The rise and demise of Egypt's largest pyramids: A builders view

My love of Egypt and my first contact with Egyptian construction started in 1994 when I was asked to provide a scheme to strengthen parts of historic Cairo after the devastating earthquake in 1992. This initial contract was to work with the state owned Arab Contractors to structurally strengthen the Al Ghory Mosque that have been extensively damaged. It was at that time that I was able to visit the Giza Plateau to see the pyramids.
My first view of the Great Pyramid was in the early evening when I got out of my vehicle at a local hotel. I was expecting to see a pyramid but I was not prepared for the scale and size of the monument that was in deep shadow at that time of the day and almost obliterated half of the sky.
Like all others who first visit the monument the first question is "How could the builders with primitive tools build these fantastic monuments in such a short time?"

At that time I didn't take any professional interest in the construction of the pyramids but just a great deal of respect for the constructors. It was after completing structural renovation on almost twenty historic structures in Cairo that we were considered for the structural strengthening of pharaonic structures. The first was Temple Hibis in the Karga Oasis and the second was the burial chamber in the Red Pyramid of the Pharaoh Snefru.

This was the precursor to the most difficult project I have ever undertaken which was the strengthening of the burial chamber ceiling in the Step Pyramid of Djoser.

This monument is probably the most import structure in the world in construction. Built 4700 years ago it leads mankind out of the ground towards the sky with a bold innovative structure that makes a statement of man's ingenuity paving the way for all modern construction. Prior to this monument most known structures have been little more that a handful of meters high. However, the final size of the monument is more than sixty meters high and leaves a footprint 121 meters by 109 meters.
It was originally built as a single storey mastaba (a bench or seat in Arabic) the traditional structure for the afterlife in the very early days and then extended by additional three steps and later another three steps to give the appearance of a layered wedding cake.
The first question in most peoples mind is why a step pyramid and not a true pyramid? The answer is very simple and obvious when you consider the time and age and the equipment available to those early pioneers. To reach the heights of 62 meters in one single bound would have been very difficult to builders who have not gone above 10 meters in height in the current experience. They had no experience working at that height nor did they have any working knowledge of the scaffolding requirements needed to span the full 62 meters. It needed lots of innovation and trial and error to master the art of scaffolding to rise self-supporting with only timber and rope lashings.

The safest way to do the work would be to carryout the work in lifts of size that was no more than was necessary to build a single mastaba. Hence, the Step Pyramid.

This is the view at the top of the Step Pyramid, which would have caused concern among the ancient builders who had only worked on buildings approximately 10 meters high at that time.

In many ways this first attempt at a high-rise monument was a great success from the outside. The problem was not of the general construction of the pyramid but the most important element the burial chamber for the pharaoh. Constructed some 28 meters from the external face of the pyramid the burial chamber is roughly 8 meters square and descends a further 29 meters down to the final position of the sarcophagus. Unfortunately, the length of stone beams in those early days was less that 3 meters and so the builders choose to use palm tree trunk to span the top of the burial chamber.
This technique was probably good for a single mastaba but it had no chance of supporting the colossal weight of a pyramid reaching upwards of 62 meters. Timber deflects (bends) under load and never recovers to its original position. It gradually fails with more and greater deflection particularly at the centre. This could also have been accelerated with any seismic action in antiquity. The photograph below shows one of the only remaining original ceiling beams still in place. Notice the amount of deflection that has occurred in the beam in the last 4700 years. The stones immediately above and supported by the beam have moved and separated with obvious voids being visible around each stone. The only reason that the beam has not collapsed is that it is at the very edge of the chamber and received support from the sides of the chamber. This problem was obviously known to the builders at an early stage of the pyramid development as a change of design was made in the next pyramid to be constructed at Meidum.

This pyramid incorporated a first attempt of a corbel ceiling to overcome the need to use the failed timber ceiling beams design.

My first view of the defect ceiling was at the base of the chamber looking up some 29 meters at the damage. A matrix of small stones like a broken jigsaw puzzle would be the best to describe the view from this distance. This was going to be the most dangerous project we ever attempted and would need some delicate and innovative ideas to reduce the risk.

The issues revolved around how we safely support such a haphazard collection of unconnected stones without triggering a further collapse together with providing a solid base support at the bottom of the chamber to carry the weight of scaffolding. We were also informed that there was a good chance that there could be undiscovered tunnels below the sarcophagus made by tomb robbers.

