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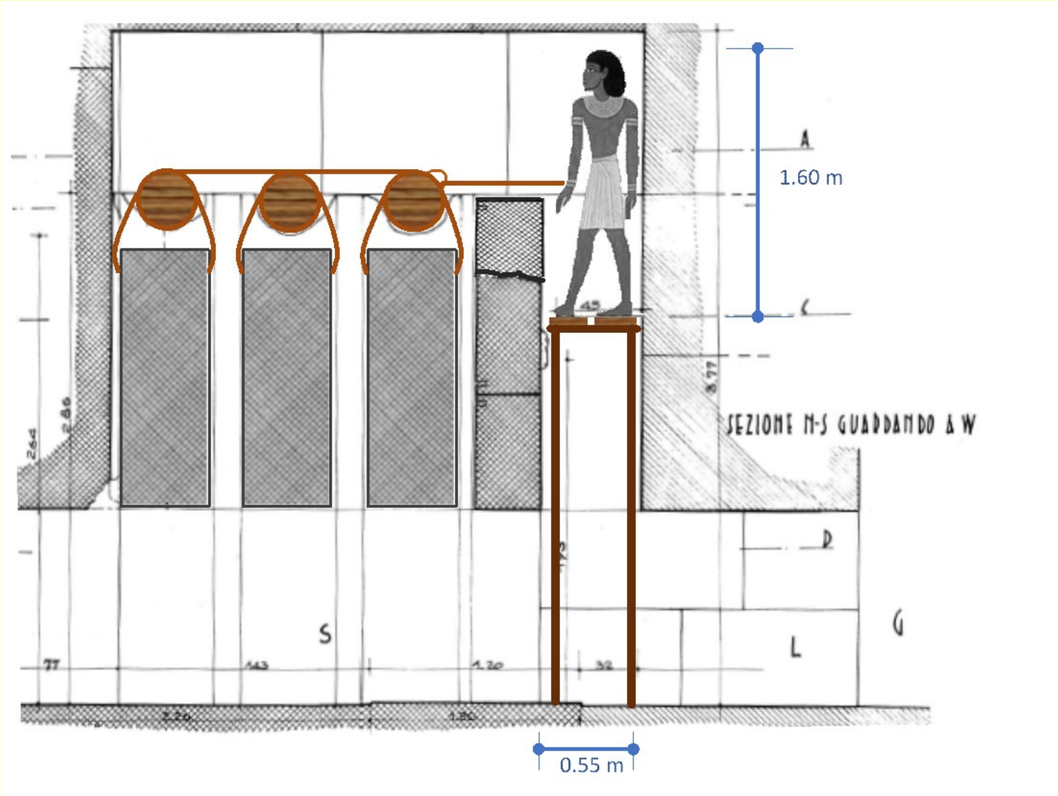

Experimental Investigation on a Full-Scale Replica of the Closing Mechanism in Cheops' Antechamber

Research Report

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Part 1: Motivation, reconstruction and major insights

Uwe E. Dorka

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Purpose of investigation

The antechamber in the Cheops Pyramid (also called Great Pyramid) allows for a very detailed reconstruction of the closing mechanism because every important technical feature is well preserved and documented. Smyth[1] already provided an excellent technical drawing in 1880 (fig. 1).

