotheses of pyramid construction look to the shadoof as a historical and ethnographic connection to a possible lifting device via indirect evidence.

Nubian Pyramids and Levers

The approximately 180 pyramids of Nubia serve as another link between levers and ancient Egyptian pyramid construction. Nubia and Egypt have a long history of interaction. Pharaonic Egypt dominated Nubia for more than a millennium. However, issues arise when making direct connection between the Nubian and Egyptian pyramids. The Nubians began constructing their first pyramids more than 8 centuries after the last

Egyptian Pyramid. The Nubian pyramids, have much steeper angles (68-77 degrees) than the pyramids created in Egypt. They also differ in their internal construction and in their block sizes. Nubian pyramids are constructed with a core of rubble with exterior blocks only two layers thick (Brier 2002: 57-58). Friedrich Hinkel suggests that the actual models of the Nubian pyramids were after the small pointy pyramids private people built above their homes (Brier: 2002). For these reasons, it is likely that, although the Nubian pyramids may not have been directly modeled after the Egyptian Pyramids, their influence is probable. Hinkel (Brier: 2002) also makes the point that some of these differences in the superstructure derive from differing construction methods.

Hinkel proposes that a shadoof-like levering device was used to construct these pyramids. He found the base of one still imbedded within the top of one of these pyramids. The lifting device with these pyramids is attached to the top of a pile of rubble where it would lift the exterior blocks into position. The centrally located shadoof helps to explain the steep angle of the Nubian pyramids. With the shadoof in this location "it is extremely difficult to place blocks far from where the shadoof is anchored (Brier 2002: 58). The connections between Egyptian and Nubian pyramids, however tenuous, do stem from a deep history of contact and subjugation. The possibility that the Nubians employed a known method of Egyptian pyramid construction to their pyramids is persuasive, or certainly possible.

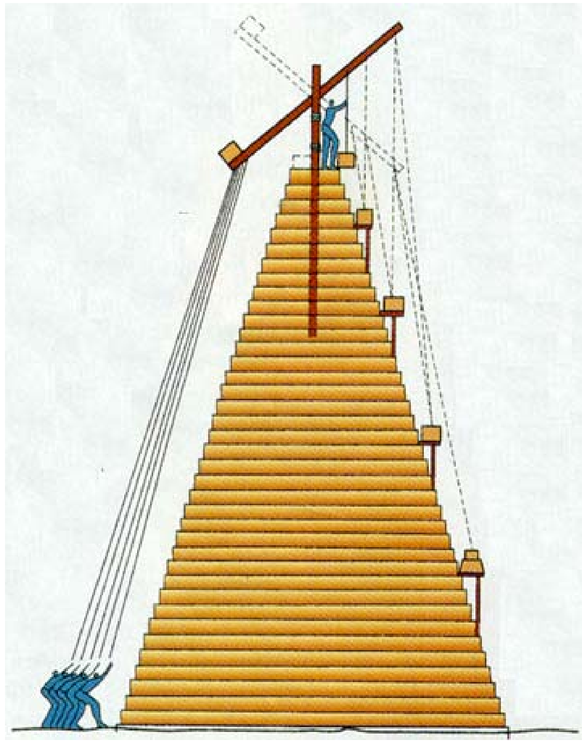


Figure 5-5. Friedrich Hinkel's proposal of Nubian pyramid construction (Brier 2002: 56).

While there are representations and archaeological examples of levers in Old Kingdom Egypt, there are no direct inferences placing a levering device that can move large weights vertically within Old Kingdom Egypt. There is evidence for such a device, the shadoof, during the 3rd millennium B.C. within Sumer, a major trading partner of Egypt. The Shadoof is also known to have diffused out of Sumer to one of its Eastern trading partners: the Harrappans. There is also evidence that the Nubians used shadoof-like levers to construct their pyramids, which were influenced by the Egyptian pyramids. Though there is no direct evidence for levering devices used in the construction of the Egyptian pyramids, there is a considerable amount of indirect inferences.

CHAPTER 6
LEVERING DEVICES

Much like ramp methods, levering devices are varied due to a lack of historical and archaeological evidence. There is a myriad of indirect evidence pointing to the use of levers, starting with Herodotus and ending with recent archaeological discoveries involving the possibility that levers were used to move blocks up the pyramid superstructure. The lack of any direct archaeological or historical examples contributes to a lack of solid explanatory models of levering devices used within this context. Invariably what seems to drive hypotheses of this genre are reasons less grounded in history and archaeology, and more with issues of function and efficiency. While ramps remain the most acceptable, yet incomplete method, levering hypotheses remain the most tenable method of completing the pyramid at the highest levels. Mark Lehner, encapsulates this sentiment by saying, “It is possible that despite all its attendant difficulties, levering was the best option for completing [the top 3percent by volume] of the pyramid” (Lehner 1997: 222).

While 3 percent of the pyramid superstructure is a small portion of the volume, this small percentage constitutes a deceivingly large amount of vertical distance. To put this small volume of the pyramid in perspective, no more than 4 percent of the volume of the pyramid constitutes the top third of the superstructure (Edwards 1985: 254). In the case of Khafre’s pyramid, the upper 3 percent by volume consists of the mass of the pyramid spanning the upper 46.5 meters (152 ft 6 in) of the superstructure (Lehner 1997: 222).

While ramps are unable to complete a small percentage of the pyramid, a levering device requires work on a considerable number of tiers to lift this small amount of material.

Lehner (1997) succinctly summarizes the approach held by many Egyptologists that are forced to revert to models of efficiency in order to address the incomplete inferences and unfinished hypotheses for the construction of the pyramids. While to use models of efficiency and functionality to determine the credibility of a ramp or lever method is somewhat frustrating to many historians and archaeologists who understand that, historically, technologies are not always selected on mere principles of functionality and economy, it remains a major issue regarding all methods of pyramid construction due to the lack of historical and archaeological data. This approach of functionality has also helped attract people with engineering and architectural backgrounds, as well as many amateurs to provide hypotheses for pyramid construction. Curiously, despite the weight given to efficiency and functionality, there has been much more argumentation on paper and much less experimental archaeology.

There are two basic types of levering hypotheses. The first type involves small incremental movements upward from one movement to the next. The second type utilizes a lever that performs either the vertical or vertical and horizontal movement of the block up one tier. Testing projects at or near full scale more often than not reveals issues overlooked when drafting the design on paper. Since most of the critiques of the levering method seem to come from issues of practicality, an experimental archaeological examination at this scale would at least be able to assuage criticisms of a functional nature. Furthermore, experimental tests would allow the issues and problems to be resolved in the effort to design an elegant, safe, and efficient working design.

Incremental Levering Methods

Hypotheses using levering motions to perform small incremental vertical movements involve lifting one, or both sides of the block, then the insertion of a wooden plank or stone under the raised side to maintain the new vertical position. The process is repeated on alternating sides to gain elevation. The wooden or stone cribbing under the block continues to rise with each jacking movement until the block has reached the appropriate elevation to then be moved off onto the next tier.

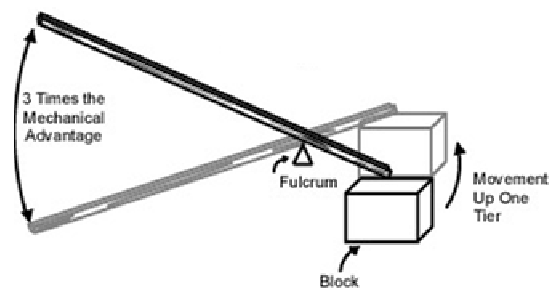


Figure 6-1. Levering methods using one large movement to lift the block up one tier.

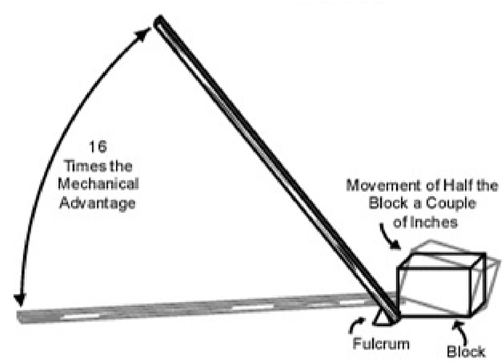


Figure 6-2. Incremental levering methods.

Hypotheses of this type enjoy certain advantages over the hypotheses utilizing one large vertical or vertical and horizontal movement. The strength of the beam is utilized in a much more efficient manner compared to incremental levering hypotheses, since the distance between the fulcrum and its contact with the block are so much shorter, there is much more mechanical advantage and much less force required to move the block vertically, given levers of equal size (Figures 6-1 and 6-2). The levers are usually smaller than those used in hypotheses utilizing one large levering motion. The close distance between the block and fulcrum as well as the reduced lever thickness increases the shearing stresses of the wooden levers, a strength wooden beams have in excess. The result is a much more efficient use of the mechanical properties of strength for the lever. Moreover, hypotheses of this ilk have more large-scale experiments in comparison to the large lever method. Hodges, Keable, and Isler all have performed large-scale tests on this method of lifting pyramid blocks.

However, there remain broad problems with this method of levering. With this method, you need at least a working space on a staircase ramp equal to the size of the block you intend to use. Since block sizes vary within the pyramids, the working space on the staircase ramp must equal the largest block one intends to lift. The workspace required would necessitate a more obtuse rise over run over than the superstructure. To address this issue, the staircase ramp would need to employ one of the various methods of ramping addressed earlier in this paper. In employing these ramping hypotheses, this method inherits their problems, namely issues of reduced space at the top.

There are methods of circumventing this problem of workspace and diminishing workspace due to the angle of ascent. Isler (2001) presents a method, discussed below, of creating a temporary increased work area made from masonry to lift the large burial chamber blocks. In Khufu's pyramid, there are 56 chamber blocks weighing approximately 50 tons each (Isler 2001: 255). This temporary workspace would need to increase with each tier of elevation, and then need to be removed for the movement of the following blocks below the one supported by the masonry structure, involving a labor intensive process of constructing and dismantling stairways to move these blocks. This labor-intensive remedy is not a tested portion of these hypotheses.

John Fitchen (1978) provides an alternate method of adapting the workspace to follow the the pyramid superstructure angle of ascent. He discusses a method, first presented by W. M. Flinders Petrie (Petrie 1923: 75-76) and Auguste Chiosy[1] of using rockers, or small crescent shaped wooden devices found as small models within New Kingdom archaeological contexts. These small rockers are interpreted by these authors as a possible model for a larger device that could have been used to move the blocks up the pyramid superstructure, despite the fact that their function is unknown and that these devices have not been found within Old or Middle Kingdom contexts. In Fitchen's article, rockers would let the block rock from side to side, allowing wooden shims to be placed on the raised side. The other side of the block would then rock back, and raise the opposite side, thus moving the block vertically. In his 1978 article, he illustrates his method of allowing for workspace and following the angle of ascent of the superstructure by requiring the block to travel two tiers vertically (Fitchen 1978: 9). While this method satisfies the requirements of workspace and angle of ascent, the weakness here is the tall cribbing required for the block to reach this height. Cribbing, and its diminishing stability at increasing heights, presented tremendous problems for Isler[2] in his Nova Experiment even though his experiment was designed to lift up a block only one tier.

John Fitchen proposes an untested, yet clever method of moving the ponderous capstone up the growing superstructure. He suggests that the capstone could have been levered up, one course at a time, from its position in the center of the developing

[1] Choisy, in L'Art *de Batir chez les Egyptiens*, modifies Petrie's method to lift the blocks via a staircase ramp rather than directly on the pyramid superstructure.
[2] See pages 40-42 in this thesis

superstructure (Fitchen 1978: 11 1986: 238-240). That is, the capstone would travel upward, by levering, with the completion of each tier (Fitchen 1978: 11 1986: 238-240). At the last few courses at the top, the casing stones would need to remain stepped, in order to give space for the insertion of casing blocks from all sides of the pyramidion, due to the presence of the timber cribbing from his model (Fitchen 1978: 11 1986: 238).

The Nova Experiment

Isler, in his 1985 and 1987 articles, *On Pyramid Building* and *On Pyramid Building II*, proposed a very compelling and excellently drafted argument whereby a pyramid block is gradually raised from one tier to the next by small levering motions. Two levers occupy opposing sides of the block and lift each side in increments. As one side is lifted, a board is slid under that side. As the process is repeated, the fulcrums also move up incrementally. The block then rests on top of a slowly rising cradle of wood that eventually reaches the height of the next tier. At this point, the block is then pulled onto the next tier by flipping the stone over off the wooden cradle and onto the next tier.

The Nova film, *This Old Pyramid* (Nova 1997), documented the efforts of Mark Lehner, Roger Hopkins, a stonemason from Sudbury, Massachusetts, and Martin Isler to build a small pyramid in the Giza Plateau. In this film, Isler tests his apparatus by lifting up one block; however, the experiment did not go as planned. Isler needed to modify the block in order to facilitate the lifting process in a way not mentioned in the 1985 and 1987 articles. These modifications were two deep notches placed on the bottom of the 2-ton block to be moved. While these notches are not discussed in Isler's 1985 and 1987 articles, they were necessary during the experimental test to make room for the levers. These notches are not found on pyramid core stones (Lehner 1997: 209).

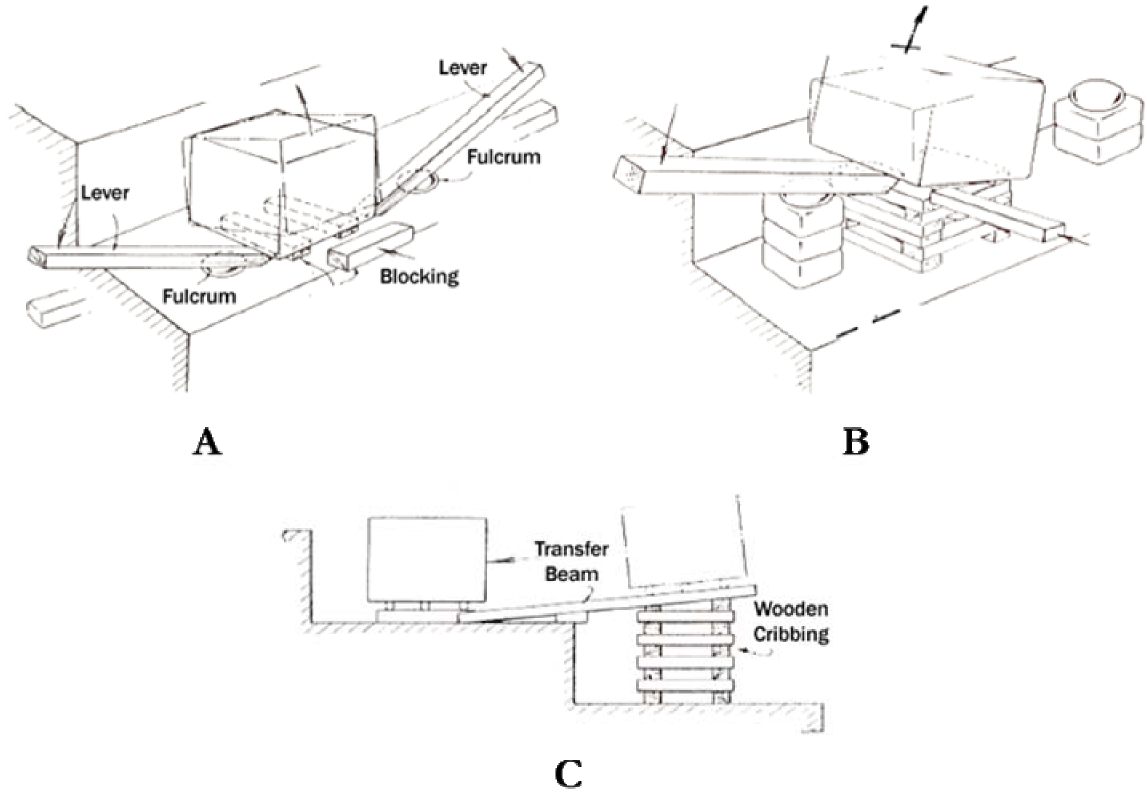


Figure 6-3. Martin Isler's incremental levering method. A) shows the components used in his levering method. B) illustrates the method of raising the fulcrum as the block rises. C) demonstrates the method of transferring the block from one step to another (Isler 1985: 139).

The experiment also took much longer and was much more dangerous than expected. Isler describes the experiment by stating the following: "Although successful at the first try, the inexperienced crew took far too much time – an hour and a half – to make it practical" (Isler 2001: 251-252). While Isler places blame at the inexperience of the crew, Lehner has a completely different opinion regarding the experiment: "More critically, the wooden supports were precarious and unwieldy, in spite of our using planed lumber. Similar difficulties arose with the fulcrum, which had to rise with the load" (Lehner 1997: 209). These problems led both Lehner and Hopkins to surmise during the Nova experiment that levers seemed to be useful only when absolutely necessary.

Peter Hodges' and Julian Keable's Incremental Levering Experiments

In Peter Hodges book, *How the Pyramids Were Built*, Hodges, and Julian Keable, who edited and published Hodges work after his premature death, both perform experimental tests on a similar jacking method. Hodge's tests explored preliminary aspects of his lifting device. Keable took the testing further and assembled a large-scale experiment.

Keable's experimental tests used four oak levers, 100mm at the fulcrum end and tapering to 50 mm at the handle (Hodges 1980: 134). After a few experiments, Keable and others were able to lift a pallet fitted with 1 ton of concrete blocks up a 0.76-meter pit with jacking cycles, with the interval between one jacking operation and the insertion of packing blocks being as fast as 25 seconds (Hodges 1989: 135-136).

It is difficult to determine the reasons for Keable's success and Isler's later failure in face of the fact that Keable's experiment was performed earlier than Isler's was and that Isler was knowledgeable of Keable's experiment. It should be noted that Keable, when attempting to lift a load of 2.5 tons, experienced problems very early in the jacking process of shifting loads, which prevented the completion of this full size experiment (Hodges 1989: 135). Keable also had problems with the pallet supporting the weight of the stones, as the levers crushed into the pallet with the jacking operations under the 2.5-ton load. Some of the different variables between the two experiments were the differences in the load to be lifted, weight, and packing blocks. It is not certain what variables contributed to the problems in Isler's later, more appropriate test from the viewpoint of reproducing ancient Egyptian materials, but some glaring differences stand out.

Since the stability of the cribbing seemed to be the crucial point where Isler's experiment failed, the load upon this foundation as well as the construction of the cribbing must be examined. Indeed, differences in packing material and the success of Keable's experiment vis-à-vis Isler's is briefly mentioned by Keable in his 1992 KMT article. That Keable met with shifting load problems early in the jacking process when attempting to lift a weight of 2.5 tons; he then reduced the weight-to-1 ton is something to consider. While Isler's block resembles a block found on the Great Pyramid superstructure, Keable's pallet with blocks is much lower and wider, contributing to a wider and more stable cribbing base. Keable also used a more stable material for packing blocks. Though Hodges suggested that timber be used for the cribbing, or material to be placed under the pallet during each jacking operation, Keable used the same readily available solid concrete blocks used on the pallet for this material.

Figure 6-4. Martin Isler's cribbing, composed of planed lumber, from the Nova experiment (Lehner 1997: 208).