The problems were solved incrementally by tackling the issues from the top to the bottom. To overcome the possibility of a further ceiling collapse if a key component were unlocked by the insertion of traditional steel or timber being used releasing many more tons of loose stones on our heads we used another product I had developed known as Waterwall. Essentially, this product was the use of water in patented internally reinforced PVC bags to mitigate against improvised explosive devices. However, some of the more exotic applications needed columns of air using the same material to support tons of water when large spans of Waterwall were required. The great advantage of the system was it was dimensional stable particularly when inflated with air. It could be made to any shape that was needed and all the air columns could be interconnected to provide total control of the installation in this particularly dangerous environment. The final design was circular columns of varying height 1.5 meters in diameter to support the dead load with high density foam cut and fitted

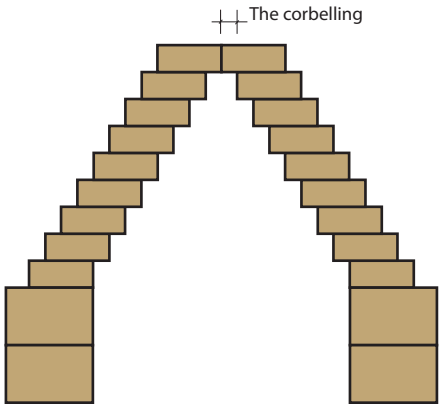
around the hanging stones to transfer the load into the air columns. The work commenced with the removal of the stones from the top of the sarcophagus and consolidating the supporting piers that were damaged by the tons of falling stones. The entire area of the base of the chamber was consolidated with sand bags to cover the entire sarcophagus and provide a flat surface for the erection of the internal scaffolding. After the scaffolding was erected the most delicate work of placing the air supports was carried out.
Once these were in position and we were confident that the damaged stonework had been well supported we were then able to deep point the gaps and joints between hanging stones with a lime grout mixture to lock the stone face together.
Once the entire ceiling had been pointed we were able to slowly commence the drilling diamond drilled hole to install the stainless steel Cintec Anchors.
This work is still in progress at the moment but the most surprising observation was that although we were drilling up to 4 meters at roughly 90 degrees to the damaged face of the filling core of stones we never experienced drilling through stones that were more than 400mm wide. This appeared to be in direct contradiction that the stones on the outside of the pyramid were the same all the way through the pyramid. In some cases the fill was a great deal smaller and included the use of tufla grout to bond the smaller stones together.

It was this observation that prompted me to question the generally accepted theory that the entire volume of the pyramids were made of the blocks that made up the core stones on the outside of the pyramids.
The next pyramid to be constructed was the pyramid at Meidum.

The Meidum Pyramid.

It is difficult if not impossible to surmise why the next pyramid was built in the shape and form of the pyramid at Meidum. The remaining uncompleted structure has the appearance of a truncated box sticking of the ground. It seems that the builders had built a solid internal core and added the external sloping sides to give the final appearance of a pyramid.

The resounding mass of debris at the base of the pyramid is what remains of the sloping façade that was placed externally in layers from the outside. The result of a catastrophic failure due mostly to the external attachment not being bonded to the inner core or having adequate expansion joints to prevent movement failure. It was seen that when the next set of pyramids that were built the inner blocks were stepped to secure and support the outer facing stones to carry its weight and to lock the slabs to the pyramid sides.
However, this pyramid was the first to use a corbelling technique to overcome the problem of long timber beams to create openings in the pyramid for the burial chambers.



SECTION THROUGH BURIAL CHAMBERS

It could be that this new method of constructing a chamber using this technique was why the builders built this reversal of constructing the pyramid with good blocks on the outside with smaller stones on the inside to good stonework on the inside and smaller stones on the outside. Perhaps they thought that the transfer of the internal loads for the corbel system of providing a burial chamber needed a more structurally secure core.
This was also the problem with the next pyramid to be built at Dashur called the Bent Pyramid.

The Bent Pyramid

There are two major questions raised by the pyramid. The first one was why was it built at an angle of 53 degree for two thirds of its height and then bent over to an angle 43 degrees?

The second question was regarding the outer casing, which is still attached although only just and what was the reason for its failure?

Leaving the second question until later in the report because this affects all the pyramids. The question is why was there an abrupt change in angle to the outside of the pyramid and was it ever used?

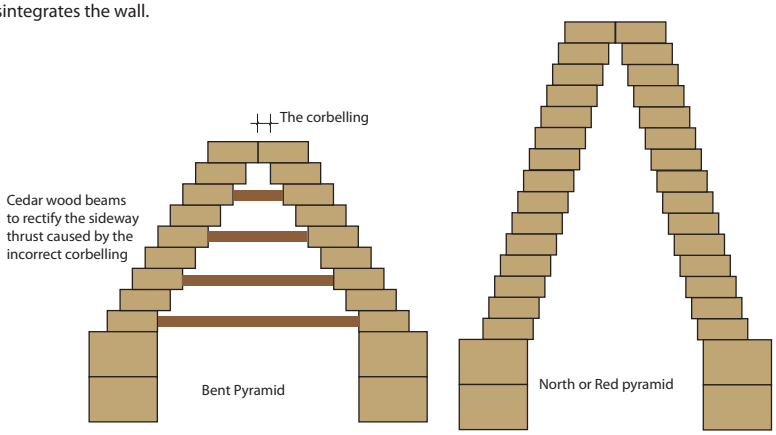
I believe the answer is in the burial chamber construction that was the second to use the corbelling technique to form the ceiling of the chamber. Corbelling stone and masonry is now a well known technique in general construction but there are rules regarding the amount of cantilever or overhang that can be achieved in relation to the loads to be carried and the number of corbels. In both the pyramids at Meidum and the Bent pyramid these cantilevers were exceeded resulting in the chambers being squeezed together and the burial chamber not fit

for purpose. This is particularly so in the case of Bent Pyramid, where the corbelling was greater than the Meidum, pyramid. When the builders observed the effect they would have adjusted the angle of the outer casing to reduce the weight on the burial chamber and also a large quantity of cedar beams were found in the burial chamber probably to be used in propping the walls together to prevent further crushing.

