A Computer Simulation to Determine When the Beams in the King's Chamber of the Great Pyramid Cracked

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Abstract

For more than a century it has been widely known that the beams forming the ceiling of the King's Chamber and those of the first and second Relieving Chambers in the Great Pyramid are cracked. However, it was not known when they cracked. This paper reports the results of a virtual reality 3D computer simulation designed to determine precisely when the beams cracked. It is suggested that such computer simulations might have a broad range of applications to archaeological questions.

Introduction

One of the first scholars to discuss the cracks in the Burial Chamber of the Great Pyramid was Flinders Petrie who surveyed the pyramid in 1880–81. Petrie believed that the damage was caused ". . . probably by an earthquake, when *every* roof beam was broken across near the S. side. . . ."[1] Petrie was not quite right. Of the nine ceiling beams, only seven were cracked on the bottom. The cracks are approximately one centimeter wide and continue upward through approximately half the beam. The beams also cracked on top, but on the north side, almost a mirror image of the cracks on the south side, again about a centimeter in width but with eight of the nine beams cracked. Petrie reiterated the earthquake notion by saying, "All these motions are yet but small—only a matter of an inch or two—but enough to wreck the theoretical strength and stability of these chambers and to make their downfall a mere question of time and earthquakes."[2] Although such statements might suggest that Petrie believed cracks occurred some time after the pyramid's completion, it is clear that Petrie believed at least some of the cracks appeared as the pyramid was being built. "The crack across the Eastern roof-beam has also been daubed with cement, looking, therefore, as if it had cracked *before* the chamber was finished." Petrie, of course, referred to plaster placed inside the crack to serve as a 'telltale' to indicate if the crack widens. Such a measure certainly indicated that the cracks appeared during construction, but as we will see, not necessarily before the chamber was completed.

Dieter Arnold agreed with Petrie's suggestion that the cracks occurred during the construction of the King's Chamber and suggested that the relieving chambers above the King's Chamber were a response to the cracks. "But its builders—perhaps irritated by cracks that opened during the construction—distrusted its stability and added a fantastic system of five relieving chambers on top."[3]

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[1] W. M. Flinders Petrie, *The Pyramids and Temples of Gizeh* (London, 1990), 27.

[2] Petrie, *Pyramids and Temples*, 27.

[3] Dieter Arnold, *Building in Egypt* (Oxford, 1991), 183.

There is certainly evidence to support the theory that the cracks appeared during construction of the pyramid. In addition to the plaster on the beams of the Burial Chamber, there is also plaster on the beams in the first Relieving Chamber. To gain access to the Relieving Chamber, a small tunnel was cut at the top of the Grand Gallery. It would seem as if only someone with intimate knowledge of the pyramid's construction could have cut the tunnel. How else would one know that there was a Relieving Chamber above the Burial Chamber and that such a hole would yield access to it? Also, if such an entrance were cut by later treasure hunters, why did they stop with the first relieving chamber? Why not continue when they saw there was yet another room above? All of this points to the conclusion that the beams cracked during the pyramid's construction. The question is, precisely when?

The first step to answer this question was the construction of a detailed geometric model of the pyramid in three dimensions. Especially crucial would be the rendering of the Burial Chamber and the five Relieving Chambers. Only the Great Pyramid has Relieving Chambers and they are unique in several aspects.

The structure is not homogeneous. While the Burial Chamber is built entirely of granite, the Relieving Chambers are composed of both granite and limestone blocks with limestone used only in the upper chambers. The walls of the Relieving Chambers are free standing, not tied in to the nucleus of the pyramid and as Maragioglio and Rinaldi point out, "Perhaps only the rafters on the top are bonded to the nucleus."[4] With such an eccentric structure, it was crucial to have the most accurate 3-D model possible for our test.

The earliest published survey of the Burial Chamber was by the Oxford astronomer John Greaves in 1620. He came prepared with precisely machined brass measuring rods, but it seems he was overwhelmed by his pyramid experience and made errors about even the simplest features. He reported that the Burial Chamber's walls are made of six levels of stone; they are five.[5] Also, he had no idea that Relieving Chambers existed above, so his study was of little use to our project.

Although the relieving chamber undoubtedly had many visitors before the Oxford astronomer Nathaniel Davison visited it in 1765, it is named Davison's Chamber in his honor. Although Davison explored the pyramid, he did not attempt to enter the second relieving chamber visible above the first. Nor did he leave a careful description of the first chamber.

The first to push beyond the lowest Relieving Chamber was Colonel Howard Vyse who in 1837 used dynamite to blast his way up to the last relieving chamber. His three-volume account of his work on the Giza Plateau[6] is still of value to modern researchers, and while he devoted two engravings to a careful recording of the workmen's graffiti in the Relieving Chambers, he left no detailed plans of the chambers he discovered.