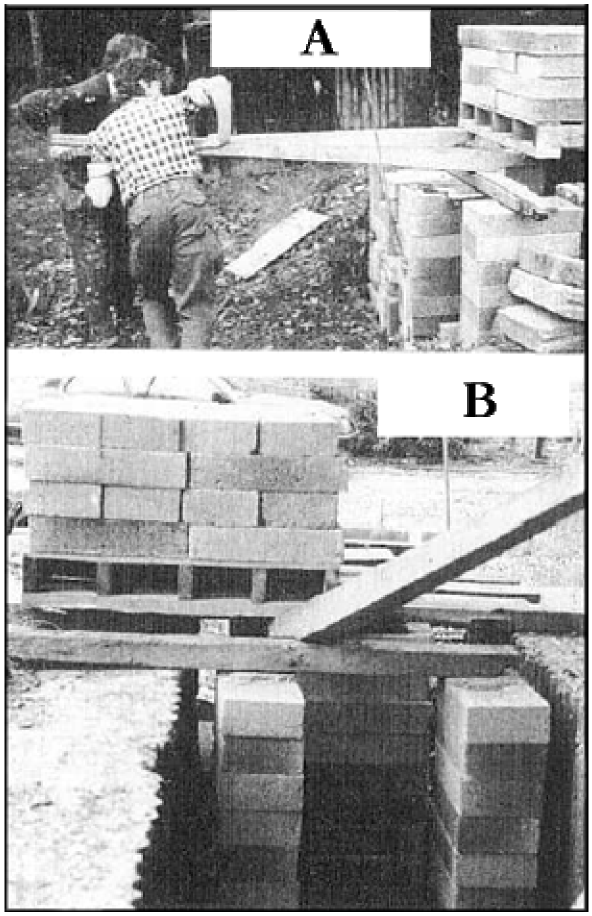


Figure 6-5. Julian Keable's incremental levering method of lifting pyramid blocks[3]. The blocks are substituted for a pallet loaded with 1-ton of concrete blocks. A) Shows the 'paddling' method of method of transferring the pallet from the cribbing to the next tier. B) Reveals the level, uniform concrete blocks used in the experiment. (Hodges 1989: 140)

While these level and uniform blocks provided a much more stable foundation for this lift, there was no effort to discuss the evidence for the large quantity of these small and precise masonry blocks. This quantity would be multiplied by the large amount of jacking operations performed on the superstructure. Another material, such as mud brick, could have been used to reduce the time and effort to construct these precise blocks, but since both experiments experienced problems due to cribbing, the experiment should have attempted to reproduce the packing material as well as the other variables within the

[3] Figures 6-5 A & B are from Hodges 1989: 140

experiment through strong connections to historical or archaeological evidence. This way, the problems found in Isler's Nova experiment, where the materials used in the experiment were much closer to the ones used by the ancient pyramid builders, can be addressed. The problems found with Isler's experiment with the unsafe and unstable wooden cribbing were most likely eliminated in Keable's experiment by a combination of this uniform masonry foundation, a wider cribbing foundation, and a reduced load. Though Lehner and Hopkins attacked Isler's method from issues of speed and safety, the success of Keable's 1-ton experiment warrants another exploration into this design with careful attention paid to reproducing the experiment with materials available to the ancient Egyptians.

Isler's Additional Levering Methods

Isler withdraws somewhat from the levering method shown in the Nova film in his 2001 work, *Sticks, Stones, and Shadows,* where he briefly describes his preceding method and ends his description by stating the following: "This method is presently shown as a supplement to a more efficient delivery system that also makes use of levers" (Isler 2001:252). He is reluctant to accept Lehner's conclusions that the "wooden supports were precarious and unwieldy" (Lehner 1997: 209) and Lehner's and Hopkins' statements in the Nova video regarding the excessive time needed to move one block. Isler maintains, in both the Nova video and his 2001 work, that experience might reduce the time in which the task is accomplished (Isler 2001: 252).

The "more efficient delivery system" to which Isler was referring, are complex additions to his first method of levering the blocks as well as a method of sliding the blocks up the superstructure's angled sides. Isler provides modifications to his first levering design, including new methods to tumble the blocks off the cribbing and to lift the larger 50 ton blocks found within the burial chambers. This incredible amount of weight would be lifted with a number of levers made possible due to the increased workspace allowed by these larger blocks. He suggests that a stone beam weighing 100,000 pounds could have half of its weight supported by ten levers, thereby lifting one side with each lever supporting 5000-pounds of weight, to place cribbing underneath. The great size of the stone beam would be supported by Isler's hypothetical temporary masonry structures, discussed above. Therefore, this process employs a method of lifting the blocks up the superstructure, which was, when tested, determined to be unsafe and slow by Lehner and Hopkins on the Nova Experiment when lifting a block of 2 tons with modern, planed lumber. This process is then writ large to carry blocks 25 times greater in weight, with 10 times the levers on temporary masonry foundations and the size of each lever increased to support a 5,000 load.

Isler's next method of moving the blocks up the superstructure borrows from the concept of sliding the blocks up the pyramid. Isler refines this concept again with excellent detailed drawings answering specific problems. Levers are used to lift the blocks up in increments, while a group of people pull a rope attached to the block up a staircase ramp following the rise and run of the pyramid. The rope is looped once or twice around a horizontal log, connected to a wooden structure comprised of two askew A frames and a cross beam, thereby preventing the block to travel back down the pyramid. As the block moves upward, slack on the rope is taken up and gives the workers a short break between efforts to move the block upward.

Isler presents another addition to this method, which utilizes a simple pulley found in an archaeological context within the Giza plateau. This device utilizes two of these tools (not true pullies) that do not increase mechanical advantage, but rather change the direction of rope under tension. This device would not have space to work at the top of an incomplete superstructure nearest to the intended summit, due to issues of reduced space. Isler's mechanism would allow for the smooth change in direction of rope, in turn allowing large gangs to pull the blocks up the superstructure while standing on the top or while pulling down from the opposite side. This apparatus is intended to be used where a large work area is available, such as at the top of the incomplete superstructures.

While these new hypotheses by Isler are lucid and coherent arguments, they need experimental tests to be validated. Isler's method from the 1985 and 1987 articles were similarly well thought out, but failed from unforeseen variables. In the example of Isler's 2001 block-lifting hypotheses, it is essential to test the argument that blocks were slid up the pyramid surface, considering that most previous ramp hypotheses settled on a 10-to-1 incline as the most feasible gradient that the pyramid blocks could move up the superstructure.

Levering Devices Using One Large Movement to Raise the Blocks

The hypotheses involving one levering operation to perform the vertical or vertical and horizontal actions of moving a block up one tier utilize one or two levers, and a variety of wooden structures to support the lever. The operation of these hypotheses vary from simply transporting the block vertically, where the block then must slide or tumble onto the next tier, to moving the block both vertically and horizontally, where the block rests upon the next tier. The historical foundations of these hypotheses usually employ Herodotus' vague description of levering machines and largely borrow from the historical and ethnographic examples of the shadoof.

Since the operation of the lever must move the block up one tier in one movement, the distance from the fulcrum to the block is much larger in comparison to hypotheses that move the block upwards in increments. This forces certain complications upon the efficient design of these levering devices. Since the distance from the block to the fulcrum is greater in comparison to the distance in incremental levering hypotheses, there is a reduced amount of mechanical advantage given an equal sized lever. Likewise, there are greater stresses on these levers due to the increased counterforce needed to lift these blocks. These problems force hypotheses of this variety to employ much longer and thicker levers in comparison to the other levering hypotheses.

Even though hypotheses of this type were depicted in engravings as early as the 19th century (Siliotti 1997: 18-19), there is a dearth of experimental tests on behalf of these levering hypotheses. Though engineers and archaeologists alike have presented detailed hypotheses of this variety in a myriad of forms, none have attempted to test them using large blocks. In the wake of this deficiency of experimental tests lies an array of oversights concerning the operation of this levering method. Some of the major oversights of this method concern the operation of the large lever.

Louis Croon

Louis Croon, a German Engineer, proposed a levering device modeled after the indistinct descriptions of Herodotus and historical evidence of the shadoof. This device is comprised of a single large lever swiveling in a vertical plane. A large central column, buttressed by small legs, supports the lever. The lever is attached to the block on one end and pulled down by a series of ropes on the other. When the block is lifted to the appropriate vertical height, the suspended block is then moved down to the next level by use of some type of ramping device. This ramping device attaches to the large central column and angles down to the pyramid superstructure.

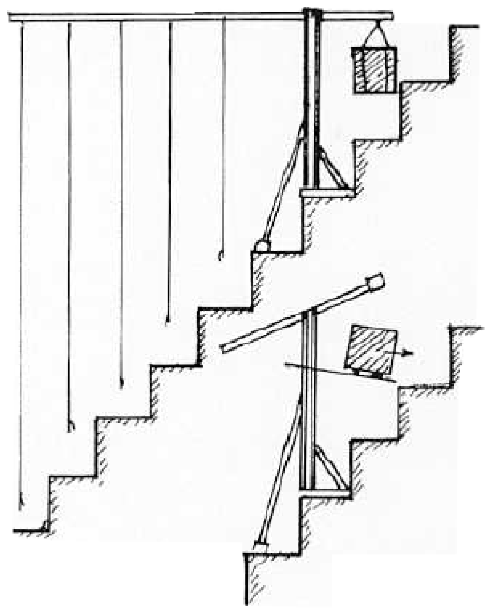


Figure 6-6. Louis Croon's proposed levering device (Goyon 1977: 64).

Croon's rough design is not without problems. The most critical problem with this method is that Croon neglects to take into account the lateral movement of the arc of movement. In other words, when the block is connected to the levering device, the block will move forward and upward, inevitably hitting the pyramid superstructure. The block will cease to move forward due to the limited space available for the block to move in this direction. The block could be placed closer to the machine and 'hang over' the tier to give space for this movement, but then the block would be too close to the levering device to attach to the block. If the levering device is moved backward as well, you compound the next issue, the occupation of space on the pyramid superstructure.

While his device utilizes the rise over run of the growing pyramid superstructure, and thus alleviates the issues involved with ramping hypotheses, his machine, occupies two tiers, none of which involve two tiers of movement used by the block. Thus, this design occupies four tiers of the pyramid superstructure. When moving a block upwards, the device would have to be arranged so that three machines would have to slide out of the way in order to move one block up one tier. This device would have to be moved out of the way, along with the other three machines, in order to make room for the next device in preparation to move the block up one more tier. If the machine is moved downward, as described in the preceding paragraph, the device would have to increase in height, due to its position downward, the ramp would have to lengthen, and the movement of five devices would be needed to move one block.

The levering principle works on the premise, in this case, that the distance from block to the fulcrum is regarded as one unit. The multiplication of this unit in length on the other side of the lever equals the amount of mechanical advantage. In other words, if the distance from the fulcrum to the block is 2 feet, and the distance of the lever from the fulcrum to the point where it is pulled down is 10 feet, then the force you would need to generate in lifting an average sized Great Pyramid block weighing 2.5 tons would be 1000 pounds.

With Croon's device, you lose mechanical advantage because of the manner in which the lever is pulled down. The force generated at the end of the lever would have a mechanical advantage of approximately 5-to-1. The next point would have a mechanical advantage of approximately 4-to-1 and so on, to the last point, which appears to have almost no mechanical advantage. With this method, there is an inefficient use of force on the lever, which greatly increases the loads and strains. This increased load requires an increase in the strength of the lever. Unless a stronger wood is used, you must increase the size, and therefore, weight of the beam.

Olaf Tellefson's Double Lever Device

Within Olaf Tellefson's method of using the angled sides of the pyramid superstructure as ramps, he describes, along with the device to lift blocks on and off sledges, a double counter-weighted levering device that would operate in 'tight places.' In Tellefson's drawing (Fig. 6-7), two levers are attached by a large tower that occupies three tiers. The levers operate on the tower by moving vertically. This motion is controlled by a hinge joint that prohibits tangential movement by a groove made on the beam that fits into a raised arch of wood on the tower. The lever farthest from the pyramid superstructure lifts the block vertically. While the block is suspended, the second lever operates to move the block horizontally. While the second lever (lever closest to the superstructure) moves the block horizontally, the first lever releases tension on the ropes in unison as to gradually shift the entire weight of the block onto the second lever, moving the block onto the second tier.

Though Tellefson's double-lever concept is intended for use in tight spaces in conjunction with sliding blocks up the pyramid superstructure, it is possible that this design could work in a way unintended by Tellefson as a combined ramp & lever method to lift blocks up the pyramid superstructure. The horizontal leg providing support on the highest tier could be shortened, or be made vertical to rest on the tier beneath, thereby only occupying two tiers. Here a tower could be placed on alternate sides, so the towers would not have to move and the blocks could move up the pyramid superstructure, single file.

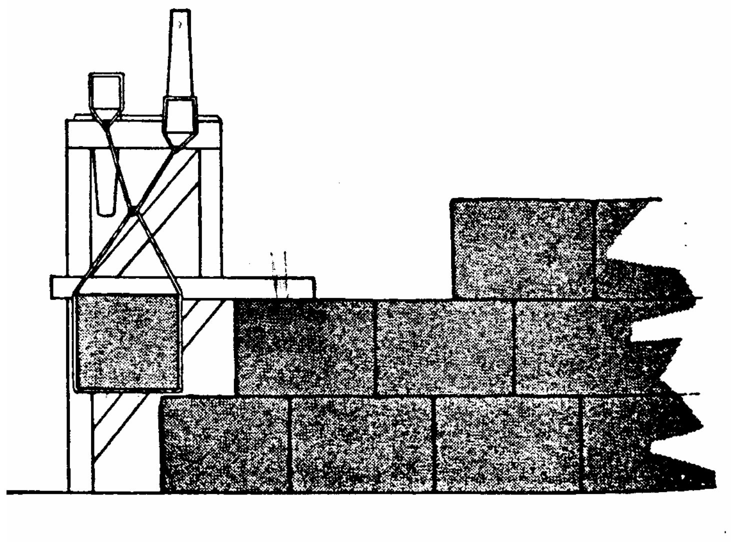


Figure 6-7. Olaf Tellefson's double lever device intended for use in confined areas of the superstructure (Tellefson 1970: 18).

J. P. Lepre's Double Fulcrum Device

J.P. Lepre is an Egyptologist who presents a levering apparatus for an amalgamated ramp and levering method to move blocks up the pyramid (Figures 6-8 and 6-9[4]). Likewise, he bases his ethnographic connections on the Shadoof, and on Herodotus' vague description of the possible levering techniques and principles used by the ancient pyramid builders. In his method, a double fulcrum device works by combining the simple, counterweighted levering device with another counterweight. As the lever moves down, the second counterweight travels upward, which generates more force. Lepre's method comprises of a complicated device made up of many timbers. His diagram, similar to the other levering authors of this variety, does not take into account the stresses and loads on the device. Similarly, he does not specify the type of materials comprising the proposed device.

[4] From Lepre 1990: 258-259

The problems visible from the rough schematics show that the device requires a great deal of space in which to operate. In other words, as drawn, it cannot operate under an angle of ascent that follows the pyramid superstructure, and therefore suffers from a lack of workspace at the top. In addition, the drawing shows the placement of the block on the next tier. However, since the arc of movement would push the block away from the superstructure as it traveled upward, the device would have to travel backwards, under load, in order to bring the block to the next tier.

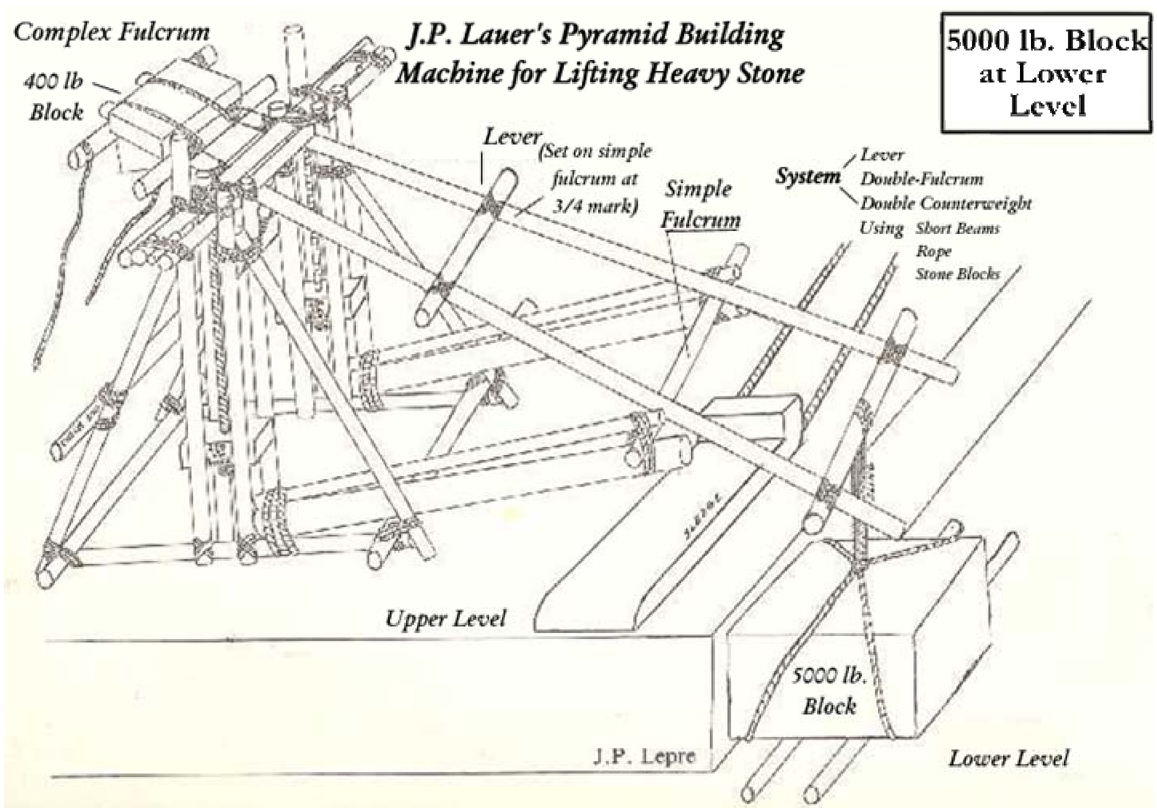


Figure.6-8. J.P. Lepre's levering device, its components, and its location when raising a block from a lower tier (Lepre 1990: 258).

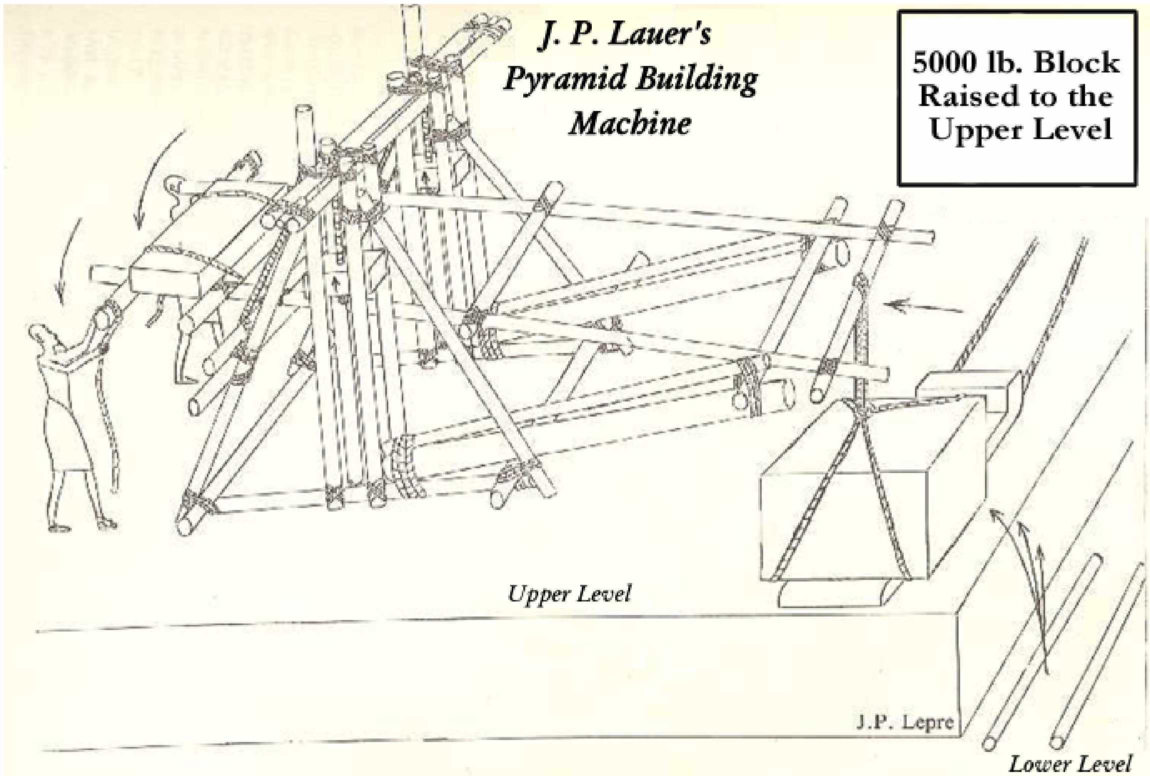


Figure 6-9. J.P. Lepre's levering device lifting a block onto a sledge resting on a higher tier (Lepre 1990: 259).

Pierre Crozat

In his 1997 and 2002 publications, Pierre Crozat, a French civil engineer, proposes a method of pyramid construction that employs an algorithm to demonstrate predictive growth of the pyramid superstructure. This growth begins with a small stack of blocks and develops upward and outward to end with the placement of the casing stones. While his books do not outline an original levering device, his website shows a modeled levering device, resting upon a tripod that operates in both vertical and horizontal axis (Figures 6-10 and 6-11).