Corbel or cantilever ceilings to the burial chambers

Corbelling renders the wall less stable by bringing the centre of gravity of the mass away from the centre of the wall, causing a greater compression on the side of the wall under the load than on the side remote from the load, and the distance of the centre of the bearing is known as an eccentricity of the load. If this is too great it leads thrust sideways with a tendency to rotate and disintegrates the wall.

A corbel is a block that has one end embedded in a wall while the other end projects beyond the face of the wall. Its structural use is to support the member above it, and it may consist of a unit of a number of blocks. It structural behaviour is essentially that of a cantilever, it's strength being determined by its resistance to shear and flexure of the stone.



SECTION THROUGH BURIAL CHAMBERS

This problem was resolved at the next pyramid under construction called the Red or North Pyramid. The burial chamber here is a perfect example of the correct use of corbelling as shown above.

I then thought about all the present accepted theories on how the pyramids were built and was it social reasons that determined the shape and design of he wonderful monuments or was it a logical construction problems that influenced the evolution from the Step Pyramid to the Great Pyramids at Giza.
Having worked in the construction industry for 54 years I started to think like an ancient Egyptian builder faced will all the project problems with limited tools and no experience of large scale construction. It was obvious that there would be a giant learning curve and a willingness to over come these problems and rapid innovation.
Faced with this problem I would have learnt the lessons of the failures and tried to correct them as each successive pyramid was constructed.
My first thought would be why make the problem more difficult than it really needed to be?

Why haul huge stones kilometers away unless it was absolutely necessary? The internal core and filling of the pyramids would never be seen so why fill it with quarried blocks that took time and presumably money to extract and cart to site.

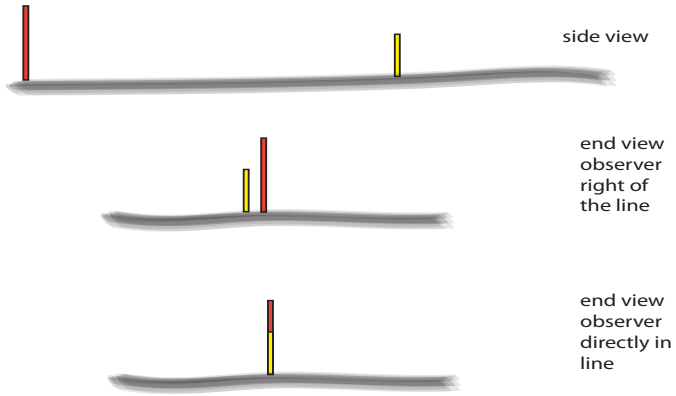
Why delay the construction of the project for the Pharaoh with un-necessary delays? The logistical problems were already enormous coordinating all the elements from quarrying, transport, scaffolding, design, setting out and manpower requirements. These are well cataloged in many publications on the construction of the pyramids and I cannot add much to what has already been written.
The setting out and leveling of the monuments would have been completed using all the accumulated data that had been gathered concerning the heavenly bodies and their movements through the sky. The perimeter foundation would have been leveled using water filled trenches and the setting out of the pyramid by the setsquare and the three, four and five rule.
I believe that they could also use visual sighting methods such as transits to mark out and measure lengths. The transits would be used to project a straight line and I would have poles marked in cubits say 15 to 20 cubits long to measure the distances and not any rope or cordage. The transits would also be very effective if used at night with small lights or lamps instead of poles. ----

The lights indicate that viewer is right of the true line

The lights are in transit and in a straight line

In the desert at night this would be an obvious way to create straight lines and also to set out the foundations of the pyramids also using small lamps at each corner of points of interest.

A series of marker poles can be used with the same principles and with primitive sighting tools prove extremely accurate.



I would also suggest that the linear dimension would be more accurately achieved using long poles say six metres long to mark and move in line to the desired length. Although, this method has errors it has far less errors than ropes or lines that sag badly over any distance and elongate when pulled.

It was more than possible to use scaffolding to construct the pyramids as can be seen in this photograph showing the current work being undertaken on the Step Pyramid with only tradition timber and rope lashings to replace the damaged outer façade. I believe that this would have been the preferred method of building the pyramids together with internal ramps and not with any external ramps that have been suggested by many archeologists.

Another indicator is a number of rectangular sockets set at the bottom casting blocks of the pyramids of Khufu and Khafre at Giza. The sockets are formed at regular intervals and of varying sizes and depths in a straight line or staggered. These were undoubtedly used as sockets to receive the first large up right standard legs of the scaffolding used when high level of loading was expected to prevent and sideways movement of the scaffold under large loads.