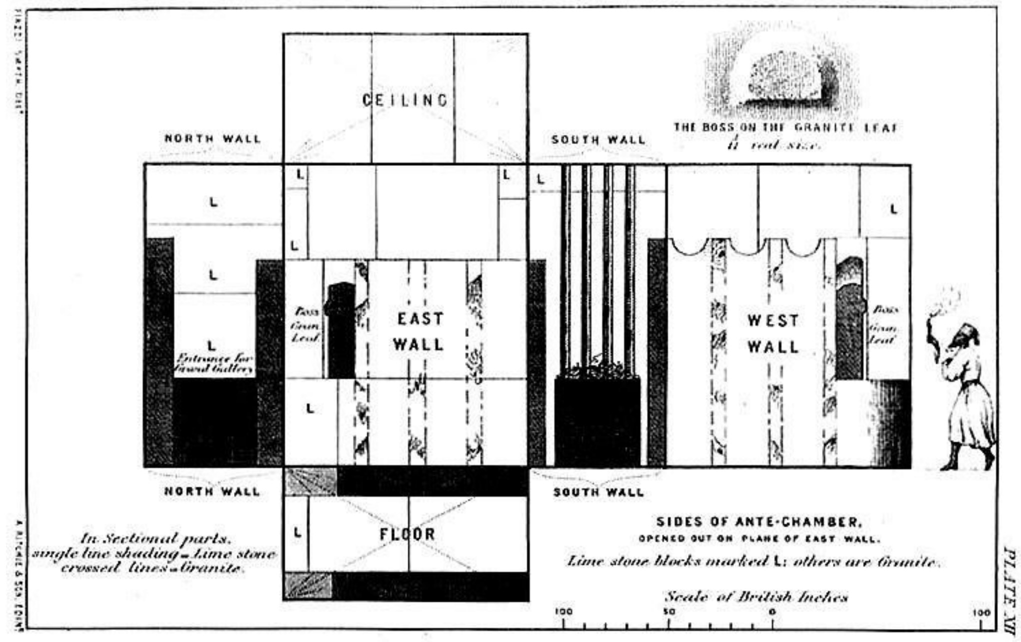

Fig. 1. First accurate and detailed technical drawing (to scale) of the antechamber by Smyth[1] with its sides folded out.

Flinders Petrie[2] provided accurate measurements. His scale drawings of details are an excellent source for local geometric information (fig. 2)

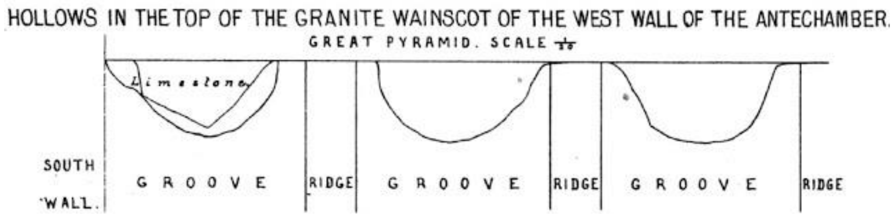

Fig. 2. The scale drawing of the hollows by Flinders Petrie[2] allow for an excellent reconstruction of this part of the chamber and the logs that held the ropes.

The size of the three granite portcullises can be reconstructed with cm accuracy thanks to the vertical ridges in the west- and east walls and the upper and lower limits provided by the positions of the hollows in the west wall and the opening to the burial chamber. The position and size of the round timbers can also be reconstructed with excellent accuracy thanks to these hollows. Even the number and location of ropes and their approximate diameter can be reconstructed with good accuracy thanks to the four vertical grooves in the south wall. These grooves also allow for a very good positioning of the holes for the ropes in the portcullises.

Thus, a reconstruction of the closing mechanism in the antechamber is not only possible but provides important insights into one of the key technologies of the time: The delicate placing of heavy blocks with mm accuracy by lowering them into position with ropes. This task was performed many times, especially

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[1] Smyth (1880)
[2] Flinders Petrie (1883)

when constructing burial chambers, temple interiors, and even the facades of pyramids. The remains of many bosses on heavy blocks bear witness to this (fig. 3).

Fig. 3. Bosses on the facade blocks of the Mykerinos Pyramid (left) and one of Cheops' side pyramids (right) bear witness to the fact that, they were lifted into position. (photos by U.E. Dorka)

Note that the flat face of the bosses is always down, not sideways or up. This is the only face were a rope can exert a force on these bosses, which therefore will always point upwards. Thus, these bosses can only be used for lifting and lowering, not for pulling sideways.

It is important to note that, only a full-scale reconstruction enables accurate results, because the local contact mechanics between ropes and portcullises, ropes and timbers and portcullises and walls depends heavily on the forces acting in these contact zones. Thus, realistic results can only be expected when the weight of the portcullises is realistic, requiring them to be full-scale.

Before these experiments were performed it was unknown, which rope configuration was used to lower the portcullises and the forces that developed in the ropes. We therefore investigated a number of possible configurations to gain insight into their principal behaviour and identify the configurations that were most likely. We also devised a system that allowed us to measure the force at the end of each rope. Based on these measurements, it was then possible to determine the number of persons necessary to operate the mechanism in its various configurations.

Reconstruction of the closing mechanism

Dimensions

Fig. 4. Top view of the antechamber replica with the south wall to the right. The northern portcullis (N-block) is in its topmost position sitting on a timber beam (fig. 5) while a test is prepared. Note the rounded-out timber wedges on the flat recess of the east wall that provided proper bearings for the logs. (photo by A. Klarendic)

Only those parts of the antechamber were reconstructed, which are important for the closing mechanism. Besides the three portcullises, these are the east and west walls (which differ at the top: see fig. 1), the south wall with its four vertical grooves and access to the burial chamber and the stone leaf to the north.

Fig. 5. North entrance of the replica with timber beams placed underneath the portcullises for safe handling during test preparations. The beams were removed just prior to testing. Note the end plates of two steel rods (out of four) that connect the prefabricated concrete elements. The steel frame and log in front are part of the force measurement system. (photo by C. Nguyen)

East, west and south wall reconstructions ended just above the hollows of the west wall in order to provide safe seating for the timbers and easy access during test preparations (fig. 4). East and west wall have rectangular openings at the height of the entrance to the chamber so that wooden beams could be placed safely from the sides underneath the portcullises when they had to be handled during test preparations (fig. 5).