In 1864 Piazzi Smyth, the Astronomer Royal of Scotland, conducted a detailed survey of the Great Pyramid, but it was both influenced and obscured by his eccentric religious beliefs and his published data, though still in print, in most cases are of little scientific value.

The first survey of real scientific value was Petrie's of 1880–81 mentioned above. To a great extent, all subsequent studies of the pyramid are indebted to him. His survey is now more than a century old, but is still widely used. In their visual survey of the Memphite pyramids, Maragioglio and Rinaldi state that they rely upon Petrie's measurements because he used ". . . very high precision measurements."[7]

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[4] Vito Maragioglio and Celeste Rinaldi, *L'Architettura Della Pirimidi Memfiti. Part IV (Cheops)* (Rapallo, 1973), 133.

[5] John Greaves, *Pyramidographia* (London, 1736).

[6] Howard Vyse, *Operations Carried on at the Pyramids of Gizeh in 1837.* 3 vols. (London, 1837–42).

[7] Vyse, *Operations*, 5.

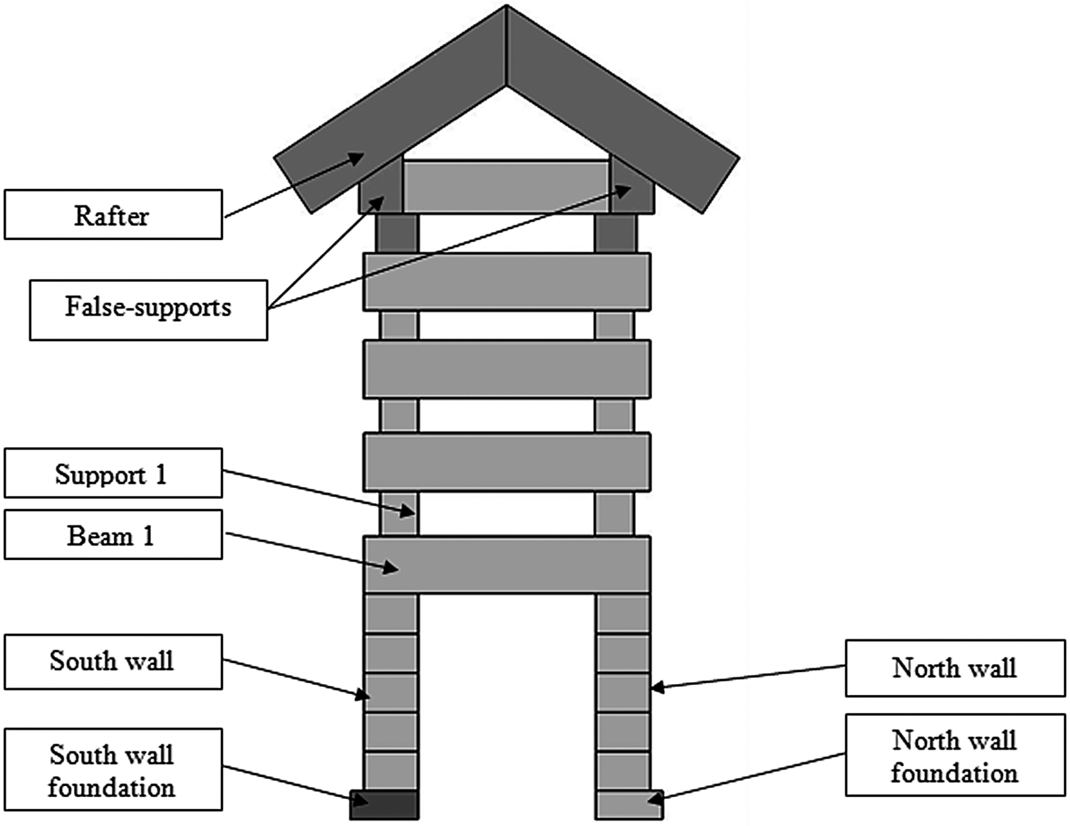


Fig. 1. Complete assembly of the Burial Chamber. Granite in grey, limestone in yellow, south wall subsidence in red.

Requirements for a 3-D Computer Simulation

For a virtual 3-D computer simulation of the building of the Great Pyramid even more data than that provided by Petrie was needed. Fortunately the French team that conducted a microgravemetric study of the pyramid[8] also produced detailed architectural plans of the Burial Chamber and the Relieving Chambers.[9] These plans served as the basis of our computer model (figs. 1–2).