The method of building the pyramid would have been to construct the inner fill initially with large blocks to consolidate the foundation area and slightly higher than the outer core walls. The blocks for the outer core walls would be raised via internal ramps constructed of small stones and any rubbish the builders wanted to hide that could be used effectively. The outer core walls would have a greater thickness at the base (say three blocks wide) and slightly reduce this as the structure nears the apex to a single block and would have been built concurrently with the inner core but slightly lower to facilitate the placement of the larger blocks that would have been moved up the traversing road ways via on of the centrally formed entrances. The ramps would not need to be very wide

and could have had small palm trees embedded into the surface to provide a sliding mechanism to assist the craftsmen transporting and placing the stones. As the pyramid extended in height the outer core stones were reduced in size and the ascending ramps adjusted to both angle and size necessary to transport the core blocks.

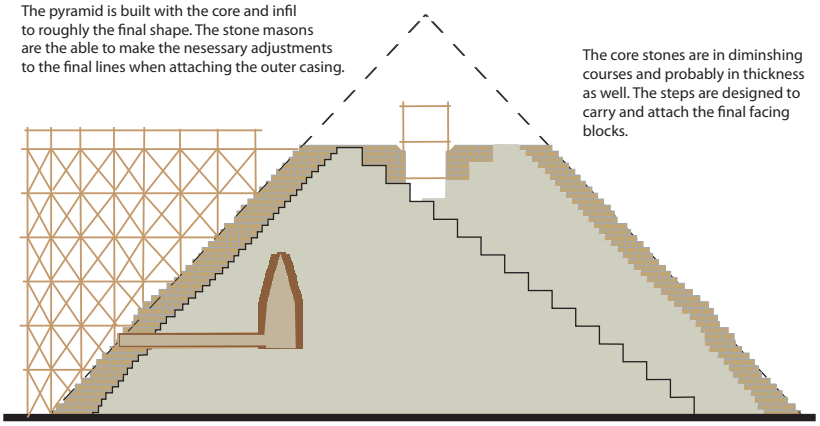
Attempts were made in the eighteenth century to conduct archeological or treasure hunting with gunpowder at the base of Khufu's pyramid. This gash exposed a jumble of large blocks that were neither coursed or aligned and would give credence to my opinion that the internal fill is a mixture of material and not the block work that is visible on the outer core.

There is a way to easily prove this theory and I would volunteer to carry out this work at no charge to the Egyptian Antiquities. We could diamond drill 100mm core holes into the pyramid at varying heights to a depth of 30 meters and provide a drilling log of all the contents of the bored hole to establish the true nature of the fill. The drilling would be done with the latest dry drilling techniques to prevent damage to the pyramid and the core plugged and filled to match the external appearance.

There has been sum speculation that there was insufficient timber available to scaffold the entire pyramid and also would the builders have the skill to erect a scaffold to the heights needed to build the pyramids. Firstly, the availability of scaffold over such a long construction period would I my view not have been a problem. Particularly if the scaffold was reusable and could be built up in quantities and initially moved to each section under construction and not scaffolding the whole pyramid. The scaffolding could also be transferred to the next pyramid under construction albeit some would have to be replaced. The skills need to create large runs of scaffolding would be easily possible as at that time they were able to build ships, barges and river craft and the skill level would have easily been transferred.

Section through pyramid

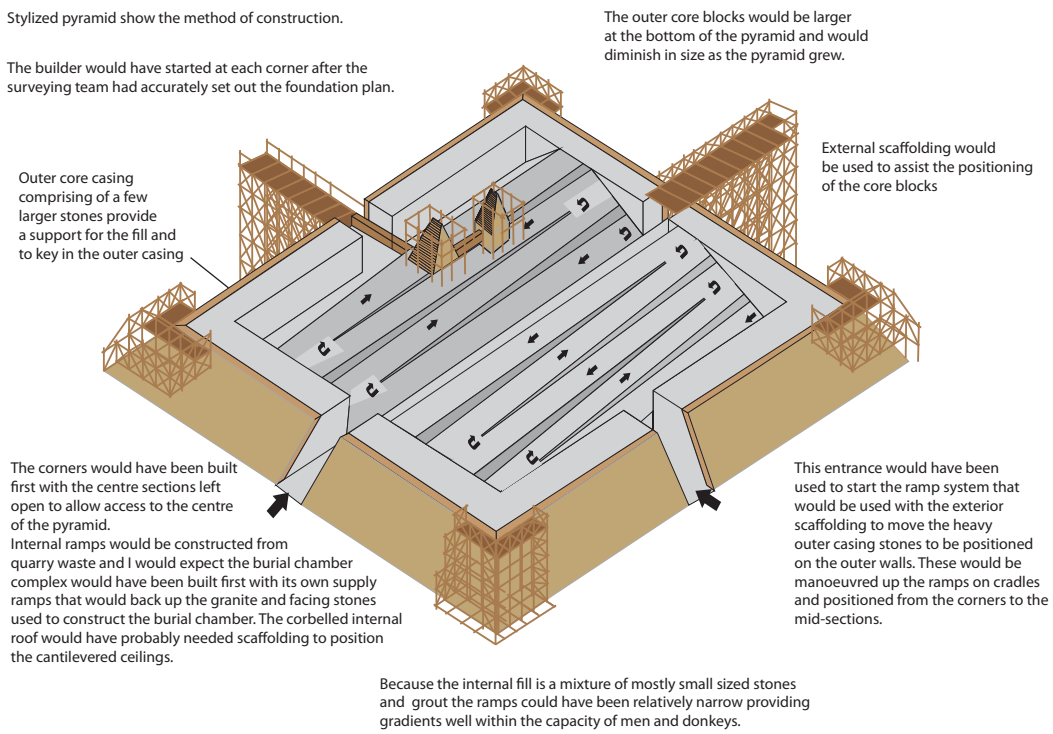
The pyramid is built with the core and infil to roughly the final shape. The stone masons are the able to make the nesessary adjustments to the final lines when attaching the outer casing.