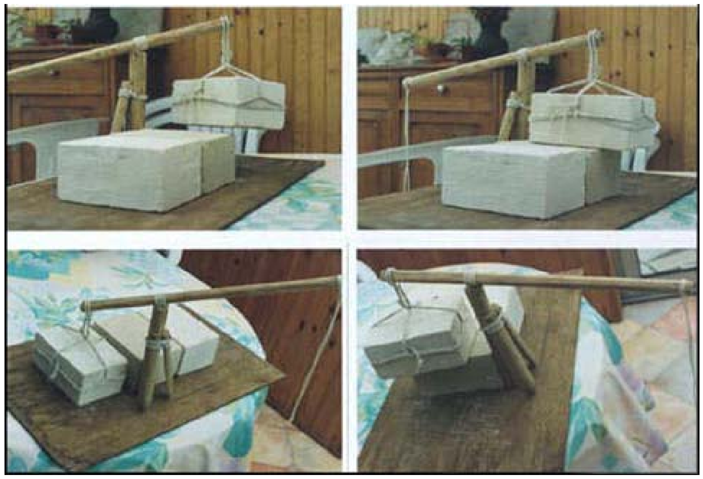


Figure. 6-10. Pierre Crozat's levering device at 1/10th scale (Crozat ND).

Figure.6-11. Pierre Crozat's levering device at 1/3rd scale (Crozat ND).

The major problem with Crozat's model pertains to the fulcrum. The lever rests on top of the upright structure and cannot be secured to the fulcrum due to its requirement to move both vertically and horizontally. This limits the levers ability to move vertically in shallow angles due to the danger of the lever either slipping toward the block during the beginning portions of lifting or slipping towards the workers pulling on the lever once the lever has moved the block to the height of the next tier.

In the other levering hypotheses presented in this thesis, there were ropes or sockets to prevent the lever from slipping toward the block or away from the block when moving vertically. Crozat is limited in his options to prevent the lever from slipping toward the block or towards the laborers when the block is raised. Since his lever needs to move on a horizontal axis, he is unable to employ the groove and socket method described by Tellefson.

Crozat's limitations to shallow angles of vertical operation require him to use a much larger beam due to an inability to utilize large angles of movement. These shallow angles force Crozat to increase the distance between the fulcrum and the block in order to generate enough vertical movement to move the block up one tier. If the distance from the fulcrum to the block is increased, then the board must be lengthened to generate the same amount of mechanical advantage. If the board is not lengthened, then its width must be increased to account for the increased loads created by an increased amount of force needed to lift the block. These circumstances create a difficult conundrum. If larger levers are required, there are problems procuring timbers of great size in a geographic region where large timbers are limited and larger imported timbers carry a great cost. A loss of mechanical advantage can also be problematic when lifting blocks of 2 to 2.5 tons. Decreasing the mechanical advantage from five to four when lifting a 2-ton block increases the amount of weight required by 200 pounds.

It is also important to consider the effects of friction between the lever and the fulcrum. The weight and friction damages the lever where it begins to fail first, at the fulcrum. The loads of the block, counterweight, and dead load of the beam all converge on a small portion of the lever where the fulcrum is located. This problem is critical since wooden bending members first fail at the compressive mechanical property, then, ultimately break under tension (Fig. 23). In other words, these wooden levers first start to give with small compression failures, which cause the lever to bend too much and snap along the tension side.

The minimum of 6000-lbs generated at the fulcrum from lifting an average sized 5000-lb block with a 5-to-1 mechanical advantage (not including the weight of the lever), would help to compress and smooth the lever at its most critical part. Damaging the lever at this crucial point would require some remedy, by either increasing the size of the beam or applying some replaceable barrier that would not exacerbate the slippage of the beam. Smoothing the surface would require more shallow vertical movements, since there is less grip on the lever. This would increase the chances of the lever either slipping from its fulcrum towards the block in the early portions of the vertical lift or towards the counterforce, or people operating the lever, during the rest of the levering operation. The effects of sand entering the space between the lever and the fulcrum surfaces must also aid greatly in creating an abrasive surface that accelerates both of these problems of smoothing and damage.

While the hypotheses that utilize one large levering motion to lift the block up one tier have a deep history, they unfortunately do not have enough experimental tests to bolster their claims. This situation renders hypotheses of this ilk as only worthy of a footnote, since, ultimately, the arguments they present on paper cannot be substantiated without experimental tests.

CHAPTER 7
ALTERNATIVE LEVERING DEVICE

An alternative levering apparatus, that I designed utilizes two levering apparatuses and employs one large movement to lift a block up one tier (Figures 7-1 and 7-2). This levering device, which is modeled after materials and technology available to Old Kingdom Egypt, is constructed from wooden poles and rope. The lever rests within a rope harness, which is looped around the lever in order to constrict and secure the lever when under load. The support for the lever comes from four wooden poles, or columns, bound together as two A frames, which connect together in a pyramidal shape. The rope fulcrum is connected to a cross beam which is supported by the two A frames. All of the wood of the device is modeled after *Acacia nilotica*. The rope is modeled after general traits common to natural fibers.

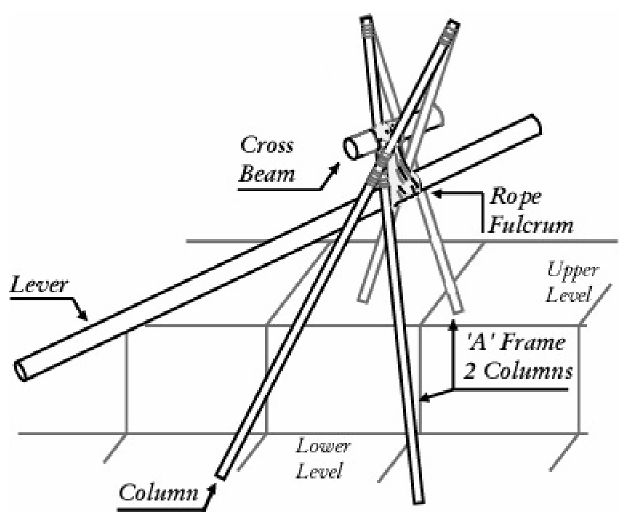


Figure 7-1. Diagram of an alternative levering device.

This levering design focuses on the aspects of Egyptian pyramid construction concerning moving the block up the superstructure. This operation involves the placement of the device on two tiers of a staircase ramp, lifting the block onto the completed tier.

Figure.7-2. The alternative levering method that I propose.

Placing the device on the two-tiered workspace involves having columns of different length, two of which are shortened to fit onto the higher tier. One shorter column set is placed on a higher tier and one longer column set is placed on the lower tier. Thus, the device occupies two tiers. The columns closest to the block are shorter than the columns farthest from the block to tilt the device towards the block in order to move the fulcrum closer.

Lifting devices are placed on both sides of the block, and two devices operate on each tier. Since the devices occupy two tiers, the devices share space on the tier by the different sizes of the columns. Shortened columns fit within the space given by the larger columns of the device on the next tier.

The process of moving the blocks up the superstructure differs slightly between completed and uncompleted, or terminus, tiers. On completed tiers, the block does not have sufficient space to rest on the tier without support. Therefore, a wooden support would be used to prop up the block between lifting operations. When moving the block onto the completed tier, the levers will move the block entirely onto the terminus level.

Origins of the Design

This project began as an assignment for Peter Schmidt's Experimental Archaeology class, spring semester 2000. The project at this point was to test a levering device, inspired by Tellefson's 1970 article, that utilized one large movement to lift the blocks by building a four-tiered pyramid on campus. The levering device proposed by this group first planned to use a ball and socket or pivot, mounted on a tripod, and lubricated by grease. My role within this experiment was initially limited, as I was not enrolled within the class. As an outsider offering some help, I took the position of handling the safety aspects of the experiment.

Dr. William Properzio, the person in charge of determining whether an experiment of this type would be safe enough to conduct on campus, had various reservations with the project at this juncture. His reservations revolved around issues regarding the safety of the project, the lack of a clear description of the levering device, and a lack of information regarding the strength of the device or its safety.

Issues with the Fulcrum

Addressing Properzio's concerns of safety necessitated the fabrication of a new device. One of the critical issues to attack in the creation of this device was the problem of the fulcrum. Levering hypotheses that utilize one large movement to lift the block place the lever on top of a rigid structure. This structure is often made of wood, such as Crozat's tripod and Croon's buttressed wooden support.

The placement of the lever on top of a rigid structure creates certain problems for the movement and safety of a lever. If the lever is allowed to rest on top of the structure, as in Croon's Method, then the lever's arcs of movement are reduced because the lever is not secured. Therefore, this method limits the safe angles from which the lever can operate. If the lever moves at too large angle of a vertical sweep, the lever may slip either towards the block at the beginning of the lift or towards the people lifting the block at the apex of the vertical lift.

The method proposed by the group presented other issues of safety. With this type of levering, the greatest bending stresses are located at the fulcrum. Creating a lubricated ball and socket fulcrum would place the greatest stresses on a section of the beam with removed material for the joint. In other words, a portion of the lever would be removed in a location where it is needed most.

In addition, I was unclear how these large frictive and compressive forces might damage the beam and the joint in this critical location. The large downward forces could compress the lever in the critical area where the most bending takes place, and, therefore, weakening the lever at a critical area. The effects of friction and the joint were also unknown. It was unclear whether the repetitive back and fourth movements would shear off the joint when under load.

What was needed was a new device that would address the safety issues presented by Dr. Properzio and the problems of the fulcrum. Addressing these issues would, in turn, necessitate framing the device within appropriate materials and technologies available to the Old Kingdom pyramid builders. Afterwards, the apparatus could be then modeled and tested in order to calculate and determine a safe operation.

Evidence for the Lifting Device

Rope Tourniquet Fulcrum

The solution to the fulcrum problem was found through the illustration of the shadoof within Tellefson's article. This illustration shows the large, counterweighted lever not supported on top of the crossbeam, but supported underneath it by a rope harness.

Moreover, a preponderance of photographic depictions of the shadoof locate the lever underneath the cross bar supported by a rope harness (Fig. 7-3). Furthermore, figure 5-1 and 5-2's representation of wood processing demonstrates a rope fulcrum for the small counter-weighted lever that dates to the Old Kingdom. Placing the lever within a rope harness provided an effective solution to this problem of friction, compression damage, and removed material on the portion of the lever with the most bending stress. This rope harness would form a loop around the beam, constricting under load and, thus, securing the lever in place without damaging the beam.

Figure 7-3. Shadoof with the lever secured under a cross beam inside a rope harness (Zangaki: 1865).

Utilizing a rope fulcrum necessitated the fabrication of a structure that would both fit within the material and technological boundaries of the Old Kingdom yet lift a block up the rise and run of the pyramid superstructure. The product of this research led to the creation of levering devices, comprised of two A frames, a cross bar, and rope bindings mentioned in the introduction of this chapter.

The A frame technology is used in architecture, ship masts, and comprised some of the tools used by the pyramid builders. The A frame is a ubiquitous architectural device, often used to support loads and relieve stress, seen in many monuments and pyramids (Figures 7-4 and 7-5). Saddle Roofs, a variant of the A frame technology, consist of pairs of roof beams leaning inward and joining at the top.

The A Frame

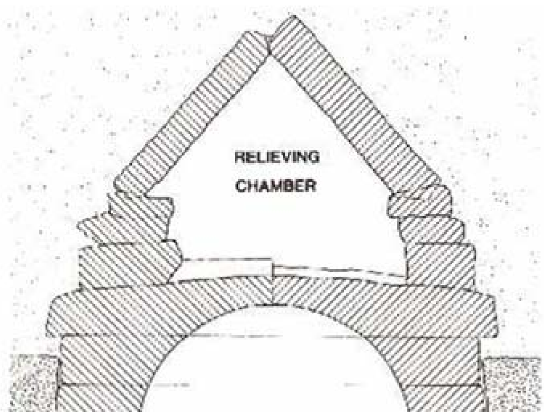


Figure 7-4. Section of the relieving chamber of the Amun sanctuary in the Deir el-Bahari temple of Hatshepsut (Arnold 1991:189).

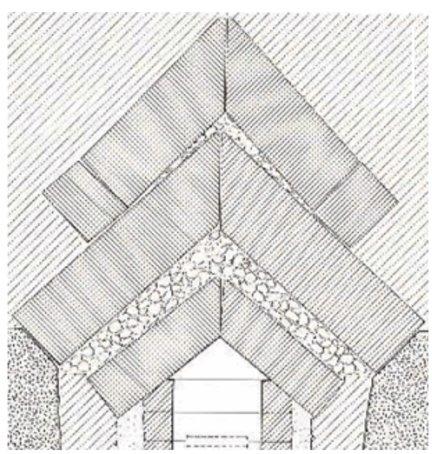


Figure 7-5. Roof of the crypt of Niuserra at Abusir (Arnold 1991:192).

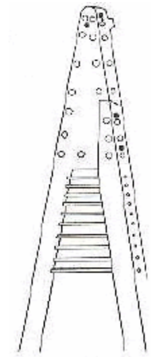


Figure 7-6. Ship mast A frame (Clarke and Engelbach 1990: 39).

This directs the weight away from an open space and downward to the walls (Arnold 1991: 191). The earliest examples of saddle roofs come from Senefru's private tombs (Arnold 1991: 191). Saddle roofs were used in a greater scale within Khufu's pyramid and were in constant use for the burial chambers of all of the pyramids of the Fifth and Sixth Dynasties (Arnold: 1991: 191). Its usage extends into the Middle Kingdom.

Ship masts employed a large A frame technology in their design (Fig. 7-6). This two-legged shape was first intended for use on fragile reed rafts, where immense pressure from the mast and sail had to be distributed over a large area in order not to break the weak fibers of the boat (Jenkins 1980: 123). This design continued past the Old and into the Middle Kingdoms, where it no longer served any practical utility (Clarke and Engelbach 1990: 39, Jenkins 1980: 123).

The A frame was used in the construction of the leveling tools of the Old Kingdom pyramid builders as well (Fig. 7-7). This tool is shaped as a large A. A suspended weight is connected to the apex of the 'A,' and hangs between the straight horizontal section connecting the two angled pieces of wood and the portion to be measured.

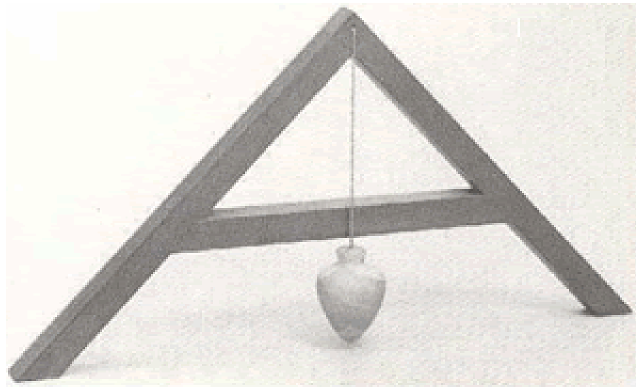


Figure 7-7. A frame level (Arnold 1991: 254).

Rope

Rope was used in many forms in Pharaonic Egypt, including ship construction and rigging, weaving, clothing, timber processing, and indeed in most crafts. From the archaeological record, we know that rope was made from papyrus, dom palm, linen, esparto and halfa grass, flax, and even hide are documented from excavated examples (Arnold 1991:268, Ryan and Hansen 1987, Isler 2001: 254, Weindrich 2000: 254-255). Some of the more famous examples of ropes found within the context of the pyramid mortuary complex can be seen in evidence from Khufu's royal ship (Jenkins 1980).

Although it can be difficult to determine how much weight ancient Egyptian ropes can hold from the archaeological examples due to their deteriorated state (Ryan 1993), there are archaeological examples of the use of ropes to move tremendous weights. Examples of vertical lowering of heavy blocks, in the form of drill holes and grooves cut for ropes, can be seen dating from the 1st dynasty in Saqqara, 3rd dynasty Tombs at Beit Khallaf, where portcullises of 6-7 tons were lowered down 25 meters, and in numerous sarcophagus lids post-dating the 3rd dynasty (Clarke and Engelbach 1990: 86, Arnold 1991, 73-79, 118). Ropes with a large circumference have been found in the ancient Tura quarries with a diameter of 2.5-inches, and in an earlier 18th dynasty rope knot made from halfa grass and twisted papyrus culms with a 2.75-inch diameter (Hansen and Ryan 1987: 9-10, 13).

The Old Kingdom depictions of wood processing provide a unique insight into binding wood and levers with ropes. A 5th dynasty depiction of splitting wood demonstrates a counterweighted levering technology, wedged in a rope bands. The illustration depicts a person splitting a log (Figure 5-1). Rope bands are tied above the portion to be split and a small lever and counterweight is placed within these bands to tighten them around the log (Gale et al. 2000: 354, Clarke and Engelbach 1990: 37). Another depiction shows a method of timber conversion with rope bands securing the end of the rough log (Figure 5-2).

The range of plant life in modern Egypt is much different from what was available during the era of pyramid construction. One stunning example is the lack of naturally occurring papyrus in modern Egypt, a major source of Ancient Egyptian rope, (Ryan and Hansen 1987: 8). There are agricultural and cultural reasons for the lack of naturally occurring papyrus. Obstructing channels for purposes of irrigation have changed the Nile. Certain branches of the Nile completely dried up during the Christian and early Islamic periods, destroying some of the natural habitats where the shallowly anchored plant naturally occurs (Leach and Tait 2000: 228). The papyrus plant may have been depleted through overuse, given its wide range of uses as paper, matting, ropes, boats, sandals, decorative functions, and food (Leach and Tait 2000: 228). This depletion was exacerbated by the Greeks control over papyrus production, whereby they destroyed plants not within their official jurisdiction (Leach and Tait 2000: 228).

Acacia nilotica

The trend of over-harvesting Egypt's resources extends to one of the most used trees, the *Acacia nilotica*. *Acacia nilotica* grew abundantly in Egypt until the early medieval period (Gale et al. 2000: 367). The use of *Acacia nilotica* charcoal was extensive in the Ptolemaic period for smelting and probably significantly contributed to the loss of Egypt's trees (Gale et al. 2000: 353-354). Historical documents note the scarcity of wood during the Hellenistic periods. While there is no reason to believe that there was a shortage of wood before the Hellenistic and Roman periods, it is during these periods that papyri clearly show that wood was very scarce (Meiggs 1982: 57). These trends of population stress and over use of *Acacia nilotica* have restrict its quantity and its preferred habitats, thus limiting the ability to use modern acacias as a reference to the possible sizes of these trees during the era of pyramid construction. These changes separate the quantity and sizes of modern day Egyptian *Acacia nilotica* and those available from the era of pyramid construction.

Given the unique climate of Egypt, which is favorable to the preservation of wood in the archaeological record, there is a good body of samples from which to view the types of wood used during the time of pyramid construction. The most common tree harvested for timber was *Acacia nilotica*. The timber from *Acacia nilotica* was used for boat building, construction work, furniture, coffins, bows, arrows, and dowels (Gale et al. 2000: 335). Examples of this wood range from the predynastic period onward to the late period. Examples of *Acacia nilotica* in the archaeological record are more often small fragments or short pieces. However, it would be misleading to infer that *Acacia nilotica* could only produce timbers of short length (Meiggs 1982: 59). Theophrastus describes that timbers of 12 cubits (20.62 feet) could be cut from this tree (Meiggs 1982: 59).

The lengths of *Acacia nilotica* that Theophrastus mentions may not be visible in the archaeological record or in modern Egypt, but large *Acacia nilotica* trees are visible in the modern era along the Blue Nile in the Sudan (Figures 7-8 and 7-9). Pure stands of *Acacia nilotica*[1] grow approximately 15-20 meters high along the seasonally flooded basins of the Blue Nile (Bunting and Lea 1962: 552-553). In managed plantations, *Acacia nilotica* in this area reach a height of 25 to 30 feet (7.5 – 9 meters) in five years (Hassan 1989: 68). *Acacia nilotica* is of great value in the northern part of the Sudan due to its valuable capability of sustaining itself on river floods in a region where rainfall is too low to support trees of any size (Badi 1989: 72).

Figure 7-8. *Acacia nilotica*, ready for harvesting after a 5-year growth cycle (Maguire 2001).

Figure 7-9. Large *Acacia nilotica* pieces ready to be cut into railway sleepers (Ciesla 2003).

[1] See appendix A for the mechanical properties related to strength.