East, west and south wall were just thick enough to provide structural stability. The stone leaf to the north was done in one piece. The original consists of two granite blocks of approximately equal size, which has no effect on the mechanism, but would have increased construction complexity and costs.

The height of the portcullises was taken as the distance from the top of the entrance to the burial chamber to the beginning of the flat recess of the east wall (149 cm). Thus, the portcullises would not cover the entrances or obstruct the movement of ropes when in their topmost positions (N-block in fig. 4). To prevent the portcullises from locking when in motion, some space is needed between them, the walls and their ridges. A gap of 5 mm was chosen for this purpose on all sides. This resulted in a width of 119 cm and a thickness of 53 cm respectively.

The four holes in the portcullises that have to accommodate the ropes have a diameter that is slightly smaller than the width of the vertical grooves in the south wall, because we used a standard plastic tube as formwork. They were aligned with these grooves. Their distance from the top of the portcullis was determined by static analysis to avoid vertical cracks from forming above the holes.

There is a fragment of a granite block with two holes outside the Great Pyramid. Measurements were taken some time ago[3], which confirmed that this is indeed a fragment of one of the portcullises. We were not aware of these measurements when we designed the portcullis replicas based only on information provided by the antechamber itself. As it turned out, we are very close to these measurements. Thickness: 53.5 cm measured, 53 cm chosen; Width: 119 cm derived from measurements, 119 cm chosen; Holes: 7.1-7.6 cm measured, 6.3 cm provided by a standard plastic tube. These small differences are of no concern for the working of the mechanism. They show though that, a faithful reconstruction is possible even for missing components (portcullises, logs, ropes etc.) with information coming only from the antechamber itself.

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[3] Haase (2004)

The shapes of the hollows in the west wall were taken from Petrie's sketch (fig. 2), which is to scale. Exact inlays were produced for the concrete formwork based on this sketch.

Where recorded dimensions were insufficient or questionable, photogrammetric measurements were taken (fig. 6). In this case, they can be obtained with mm accuracy from appropriate pictures that have a reasonable resolution.

Fig. 6. Using an appropriate set of pictures, photogrammetry can create a three-dimensional image in the computer, here of a vertical groove in the south wall. In this case, local measurements were taken with mm accuracy from this 3D image to confirm the shape of the grooves. This provided important information on the likely diameter of the ropes (about 20 mm).

All concrete parts were prefabricated, delivered to the lab and assembled on site. They were connected with four 40 mm steel rods (the ends of two are seen in fig. 5) that ran through the south wall and northern stone leaf. This reconstruction can be easily disassembled, moved and reassembled in another location.

Geometrically feasible diameters for the three logs can be derived from the hollows in the west wall. They must be around 15 - 20 cm in order to avoid single point contacts, which would split the timber under such loads. They also provide enough bearing in the hollows against sideway motion. The east wall does not have hollows, but a flat recess approximately at the height of the low points of the hollows and a depth similar to them. To provide the necessary bearing stability for the logs here, we chose rounded out timber wedges with radii similar to the ends of the logs (fig. 4).

The exact dimensions of all elements can be found in the production drawings provided in the annex. Included is also the reinforcement of the concrete elements, which was mainly needed to reduce cracking during concrete curing, but also to provide safety against possible catastrophic failures that can occur due to the repeated use of the portcullises in multiple tests. Something that was not intended for the original design by Cheops' scribe-engineers.

Materials and surfaces

When dealing with mechanical contact problems, the material pairing and the local (even micro) geometry in the contact zones are very important. It was not possible to use the same granite (which most likely came from quarries in Aswan) and the original state of the granite surface is not known due to ages of weathering: There is an internal climate in the pyramid, which is quite moist today, but would have changed over the millennia. These changes are unknown but weathering on the surfaces of the antechamber is evident.

To solve the material problem, we developed a "granite concrete" that is, a high-performance concrete with similar material properties and grain size as the original (tab. 1).

Tab. 1. Mixture and mechanical properties of "granite concrete" in comparison to Aswan granite. Concrete compressive strength was determined from standard 100x200 mm cylinders (DIN EN 12390-3:2017) and prism strength from 150x40x40 mm 4-point prism tests (DIN EN 12390-5:2009) at AMPA, Universität Kassel. Properties of Aswan granite were taken from Egyptian Marble & Granite.[4]

	quartzite sand	quartzite dust	granite split	basalt	micro silica	FM super plasticizer	cement white	water	oxide red
grain size (mm)	0-2	QI	1-3	0-2	---	---	---	---	---
kg/m^3	270	290	800	240	92	29	700	175	14

	Granite concrete		Aswan granite	
strength	compression	prism	compression	prism
MPa	157.9	8.2	167.0	15.5

Concerning the surfaces in contact, we opted for grinding them only once, providing for a smooth and even, but not polished surface. Thus, these surfaces are a little smoother than the surfaces in the antechamber today.