The core stones are in diminshing courses and probably in thickness as well. The steps are designed to carry and attach the final facing blocks.

Any internal chambers, corridors and tunnels are constructed at each level as the pyramid is constructed.

The isometric views of the first section

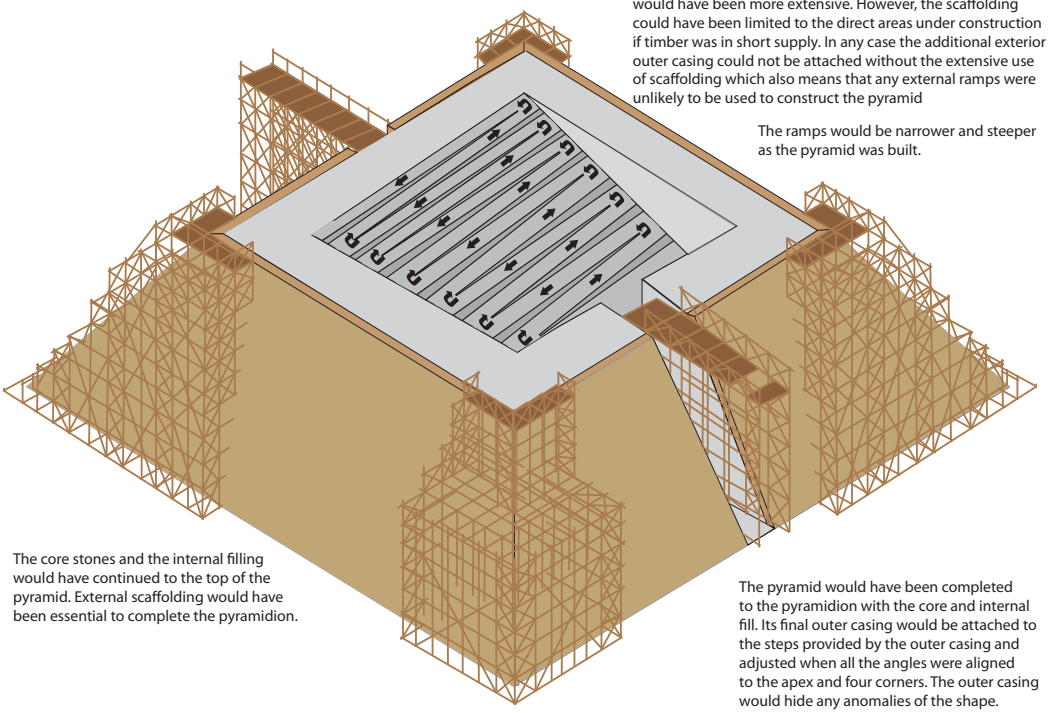


The next level would be

Second stage construction

As the outer walls were built so the scaffolding requirements would have been more extensive. However, the scaffolding could have been limited to the direct areas under construction if timber was in short supply. In any case the additional exterior outer casing could not be attached without the extensive use of scaffolding which also means that any external ramps were unlikely to be used to construct the pyramid

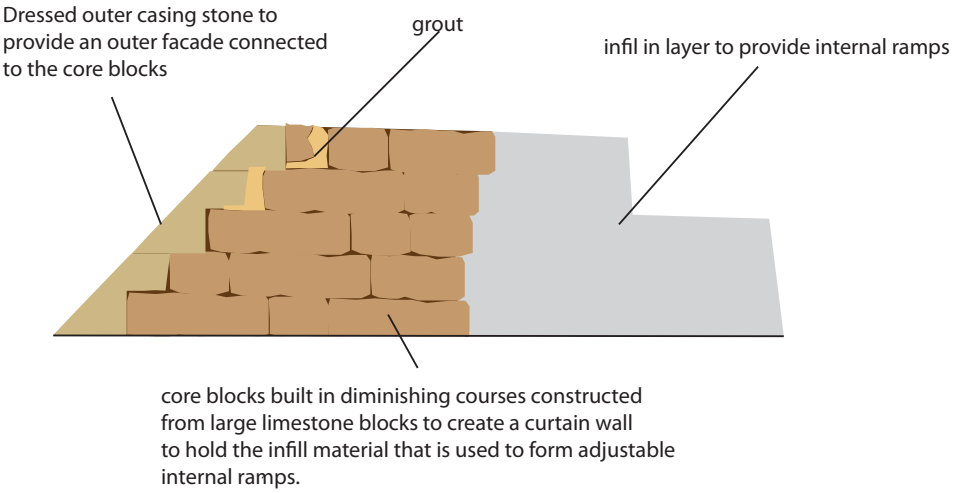
The ramps would be narrower and steeper as the pyramid was built.