While population growth, agriculture, desertification, and overuse have contributed to the limitations of modern day *Acacia nilotica* in Egypt, it is possible that the environment in Northern Sudan simply provided improved ecological conditions that result in its larger growth. Egypt's long period of interaction with its southern neighbor involved a large expanse of time that began with predynastic era trade and the later, Old, Middle and New Kingdom periods of colonial exploitation spanning from 3200 BC-to-1200 BC (Adams 1984: 40-42). One of the many resources harvested by Egypt was *Acacia nilotica*. When *Acacia nilotica* is mentioned in ancient Egyptian texts, such as the 6th dynasty inscription of Weni from Abydos, it is sometimes said to be obtained from Wawat, the Northern part of Nubia (Gale, et al. 2000: 335). While there is limited evidence for tall *Acacia nilotica* trees in Egypt due to historical and ecological reasons, the strong evidence for the importation of the large *Acacia nilotica* trees growing in present day Sudan make a compelling argument for the availability of big *Acacia nilotica* timbers mentioned by Theophrastus.

Lebanese Cedar and Cilician Fir

Other larger, yet weaker timbers such as the imported Lebanese Cedar[2] and the Cilician Fir[3] could have been employed as levers. Lebanese cedar grows between 30-40 meters in height, and cilician fir grows up to 30 meters tall (Gale et al. 2000: 348-349). These various Lebanese timbers were prized for their long lengths and utilized for resin in mummification, construction of naval vessels, flagstaffs, coffins, doorways, small items, and furniture (Meiggs 1982: 406-409, Gale et al. 2000: 348-350). Cedar was also

---

[2] See İstanbul Üniversitesi 1992 for the mechanical properties related to strength - . http://www.orman.istanbul.edu.tr/abis2001/liste/Cedrus_libani.htm Last visited on 11/02/04
[3] See İstanbul Üniversitesi 1992 for the mechanical properties related to strength. – http://www.orman.istanbul.edu.tr/abis2001/sorgular/fizik.htm Last visited on 11/02/04

selected for its fragrance as well as resistance to decay and insects (Meiggs 1982: 407). These timbers were imported into Egypt from the predynastic period and through the era of pyramid construction. There is historical and archaeological evidence to support this. The Palermo stone, dating to the reign of Snefru, describes the importation of forty ships filled with cedar and *meru*-wood (Meiggs 1982: 63). The boat found within Khufu's pyramid complex contained large amounts of Lebanese cedar.

Given the evidence presented, I believe that *Acacia nilotica* was a possible choice for levers of lengths given by Theophrastus of approximately 20 feet and under. These large sizes may represent a height that only the largest trees could produce. If sizes under 20 feet were used, it is likely that there would be much more *Acacia nilotica* trees to select from to produce timbers. Lengths larger than 20 feet would benefit from the larger and straighter growing Lebanese conifers. These timbers, while of less strength than the *Acacia nilotica*, would be easily available in lengths of 20 to 30 feet.

CHAPTER 8
EXPERIMENTAL TESTS

> "Argumentation cannot suffice for the discovery of new work, since the subtlety of Nature is greater many times than the subtlety of argument."—Francis Bacon

Experimental tests were performed in order to test the loads, stresses, and functional operation of the device. Calculations were performed by hand and by computer, with the assistance of Orand's Beam program[1]. In each experiment, block size determined scale. The full-scale block size was derived from an average sized 2.5 ton Great Pyramid block with a volume of 1 m^3. To ease the fabrication of these experiments, the block shapes were made uniform. The first experimental test, a 5-to-1 scale model, was a preliminary exploration into the strength of the upright columns and the lever. The first 3.63-to-1 scale test explored the functional operation, loads, and stresses of the single levering device method of lifting a block. The full-scale column test explored the strength of the upright columns at full scale. The second 3.63-to-1 scale column test investigated the functional operation, loads, and stresses of the double levering device method of lifting up one block. The last experiments, the large-scale tests, lifted 2500-pound, or 1.25 ton blocks at the University of Florida to accurately test the device.

---

[1] I am truly grateful for engineering programs, such as Orand's beam 2d, which enabled me to perform a tremendous amount of calculations in a very short amount of time. While processing the figures for a simple bending member may take 10 minutes on paper, I could easily accomplish 15 calculations on my computer. The beam calculations and graphics for appendix C and D were computed by Orand's program.

The 5-to-1 Scale Model

A 5-to-1 scale model was constructed to test the apparatus' ability to sustain weight. A calibrated industrial scale weighed each mass. The A frames were made from ½-inch hardwood dowels, and the lever was a 1.25-inch diameter, four foot long dowel. These dowels were most likely made from poplar. When exploring the load bearing capacity of a wooden structure, small scales are not the most appropriate method of accurately testing weight. The strength of wood is greater at small scales. Moreover, the problems related to knots, splits, shakes[2], grain, decay, and other imperfections within wood magnify at larger scales. Therefore, the purpose of this experiment was to roughly determine the strength of the design.

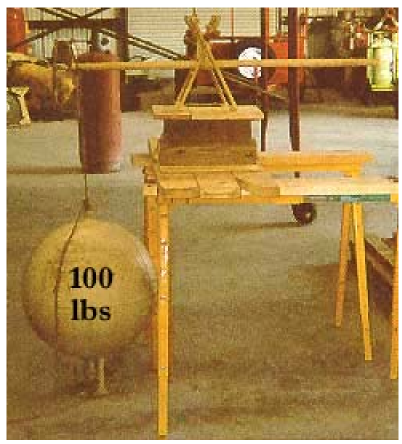


Figure 8-1. The 5-to-1 scale model with 100 pound weight

For this experimental model, a 40-pound weight was easily lifted and sustained to replicate the weight of a 5000-pound weight at fifth scale[3]. To examine the inherent weaknesses of this design, a 100-pound weight was then lifted and sustained (Fig. 8-1).

[2] "*A shake is a separation or weakness of fiber bond, between or through the annual rings, that is presumed to extend lengthwise without limit. Because shake reduces resistance to shear in members subject to bending, grading rules therefore restrict shake most closely in those parts of a bending member where shear stresses are highest." (USDA 1999: 6-4)*. For more information regarding shakes or other visual sorting criteria, please refer to the Wood Handbook (USDA 1999), pages 6-3 through 6-5.

[3] 5-to-1 scale reflects scalar differences in size. On the other hand, mass is decreased by cube root, or increased by the third power, depending on the direction of scale.

During this test, the lever was the only part of the device that demonstrated any visible stress. A third test was performed, by first removing the weakest portion of the device, the wooden lever, and replacing it with a metal pipe. During this test, a 188-pound weight was lifted and sustained with a mechanical advantage of 3-to-1 to result in a total force on the upright columns of 251 pounds.

This experiment demonstrated that the moment arm itself was by far the weakest part of the fifth scale device. This weight, when increased from fifth scale to full scale represent 31,333.334[4] pounds of full-scale force. Of course, stresses and loads react differently on wooden structures from small modeled sizes to full scale, and thus this should not be used as an ideal example. It should, however, point to the tremendous loads exhibited on the model that can be masked by the geometric increase in weight from scale models to full-sized loads. To appropriately test the strength of the upright columns, it was necessary to perform a full-scale test on the strength of the upright columns after the construction of another model to determine the appropriate dimensions of the device.

The 3.63-to-1 Scale Single Lever Model

The purpose of this model was to determine the dimensions of the entire experiment and investigate the operation of the device at scale. The material used for the model were 2 concrete blocks fabricated to represent an average pyramid block, cinderblocks, dowels, and hemp rope (Figures 8-2 and 8-3).

---

[4] 250.667 pounds x 5(scale)^3 = 31,333.334

Figure 8-2. The 3.63-to-1 scale single lever model raising a block

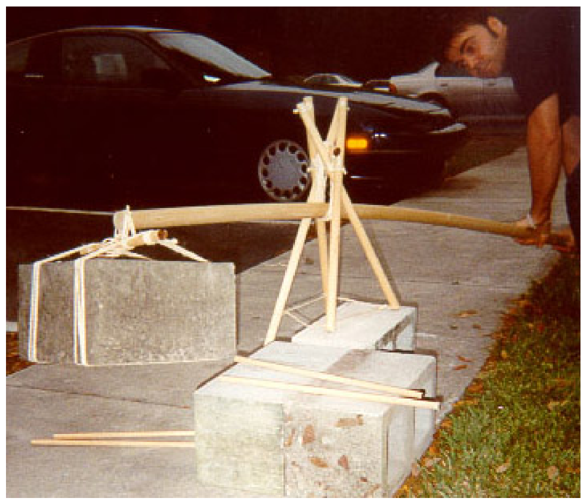


Figure 8-3. The 3.63-to-1 scale single lever model raising a block

The first step in the creation of this model began with the study of the dimensions of the pyramid blocks. Egyptian pyramid blocks vary greatly in size and shape within and between the pyramids. In order to isolate variables and facilitate the construction process, I have chosen the mass of blocks of the 4th dynasty Great Pyramid, which has some of the largest interior blocks and casing stones and presents the largest quantity and size of loads for a lifting device. These stones are an average of 2.5 tons and a cubic meter of limestone.

Making a pyramid with the correct angle was crucial due to the workspace given by the rise and run. The solution to the problem was to design truncated versions of these blocks, where the top and base remained a square, but the sides now formed golden proportion rectangles. Coincidentally, the use of the golden proportion[5] gave the pyramid an angle of inclination of approximately 52 degrees.[6] This ratio was then used to determine the dimensions of a full-sized block with a volume of 1 m^3 and a mass of 5000 pounds. These dimensions for this block are 72.56-cm in height and 117.40-cm in length and width. From these full-sized dimensions, scaled block dimensions were calculated for accurate modeling.

The next step involved making a scaled-down version of this block. Since there were quite a number of cinder blocks at my disposal, I made the height of the block equal to the cinderblocks. Therefore, the cinderblocks could serve as a simple representation of the uncompleted superstructure, and thus, limiting the model block fabrication to two blocks, which reduced the time and money spent on this model. The final dimension of this block was 20-cm high and 32-cm wide and 100 pounds. The dimensions of length and width were divided against the dimensions of the full-sized block to arrive at a scale of 3.63-to-1.

Construction of this model began with attempts to closely replicate the wood and rope available to the ancient Egyptians. Since the A frame structure would require lengths much shorter than 20 feet, these pieces of wood were modeled after *Acacia nilotica*. Since the lever would exceed 20 feet, cilician fir was selected as the appropriate wood. Since neither of these timbers were readily available in retail outlets in Florida, appropriate analogs were selected from commercially available wood. Poplar dowels with a 7/8-inch diameter were used for the upright columns and cross beam. A round

---

[5] 1.618. Also called the golden mean or golden number.
[6] For a listing of many other coincidental mathematical theories associated with the shape of the pyramid, read *The Shape of the Great Pyramid,* by Robert Herz-Fischler. 2000.

douglas fir[7] banister rail with a 1.5-inch circumference and 6 feet in length would be used for the cilician fir lever.

The douglass fir banister rail was thinner and shorter than the beam intended to be used at full scale. An appropriate dimension for the lever would have been at the minimum 2.2-inches in diameter and 6 feet, 10.6-inches long. Unfortunately, I was unable to locate a dowel of this large size, thus the model had reduced mechanical advantage, lever strength, and lever movement[8].

While the experiment performed effortlessly, there were concerns arising from the large size of the lever. This beam in a full-scale size would be 8-to-10-inches in diameter and 25 feet long and give the device a mechanical advantage between 4-to-1 and 5-to-1. Regardless of these problems, the immense figures for the beam prompted an investigation on how to decrease the large sizes of the lever.

The Full-Scale Column Test

Concomitant with my efforts to reduce the large sizes of the lever, I was working on a full scale A frame stress test to assuage and address concerns that such a structure could even hold such loads. However, I ran into some difficulty in determining what sizes of wood were needed for this test. Calculating the stresses of the upright columns would be difficult considering that the upright column's angles are determined whilst placing the A frames on the worksite. To help me determine what size wooden columns to use on this experiment, Mike Hicks, an engineering graduate student used a FORTRAN program to compute the point of buckling failure on the upright members.

---

[7] See B-1 for the mechanical properties related to strength.
[8] For more information regarding lever movement, read *Arcs of Movement* on pages 84-85 in this thesis.

To ensure the safe operation of this experiment, and to account for the inability to determine precise angles, the engineering graduate student, took the angles from my 3.63-scale model, and increased the mass exerted on the columns. The values for the compression failure of this test is 525 psi for number 2 yellow pine when allowed for 10 years of total time under load (American Wood Council 1997: 41). These figures for the square nominal 4x4 number 2 grade yellow pine posts were determined to be well within the safety variables of the full-sized column test.

One oversight with these figures is the lack of information from visually graded specimens. Since the figures that were used were from the *Wood Handbook: Wood as an Engineering Material (1999)*, correcting these values is a matter of adding the limits presented in the *ANSI/AF&PA National Design Specification for Wood Construction.*

Armed with information from my models and engineering calculations, I set to construct and test a full scale A frame device. The test occurred at CSR Rinker, Cocoa, FL on February 15, 2001. The lifting arm was not a focus of this test due to financial constraints. The 2780-pound concrete "mack" block was weighed on a scale at Rinker to accurately determine mass. The upright columns were nominal 4-inch x 4-inch no. 2 grade yellow pine. Actual sizes of this commercial wood measured at 3.5-inch x 3.5-inch. The area of the 3.5 x 3.5-inch square posts is similar to round 4-inch posts: 12.25 in^2 and 12.57 in^2 respectively.

Columns

The mechanical properties associated with the strength of yellow pine are weaker than *Acacia nilotica* and slightly stronger than cilician fir. Compression parallel to grain, the modulus of elasticity, and the modulus of rupture are the important mechanical properties associated with strength to the upright columns. Additionally, the yellow pine posts used in this test is one of the weakest commercially available grades of yellow pine.

The wood used during testing was number 2 grade, wet, pressure treated posts[9]. Number 2 grade pine is one of the lowest commercially available grades. While this grade has a safe working compression parallel to grain limit of 1,650 psi, and 1,320 psi when wet, the number 1 dense grade pine used in the large-scale experimental test (discussed later within this chapter) has limit of 2,000 psi for the same mechanical property and for sizes of 4 inches x 4 inches (American Wood Council 1997: 32) (B-3). It is important to point out that these values drop for timber 5" x 5" and larger: 525 and 975 psi respectively (American Wood Council 1997: 41) (s B-2 and B-3). For higher grades, such as select structural 86, this value is 1300 psi (American Wood Council 1997: 41). These large differences in safe working stresses illustrate the large differences between different grades of the same timber.

The moisture content of timber also is a significant factor in determining its strength. Seasoned lumber, or lumber that is dried to approximately 12 percent moisture content, has increased values for these properties of strength when compared to wet timber (Hoyle 1972: 16, 47, USDA Forest Products Laboratory 1977: 139, USDA Forest Products Laboratory 1999: 4-34, 4-36).

In comparison with the environment and wood chosen for this experiment, the regional location of the pyramids are is the second driest region in the world. Egyptian

[9] Adjustment factors for Wet Service Factor (-cm) figures used from B-3 are:

Fb	Ft	Fv	Fc⊥	Fc	E
0.85*	1.0	0.97	0.67	0.8**	0.9

* when (Fb)(Cf) < 1150 psi,-cm = 1.0
** when (Fc) < 750 psi,-cm = 1.0
From (American Wood Council 1997b: 31)

carpenters were experienced in estimating the moisture content, where values between 8 and 10 percent were deemed acceptable (Gale et al. 2000: 355). Old Kingdom evidence for this comes from Khufu's funerary boat timber samples, which had been sealed from atmospheric changes, containing a moisture content of 10 percent (Gale et al. 2000: 355).

These seasoned moisture contents stand in stark contrast to the low-grade pine posts used in this experiment. While it was difficult to tell the moisture content of the wood because of a lack of instruments to measure moisture, the dampness in the wood used in this experiment reduced the strength of the wood to some degree. Further contributing to a reduction in strength was the low grade of the wood and the length of the wood. The wooden columns were left uncut and of longer lengths than the 3.63 model to further weaken the A frames. Since this test was conducted near coastal Florida, a region with much more humidity than the areas of pyramid construction, with wet and wood of a reduced strength and increased lengths, the results of this experiment would, at least, be able to give a good test of the upright columns by replacing ancient Egyptian conditions and materials with weaker analogs.

An additional problem with this test was my limited personal budget that forced me to buy the cheapest materials in order to test the uprights. The square uprights did not allow for the proper construction of the weight arm, and the square boards did not allow the columns to be tied together correctly at the top bindings. The round dowels (picture below) are able to join at angles other than 0, 90, 180 degrees at the top bindings. The square posts forced me to tie the top bindings together facing each other, in turn, encumbering the natural splaying motion of the legs at the bottom (Figures 36-38).

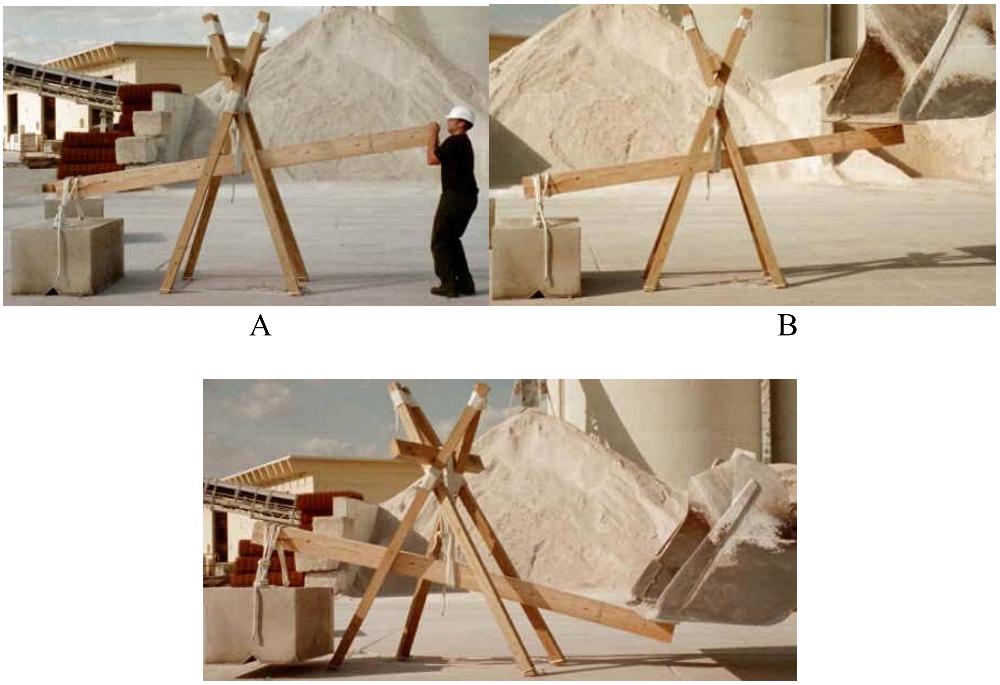
A)  B)  C) 

Figure 8-4. Bindings, column shape, and the ability for the columns to spread out. A) Bindings and the round columns of the 3.63 scale model. B) Shows the bindings and the square columns of the full scale column test. C) Results of the limited ability provided by the square columns.

Rope

Financial concerns also limited the choice of rope used for this test. Instead of selecting the more expensive manila rope, cheaper nylon rope was purchased for the experiment in 5/8-and-1/2-inch diameters. Half-inch nylon rope was used to bind the uprights together. The 5/8-inch was used on the fulcrum and on the block. Half-inch nylon rope used for this experiment has a working load of 525 pound, and a breaking strength of 5760 pounds. The 5/8-inch nylon rope had a working load of 935 pounds and a breaking strength of 9360 pounds. Nylon rope may have been cheaper, but it has the tendency to stretch, having a negative impact on my test. Manilla, like most other natural fiber ropes, does not have the tendency to stretch.

While stretching rope had a negative impact on the geometry of the device, it also provided valuable insights (Figures 8-5 A, B, and C). For example, the points where the rope stretched the most indicated the points of the most stress—the fulcrum and some of the upright columns. Conversely, the points that did not stretch—the bindings at the middle of the columns—showed a minimum of stress. The top bindings did not stretch, because the top bindings were not accurately loaded, due to the failure of the columns to slide past each other. Thus, I could not assess stress at these binding points.



A B

C

Figure.8-5. Full Scale Column Test and stretching rope. A) shows the lever device with the operator to show scale. B) demonstrates the process of lifting the block with the front end loader. C) shows the stretched fulcrum and the splayed legs due the effects of stretching nylon rope.

The fulcrum stretched to more than double its length, despite the multiple wrappings of nylon rope. While this situation limited the lever's vertical movement, it demonstrated the need to place rope at this location that could sustain the weight.