Fig. 7. Twisted halfa grass rope in a sophisticated configuration found with Cheops' sun bark (left, photo by U.E. Dorka) and diameter 20 mm 4-strand twisted hemp rope used in the tests (right, from KANIROPE product description)

Concerning the ropes, we opted for twisted hemp ropes, which have a similar surface geometry and texture as the ropes found with Cheops' sun bark (fig. 7).

The original logs were most likely Lebanon cedar. The mechanical properties of cedar and Nordic fir are very much alike, so we used natural undressed fir logs that fit into the hollows of the west wall.

Important technical details

An important detail is the contact between rope and timber. Already under small forces, a moving rope will damage the timber surface and then cut it because wood is very weak against such action (fig. 8 and Part 3.1).

Knowing that this would certainly happen to the logs in our reconstruction, we had to protect the timber surfaces. Since lowering heavy blocks with ropes moving over timbers was a key technology of the time, the scribe-engineers certainly knew this even before Cheops' time and must have applied appropriate protection. We are very fortunate that they have left us evidence: There is a construction log still present in the unfinished vertical shaft leading to the burial chamber of the Meidum Pyramid, which has a revealing detail[5] (fig. 9).

[4] Egyptian Marble & Granite (2019)
[5] Dorka and Dorka Moreno (2010)

Fig. 8. Damage to a diameter 20 cm Nordic fir log caused by a 20 mm moving rope with weights of 116 kg, 330 kg and 540 kg respectively (from left to right, see Part 3.1). (photo by A. Ansalone)

The author discovered this unique archaeological evidence during a fact-finding trip in 2009. A close inspection of this log reveals substantial damage close to its bearing from halfway up the circumference down to its lowest point. In this region, the timber fibres are cut and pushed to the sides, a typical damage inflicted by a moving rope (compare fig. 8). In this particular case, the force in the rope was obviously large enough to cut the timber.

Fig. 9. A construction log in the vertical shaft of the Meidum Pyramid (left) shows damage from a moving rope near one of its bearings (center). The cut-out for a protective plate with tenons is clearly visible. The plate was too short in this case. (photos by U.E. Dorka). Copper plate (right) with tenons (diameter 10 mm, 10 mm deep) used for protecting the logs in the replica (photo by S. Schuster).

This archaeological find also shows how the scribe-engineers dealt with this problem: A cut-out for a plate with two tenons at its end is clearly visible on top of the log. Such tenons prevent a plate from sliding when the rope is moving. The plate ended half-way down the circumference of this log, just where the damaged region starts. Evidently, this plate was too short.

Considering that in those days copper was the material of choice for metallic connections in timber structures (see the bed canopy of Hetepheres, fig. 10, left), we provided copper plates where the ropes moved over timber (fig. 9, right).

Most probably, the ropes were tied to the logs since no other location can be identified in or near the antechamber. A simple knot around a log will do for a fixed end, but for the end that has to be released, a more sophisticated connection is needed. In the time of the Old Kingdom copper hoops embedded in timber were used in such cases, as is evident from the bed canopy of Hetepheres (fig. 10, left) and also for much larger forces on ships (approach to Unas' pyramid, fig. 10, centre). After several trials, a suitable solution was found by running two of the ropes in a chain-like configuration through copper hoops embedded in the northern log (fig. 10, right). This provides a device that gives one handler full control over two ropes. It allows the synchronization of both ropes by keeping the "chain" in the centre between the copper hoops. It is activated gently when a helper gradually releases the simple knot around both ropes (seen in the foreground of fig. 10 right). This configuration is less complex than the one found with Cheops' sun bark (fig. 7, left).

Fig. 10. Copper hoops provided releasable connections and enabled prestressing in the bed canopy of Hetepheres (4th dynasty, left, picture from[6]) and on a 5th dynasty transport ship to tie and release the mast (approach to Unas' pyramid, centre, photo by U.E. Dorka). We used them in a similar fashion on the northern log for simultaneously releasing and controlling two ropes (right, photo by C. Nguyen).

Testing program and process

Although the main focus was on different rope configurations, other variables were also considered, like winding the rope once or twice around a log in order to provide a 1-stage or 2-stage "rope brake". In tabs. 2 and 3, 1S means a 1-stage rope brake around the southern log (S-log), 2N a 2-stage brake around the northern log (N-log) and so on. As we learned more about the development of the forces in the ropes and what influenced them, the testing program also developed, starting with only one portcullis before going to two and finally three.