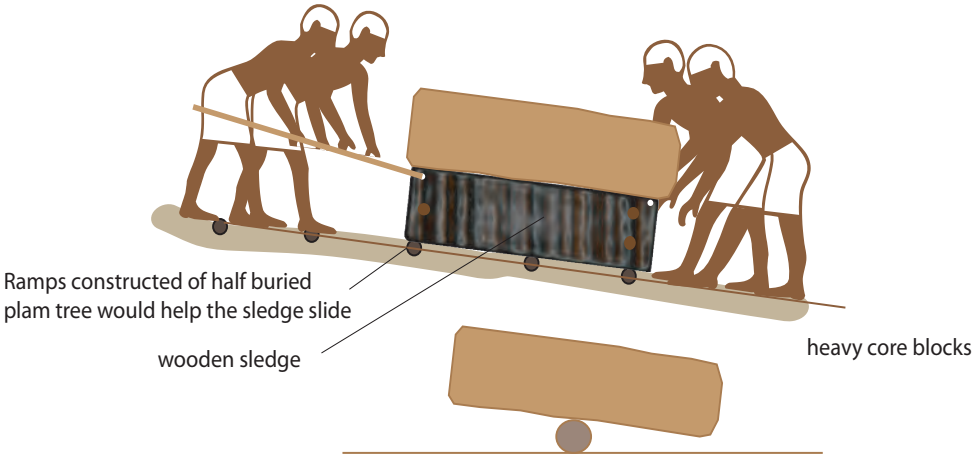
The core stones and the internal filling would have continued to the top of the pyramid. External scaffolding would have been essential to complete the pyramidion.

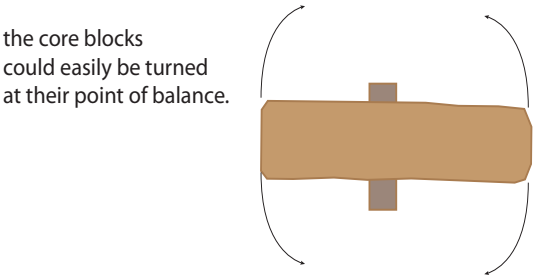
The pyramid would have been completed to the pyramidion with the core and internal fill. Its final outer casing would be attached to the steps provided by the outer casing and adjusted when all the angles were aligned to the apex and four corners. The outer casing would hide any anomalies of the shape.

Section through outer wall



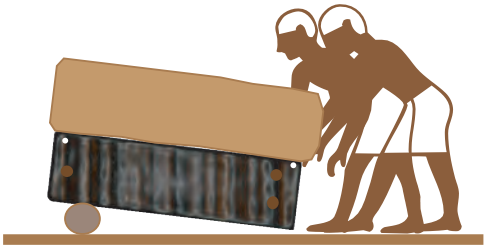
The pyramid would be formed to its final shape with just the core blocks and the inner fill. The builders would then be able to have for the first time complete access to all the corners, angles and slopping faces of the monument. Varying the depth of the outer casing could make final adjustment for any miss-alignment.


Ramps constructed of half buried
plam tree would help the sledge slide
wooden sledge
heavy core blocks


the core blocks
could easily be turned
at their point of balance.

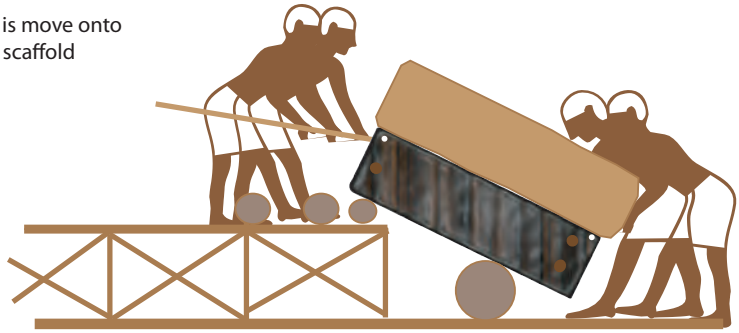
Possible ways of moving and lifting core slabs

Core slab is lifted onto a sledge near a half lift scaffold.



Core slab is rocked at point of balance to raise on end

Sledge is move onto half lift scaffold



Another way of rolling the core slab would be to fit segments of a large tree to the edges. Effectively using the core as an axle. This would be very easy to move with levers.

Bent Pyramid.