The ropes binding the bottom of the columns together stretched and allowed the legs to splay apart at dramatic angles. The bindings holding the upright columns together at the fulcrum and the top seemed unaffected. During this test, it became apparent that the method of binding the bottoms of the upright columns was ineffective and clarified the need to bind the two legs of each A frame column pairs together. Individually, the A frames themselves did not have a tendency to separate. Therefore, it was more important to secure the two separate A frames together and just loosely connect the columns comprising the A frames.

While the problems related to the elongation and stretching of the rope illustrated weak points, it further weakened the A frame structure and, thus, provided a stronger argument for the strength of the device. Stretching rope forced the upright columns outward, and directed force away from the stronger properties of compressive strength and more toward the weaker properties of bending strength. Despite these problems, the full-scale test was able to sturdily support the weight.

Lever

The lifting beam was built out of three 2 in x 8 in x 12-feet pine planks and two pieces of 5/8-inch thick plywood sandwiched in between, glued and screwed together. The fulcrum rope "saddle" was set extra low to reduce risk in the event of failure. The lifting beam was balanced before it was tied to the "mack" block to ensure that any force used to pick it up was equal to the "mack" block's weight. The "mack" block's weight was 2,780 pounds and the total weight put on the upright columns was a minimum of 5,560 pounds.

In order to accurately determine the force applied to the device, I balanced the lever in order to ensure that the bulldozer, which would provide the counterforce, would provide a measured counterforce. However, this effort was negated by the bulldozer's position of contact with the lever, which was closer to the fulcrum on the weight arm (Figures 8-5 B and C). This downward pressure closer to the fulcrum means that the force exerted by the bulldozer was more than double the weight of the 2780 lb block and that a weight greater than 5560 pounds was actually exerted on the full-size test.

Despite the issues of replacing ancient Egyptian materials with weaker analogs of wood and other problems, the test successfully demonstrated the strength of the upright columns.

The 3.63-to-1 Scale Model Revisited

With solid evidence concerning the ability of the A frames to sustain the forces of lifting these blocks, it was necessary to find methods to reduce the size of the large lever used in the first 3.63-scale model. Reducing the size of the lever was necessary to cut the size and weight of the beam, increase mechanical advantage, and to allow for the possibility that the entire device be constructed from *Acacia nilotica*. Reducing the size of the lever resulted in a study to resolve the limitations of this method, examine the arcs of movement, and to refine the method in order to provide a working model and accurate dimensions for a new large-scale test.

Fabrication of the 3.63 double apparatus model utilized ramin[10] dowels and hemp rope. 5/8th-inch diameter dowels were used for the upright columns and 1 ¼-inch diameter, 48-inch length dowels were used for the levers. The hemp rope used for the upright columns had a breaking strength of 48 pounds, and the rope used for the tourniquet harness and for connecting the block to the lever had a breaking strength of 70 pounds.

The double apparatus 3.63-scale model was modified somewhat from the first 3.63-scale model. The levers make contact with each end of the block, rather than in the middle. The A frames are modified slightly, by shortening the 2 legs of the columns closest to the block and lengthening the 2 legs away from the block in order to tilt the upright structure closer to the block. This was done to bring the fulcrum closer to the

---

[10] For a listing of the mechanical properties related to strength, see table B-1

block as well as reduce to the space taken up by the upright columns closest to the block. Two clear advantages of employing two devices is that each lifts half of the mass, and produces twice the mechanical advantage; also, the diameter of wood used on the device can be reduced since the apparatus now only sustains half of the weight.

This model was able to generate approximately an 8.5-to-1 mechanical advantage over the block, in comparison to the approximately 3.5-to-1 exhibited in the first 3.63-scale model. The 1.25-inch diameter, 48-inch dowels were much smaller than the large, and yet undersized 1.5-inch diameter, 6 feet long banister railing used in the first 3.63-scale model. The upright columns used in the second test were also thinner, ½-inch diameter dowels vis-à-vis the 7/8ths dowels used on the first 3.63-scale test.

While this model successfully demonstrated the capability of reducing the dimensions of the lever and columns used in the first 3.63-scale model, there were certain considerations that needed to be addressed concerning the arcs of movement of the levers.

Arcs of Movement

Reducing the distance between the fulcrum and the block required the consideration of a number of factors: namely, the vertical and horizontal arcs of movement for the lever and position of the A frames. An arc or sweep of movement is the space and distance traveled by the lever during operation (Fig. 8-6). This arc or sweep, is part of a large circle of movement that has a impact on the efficiency of the device.

An efficient levering operation utilizes the area within the sweep that travels with the minimum of movement. An efficient use of a vertical arc, for example, has at its center a level halfway point. The vertical movement of the lever in lifting the block moves within part of a large imaginary circle. Movement at the top or bottom of the arc or sweep, would not move the block up or down. The sweeping motions closest to the sides of the circle generate more vertical motion, especially near the portions of a horizontally level diameter. Therefore, there are diminishing returns on vertical movement when the lever is traveling up and down beyond the center, or level point. In other words, with each degree away from the level halfway point, the levers lose some of their ability to generate movement upward in exchange for movement toward, or away from the device.

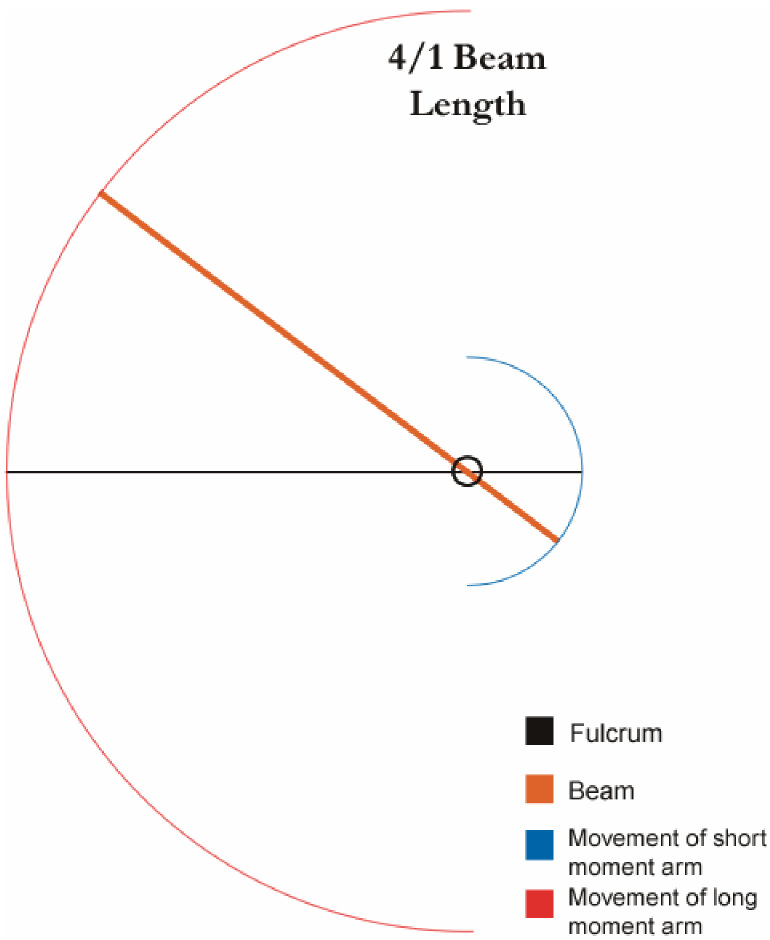
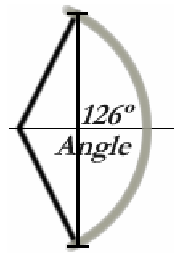


Figure 8-6. Arcs of movement of a 4-to-1 mechanical advantage lever



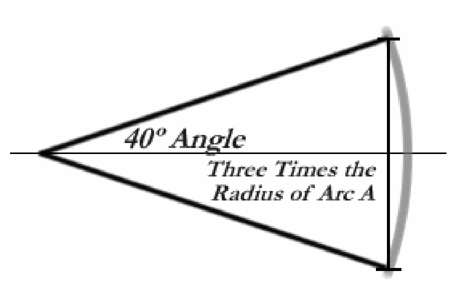


Figure 8-7. Different arcs of movement due to changes in radius. Arc A has an 'X' radius length with a 126-degree angle arc of movement to reach 'Y' in height. Arc B has three times 'X' radius in length and needs a 40-degree central angle of movement to reach 'Y' in height.

The degree of the central angle[11] of the sweep correlates conversely with lever efficiency (Figures 43 and 44). The use of smaller central angles results in a more efficient levering operation and the use of a larger central angle results in a less efficient levering operation. To use the vertical sweep as an example, larger sweeps resulting from larger distances between the block and fulcrum employ a much larger circle. Therefore, when moving a block vertically, the arc is larger and flatter, utilizes a larger portion of the area near the efficient level halfway point, and is further away from the inefficient top and bottom of the circle. Conversely, smaller sweeps, or smaller distances between the block and the fulcrum, use a less efficient vertical movement because the movement of the sweep of the lever quickly moves toward the inefficient top and bottom sections of the arc. Thus, an effort to reduce the distance between the block and the fulcrum runs into a requirement to factor in proportionally more movement from the lever to generate the same distance of movement due to this problem of diminishing returns from a smaller arc of movement.

[11] A central angle has its endpoints on the circumference of the circle and its center at the center of the circle.

Issues with the Double Arcs of Movement

Operating the 3.63-scale double levering device model illustrated unforeseen issues regarding the synchronized and unsynchronized lever sweeps   Since this model calls for two coordinated lever sweeps, the movement of the block needs to consider the combined effect of non-vertical movements of these levers when moving the block up and over onto the next tier. The push and pull of each arc of movement are compounded during the points where the levers are at their most vertical and horizontal. In other words, in the positions where the block is resting on the lower or higher tier, the levers pull away from the block. When the levers reach the level point of the arc, the levers are closest together; the levers then again pull away from the block at the maximum vertical height. At the point where the levers have reached the maximum vertical height, the levers then operate on the horizontal movement onto the next tier. During the horizontal operation of the lever, the push and pull from the arcs of movement are repeated.

A solution to these problems related to the arcs of movement, was accomplished by a small amount of rope separating the lever and the block. For this model, a 1-inch length of rope between the block and the lever, and to a much lesser degree, the movement of the rope fulcrum easily addressed these issues.

Problems arose during this model’s lift if the combined levering operations were not coordinated during the horizontal levering operation. Once maximum vertical lift had been achieved, if the levers did not operate in a relatively simultaneous horizontal movement, the block had a tendency to twist. Twisting does not allow the block to be placed onto the next tier. During the multiple experiments of the double apparatus of 3.63-scale experiments, it was clear that the levers did not need to move in an entirely synchronized motion in order to guard against block twist. The levers needed to be coordinated enough to ensure that one lever did not attempt to move the block horizontally much faster than the other.

This problem needs special attention when moving the block up to the terminus tier. Due to the homogenous size of the blocks in my experiment, there were two different lengths of horizontal block movement. The first, and shortest, occurs when the block is moved up to a completed tier. The second type occurs when moving the block up to the terminus tier and requires twice the horizontal distance of the first movement – creating a greater opportunity to twist the block because of the increased horizontal movement.

Arcs of Movement and the Staircase Ramp

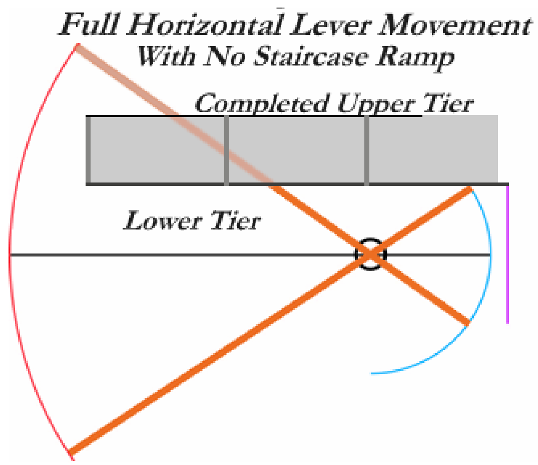


Figure 8-8. Encumbered horizontal lever movement due to the pyramid superstructure.

Levering hypotheses that employ one large levering movement to lift the block benefit spatially from a staircase ramp. Hypotheses of this ilk utilize much larger levers, with much larger sweeps than incremental levering hypotheses. The method proposed here also employs a large horizontal sweep. If this device were to operate on an unfinished tier, the lever would be limited by the tier on vertical movements and blocked by the superstructure during horizontal movements. A staircase ramp allows the lever to swing below the device to employ an efficient vertical sweep and it allows some space between the device and the superstructure to allow the lever to employ a more efficient horizontal sweep.

Unfortunately, the level ground in both the models and the full-scale tests imposed limits upon the vertical arc of movement that would not be present in an actual pyramid construction effort. Since my model and full-scale tests rested on the ground, their positions limited an efficient arc of movement, and thus, constrained my ability to shorten the distance between the block and the fulcrum. This problem forced these models and the full-scale test to employ larger beams than necessary in order to maintain the mechanical advantage.

Refining the Device

Efforts to reduce the distance between the fulcrum and the block required modification of the apparatus to allow the block to be positioned closer to the upright columns. This was achieved by shortening the columns on the side facing the block, and lengthening the columns furthest from the block to tilt the device towards the work area. This moved the fulcrum closer to the block as well as reduced the distance the A frames extended past the fulcrum.

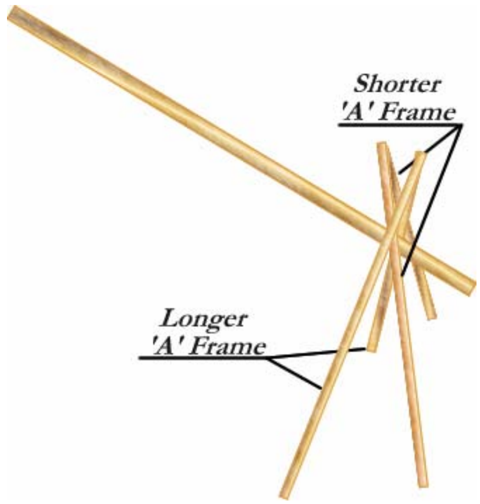


Figure 8-9. Device after column refinement.

Narrowing the base of the device by pushing all of the upright columns together was also considered as a viable option to reduce this space between the A frames and the block. The major concern here was to not impede on the space given for the placement of devices on tiers above and below. Since there are two levering devices for each tier, this space is necessary to provide some room for the upright columns for the devices on the tiers above and below. The results of this 3.63-scale model, which was spread out to provide lateral movement onto an uncompleted tier, still provided ample space for other devices. Levering devices that serve to operate on completed tiers require half of this horizontal movement and require even less space on the staircase ramp.

The results of these double lever 3.63 tests demonstrated that much more mechanical advantage can be had while reducing the size of the wood used in the levering devices. While the double apparatus method required twice the amount of wood components, the diameters and, in the cases of the levers, diameter and length, of the beam, crossbeam, and columns could be reduced to a significant degree. These reduced dimensions of the timbers required for the device allowed *Acacia nilotica* to serve as a principle choice of timber.

The Large-scale Experiment

The purpose of this experiment was to test the device at a large-scale. The sizes of the materials used in this experiment were derived from information gleaned from the second 3.63-scale model and from limitations imposed by the University of Florida for safety reasons. This experiment succeeded in lifting two 2500-lb concrete blocks and one 1250-lb concrete block.

The dimensions of the blocks for this test resembled the proportions from the second 3.63-scale model. The block height was 56.80-cm. The blocks length and width was 91.90-cm. The blocks were fabricated from concrete, which has a similar density to the limestone used on the Egyptian pyramids[12].

The dimensions for the wood and rope were only partially derived from the 3.63-scale model. Safety and commercial availability were the overriding concerns. The wood and rope that I was able to purchase commercially needed to exceed the minimum of ANSI standards for the weakest portions of the device: the lever and the rope.

The wood used for this experiment was the closest commercially available analogs for *Acacia nilotica* in terms of mechanical properties related to strength. While they are not perfect analogs to *Acacia nilotica*, they represent the closest similarities to *Acacia nilotica* from all the previous experiments.

The rope used for this experiment was stress-rated manila. The fulcrum and connections to the block used 1-inch diameter rope. The rope used to tie the bottom of

---

[12] Concrete has a density of 0.084 lb/in^3 (2320 kg/m^3) (Ugural 1991: 404-405) Dense limestone has a density of 2850-2650 kg/m^3 and porous limestone has a density of 2600-1700 kg/m3 (Arnold 1991:28).

the upright columns was ½-inch. The rope used to bind the upright columns together at the middle and top had a diameter of 3/8-inch.

The experiment focused on lifting fifteen 2500-lbs blocks, and two half-sized blocks[13] in the construction of a three-tiered pyramid. The full sized blocks would form a simple, stepped pyramid that would not require the construction of a separate staircase ramp due to the small size of the superstructure. In other words, the levers would be free to operate horizontally without interference from the superstructure due to its small size.

Due to issues discussed below, the complete construction of the pyramid never took place. However, this experiment adequately tested the device twice by lifting 2 blocks with lifting devices operating on the same space needed for levering operations on completed tiers, completed tiers, and the last blocks at the top.

Materials Used in the Large-scale Experimental Tests

Blocks

While the focus of this experiment centered on lifting the blocks at the top of the pyramid, there were certain limitations imposed on the project that restricted the weight of the blocks. As a result, this experiment could not involve full-scale blocks, or larger weights to represent the capstone. This experiment does not incorporate the capstone and the blocks used are smaller than the average pyramid block, but it nonetheless still provides a good test of the device.

The location of the experiment at the University of Florida imposed some liability concerns on this project in order to limit the chance of injury. Dr. Properzio and Glenn

[13] The half-sized blocks were to be used as a removable support for the levers when lifting the top block. These blocks, which were of the same height of the other blocks but half the width, would fit on the second tier to give three blocks width of space for the levering devices engaged in lifting the final block.

Ketcham of the Department of Environmental Health and Safety of the University of Florida, required the reduction of the mass of the blocks by half-to-1.25 tons and the addition of rebar connections for the ropes on the blocks for safety and liability issues. When compared to an average Great Pyramid block, the scale of this test is approximately 1-to-1.277. These rebar connections for the ropes sat within recessed pits to allow the blocks to sit on top on one another. Though these weights were reduced from the average Great Pyramid block, this average does not consider the reduced size and weight of the blocks at the top of the superstructure.

Most block-lifting hypotheses utilize the 2.5-ton average sized block from Khufu's pyramid, it therefore is important to point out the reduction in block size at the top of the pyramid, where this method applies. The blocks near the top of Khufu's pyramid are of a smaller size and a lower density than the average pyramid block (Arnold 1991: 167, Lehner 1997: 67). Results of a microgravimetric study, normally used to assess the foundations of damns and nuclear power plants, by two French companies at the behest of the Egyptian Antiquities Organization (EAO) indicated that the Khufu's pyramid's macrostructure consists of 34 major 'blocks' with a low density block at the top (Lehner 1997: 67). While the 5-foot high (1.49 m) first course indicates an approximately 7 ton casing stone, the stone in the 1.75-foot-high (0.54 m) courses near the top had a weight of no more than 1 ton (Arnold 1991:167, Isler 2001: 284).

These blocks at the top are also more homogenously shaped, with the no exception of the capstone, in relation to the wide variety of block sizes found in the rest of the monument. These homogenous shapes help the incremental and one large levering method to function efficiently and quickly. In other words, since these blocks are similarly sized, there is a reduced need to modify the methods to account for large blocks.

The capstone was not a focus of this experiment. The techniques of moving the capstone up with the development of each tier proposed by Fitchen (1978, 1986) and later by a Craig Smith (1999), a civil engineer, seems to work well with my levering method, with the addendum that the capstone be brought up to the top third of the pyramid or the terminus tier reachable by ramp (Smith 1999), because it does not use wooden cribbing that interferes with the placement of the blocks under the capstone. Instead, levering devices could be positioned around the capstone and simply lift one side, like Fitchen's method, or the entire stone, and then blocks could be inserted underneath.

Though this experiment was forced to utilize blocks of a 1.277-scale[14] of an average Great Pyramid block, it is important to recognize that an average pyramid block within the top third of this pyramid is reduced in dimensions, density, and mass. Therefore, the difference in weight from this experiments' block size and the average block size of the section of the Great Pyramid from which this method is designed to work, is much closer.