After a completed test the portcullises were lifted by a crane, placed on wooden beams (fig. 5) and the ropes were re-configured for the next test. Then, the crane lifted the portcullises one by one, the wooden beams were removed, and the portcullises hung into the ropes, which all the while were held by the handlers. The forces were measured during the whole process until the handlers had lowered the portcullises.

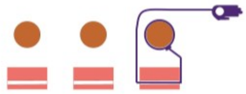
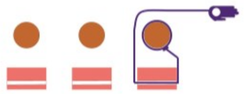
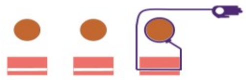
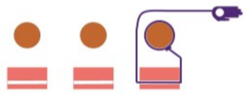
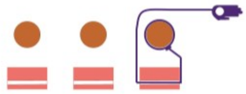
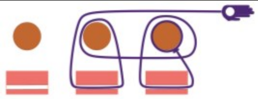
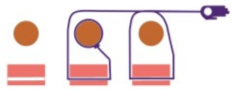
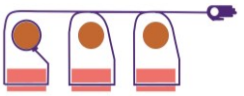
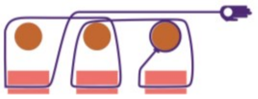
A number of trials were done without the measurement system after test 9. At this point, we knew that the forces at the ends of the ropes are small but could not be handled without a suitable "control device". After gaining enough experience with different rope configurations, we developed the final "controller" on top of the N-log (fig. 10), which is based on technical details known at the time. It allows a very delicate control of two ropes by one handler.

We reinstalled the measurement system for tests 24–26 using the rope configuration that allowed us to operate all three portcullises smoothly (tab. 3). It is similar to the configuration in test 9 (tab. 2).

We also decided to investigate the effect of lubrication. Lubrication reduces friction where the portcullises come into contact with ropes and walls. This increases the forces in the ropes, which are then easier to control, especially when operating the last portcullis. Animal fat from a number of domesticated or wild animals (from cows to geese) was available at the time as well as various oils from plants. Where a rope enters the hole of a portcullis, "corner friction" occurs, which is very different when compared to regular friction between standard surfaces[7]. Therefore, we performed tests with single ropes under such conditions. They are presented in Part 3.2 of this document. They showed that, such "corner friction" produces very large frictional coefficients μ, which do not differ much between lubricants, may they be plant oil (rapeseed oil: $\mu = 0.76$), animal fat (butter: $\mu = 0.73$) or modern high-tech carbon based grease (PG-75 Molykote $\mu = 0.69$). We used butter to lubricate the ropes and also the contact surfaces between portcullises and walls. It is cheap and readily available. Rapeseed oil was also considered, but was too difficult to apply, so we did not use it on the replica.

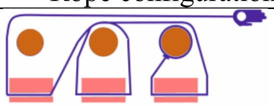
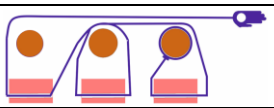
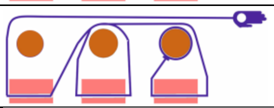
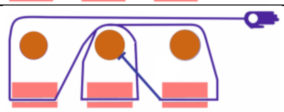
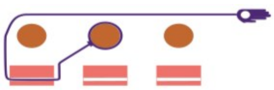
[6] Reisner (1932)
[7] Fernando and Hanna (2006)

Tab. 2. Initial testing program. In column "rope configuration", 2N means 2 loops around the N-log as a 2-stage rope brake (only in test 1). After test 3, no rope brakes were applied. North block is to the right. Maximum rope forces $F_{1\text{-}4}$ are from East to West.

Test no.	Rope configuration	Observations
1	 2N	Forces are surprisingly low. Measurement system checked and o.k. 2-stage rope brake almost prevents operation. F_1 = 172 N, F_2 = 131 N, F_3 = 140 N, F_4 = 107 N
2	 1N	Crane remains attached for safety. Picks up block during operation at 55 s, 112 s and 135 s F_1 = 144 N, F_2 = 206 N, F_3 = 181 N, F_4 = 242 N
3	 1N	Test 2 repeated without crane: Uneven rope handling tilts block sideways, creates friction on sidewalls. F_1 = 195 N, F_2 = 248 N, F_3 = 182 N, F_4 = 100 N
4		Forces jitter due to friction. Rope 4 locks in its red control hoop and ruptures. Small pieces break off N-block corners. F_1 = 530 N, F_2 = 1198 N, F_3 = 621 N, F_4 = 1762 N
5		Test 4 repeated. Uneven rope handling causes serious force re-distribution. Forces about 4-times larger than with rope brake. F_1 = 844 N, F_2 = 828 N, F_3 = 1163 N, F_4 = 493 N
6		Crane hangs M-block first, then N-block. N-block operation is difficult: forces are too small. F_1 = 172 N, F_2 = 131 N, F_3 = 140 N, F_4 = 107 N
7		Crane hangs N-block first, then M-block. Smooth operation of M-block. F_1 = 497 N, F_2 = 1141 N, F_3 = 1376 N, F_4 = 655 N
8		Crane hangs N-, then M-, then S-block. Roller 2 blocks temporarily. S-block operation is difficult: forces are too small. F_1 = 629 N, F_2 = 1420 N, F_3 = 485 N, F_4 = 952 N
9		Crane hangs N-, then M-, then S-block. M- and N-block operation difficult. F_1 = 686 N, F_2 = 784 N, F_3 = 566 N, F_4 = 1304 N