Returning to the second question of the failure of the outer casing on the Bent Pyramid. I was asked by the Authorities to give my opinion on saving the remaining external cladding on the pyramid.
Before any structural restoration work is considered the exact nature of the defects must be established so that the correct intervention can be carried out. From a visual inspection the structure was showing distress along all the extremities. What are the

clues? The pyramid does not appear to have any foundation movement. All the missing cladding appears at interfaces or change of direction at the angles and between the ground and the cladding. Could local opportunist thieves have taken this? At the lowest levels that could be the answer, but at high level and in such a random manner without any sign or indentations of temporary scaffolding or of any symmetrical cutting of the blocks to aid removal, it does not seem likely or possible. It would have been extremely dangerous work. Normally, to dismantle a structure you need as much scaffolding as you would to build it and opportunist thieves would hardly have sufficient resources. Indeed if they merely wanted rough stones the could have had them in the hills adjacent to the centre of Cairo without all the trouble of removing and carting them 30 miles out of town. The damage appears to be a giant whose hand has swept across the face of the pyramid with enormous energy sucking out the facing leaving the ragged empty sockets. In the case of the Bent Pyramid and I believe in the case of all the Pyramids the outer casing has been effected by thermal movement. Fortunately, the Bent Pyramid is the only Pyramid with any degree of stone casing that is still attached and the mechanism of failure is apparent. The failure of all the perimeter edges show that the outer casing has expanded from the centre outwards and movement has taken place on all of the extremities.
The photographs of the Bent Pyramid show how the thermal expansion has caused the blocks to move to the edges where they have detached. It also shows how an individual stones unsupported can cantilever and snap off and subsequently fall to the ground.

Typical damage caused by thermal expansion as two opposite edge meet.

Limestone has a coefficient of thermal expansion of 8×10^{-6} proportional to the change of temperature and to the original dimensions and many natural stones retain a minute proportion of the expansion when they cool down and do not return to their original size.

If we consider that in the day time the temperature rises to 40 degrees across the face of the outer casing and then at night cools to 3 degrees because of the lack of cover and exposure to the prevailing winds.

This would give on average temperature fluctuation of 37 degrees. Obviously, this varies through the seasons, but to illustrate my point I will build these into the calculations.

Let us say that $8 \times 10^{-6} \times (40-3) \times 100\text{m}$ run = 0.0296 m of movement per 100 metres run in all directions. However, this is also dependent on the size of the gaps between each stone. So the outer casing would expand to say 40 degrees in the day and cool to say 3 degrees at night. All the movement would be taken up initially in the joints but the limestone does not go back to its original position. This expansion will create dust and stone particles that would detach from the stones, filling the voids and gaps between the stones. This would have the effect of reducing the amount of contraction at night in addition to its nature desire not to go back to its original size and so the whole cycle will start again. Multiply the number of days the Pyramid has been

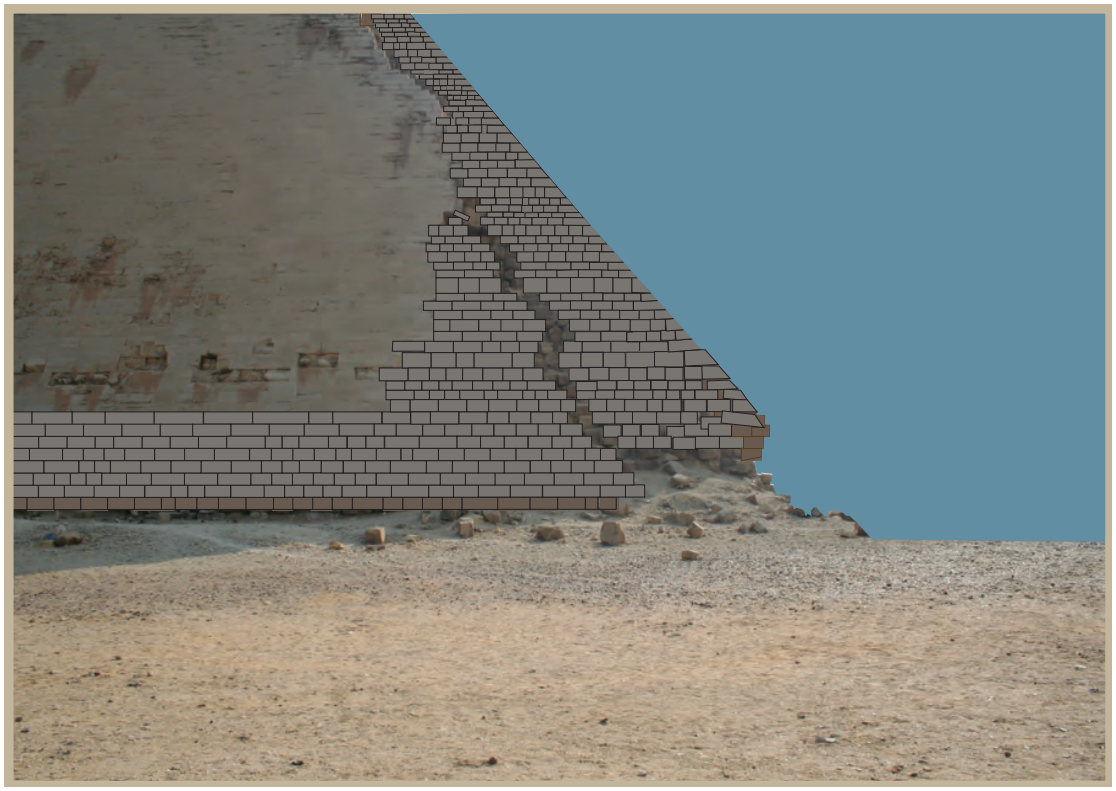
erected by this endless movement and you have the reason why all the outer casing has moved to the extremities where it has buckled or displaced against other blocks moving in the opposite direction and then it has fallen off and probably then picked up by opportunists and removed from site. I believe that this is the mechanism of failure on this and all the other Pyramids.