Wood

Since *Acacia nilotica* served as the model for the wood used in this device, I attempted to purchase wood with similar mechanical properties of strength. The results were shagbark upright columns that were only slightly weaker than *Acacia nilotica* and the use of longleaf pine for the lever (the weakest portion of the device), which is weaker

---

[14] If an average sized, 2.5 ton Great pyramid block is used as model for scale, then the scale of the large test would be at 1.277 scale.

than *Acacia nilotica* [15] . I purchased nine 2-inch diameter and 8 feet long dowels, made from shagbark hickory[16] to serve as the upright columns. The mass among these dowels ranged between 10 pounds to 6.5 pounds. The number 1 dense grade yellow pine levers were 4.91-inch x 4.91 (4 29/32)-inch square beams with beveled corners. The cross beam was cut from an ungraded yellow pine 5.5 x 5.5-inch post, cut in half with beveled corners.

The various species of true hickories were the closest commercially available analog to *Acacia nilotica* that I could find in the Southeast. However, commercially available seasoned hickory is sold in widths up to only 2-inches thick. Therefore, the upright columns could only be purchased in this timber species.

On the other hand, yellow pine beams were more easily obtained in dimensions needed for the lever. The first four beams, purchased from Red Hills Lumber in Moultrie Georgia, were not stress rated, though they were nearly free of knots. These foursquare beams were 5.5-inches in diameter and 12.5 feet long. When processing these beams, I found a large section of heart rot within one of the beams. Therefore, I used only one of these beams in the experiment to lift up a half-sized block. I used a section of the good end of the beam with heart-rot, split and half with beveled corners, as the cross beams in all the experiments.

After the heart rot problem, a source of no.1 dense yellow pine was located. I acquired three nominal 5 x 5 (4 29/32^{-inch} actual size) diameter, 12.5 feet long planed

[15] See appendices A and B for information regarding the strength of yellow pine and Acacia.
[16] See B-1 for a listing of the mechanical properties related to strength.

beams. These beams were visually rated as number 1 dense[17]. This rating allowed for an accurate measurement of the safe working stresses of the levers by ANSI specifications.

Determining the strength and structural integrity of wood can be a difficult proposition. Wood is immensely varied in its structure and is a biological material with varying properties of strength within the same species. Moisture, knots, density, shape, and direction of the grain, shakes, and seasoning checks also affect these mechanical properties. Excessive bending of standing trees from wind or snow, rough handling, or irregularities in the ground can produce excessive compression stresses along the grain, which cause minute compression failures (USDA Forest Products Laboratory 1999: 4-32). Examining for compression damage is crucial when taking into account that bending wood fails first with compression damage, then breaks due to tension failure. Moreover, wood weakens with periods of prolonged or repeated loading, otherwise known as rupture creep. For these reasons, it is very beneficial to utilize pieces of graded lumber in order to perform calculation of safe working stresses.

The outermost fibers are where the greatest loads occur during bending and the shape of the beam affect its strength. A square beam with its flat sides positioned to bear the extreme fiber load has more material working on these extreme fibers. A square beam turned to position its neutral axis on a diagonal and its corners as the extreme fibers may have less material to bear these loads but it can support more loads at these extreme fibers. This phenomenon is known as the “support theory” where the extreme fibers are supported by a larger quantity of much less stressed material (Hoyle 1972: 100-101). In the case of the square beam turned to have its neutral axis on a diagonal (a diamond cross-section), there is a 41.4 percent increase in apparent unit bending strength (Hoyle

[17] See B-2 for a listing of the mechanical properties related to strength.

1972: 100-101). This is important to consider, since the square beam may rotate during the experiment. For these reasons, it was important for purposes of safety to have the weakest part of the levering device be visually graded in order to accurately calculate safe working loads.

To accurately determine the strength of the two number 1 grade yellow pine beams, I used the ANSI/AF&PA National Design Specifications for Wood Construction figures. The variables that concerned me were the factors of load duration, size, and form. Form, or the issue discussed above concerning a square member turned to position its neutral axis diagonally, was important to address due to the possibility that the levers would twist inside the rope harnesses. s 6 and 7 show the bending strength of the levers used in this project with both square and diamond cross-sections. D-1 shows the bending strength of an *Acacia nilotica* lever, with more than a 4-to-1 mechanical advantage, when lifting a hypothetical 5000-lb block.

There were a few concerns I had when calculating the sizes needed for an *Acacia nilotica* double lever device when lifting 5,000-lbs. Since the values used for duration of load were unclear, I factored in an exaggerated time and duration into this load. For the calculations I performed, I used ANSI standards for safety that gives the beams a sufficient safety factor to sustain the load over a ten-year period. I also used the figures from appendix A-2, which calculate safe working stress levels for *green*, not seasoned wood. It is important to note that A-1 shows a 79 percent increase in strength of modulus of rupture vis-à-vis green and seasoned *Acacia nilotica*. For these reasons, the sizes here were exaggerated and well above what is needed to lift the mass.

Fabrication of the Large-Scale Test

Blocks

The blocks used in this experiment were fabricated by myself at CSR Rinker, in Gainesville, Florida, with mostly free concrete. These blocks used rebar connections, purchased at CSR Rinker in Cocoa, Florida, and recessed pits for the metal connections. Fabrication of the 2500-lb blocks involved creating a wooden form (mold) to hold the wet concrete. Late in 2003, I began assembling the concrete forms at CSR Rinker in Gainesville, FL. The forms were made from plywood and buttressed by two 2-feet x 4-feet rectangles securing the outside perimeter of the plywood box. The dimensions for the molds are shown in figure 8-10.

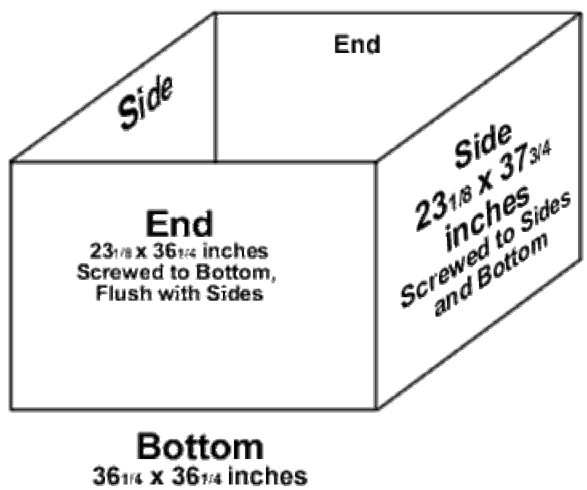


Figure 8-10. Concrete form dimensions.

Fabricating these concrete blocks involved disassembling the form to remove the dried block, reassembling the form, oiling the inside of the form to prevent the concrete from sticking to the wood, pouring the concrete, kicking the mold a few times to release trapped air, smoothing the top, placing the rebar inside the wet block, scooping out the recessed pit, and final cosmetic smoothing of the block. The entire process of fabricating these blocks took months to complete and depended on the generosity of the company, the drivers, and the loader operator. The pictures below illustrate these steps.

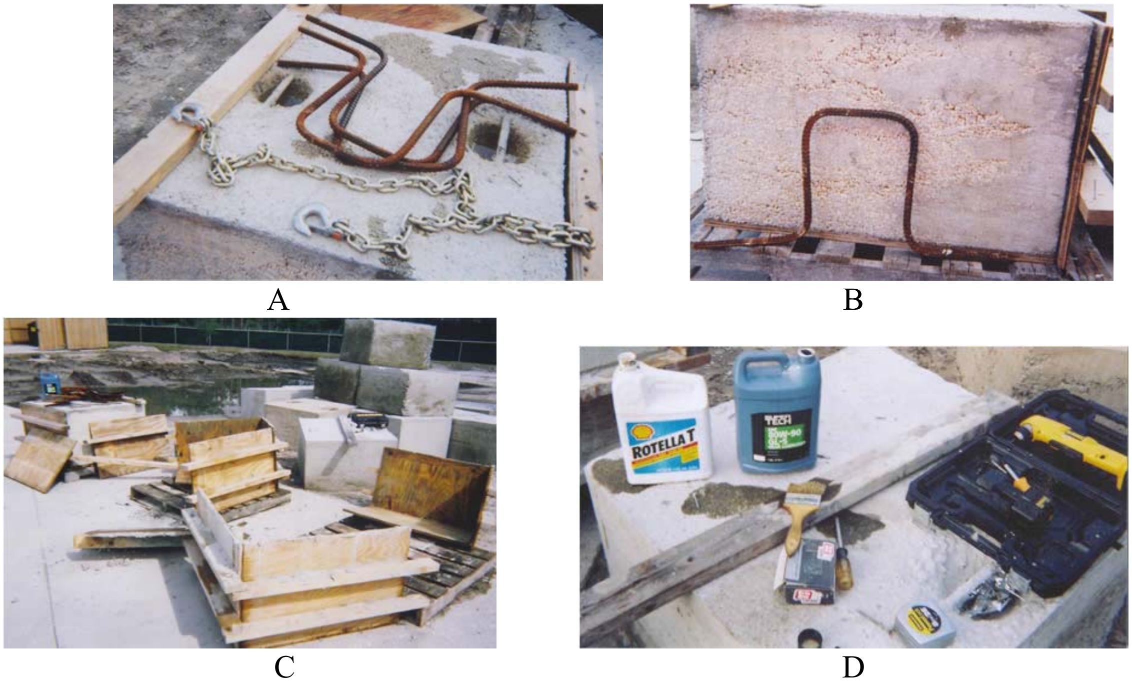


Figure 8-11. Tools and items used fabricating the concrete blocks. A) Chain used to lift the blocks and the ½ inch rebar that served as connections. B) Depth of the rebar connection against a profile of a completed block. C) Concrete forms used in the fabrication of the blocks. D) Oil used to lubricate the wooden forms against the concrete, the brush to apply the oil, the powered and manual drills to assemble and disassemble the forms, wood screws, and tape measure.

A

B

Figure 8-12. Method to remove the block from the concrete form. A) Process of attaching the chain to the block. B) Front end loader moving the block off of the concrete form.

A

B

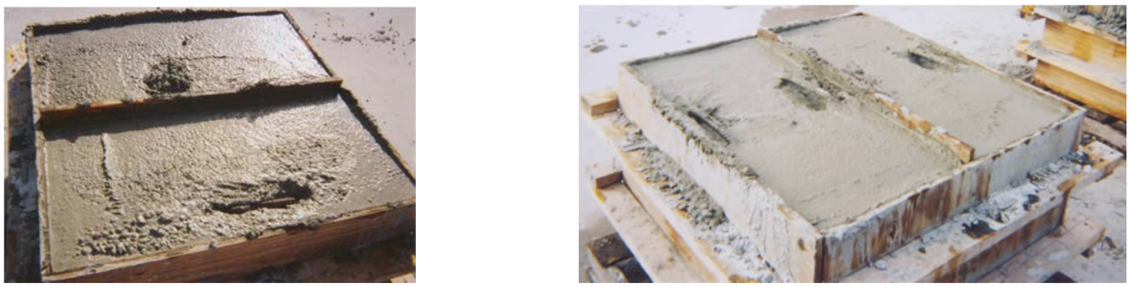
Figure 8-13. Pouring Concrete. A) Disassembled form which is half-oiled. The oil is necessary to prevent the concrete from sticking to the wood. B) Completely oiled and assembled form in the process of taking on concrete.

A

B

Figure 8-14 Smoothing the surface.

Figure 8-15. Placing the rebar inside the wet concrete block



A B

Figure 8-16. Wet Blocks with rebar. A) Block before the recessed pits are scooped out around the rebar connectors. B) Completed wet block, with recessed pits.

Wood

Fabricating the large-scale levering devices required some modifications in the dimensions provided by the 3.63-scale models. Proportionally, the 3.63-scale model's uprights would scale up-to-1.78-inch diameter uprights and the levers would scale up to 3.55-inch in diameter by 11.37 feet long. When increasing scale, the amount of weight increases at a geometric weight, specifically, to the third power. The strength of wood does not increase at this rate. Moreover, the experimental test used weaker wood for the levers than what was used for the model. For these reasons, it was important to redesign the geometry of the device for this scale. The first step was to determine the proper sizes of the wood through engineering calculations. Then I determined the geometry of the device via a full-scale mockup (Fig. 8-17).

Figure 8-17. Method used to determine the geometry of the large-scale device.

The first step of this procedure was to put together the upright columns and a cardboard representation of the lever. For this, I first cut the top bands on the upright columns. I then loosely tied these with rope to formulate the A frames. Afterward I used bungee cord to connect the two A frames together. At this point, I placed a rectangular cardboard mock-up of the lever, with a diameter of 5.5-inches, between the uprights. This cardboard lever reproduction was then situated on a cross beam and rope harness. Measuring the movements of the lever allowed me to finalize its dimensions.

Cutting the grooved bands for the bindings on the upright columns was preformed identically to those of the 5 and 3.63-scale model. I used a die grinder to cut the boundaries and the material within the bands (Figure 8-18).

A

B

Figure 8-18. Cutting the bands into the upright columns. A) Method used to cut the perimeter. B) Technique used to cut the material within the boundaries with a carbide tip.

Cutting the beams required the use of a circular saw. With a finishing blade, I beveled the corners of the beams, approximately ½-inch in depth with a 45-degree angle cut. I then rounded these edges with a hand planer. This was done primarily to ensure that no sharp angles would cut into and damage the rope harness and to allow the harness to tighten and better secure the beam. The circular saw was also used to cut the notches, placed 2-inches from the end (1.5-inches wide and 1.25-inches deep) at both ends of the levers for the rope connections to the block.

Cut portions of the beam with heart rot served as the cross beam that supports the rope fulcrum. A 4-foot section of beam was cut in half. Each of these halves were rounded by 45 degree beveled corners.

Rope

I used manila rope in 3/8-, ½-, and 1-inch diameters for this experimental test. This rope, purchased from the Indusco Group, meets design requirements according to federal specification T-R-605B, grade 1. The 3/8-, ½-, and 1-inch diameter ropes have a breaking tensile strength of 1215, 2385, and 8100 pounds, respectively. Working loads are 20percent of the breaking strength. I used the 3/8-inch diameter rope to bind the uprights together (Fig. 8-19), ½-inch rope to hold the bottom portions of the columns together, and the 1-inch diameter rope for the fulcrum and the connection between the block and the lever.

Figure 8-19. Binding the columns with 3/8th inch rope

Experimental Tests

After transporting the blocks to the Baughman Center at the University of Florida via flat bed truck, I cut a 10 x 10-foot level footprint into the ground and had the Physical Plant move the first course of blocks. It was necessary at this point to have the Physical Plant situate the rest of the blocks around the footprint, since I had been notified that they would not be able to provide a loader to move the blocks to the working area during the experiment.

The two experimental tests occurred during April 21 and 25, 2004. The first test involved correcting some oversights, which were forgotten from the 3.63-scale double lever model. The second day of lifting proceeded much more smoothly, resulting in block lifted one tier in less than a minute. At the building site I had 16 full sized blocks and 2 half-sized blocks, intended for use on the second tier. These two smaller blocks were intended to increase some of the workspace in order to allow two devices to lift the top block. The resulting space would be equal to three of these blocks. Therefore, the process of lifting one block from the bottom course that was three blocks wide would adequately test the device.

Nine of the blocks were placed onto a leveled portion of ground by physical plant loaders. The two half blocks and five full-sized blocks were positioned around this bottom course. Unfortunately, I was unable to convince the physical plant to replicate the conditions of the Nova experiment where front loaders were used to assist in the construction process. Instead, my devices, which were designed to remain in one position on level tiers, would now be required to move around to lift blocks situated around the pyramid. I believed that this movement was problematic because, while the footprint remained level, the blocks were of differing heights by approximately an-inch, so the uprights would not all touch the surface. Moreover, the ground, where two of the legs would rest, was not leveled. To address these issues, I used books as shims to compensate for these aberrations; and I used plywood to keep the upright column's legs from sinking into the ground.

I found during the experiments that the upright columns easily support the weights while only three legs sat on the working surfaces (Fig. 66). Despite the placement of books under the columns, the levers settled some during lifting; sometimes one leg would not make contact with the ground or block.

Figure 8-20. Four column device with one column not touching the ground. Books used as shims were removed for this photograph and to test 3-leg variability.

Regardless of this, the uprights were able to effortlessly support the weight. To test 3-leg variability, I kicked these three uprights under load to determine their stability. I also shifted the remaining three uprights under load with very forceful strikes, finding no problems with column stability.

April 21, 2004

The experimental test on April 21 lifted one half-sized, 1250-pound block and one full-sized, 2500-pound block (Figures 8-21 and 8-22). The half-sized block moved up and over one tier without complication. The lifting of this block was the same for the full-sized block, with the no exception that the lifting movements needed to be coordinated. I first placed the upright columns on the work area. Then I placed the cross beam and rope harness on the uprights and slid the lever through the rope fulcrum. After this, the lever was connected to the block. Lastly, the fulcrum was adjusted toward the block to maximize the mechanical advantage.

However, there were some problems with the first lift that resulted from deviations from the 3.63-scale double lever model. Due to a lack of volunteers, I helped operate one of the levers while lifting the full sized block. Since I was not able to coordinate the lifting effort, one of the levers moved much faster during the horizontal movement to the next tier and, thus, twisted the block (Fig. 8-22).

Figure 8-21. Experiment with one levering device preparing to lift a block weighing 1,250 lbs.

Figure 8-22. Two-thousand Five-hundred-pound block raised one tier, improperly and slowly placed due to the twisting caused by uncoordinated levering movements.

As a result, the block was not able to move fully onto the next tier without some help by metal crowbars. During this lift, I did not replicate the simple rope harness of the models, where the ropes harness was simply looped around the lever. Instead, I alternated each rope around and then under the lever. This type of harness did not allow me to slide the rope harness closer to the block as easily as the rope harness on the 3.63 model – thus decreasing the mechanical advantage of the levers.

April 25, 2004

The second experimental test on April 25 involved lifting one more block and moving the blocks on the second course into place. The main thrust of this experimental test was to correct some of the problems of the April 21 lifts. The problems related to coordinated lifting were easily corrected since there were enough volunteers to allow me to direct the experiment. Once this was achieved, the experiment worked as planned.

Using the information gleaned from the problems of the first lift, we moved the block up one tier in less than a minute. We were able to generate more mechanical advantage over the first lift by replicating the rope harness used in my models. Moreover, this type of harness was much simpler to slide up the beam. The rest of the activity involved moving the blocks on the second tier with rollers and crowbars.

Figure 8-23. Raising the block

Figure 8-24. Block at the highest vertical point

Figure 8-25. Moving the block vertically onto the next tier

Figure 8-26. Disconnecting the block

I was unable to coordinate a third experimental test to complete the structure. The summer had ended the unseasonably dry weather, adding complications of rain and humidity to the wood and ropes. Furthermore, volunteers had left campus. For these reasons, I was unable to complete a three-tiered pyramid.

However, lifting the blocks within the given space had proved the effectiveness of the levering device. While providing enough room for the levers to swing two full-sized blocks up and onto a higher tier in less than a minute, the device still provided ample space for the placement of other lifting devices. The entire apparatus worked well and was exceptionally sturdy. Rope did not stretch any visible distance. The rope harnesses that secured the levers functioned as intended and did not slip during the lifting operations. The wood seemed to carry the weight easily. One participant felt confident enough about the device that he 'rode' the lever upwards, during an effort to move a block down. The very por levering device worked quickly and safely, was constructed out of appropriate materials and technology to Old Kingdom Egypt, and demonstrated that a levering method could work in the small spaces offered by the pyramid angle of ascent to lift large blocks at the top of the superstructure.

CHAPTER 9
DISCUSSION

Page 209 of the University of Florida copy of Mark Lehner's book, *The Complete Pyramids*, unintentionally and appropriately encapsulates the wide range of views regarding ramp and levering methods of raising pyramid blocks. Immediately following the bold title of 'Raising stones' Lehner states, "…it is widely agreed that ramps were used to lift the blocks" (Lehner 1997: 209) and then references a page in his book that explains the topic in greater detail. After this, he describes the feasibility of levering hypotheses, through the effort of Martin Isler in the Nova Experiment. Lehner discusses in some detail about the functional and archaeological, weaknesses of Isler's levering method, yet he admits that some sort of levering device needed to be used where there were no longer room for ramps. In the margins of this brief, yet detailed, explanation of the current state of the combined ramp and levering method is the 5-word notation of an unknown student summing up the contents of that page with the words, "*Tried levers but didn't work.*" This rash dismissal of levering techniques based on functionality is frequently repeated in popular discussions on pyramid construction.

The problem Lehner and other Egyptologists face when writing a combined ramp and lever method of raising pyramid blocks is the lack of a successfully tested method of levering. Since the previous levering methods use precarious cribbing, take to much time and space, then the only resort is to say that levering methods were used only when ramps could no longer be used. In other words, since the previous experiments demonstrated levers as impractical, they state that levers should only be employed when ramps are no longer functional.