In industry, computer models of buildings, airplanes, cars, etc., are frequently constructed to predict structural weaknesses before actual construction. Our hope was that building a detailed virtual 3-D pyramid, level by level, would enable us to see structural weaknesses in the actual pyramid and retrodict when the beams cracked. To achieve the virtual 3-D graphics we used CATIA and our mechanical engineering software was SIMULIA (Abaqus for Catia), a program used in architecture, but also in the aircraft and automobile industries.[10]

[8] Hui Duong Bui et al., "First Results of Structural Analysis of the Cheops Pyramid by Microgravity," in *Proceedings of the First International Symposium on the Application of Modern Technology to Archaeological Exploration of the Giza Necropolis* (Cairo, 1988), 66–90.

[9] Gilles Dormion, *Pyramide de Cheops: Architecture des Appartments* (Lille, 1996).

[10] All software for this project was provided by Dassault Systemes, Paris. The research team that built the model and made all the calculations was headed by Emmanuel Collard and consisted of Philippe Etcheverry, Julien Lemarie, Estelle Ronsoux, and Mehdi Tayoubi.

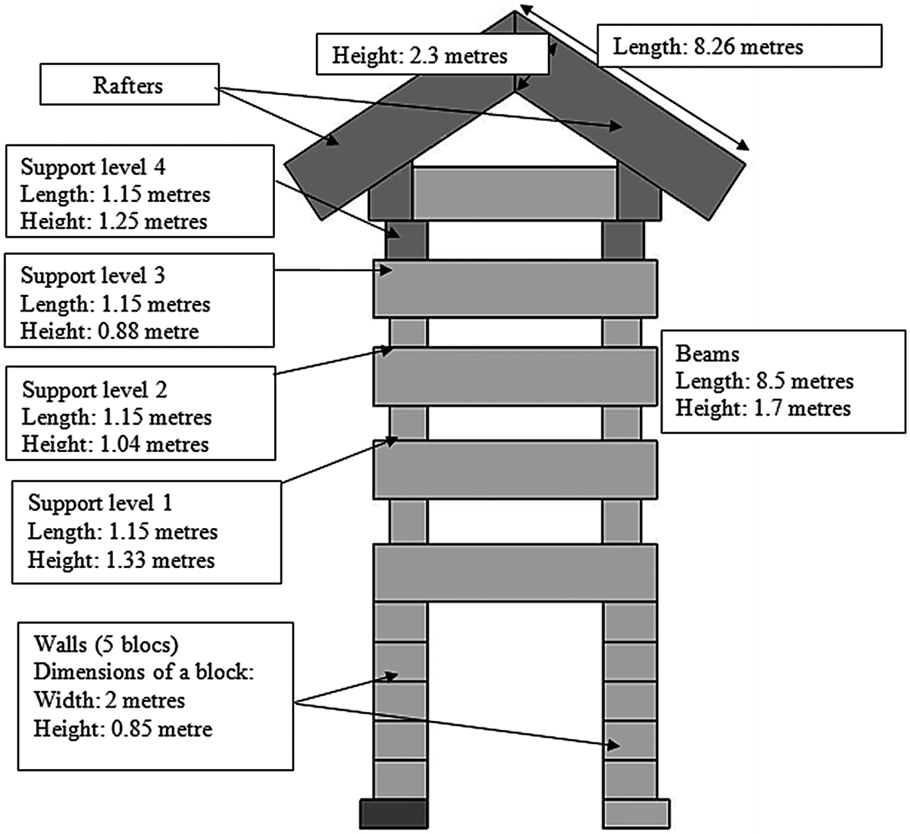


Fig. 2. Complete assembly of the Burial Chamber, with dimensions.

Once the architectural details had been entered, the structural features of each block of stone had to be added to the model. The Burial Chamber and Relieving Chambers are built of granite and limestone and the relevant physical properties of these two stones are given in Table I below.

TABLE I. *Physical properties*

	Young's Modulus (MPa)	Poisson Coefficient	Density (kg/m^3)
Granite	50,000	0.27	2,770
Limestone	12,000	0.27	2,200

Because there was slippage of several parts of the Burial Chamber and Relieving Chambers, coefficients of friction had to be factored in and they are given in Table II.

TABLE II. Coefficients of friction

Materials in contact	Coefficient of friction
Granite / Granite	0.43
Granite / Limestone	0.40
Limestone / Limestone	0.40