We also measured the sag that developed at each portcullis after the crane hung it into the ropes. This sag was foremost a result of the slack in the ropes, especially in their fixed connection to the log, plus some relatively small elastic stretch of the ropes.

Tab. 3. Further testing program with finalized rope configuration and lubrication (butter)

Test no.	Rope configuration	Remarks
24	 1S	Crane hangs M-, then N-, then S-block: Sag: M: 22.5 cm, N: 0 cm, S: 5 cm F_1 = 1722 N, F_2 = 889 N, F_3 = 530 N, F_4 = 1715 N
25		Crane hangs N-, then M-, then S-block. M-block picked up again to equilibrate sag: N: 10 cm, M: 8 cm, S: 12 cm F_1 = 1057 N, F_2 = 948 N, F_3 = 580 N, F_4 = 1677 N
26		Crane hangs S-, then M-, then N-block: Sag: S: 41.5 cm, M: 1 cm, N: 1 cm F_1 = 1032 N, F_2 = 1432 N, F_3 = 818 N, F_4 = 769 N
40	 1S	Rope brakes only on ropes 2 and 3. Rope 2 ruptures. It was too worn out. F_1 = 1735 N, F_2 = 1281 N, F_3 = 742 N, F_4 = 2432 N
41		During public presentation Feb. 9, 2018 F_1 = 1225 N, F_2 = 430 N, F_3 = 538 N, F_4 = 1110 N

After test 26, we knew that operating this mechanism smoothly requires some experience, so we had a few runs for the two handlers to familiarize themselves with the operation of the controller (fig. 10, right). This required again the removal of the measurement system. Minor changes were done to the configuration during this training (rope brakes only on ropes 2 and 3, ropes fixed on M-log), so we measured the final configuration in test 40. Although one rope ruptured due to excessive wear, forces did not vary much when compared to tests 24-26. With no new insights gained from these measurements, we decided not to repeat the test.

Observations

When hanging the portcullises into the ropes, substantial sag occurred mostly because of slack in the ropes. Most of this slack was removed when the crane hung the first portcullis and the other two were still resting on their support beams. Thus, the largest sag was always measured on the first portcullis, which was up to 41.5 cm (test 26). The sag was equilibrated in test 25 by picking up the M-block again with the crane. This re-distributed the sag with an average of 10 cm for each portcullis. It did not change the forces considerably when compared to tests 24 or 26 and therefore had no effect on operating the mechanism. There was a distance of about 3 cm between log and portcullis when it rested on the support beam. If the original portcullises were placed right underneath the logs and were about 9 cm shorter than our replicas (which is possible, because a height of 140 cm is still enough to cover the entrance to the burial chamber) then this sag will not obstruct the access. Still, a more slack-free fixture of the ropes to the logs is definitely advisable. These could be copper hooks instead of the simple knots we used: They had a lot of slack.