I have read that the original dimensions recorded by Flinders Petrie were inaccurate and that dimension taken in 2004 was larger by a small degree. This is what I would expect of a structure that is still moving and increasing in size. Also, the convex shape of the outer casing could be caused by the stones arching between fixed points. The transit of the sun across the region will vary throughout the seasons and will have the effect of heating one side more than another, giving rise to disproportionate movement particularly at the extremities.

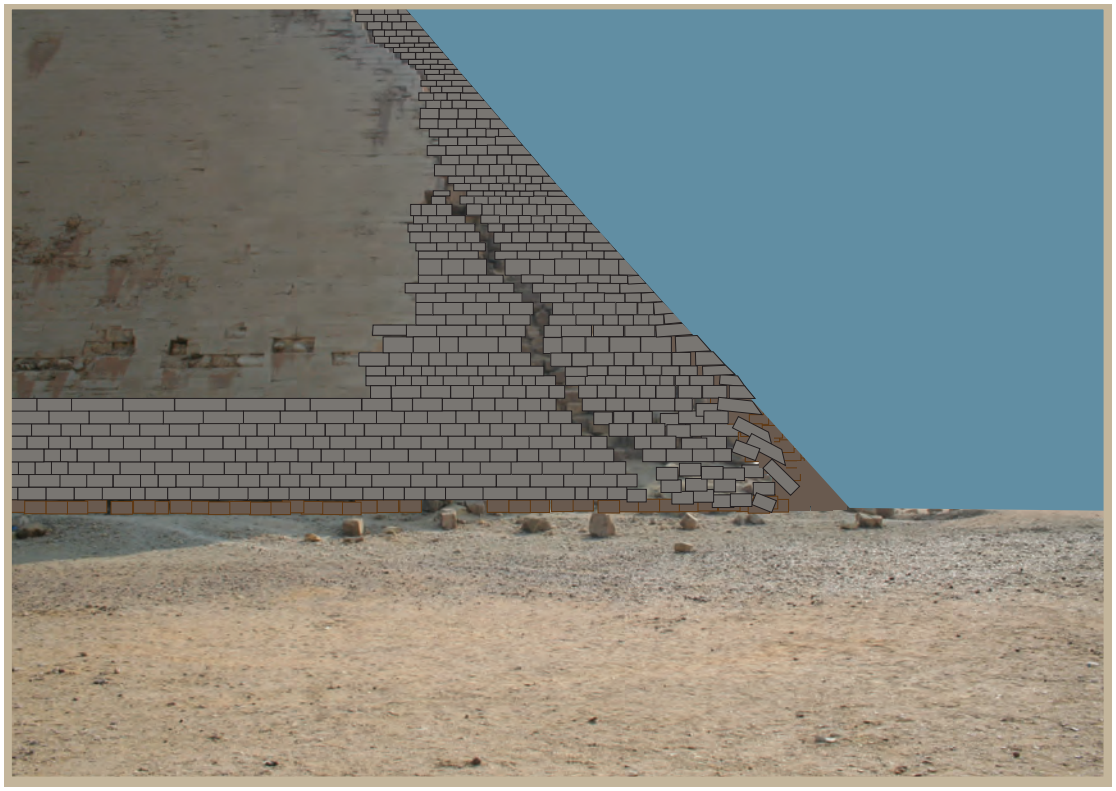
Why does the Bent Pyramid still have half of its outer casing attached and the Red Pyramid and the Great Pyramids at Giza plateau have virtually none?

I believe it was due to the increased skills of the craftsman who developed more knowledge and precision as the pyramid construction developed. They were able to provide a better accuracy and build quality and jointing the slabs. Probably, The Bent Pyramid was built with less care and with more voids between the stones that acted like expansion joints and that the casing blocks being inclined inwards at the base of the pyramid may have had an effect of limiting the expansion.

This photograph was taken in 2006 but the missing blocks have been drawn in to show what the pyramid would have looked like as built.



The photograph shows the progressive damage as the two opposing edges meet and blocks are forced out under pressure.



The pressure has moved some blocks out as far as a meter.

This is the photograph taken in 2006 showing the total amount of movement that has taken place in 4600 years.

This short period of intensive construction of wonderful massive monuments built by ancient civilization was remarkable. One can only admire the great ingenuity and effort that was required by a team of specialist builders who from the very start showed great ingenuity and the ability to adapt and over come problems and mostly learn from their mistakes. They worked to the very cutting edge of the then known technology but unfortunately in the end their technology was not good enough and the sun god Re was the instrument of the final failure of the outer casing and I believe the abandonment of pyramid construction.

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