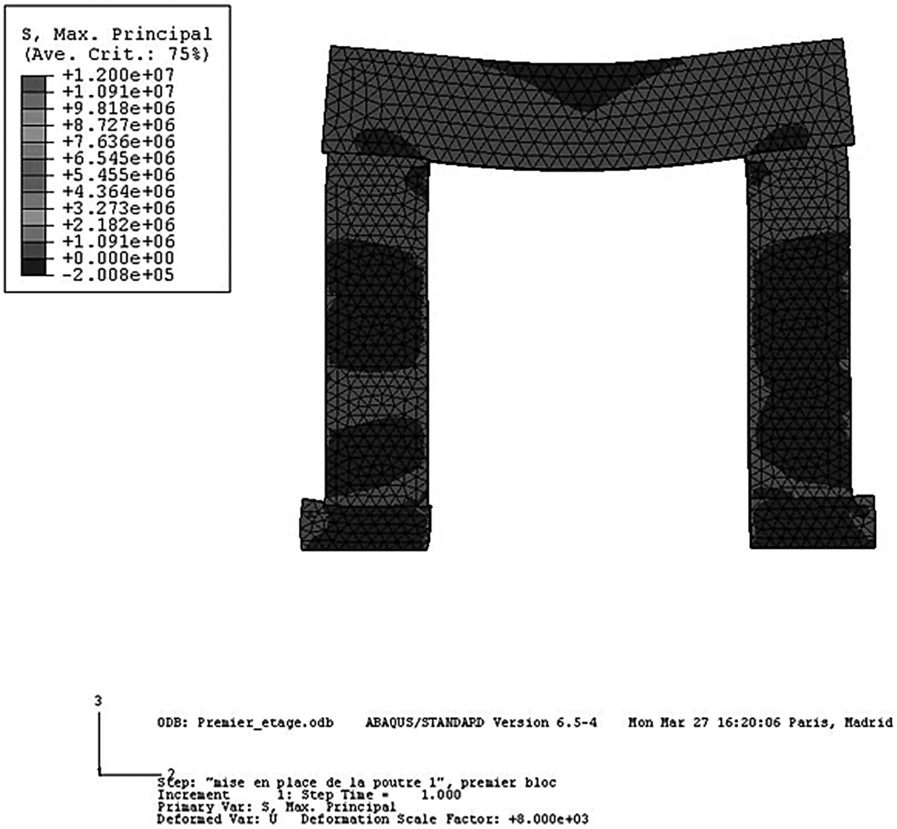
The First Simulations

The first computer simulation tested Dieter Arnold's theory that the beams cracked as the Burial Chamber was being constructed and that the Relieving Chambers were constructed in response to this cracking. This model consisted of merely the Burial Chamber and the ceiling beams and showed little stress and no cracking. Thus the effect of gravity alone on the ceiling beams was not adequate to cause cracking (fig. 3).

We continued to build the model with the second, third, fourth and fifth relieving chambers added, including the rafters above the fifth chamber, and found similar results. There were no significant stresses and certainly no cracks in the ceiling beams (fig. 4). In fact the stresses were less than 3 MPa while the tensile strength of granite is about 12 MPa. We should note that the stability and efficiency of this construction should not be surprising. Beneath the Burial Chamber, the Queen's Chamber used a system of rafters (with no relieving chambers) to support the weight of the pyramid above and it is perfectly stable. The logical place to look for the cause of the cracks was thus the imperfections in the Burial Chamber and its Relieving Chamber that had been noted by Petrie and others. This consisted of: 1) the slipping of the rafters high above the Burial Chamber and 2) the subsidence of the Burial Chamber's south wall.

Because two variables could be involved in the cracking of the beams, each was modeled separately to see the relative effects of each factor. In our first model we took into account that the rafters slipped 5 mm each (we did the same simulations with only one rafter slipping 10 mm and got the same result), but not that the south wall had subsided. With this simulated, considerably more stress (10–15 MPa) was evident on the beams at full load (pyramid completed) as compared without the slippage (2.5 MPa) (fig. 5). We should point out here that the beams remained horizontal and were still in compression. The breaking strain of granite under compression is very high (150–250 MPa) so the slipped rafters alone could not have caused the cracks. Obviously the next step was to factor in the subsidence of the south wall and see the effect of the two combined.

The new model showed that the combination of the south wall subsiding, and the rafters slipping generated significant forces at full load (pyramid completed) in the granite and limestone supports that trapped the beams in a pincer movement. This combined with the difference in the height between the south and north walls generated shearing stresses in the beams. The ends of the beams were pinned between their supports and remained horizontal, but the long section of the beam spanning the chamber inclined (fig. 6). The model showed the first three levels of beams were the most stressed because their supports were made entirely of granite and did crack while the pyramid was under construction. The fourth and fifth levels were less stressed because their limestone supports (partial for the fourth ceiling) depressed and permitted a smaller deformation of the beams below them; they did not crack.



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ODB: Premier_etage.odb    ABAQUS/STANDARD Version 6.5-4    Mon Mar 27 16:20:06 Paris, Madrid

Step: "mise en place de la poutre 1", premier bloc
Increment      1: Step Time =    1.000
Primary Var: S, Max. Principal
Deformed Var: U   Deformation Scale Factor: +8.000e+03
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Fig. 3. Burial Chamber ceiling beams + gravity.