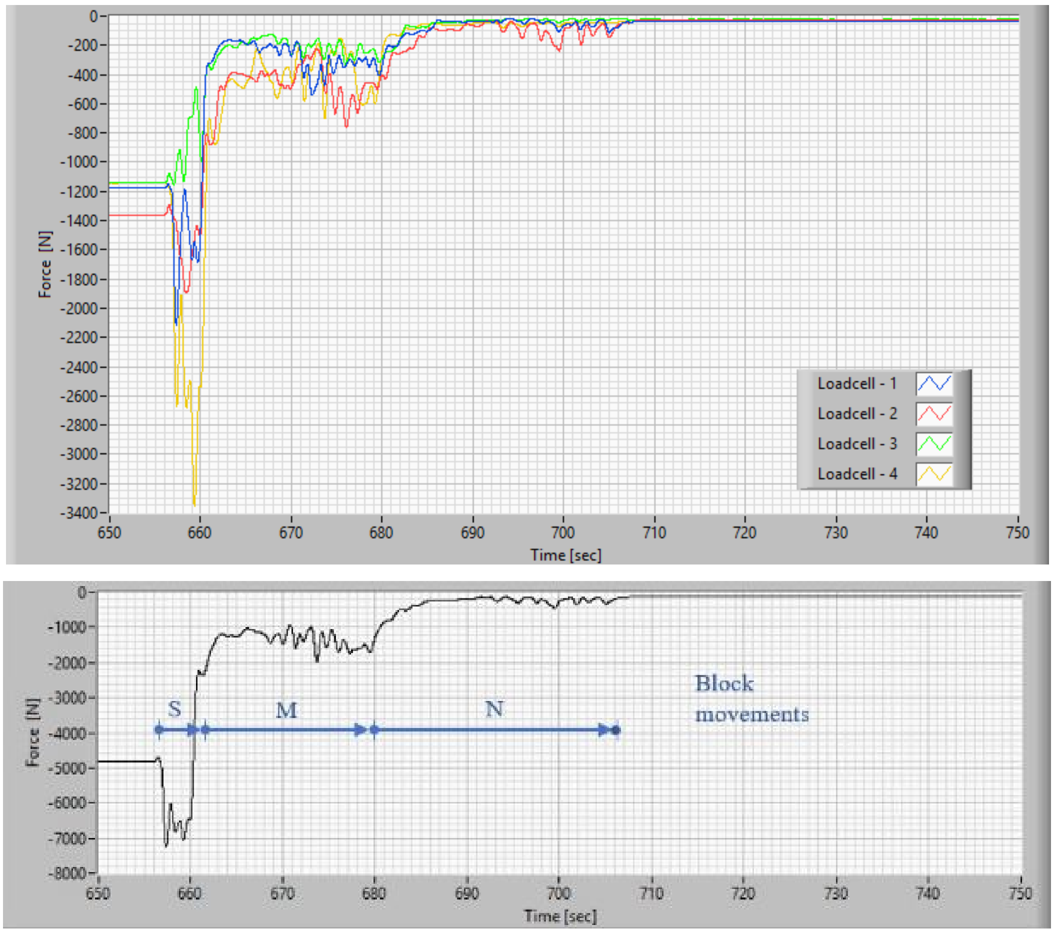


Fig. 11. Test 25: Forces (factor 2) during release. Note the large difference between each rope caused by individual handling (top diagram). The sum of all forces (bottom diagram) shows small jitters when a portcullis is moving and a rapid but gradual drop when it reaches the floor. Three phases are visible: S-block moves at 656 s with 3200 N and is down at 661 s when M-block moves with 750 N. M-block is down at 679 s when the remaining N-block moves with a mere 150 N.

Rope forces varied widely during operation depending on the way each rope operator handled his rope (Fig. 11). A rope can rupture because of this (as it did twice).

When rope brakes were used (one or two loops around the logs), maximum force was small at 500 N for a single portcullis (tests 1-3). It increased to 2000 N without such brakes (test 4). Maximum force remained at 2000 N to 2500 N for non-lubricated tests regardless of rope configuration.

Lubrication with butter increased the total from 3000 N to 3500 N for all rope configurations except for the last test (test 41, tab. 3), where it was back to 2500 N. This happened after new ropes had to be installed. Their lubricated surface is rougher than that of a used rope, because the butter melts into the fibres with repeated use. This increases the effect of lubrication (see Part 3.2).

For rope configurations with three portcullises, releasing the second one after the first one was down did not pose any problems: Total force was at 500 N for the non-lubricated and 750 N for the lubricated cases. Releasing the last one was often a problem: Total force was always very small, sometimes too small so that it did not move. This happened twice. In the best cases, some 200 N occurred. Thus, lubrication made operation easier. It also prevented screeching noise when the portcullises came into contact with the walls: The lubricated mechanism was operated almost without a sound.

The measurements of test 25 are representative for the configuration that allowed a smooth operation of 3 portcullises showing all phases clearly (fig. 11). Total force drops 76% after S-Block is down and 80% after M-block is down. This is in line with the "corner friction" ($\mu = 0.73$) measured in single rope tests with lubrication (see Part 3.2). To see the results of all tests listed in tabs 2 and 3, the reader is referred to Part 2 of this document.

When the forces in all ropes are well balanced, they will not exceed 800 N even in well-lubricated cases. Therefore, it is possible that one person can handle two ropes easily with a simple control device like the one shown in fig. 10. This also provides a more even distribution of forces and thus enables a smoother handling of the mechanism by only two persons. They need to see their control devices in order to operate them properly.