The argument of functionality pervades the discussion of methods of ramps and levers. Levering designs are particularly susceptible to arguments of efficiency and functionality because there are no viable levering methods.

The design and experiments described in the preceding pages outline my attempt to design a functional levering design to lift Egyptian pyramid blocks and to test the lifting device within historically and archaeologically appropriate materials and technology. I connected every piece of technology and all materials comprising the device to the cultures under the influence of Old Kingdom Egypt. Mostly, the materials and technology used by the device can be found within Old Kingdom Egypt. The technology with no stong inferences, levers used in lifting heavy weights vertically, was supported by many indirect inferences and is known to exist within Sumeria – a culture with a long history of technological exchange with Egypt predating the era of pyramid construction. While *Acacia nilotica* is found in Egypt from the predynastic period to the modern era, it is indeterminate to exist in Old Kingdom Egypt in sizes mentioned by the Greek Theophrastus. However, *Acacia nilotica* can be found along the Nile in Northern Sudan, another region with a tremendous amount of technological and material exchange with Egypt, predating the era of pyramid construction.

In regards to functionality, my design requires less space, and a reduced amount of material than the methods presented by Isler, Hodges, and Keable, since my design does not need to use cribbing as a method to move the blocks upward. My design did not have the issues of unsafe operation shown in Isler's portion of the Nova Experiment; it also lifts blocks faster than Isler's and Keable's experiments, and does not require the use of specialized and precisely cut uniform packing blocks.

A critical assessment of the device that I present will note that the blocks I use on my large-scale experiment have less mass than the average block, or the capstone of the Great Pyramid. Nonetheless, I address issues individually. The block sizes at the top of the pyramid are smaller and of less density (p. 90). Furthermore, through the various engineering equations and experimental data I present, I am able to determine conclusively that the weakest part of the device is the lever itself, and that the upright columns are able to support tremendous weights. I built and tested an upright structure, with weaker materials and dimensions that sustained over 5,560 pounds. I have presented data for the size of an *Acacia nilotica* beam[1] that can lift the 2500-pound weight. This device accommodates Fitchen's method of lifting the capstone with the development of each course, by using multiple levering devices. For these reasons, I feel confident that the final series of experiments of the device that I present address the issues of scale.

On grounds purely based from research, functionality, and efficiency, it is my assessment that the device that I present is a viable levering apparatus to complement ramping methods under an amalgamated ramp and lever method to move blocks up the pyramid superstructure.

[1] As mentioned on page 94, these calculations were computed with figures for green – not seasoned – Acacia *nilotica*.

APPENDIX A

ACACIA NILOTICA

Table A-1. Physical and mechanical properties related to strength (Shukla and Verma 1990: 805-806).

Property	*Acacia nilotica* (Haryana)		
	Green	Dry	Improvement factor (%)
(1)	(5)	(6)	(7)
Specific gravity $\frac{\text{(Wt. oven dry)}}{\text{(Vol. at test)}}$	0.738	0.771	—
Per cent moisture content	56.1	12.0	—
Weight in kg/m^3	1152	864	—
Shrinkage % Green to oven-dry			
i) Radial	2.9	—	—
ii) Tangential	6.0	—	—
iii) Volumetric	9.1	—	—
Static bending			
i) Fibre stress at elastic limit, kg/cm^2	567	884	55.9
ii) Modulus of rupture, kg/cm^2	847	1516	79.0
iii) Modulus of elasticity, 1000 kg/cm^2	83.5	147.5	76.6
iv) Work to elastic limit, $kg\text{-}cm/cm^3$	0.218	0.325	48.9
v) Work to max. load, $kg\text{-}cm/cm^3$	0.718	0.470	-34.5
vi) Total work, $kg\text{-}cm/cm^3$	1.747	1.167	-33.2
Impact bending			
i) Fibre stress at elastic limit, kg/cm^2	941	1285	36.6
ii) Max. height of drop, (22.7 kg hammer) cm	94	103	9.6
iii) Modulus of elasticity, 1000 kg/cm^2	117.9	181.7	54.1
iv) Work to elastic limit, $kg\text{-}cm/cm^3$	0.420	0.508	21.0
v) Izod value (brittleness test), kg-cm	245	140	-42.9
Compression parallel to grain			
i) Comp. stress at elastic limit, kg/cm^2	322	419	30.2
ii) Max. crushing stress, kg/cm^2	483	668	42.5
iii) Modulus of elasticity 1000 kg/cm^2	104.8	108.4	3.4
Compression perpendicular to grain			
i) Comp. stress at elastic limit, kg/cm^2	139	191	37.4
Hardness (Load to embed 1.128 cm diameter steel ball to half diameter)			
i) Radial, kg	1049	833	-20.6
ii) Tangential, kg	1079	823	-23.7
iii) End, kg	1050	946	-9.9
Shear			
i) Radial, kg/cm^2	155.4	185.4	19.3
ii) Tangential, kg/cm^2	160.2	185.0	15.5
Tension perpendicular to grain			
i) Radial, kg/cm^2	78.6	108.0	37.4
ii) Tangential, kg/cm^2	101.7	93.0	-8.6
Tension parallel to grain			
i) Tensile stress at elastic limit, kg/cm^2	790.8	1071.5	35.5
ii) Max. tensile stress, kg/cm^2	1233.4	1311.1	6.3
iii) Modulus of elasticity, 1000 kg/cm^2	108.6	118.6	9.2

Table A-2. Safe Working Stresses for Structural Purposes (Shukla and Verma 1990: 808).

Property	*Acacia leucophloea* (Haryana)	*Acacia nilotica* (Haryana)	*Acacia tortilis* (Haryana)	Teak
Modulus of elasticity, 1000 kg/cm² (For all grades and locations)	73.7	83.5	90.7	109.7
Bending and tension along grain Extreme fibre stress, kg/cm²				
(a) Inside location	129	169	147	168
(b) Outside location	107	141	123	140
(c) Wet location	86	113	98	112
Shear				
(a) Horizontal (All locations)	11.5	17.4	12.3	10.4
(b) Along the grain (All locations)	16.4	24.8	17.5	14.9
Compression parallel to grain Extreme fibre stress, kg/cm²				
(a) Inside location	77	121	89	104
(b) Outside location	68	107	79	92
(c) Wet location	56	88	65	75
Compression perpendicular to grain Fibre stress at elastic limit, kg/cm²				
(a) Inside location	37	79	47	49
(b) Outside location	29	62	37	38
(c) Wet location	24	51	30	31

APPENDIX B
DOMESTIC WOOD

Table B-1. Physical and mechanical properties of Yellow Pine (Longleaf, Shortleaf, Slash, and Pitch), Hickory, Douglass fir, and Ramin (USDA Forestry Products Laboratory 1999: 4-10, 4-12, 4-13, and 4-22).

Common species names	Moisture content	Specific gravity[b]	Static bending: Modulus of rupture (lbf/in²)	Static bending: Modulus of elasticity[c] ($\times 10^6$ lbf/in²)	Static bending: Work to maximum load (in-lbf/in³)	Impact bending (in.)	Compression parallel to grain (lbf/in²)	Compression perpendicular to grain (lbf/in²)	Shear parallel to grain (lbf/in²)
Pine									
Eastern white	Green	0.34	4,900	0.99	5.2	17	2,440	220	680
	12%	0.35	8,600	1.24	6.8	18	4,800	440	900
Jack	Green	0.40	6,000	1.07	7.2	26	2,950	300	750
	12%	0.43	9,900	1.35	8.3	27	5,660	580	1,170
Loblolly	Green	0.47	7,300	1.40	8.2	30	3,510	390	860
	12%	0.51	12,800	1.79	10.4	30	7,130	790	1,390
Lodgepole	Green	0.38	5,500	1.08	5.6	20	2,610	250	680
	12%	0.41	9,400	1.34	6.8	20	5,370	610	880
Longleaf	Green	0.554	8,500	1.59	8.9	35	4,320	480	1,040
	12%	0.59	14,500	1.98	11.8	34	8,470	960	1,510
Pitch	Green	0.47	6,800	1.20	9.2	—	2,950	360	860
	12%	0.52	10,800	1.43	9.2	—	5,940	820	1,360
Sand	Green	0.46	7,500	1.02	9.6	—	3,440	450	1,140
	12%	0.48	11,600	1.41	9.6	—	6,920	836	—
Shortleaf	Green	0.47	7,400	1.39	8.2	30	3,530	350	910
	12%	0.51	13,100	1.75	11.0	33	7,270	820	1,390
Slash	Green	0.54	8,700	1.53	9.6	—	3,820	530	960
	12%	0.59	16,300	1.98	13.2	—	8,140	1020	1,680
Hickory, true									
Mockernut	Green	0.64	11,100	1.57	26.1	88	4,480	810	1,280
	12%	0.72	19,200	2.22	22.6	77	8,940	1,730	1,740
Pignut	Green	0.66	11,700	1.65	31.7	89	4,810	920	1,370
	12%	0.75	20,100	2.26	30.4	74	9,190	1,980	2,150
Shagbark	Green	0.64	11,000	1.57	23.7	74	4,580	840	1,520
	12%	0.72	20,200	2.16	25.8	67	9,210	1,760	2,430
Shellbark	Green	0.62	10,500	1.34	29.9	104	3,920	810	1,190
	12%	0.69	18,100	1.89	23.6	88	8,000	1,800	2,110
Douglas-fir[d]									
Coast	Green	0.45	7,700	1.56	7.6	26	3,780	380	900
	12%	0.48	12,400	1.95	9.9	31	7,230	800	1,130
Interior West	Green	0.46	7,700	1.51	7.2	26	3,870	420	940
	12%	0.50	12,600	1.83	10.6	32	7,430	760	1,290
Interior North	Green	0.45	7,400	1.41	8.1	22	3,470	360	950
	12%	0.48	13,100	1.79	10.5	26	6,900	770	1,400
Interior South	Green	0.43	6,800	1.16	8.0	15	3,110	340	950
	12%	0.46	11,900	1.49	9.0	20	6,230	740	1,510
Ramin	Green	0.52	9,800	1.57	9		5,390	990	640
(*Gonystylus bancanus*)	12%	—	18,500	2.17	17		10,080	1,520	1,300

Table B-2. Design values for visually graded Yellow pine timbers (5" x 5" and larger)
(Tabulated design values are for normal load duration and wet service conditions)
(American Wood Council 1997b: 41)

Species and commercial grade	Size classification	Design values in pounds per square inch (psi)						Grading Rules Agency
		Bending F_b	Tension parallel to grain F_t	Shear parallel to grain F_v	Compression perpendicular to grain $F_{c\perp}$	Compression parallel to grain F_c	Modulus of Elasticity E	
SOUTHERN PINE		**(Wet Service Conditions)**						
Dense Select Structural	5"x 5" & larger	1750	1200	110	440	1100	1,600,000	SPIB
Select Structural		1500	1000	110	375	950	1,500,000	
No.1 Dense		1550	1050	110	440	975	1,600,000	
No.1		1350	900	110	375	825	1,500,000	
No.2 Dense		975	650	100	440	625	1,300,000	
No.2		850	550	100	375	525	1,200,000	
Dense Structural 86		2100	1400	145	440	1300	1,600,000	
Dense Structural 72		1750	1200	120	440	1100	1,600,000	
Dense Structural 65		1600	1050	110	440	1000	1,600,000	

Table B-3. Design values for visually graded lumber (Tabulated design values are for normal load duration and dry service conditions) (American Wood Council 1997b: 32)

Species and commercial grade	Size classification	Design values in pounds per square inch (psi)						
		Bending F_b	Tension parallel to grain F_t	Shear parallel to grain F_v	Compression perpendicular to grain $F_{c\perp}$	Compression parallel to grain F_c	Modulus of Elasticity E	Grading Rules Agency
SOUTHERN PINE								
Dense Select Structural		3050	1650	100	660	2250	1,900,000	
Select Structural		2850	1600	100	565	2100	1,800,000	
Non-Dense Select Structural		2650	1350	100	480	1950	1,700,000	
No.1 Dense		2000	1100	100	660	2000	1,800,000	
No.1	2"-4" thick	1850	1050	100	565	1850	1,700,000	
No.1 Non-Dense		1700	900	100	480	1700	1,600,000	
No.2 Dense	2"-4" wide	1700	875	90	660	1850	1,700,000	
No.2		1500	825	90	565	1650	1,600,000	
No.2 Non-Dense		1350	775	90	480	1600	1,400,000	
No.3 and Stud		850	475	90	565	975	1,400,000	
Construction	2"-4" thick	1100	625	100	565	1800	1,500,000	
Standard		625	350	90	565	1500	1,300,000	
Utility	4" wide	300	175	90	565	975	1,300,000	
Dense Select Structural		2700	1500	90	660	2150	1,900,000	
Select Structural		2550	1400	90	565	2000	1,800,000	
Non-Dense Select Structural		2350	1200	90	480	1850	1,700,000	
No.1 Dense		1750	950	90	660	1900	1,800,000	
No.1	2"-4" thick	1650	900	90	565	1750	1,700,000	
No.1 Non-Dense		1500	800	90	480	1600	1,600,000	
No.2 Dense	5"-6" wide	1450	775	90	660	1750	1,700,000	
No.2		1250	725	90	565	1600	1,600,000	
No.2 Non-Dense		1150	675	90	480	1500	1,400,000	
No.3 and Stud		750	425	90	565	925	1,400,000	SPIB
Dense Select Structural		2450	1350	90	660	2050	1,900,000	
Select Structural		2300	1300	90	565	1900	1,800,000	
Non-Dense Select Structural		2100	1100	90	480	1750	1,700,000	
No.1 Dense	2"-4" thick	1650	875	90	660	1800	1,800,000	
No.1		1500	825	90	565	1650	1,700,000	
No.1 Non-Dense	8" wide	1350	725	90	480	1550	1,600,000	
No.2 Dense		1400	675	90	660	1700	1,700,000	
No.2		1200	650	90	565	1550	1,600,000	
No.2 Non-Dense		1100	600	90	480	1450	1,400,000	
No.3 and Stud		700	400	90	565	875	1,400,000	
Dense Select Structural		2150	1200	90	660	2000	1,900,000	
Select Structural		2050	1100	90	565	1850	1,800,000	
Non-Dense Select Structural		1850	950	90	480	1750	1,700,000	
No.1 Dense	2"-4" thick	1450	775	90	660	1750	1,800,000	
No.1		1300	725	90	565	1600	1,700,000	
No.1 Non-Dense	10" wide	1200	650	90	480	1500	1,600,000	
No.2 Dense		1200	625	90	660	1650	1,700,000	
No.2		1050	575	90	565	1500	1,600,000	
No.2 Non-Dense		950	550	90	480	1400	1,400,000	
No.3 and Stud		600	325	90	565	850	1,400,000	
Dense Select Structural		2050	1100	90	660	1950	1,900,000	
Select Structural		1900	1050	90	565	1800	1,800,000	
Non-Dense Select Structural		1750	900	90	480	1700	1,700,000	
No.1 Dense	2"-4" thick	1350	725	90	660	1700	1,800,000	
No.1		1250	675	90	565	1600	1,700,000	
No.1 Non-Dense	12" wide[4]	1150	600	90	480	1500	1,600,000	
No.2 Dense		1150	575	90	660	1600	1,700,000	
No.2		975	550	90	565	1450	1,600,000	
No.2 Non-Dense		900	525	90	480	1350	1,400,000	
No.3 and Stud		575	325	90	565	825	1,400,000	

APPENDIX C
ESTIMATED BENDING STRESSES FOR THE LARGE SCALE TEST

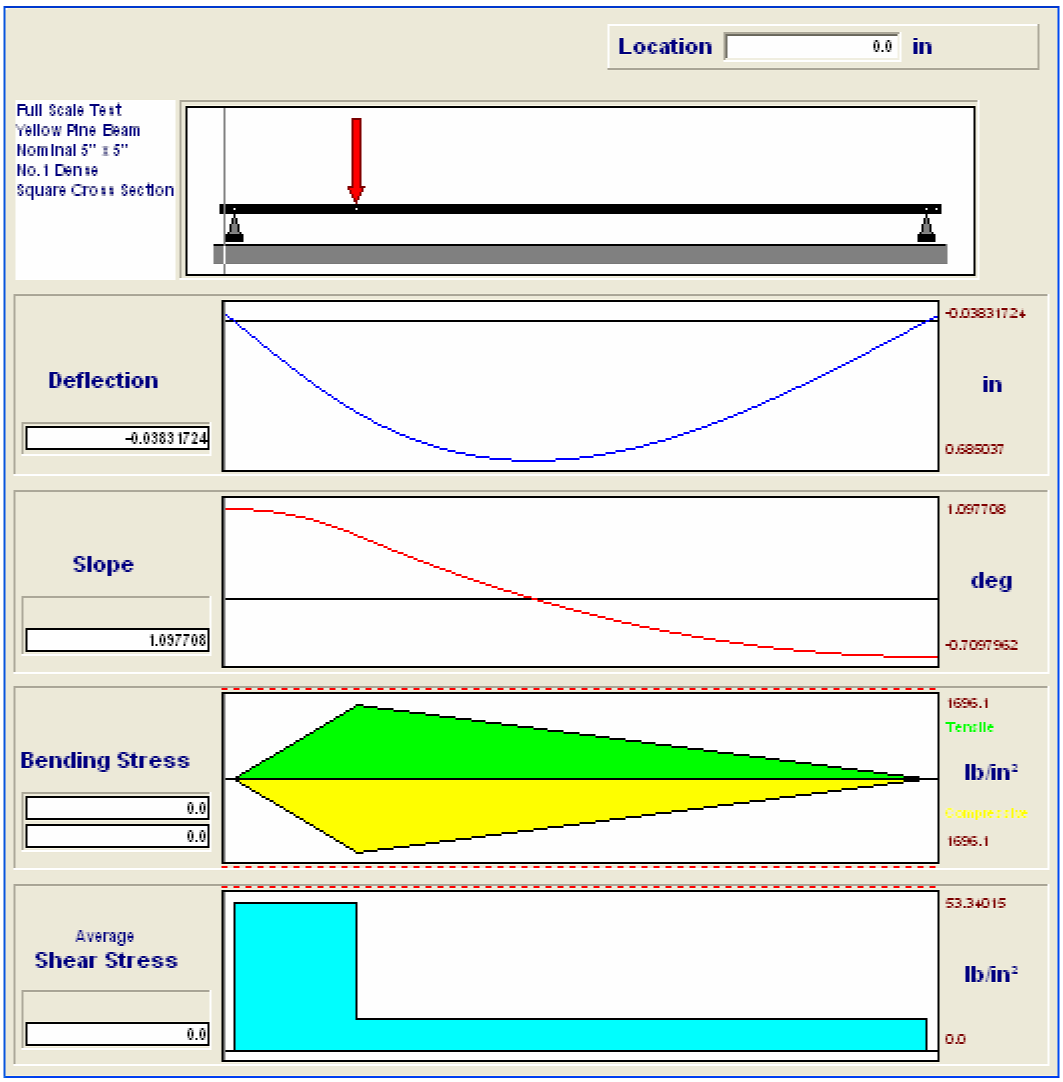


Figure C-1. Calculated deflection slope, bending stress, and shear stress on the lever for the large-scale test (Graphic from Orand Beam 2D).

Table C-1. Large scale test square cross section nominal 5" x 5" No. 1 dense Yellow pine lever.