This simulation was the only one, among all the possibilities tested, that led to an exact replication of the cracks in the beams of the first three ceilings.

This model revealed a significant defect in the design of the Relieving Chambers not discussed before. Beneath the limestone rafters are limestone filler blocks. When the rafters slipped, some of the forces that should have been distributed into the pyramid's core were transmitted downward to these packing blocks which in turn transmitted forces downward to the beams below, causing considerable stress, leading to the first three ceilings cracking. It is important to note that without the filler blocks, the forces would have been distributed into the core of the pyramid and no forces would have been transmitted to the beams. We understood that the inclusion of filler blocks was an ancient design flaw, the Egyptians not having left enough clearance between the filler blocks to absorb any deformation of the structure. We then knew that the cracks occurred while the pyramid was being built and after the south wall subsided 3 cm and the rafters slipped 5 mm each. We must keep in mind that we are talking about errors of only a few centimeters in a pyramid nearly 147 meters high. Our next step was to determine precisely when these cracks occurred when the upper part of the pyramid was being built.

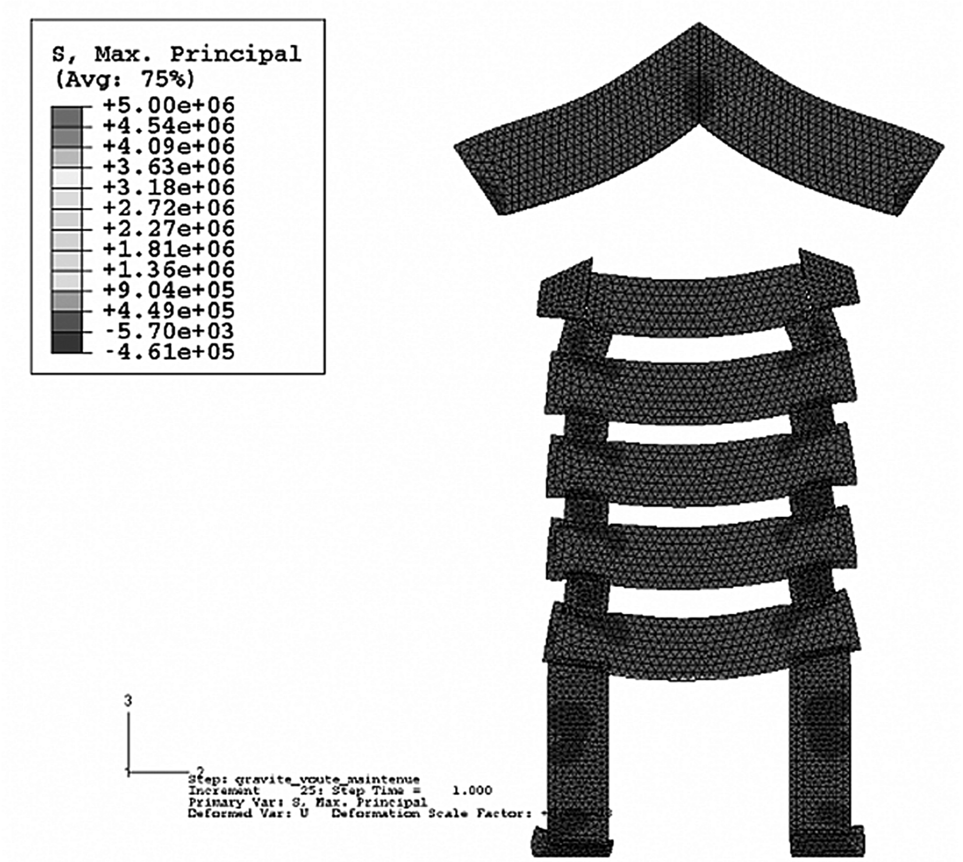

Fig. 4. Complete model: Gravity + fixed rafters.

The Last Simulations: The Beams Crack

Because the beams of the Burial Chamber did not crack even with the south wall of the Burial Chamber subsiding and the slipping of the rafter, we believed that perhaps the load of the pyramid above the Relieving Chambers was a third and necessary factor to cause the cracking. As we built the model of the pyramid layer by layer above the Burial Chamber, at first there were indications of increased stress, but no cracked beams. However, when the virtual pyramid's height at the mid horizontal axis reached approximately 120 meters (plus or minus 5 meters), after all the Relieving Chambers were completed, the beams in the Burial Chamber cracked. The pattern of virtual cracks is the same as on the actual beams, on the underside of the south ends of the beams and at the top of the north ends (fig. 7). At the time of cracking there were approximately 55 meters of stone above the rafters, which combined with the subsidence of the south wall of the Burial Chamber and rafters slipping caused the cracks. This enables us to reconstruct when in the pyramid's construction the cracks appeared.

At approximately 120 meters, the point when the beams of the Burial Chamber cracked, 98.5% of the pyramid's volume was completed. We continued our modeling of building the pyramid, and when the pyramid reached approximately 130 meters (plus or minus 5 meters), the load was sufficient to

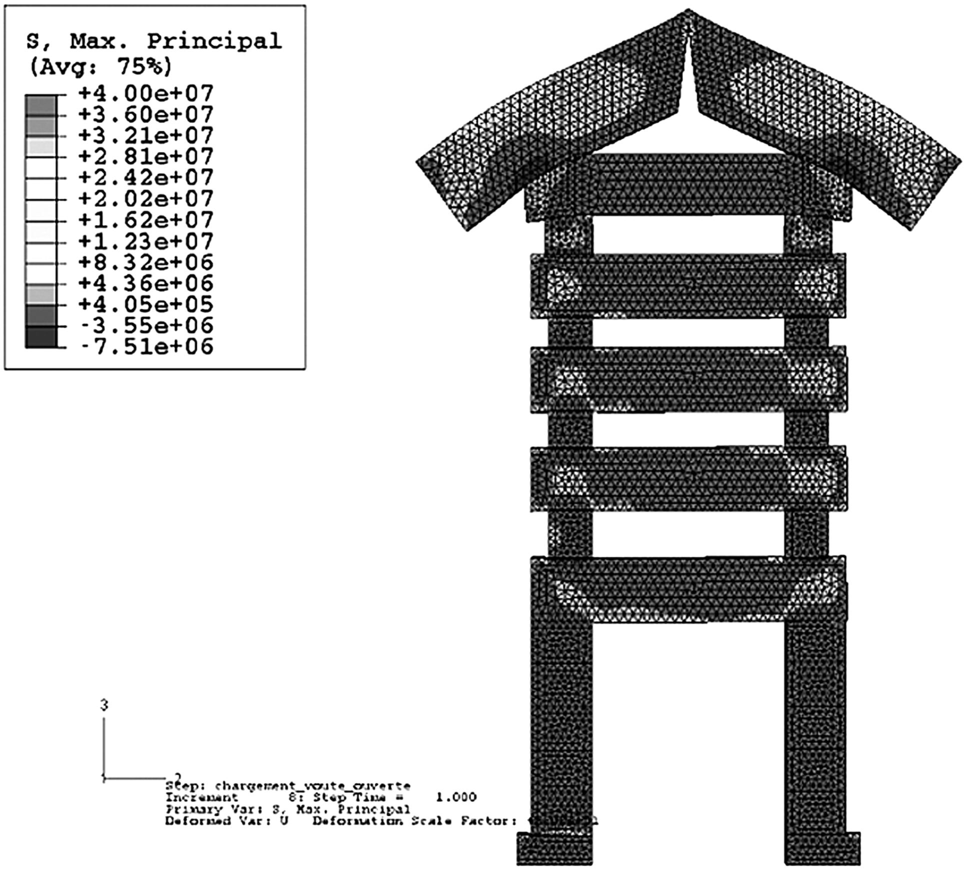

Fig. 5. Complete model: Gravity + loading on rafters + slippage of rafters.

crack the second set of beams, those above the first Relieving Chamber. Next, the ceiling beams of the second Relieving Chamber cracked when the pyramid was approximately 140 meters tall (plus or minus 5 meters), only a few meters from completion. In contrast, the fourth and fifth sets of beams never cracked because the pyramid was completed and there was not an adequate load above to crack the beams.

The Ancient Reaction to the Cracks

The computer simulation enabled us to identify the factors that caused the beams to crack and also to make a reasonable estimate of when they cracked. It also enables us to better understand the sequence of actions taken by the pyramid's architect, Hemienu, when the beams cracked.

He had already completed the Relieving Chambers and was completing the solid portion of the pyramid above them when the beams in the Burial Chamber cracked. With approximately 30 meters to complete, he needed to know if the Burial Chamber was stable enough to support additional weight above. He placed plaster in the cracks to serve as tell tales so he could monitor the cracks as the load in-