Cb= 1.15 – Load duration equals two months total load.
No adjustment for temperature

BEAM LENGTH = 150.0 in

MATERIAL PROPERTIES
Modulus of elasticity = 1600000.0 lb/in²

CROSS-SECTION PROPERTIES
Moment of inertia = 48.27574 in^4
Top height = 2.453 in
Bottom height = 2.453 in
Area = 24.06884 in²

EXTERNAL CONCENTRATED FORCES
1562.0 lb at 28.0 in

LIMITS - ABSOLUTE
Yel. Pine no1 Dens:
Tensile = 1782.0 lb/in²
Compressive = 1782.0 lb/in²
Shear = 110.0 lb/in²

SUPPORT REACTIONS ***
Simple at 2.0 in
Reaction Force =-1283.836 lb

Simple at 148.0 in
Reaction Force =-278.1644 lb

MAXIMUM DEFLECTION ***
0.685037 in at 65.05424 in
No Limit specified

MAXIMUM BENDING MOMENT ***
33379.73 lb-in at 28.0 in

MAXIMUM SHEAR FORCE ***
1283.836 lb from 2.0 in to 28.0 in

MAXIMUM STRESS ***
Tensile = 1696.1 lb/in² Safety Factor =1.051
Compressive = 1696.1 lb/in² Safety Factor =1.051
Shear (Avg) = 53.34015 lb/in² Safety Factor =2.062

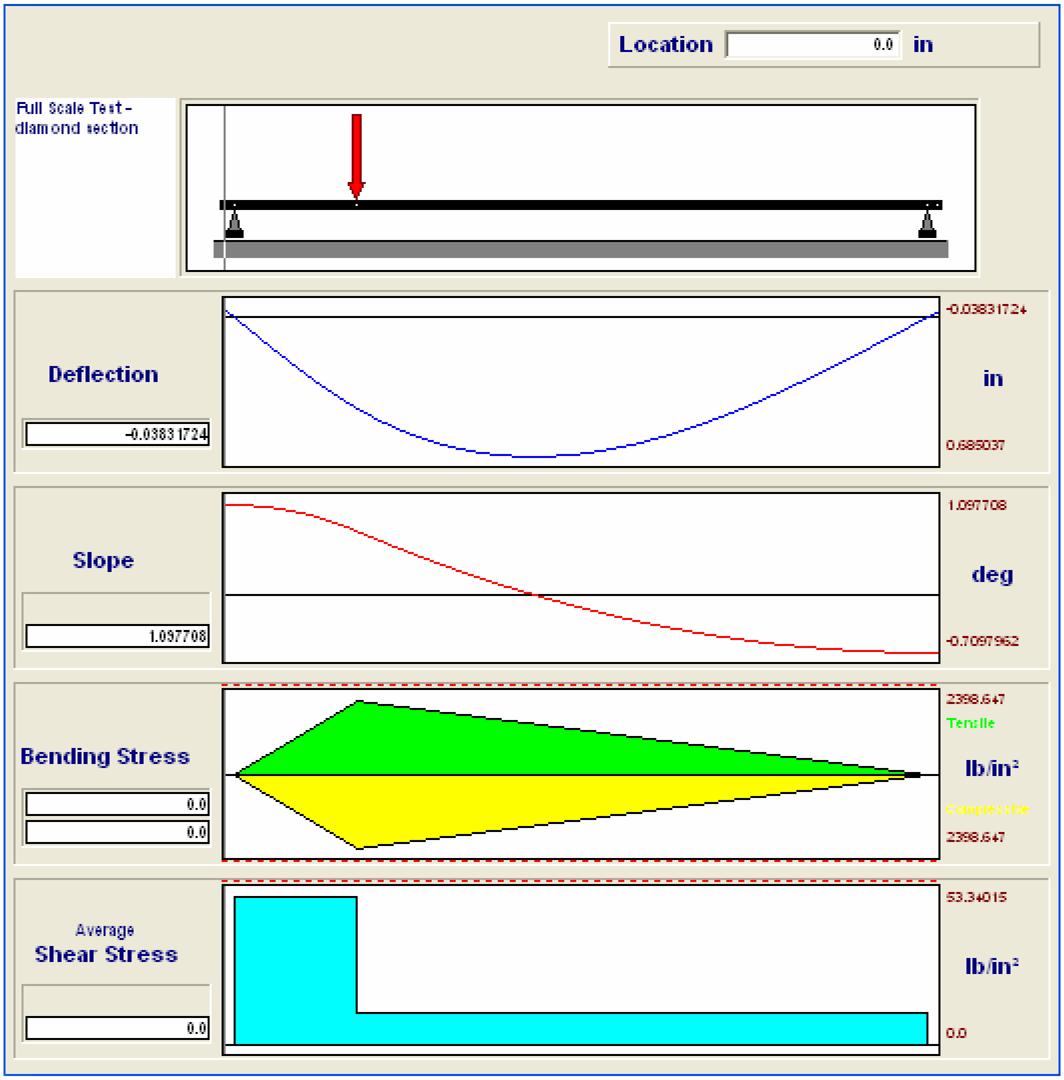


Figure C-2. Calculated deflection slope, bending stress, and shear stress on the lever, turned on its side to form a diamond-shaped cross section, for the large-scale test (Graphic from Orand Beam 2D).

Table C-2. Large scale test diamond cross section nominal 5” x 5” No. 1 dense Yellow pine lever.

Cb= 1.15 - Load duration equals two months total load.
No adjustment for temperature

Cf= 1.414 - Diamond Section form Factor

BEAM LENGTH = 150.0 in

MATERIAL PROPERTIES
Modulus of elasticity = 1600000.0 lb/in²

CROSS-SECTION PROPERTIES
Moment of inertia = 48.27574 in^4
Top height = 3.469066 in
Bottom height = 3.469066 in
Area = 24.06884 in²

EXTERNAL CONCENTRATED FORCES
1562.0 lb at 28.0 in

LIMITS - ABSOLUTE
Yel. Pine no1 Dens:
Tensile = 2520.455 lb/in²
Compressive = 2520.455 lb/in²
Shear = 110.0 lb/in²

SUPPORT REACTIONS ***
Simple at 2.0 in
Reaction Force =-1283.836 lb

Simple at 148.0 in
Reaction Force =-278.1644 lb

MAXIMUM DEFLECTION ***
0.685037 in at 65.05424 in
No Limit specified

MAXIMUM BENDING MOMENT ***
33379.73 lb-in at 28.0 in

MAXIMUM SHEAR FORCE ***
1283.836 lb from 2.0 in to 28.0 in

MAXIMUM STRESS ***
Tensile = 2398.647 lb/in² Safety Factor =1.051
Compressive = 2398.647 lb/in² Safety Factor =1.051
Shear (Avg) = 53.34015 lb/in² Safety Factor =2.062

APPENDIX D
ESTIMATED BENDING STRESSES WHEN LIFTING A 2-TON BLOCK

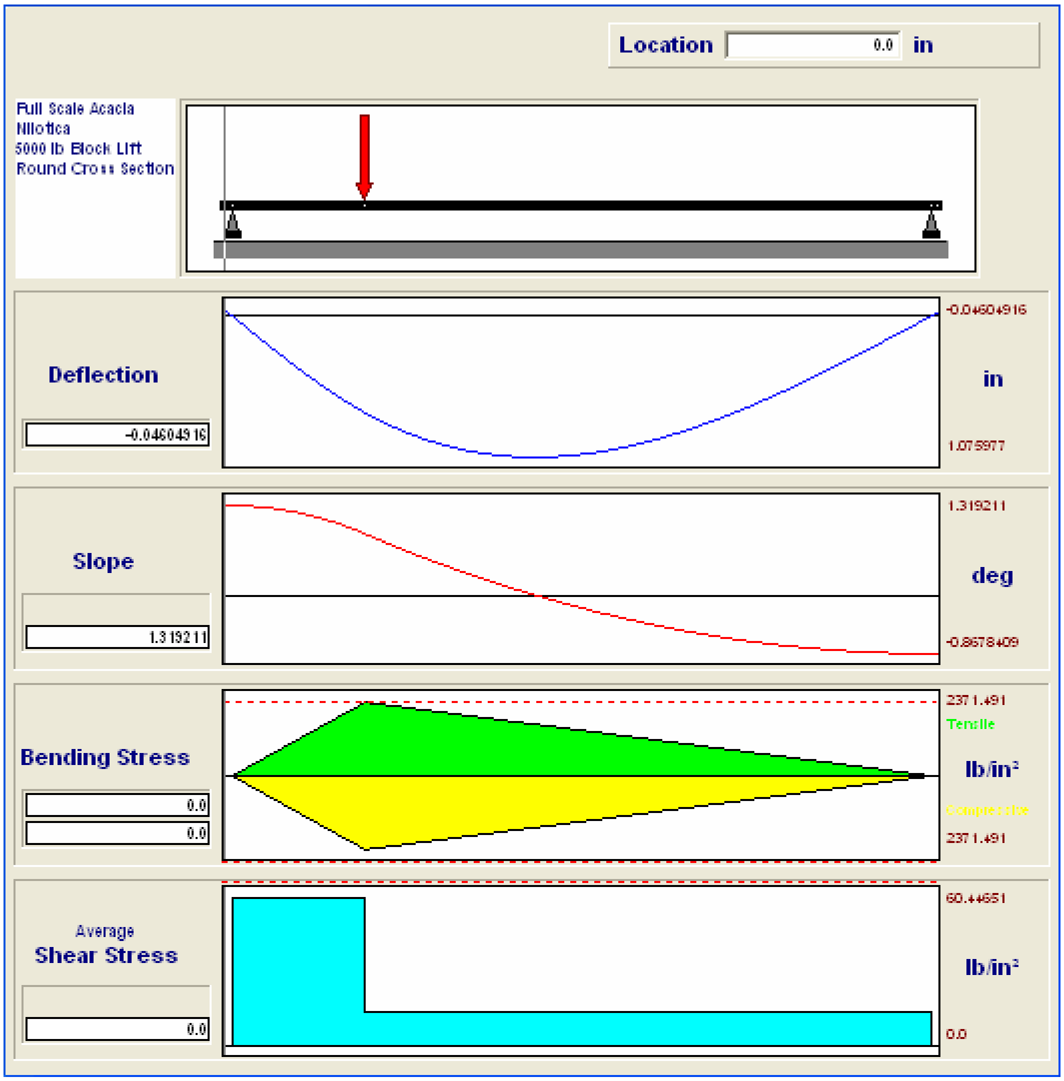


Figure D-1. Calculated deflection slope, bending stress, and shear stress on the lever composed of unseasoned, or green, *Acacia nilotica* when lifting a 2.5-ton block (Graphic from Orand Beam 2D).

Table D-1. Full scale 5000 lb block lift using a round cross section 7.3-inch diameter *Acacia nilotica* lever

Cb= 1.0- Load duration equals ten years duration of load

Cf= 1.18 - Round Section form Factor

BEAM LENGTH = 191.55 in

MATERIAL PROPERTIES
Modulus of elasticity = 1600000.0 lb/in²

CROSS-SECTION PROPERTIES
Moment of inertia = 139.3995 in^4
Top height = 3.65 in
Bottom height = 3.65 in
Area = 41.85387 in²

EXTERNAL CONCENTRATED FORCES
3125.0 lb at 37.8 in

LIMITS - ABSOLUTE
Acacia nilotica:
Tensile = 2366.479 lb/in²
Compressive = 2836.419 lb/in²
Shear = 247.4861 lb/in²

SUPPORT REACTIONS ***
Simple at 2.0 in
Reaction Force =-2529.92 lb

Simple at 190.0 in
Reaction Force =-595.0798 lb

MAXIMUM DEFLECTION ***
1.075977 in at 83.44429 in
No Limit specified

MAXIMUM BENDING MOMENT ***
90571.14 lb-in at 37.8 in

MAXIMUM SHEAR FORCE ***
2529.92 lb from 2.0 in to 37.8 in

MAXIMUM STRESS ***
Tensile = 2371.491 lb/in² Over Limit Factor =1
Compressive = 2371.491 lb/in² Safety Factor =1.196
Shear (Avg) = 60.44651 lb/in² Safety Factor =4.094

LIST OF REFERENCES

Adams, William Y.

1984. The First Colonial Empire: Egypt in Nubia, 3200-1200 B.C. *Comparative Studies in Society and History*. Vol. 26, No. 1 (January, 1984), 36-71.

American Wood Council

1997. *ANSI/AF&PA National Design Specification for Wood Construction: Supplement.* American Forest & Paper Association. Madison, Wisconsin.

Arnold, Dieter.

1991. *Building in Egypt: Pharonic Stone Masonry.* Oxford University Press. New York, New York.

Bell, Barbara.

1975. Climate and the History of Egypt: The Middle Kingdom. *American Journal of Archaeology.* Vol. 79, No. 3 (July, 1975), 223-269.

Brier, Bob

2002. The Other Pyramids. *Archaeology*. Vol 55. No. 5 September/October 2002 pp. 54-58

Bunting and Lea

1962. The Soils and Vegetation of the Fung, East Central Sudan. *The Journal of Ecology*. Vol. 50 no. 3 (Nov 1962). 529-558

Burton, Anne.

1972. *Diodorus Siculus Book I: A Commentary.* E. J. Brill. Leiden, Netherlands.

Ciesla, William M.

2003. *Sawmill where is being processed into railroad sleepers, Blue Nile Valley.* Electronic Photograph, http://www.forestryimages.org/browse/detail.cfm?imgnum=3948064 Last visited on 12/05/04

Clarke, S. and R. Engelbach.

1990. (Originally published in 1930) *Ancient Egyptian Construction and Architecture.* Dover Inc. Mineola, New York.

Crozat, Pierre

1997. *Système Constructif Des Pyramides.* Canevas Editeur Frasne. Fèvrier, France

2002. *Le Génie Des Pyramides.* Éditions Dervy. Paris, France.

2004. *Engineering of Pyramids*. Electronic Document, http://www.mines.inpl-nancy.fr/laego/Crozat/indexuk.html Last visited on 12/05/04

Delaporte,

1920. Vol. II, Pl. 72, A 156, in. Musée du Louvre. Département des antiquités orientales et de la céramique antique.1920. *Catalogue des cylindres, cachets et pierres gravées de style oriental [du] Musée du Louvre.* Paris, France.

Edwards, I. E. S.

1985. (Originally Published 1947) *Pyramids of Egypt.* Hazell, Watson, and Viney Ltd. Aylesbury, Great Britain.

Edwards, James Frederick.

2003. Building the Great Pyramid: Probable Construction Methods Employed at Giza. *Technology and Culture*. Vol. 44, No. 2 (April 2003) pp. 340-354

Fitchen, John.

1978. Building Cheops' Pyramid. *The Journal of the Society of Architectural Historians.* Vol. 37, No. 1 (March 1978), 3-12.

1986. *Building Construction Before Mechanization.* MIT Press. Cambridge, Massachusetts.

Frankfort, H.

1941. The Origin of Monumental Architecture in Egypt. *The American Journal of Semitic Languages and Literatures.* Vol. 58, No. 4 (Oct., 1941), 329-358.

Gale, Rowena, Peter Gasson, Nigel Hepper, and Geoffrey Killen.

2000. Wood. in Nicholson, Paul and Ian Shaw. eds. 2000. *Ancient Egyptian Materials and Technology.* University Press. Cambridge, England.

Godley, A. D. ed.

1920. *Herodotus, The Histories*. Harvard University Press. Cambridge, Massachussetts.

Goyon, Georges.

1977. *Le Secret Des Bâtisseurs Des Grandes Pyramides: Khéops*. Éditions Pygmalion. Paris, France.

Hansen, David H. and Ryan, Donald P.
1987. A study of Ancient Egyptian cordage from the British Museum. Occasional Papers of the British Museum 62.

Hassan Badi, Kamal.
1989. *The Forests of the Sudan.* Khartoum, Sudan.

Herz-Fischler, Roger.
2000. *The Shape of the Great Pyramid.* Wilfrid Laurier University Press. Waterloo, Ontario.

Hodges, Peter. (Julian Keable ed.)
1989. *How the Pyramids Were Built.* Dotesios Printers Ltd. Trowbridge, Wiltshire.

Hoyle, Robert. J.
1973. *Wood Technology in the Design of Structures*. Mountain Press Publishing Company. Missoula, Montana.

Isler, Martin.
1985. "On Pyramid Building." in *Journal of the American Research Center in Egypt*. XXII: 129-142.

1987. "On Pyramid Building II." in *Journal of the American Research Center in Egypt.* XXII: 95-112.

2001. *Sticks, Stones, and Shadows: Building the Egyptian Pyramids*. University of Oklahoma Press, Norman.

İstanbul Üniversitesi: Orman Fakültesi; Orman Endüstri Mühendisliği.
2001. *Ağaç Malzeme Teknolojiji Bilgi Sistemi.* Electronic Document, http://www.orman.istanbul.edu.tr/abis2001/ Last visited on 12/05/04

Janick, Jules
2002. *Ancient Near East Cultures*. Electronic Document, http://www.hort.purdue.edu/newcrop/history/lecture09/lec09.html Last visited on 12/05/04

Jenkins, Nancy.
1980 *The Boat Beneath the Pyramid: King Cheops' Royal Ship.* Holt, Rinehart, and Winston. New York.

Keable, Julian.
1993. UK Architect Responds to Latest Pyramid-Ramp Theory. *KMT* 4, No. 1 (1993): 3-4.

Koslow, Richard.

ND. *How the Egyptians Built the Pyramids.* Electronic Document, http://www.egyptspyramids.com/html/article.html Last visited on 12/05/04

Leach, Bridget and John Tait.

2000. Papyrus. in Nicholson, Paul and Ian Shaw. eds. 2000. *Ancient Egyptian Materials and Technology.* University Press. Cambridge, England.

Lehner, Mark

1997. *The Complete Pyramids.* Thames and Hudson. New York.

Lepre, J.P.

1990. The *Egyptian Pyramids: A Comprehensive Illustrated Reference.* McFarland & Co. Jefferson, North Carolina

Leshnik, Lawrence S.

1968. The Harappan "Port" at Lothal: Another View. *American Anthropologist.* New Series, Vol. 70. No. 5. (Oct., 1968), pp. 911-922

Maguire, Doug

2001. *Harvesting Acacia.* Electronic Photograph, http://www.forestryimages.org/browse/detail.cfm?imgnum=2714020 Last Visited on 12/05/04

Meiggs, Russell.

1982. *Trees and Timber in the Ancient Mediterranean World*. Oxford Univ. Press. New York, New York.

Meyers, Eric M. ed.

1997. Wood in *The Oxford Encyclopedia of Archaeology in the Near East,* New York, Oxford University Press, pp. 347-349.

Murphy, Edwin.

1990. T*he Antiquities of Egypt: A Translation with Notes of Book I of the Library of History of Diodorus Siculus.* Transaction Publishers. New Brunswick, New Jersey.

Murray, Mary Anne.

2000. Cereal Production and Processing. in, Nicholson, Paul and Ian Shaw. eds. 2000. *Ancient Egyptian Materials and Technology.* University Press. Cambridge, England.

Nova

1997. *This Old Pyramid: Transcript.* Electronic Document, http://www.pbs.org/wgbh/nova/transcripts/1915mpyramid.html Last Visited on 12/05/04

Petrie, W. M. Flinders.
1923. *The Arts and Crafts of Ancient Egypt.* T. N. Foulis, Ltd. London, England.

Postgate, J. N
1992. *Early Mesopotamia: Society and Economy at the Dawn of History.* Routledge. New York New York

Ryan, Donald P.
1993. Who cares about old [Egyptian] rope? *KMT* 4(2): 72-80.

Salonen, A.
1968. Agricultura Mesopotamia Nach Sumerischakkadischen Quellen. *Annales Academiae Scientiarum Fennicae,* Ser. B, Vol. 149

Shukla, NK, and P.C. Verma, et al.
1990. Physical and Mechanical Properties of Plantation Grown *Acacia leucophloea*, *Acacia nilotica*, and *Acacia tortilis* from Mohindergarh (India) in *Indian Forester* 116 (10) 803-811

Siliotti, Alberto.
1997. *Guide to the Pyramids of Egypt.* Barnes & Noble, Inc. New York, New York.

Smith, Craig B.
1999. Project Management B.C. *Civil Engineering*. June. Vol 69. No. 6.

Tellefson, Olaf.
1970. "A New Theory of Pyramid Building: Some Field Experiments." *Natural History*, Vol. 79, #9, 1970, pp 10-23.

Ugural, A. C.
1991. *Mechanics of Materials*. McGraw-Hill, Inc. New York.

USDA Forest Products Laboratory.
1977. *The Encyclopedia of Wood.* Drake Publishers, Inc. New York, New York.

1999. *Wood Handbook: Wood as an Engineering Material.* Forest Products Laboratory Madison, Wisconsin.

Weindrich, Willemina Z
2000. Basketry. in Nicholson, Paul and Ian Shaw. eds. 2000. *Ancient Egyptian Materials and Technology.* University Press. Cambridge, England.

Weinstein. James M
1984. Radiocarbon and Some Ancient Egyptian Thievery. *American Journal of Archaeology,* Vol. 88, No. 4 (Oct 1984) pp. 591-592

Zangaki

1865. No. 630 *Chadoufs de la haute Egypte*. Electronic Photograph, in http://www.lib.uchicago.edu/e/su/mideast/photo/Egypt.html Last visited on 12/05/04

BIOGRAPHICAL SKETCH

The author is from Cocoa, Florida and has two Bachelor of Arts degrees from the University of Florida, one in history and the other in anthropology.