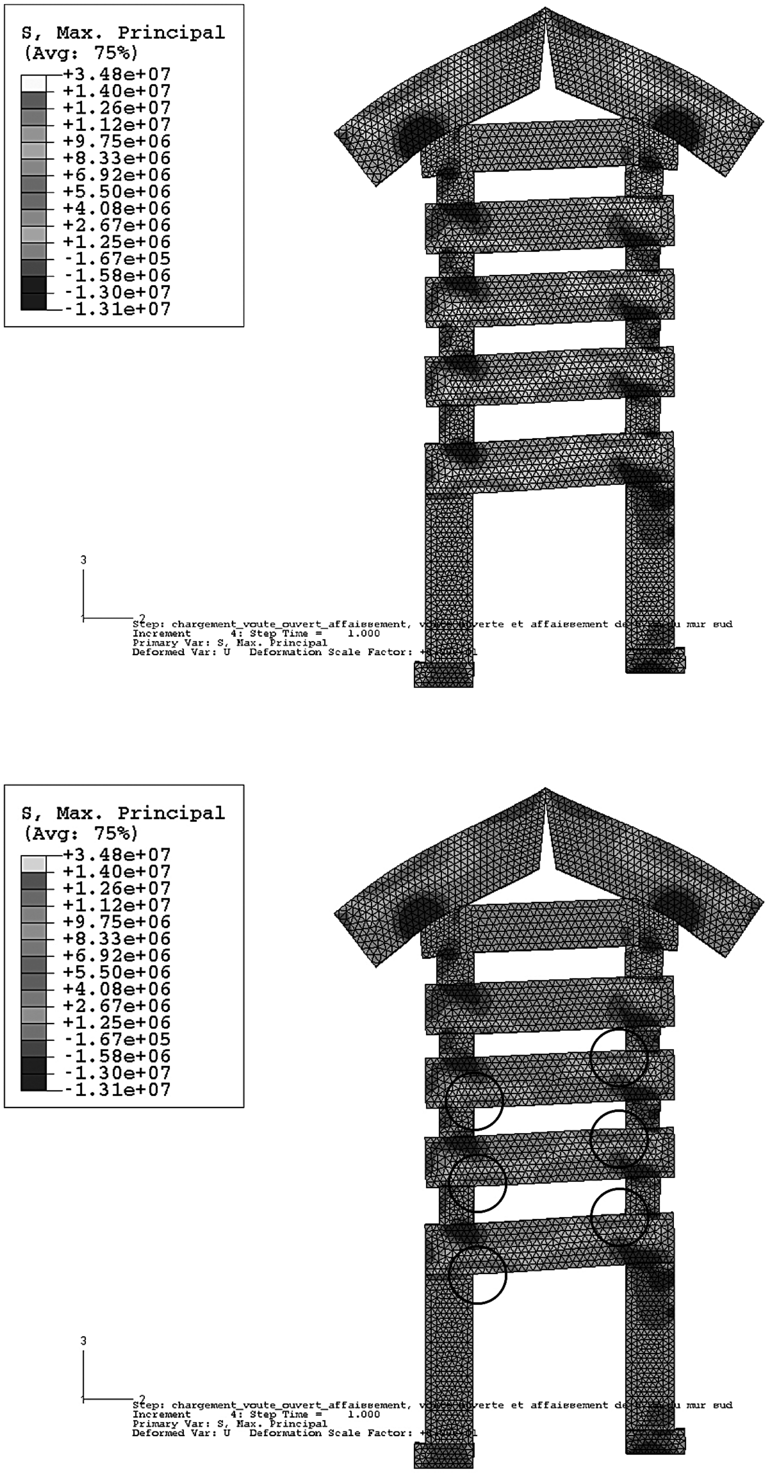

Fig. 6. Complete model: Gravity + loading on rafters + slippage of rafters + south wall subsidence (6mm).

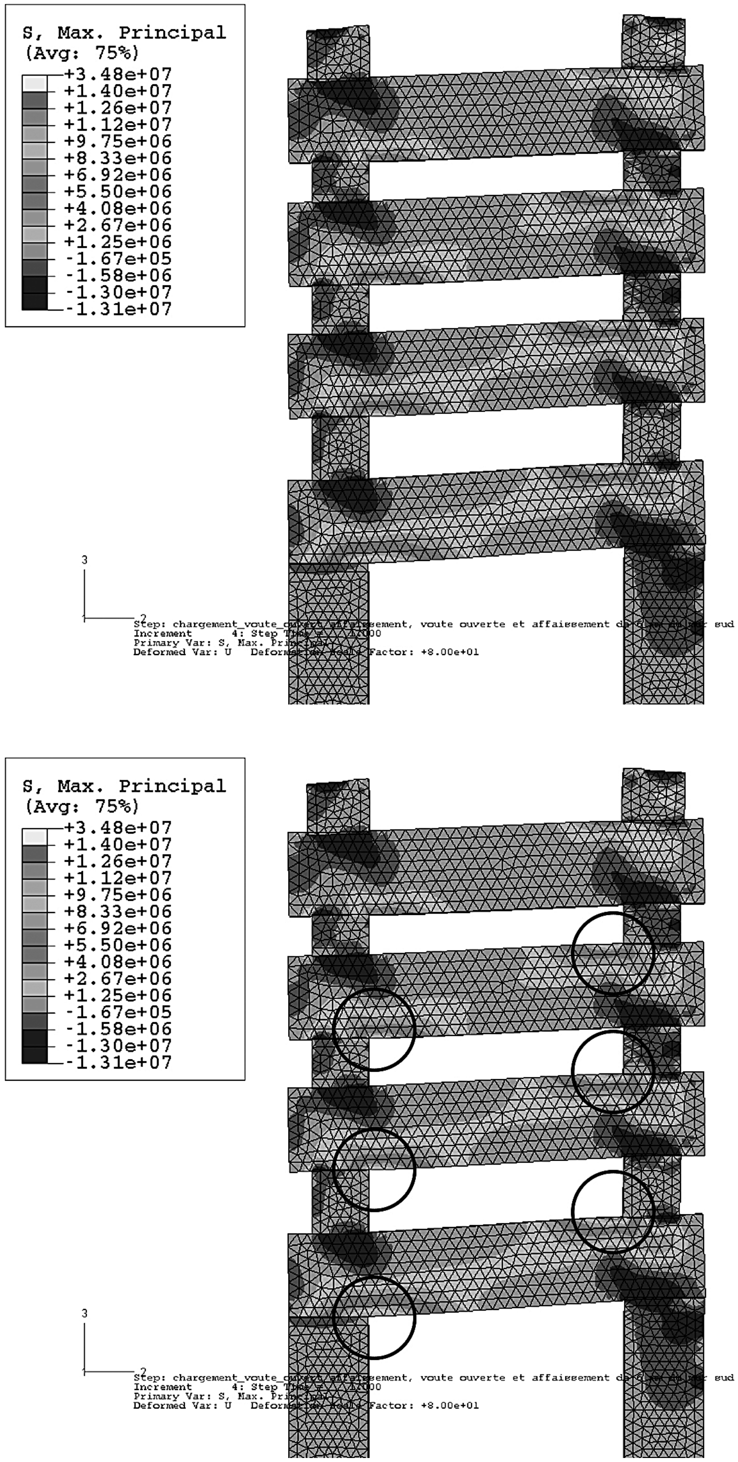

Fig. 7. Complete model, beams 1-4: Gravity + loading on rafters + slippage of rafters + south wall subsidence (6mm).

creased above them. In addition, he cut a small hole in the east wall at the top of the Grand Gallery and excavated a tunnel so he could enter the now sealed first Relieving Chamber so he could better assess the damage. He would have seen that the upper sides of the beams of Burial Chamber had cracked on their north ends, but the room was intact with the beams forming the floor of the second Relieving Chamber undamaged. Later on, when these beams cracked, he went back into the first Relieving Chamber to monitor the damage, but did not excavate a second tunnel to check the second Relieving Chamber as he felt there was no need for it. He then placed plaster in the cracks of the beams of the ceiling of the first Relieving Chamber, again to monitor the stability of the structure. As he continued to complete the pyramid, the beams on top of the second Relieving Chamber cracked, but Hemineu took no further action as the plaster in the beams in the Burial Chamber and first Relieving Chamber never moved. (Forty-Five centuries later, they still have not moved any more.) However, as the pyramid neared completion, the load above became insufficient to crack the next set of beams. Hemienu was fully confident that the Burial Chamber was strong enough to protect the mummy of the king and went forward, completing the Great Pyramid.

Conclusions

The virtual 3-D simulation of the construction of the Great Pyramid has yielded the best explanation so far of the cause of the cracks in the beams in Burial Chamber and Relieving Chambers of the Great Pyramid of Giza. All indications are that the beams did not crack all at the same time as the result of an earthquake or some other trauma. Rather, the beams cracked sequentially during the construction of the pyramid, but *after* the Burial Chamber and its Relieving Chambers were completed. The cause of the cracks was a combination of three factors: 1) the slipping of the limestone rafters above the fifth Relieving Chamber, 2) the subsidence of the south wall of the Burial Chamber, and 3) the load of the solid portion of the pyramid above the Relieving Chambers. This explanation is consistent with physical traces inside the pyramid (plastered beams and a tunnel cut to reach the first Relieving chamber) that indicate the ancient architect's reaction to the first appearance of cracks.

The use of sophisticated computer software to model ancient architecture is not new. For example, the Bab al-Barqiyya, a fortified gate in Cairo built by Salah Al Din (circa 1176) has been modeled in 3-D.[11] However, as far as we are aware, this is the first time that a 3-D mechanical design package (CATIA) has been combined with an integrated Finite Element Analysis engineering program (SIMULIA) to analyze structural elements in virtual reality. The virtual reality element permitted us to view the Great Pyramid in 3-D while testing a structural hypothesis. The success of this application to the Great Pyramid of Giza suggests that applications to other archaeological sites to determine the cause of structural failures might yield interesting results.

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[11] http://archive.cyark.org/bab-albarqiyya-intro.