The reduction in forces is mainly due to "corner friction" between rope and portcullis at the point of entry. Because this creates uneven forces on both ends of the rope, the portcullis tilts and additional friction is generated in contact with the ridges on the walls (fig. 12).

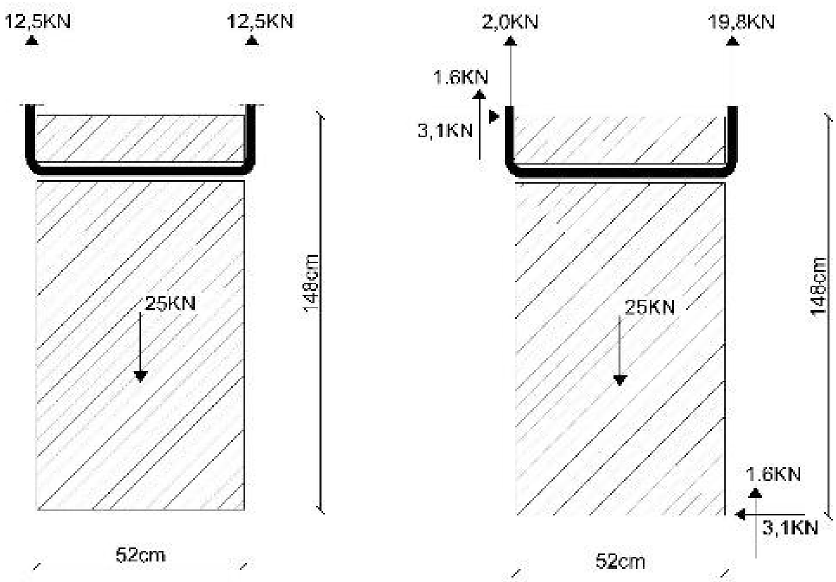


Fig. 12. Force equilibrium on a portcullis with (right) and without friction (left).

After repeated testing, the tilt caused damage to the portcullises' edges and corners, especially to the N-block, which had been used more than 40 times (fig. 13 left). In addition, cracks started to grow from the holes and eventually formed wedges that fully separated the region above (fig. 13 middle). In plain granite, these regions would have failed most likely after about 10 tests. Such damage only appeared after repeated testing and as such is of no concern when the mechanism has to function only once, as was the case in the Great Pyramid.

Fig. 13. Damage to the upper corner of N-block (left), cracks above the holes (middle) and damage to a tenon hole in one of the logs after the end of the campaign. (photos by S. Schuster)

There was also some damage to the tenon holes in the timber (fig. 13 right) attesting to the large shear forces that the copper plates had to transfer to the logs. Without the protection of these plates, the logs would have been destroyed almost immediately (see Part 3.1).

Conclusions

There is enough information available in the antechamber of the Great Pyramid to faithfully reconstruct its closing mechanism, which required the lowering of three portcullises in a very confined space, each weighting about 2.5 tons. This reconstruction allows for a thorough investigation of an important key technology in Cheops' time: The delicate placing of heavy blocks with mm accuracy by lowering them into position with ropes.

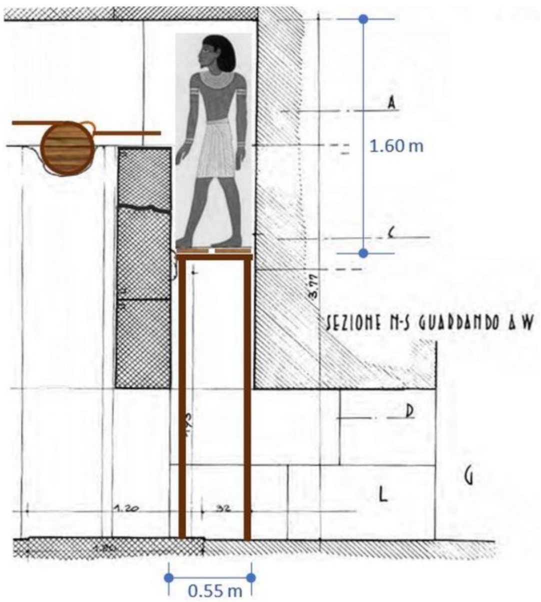


Fig. 14. A person can handle two ropes standing on a small scaffold in front of the northern stone leaf. There is space for four persons side by side (section from Maragioglio and Rinaldi[8] with overlay).

Two trained persons can lower the portcullises in a very controlled way because friction between ropes and portcullises reduces the control force to levels that can easily be handled with a simple control device (the "chain-like" rope configuration in fig. 10, for example). The two operators must see the control device in order to keep it between the copper hoops and synchronize all four ropes. There is enough room in the antechamber for four persons in front and above the northern stone leaf (Fig. 14). At least three

[8] Maraggioglio and Rinaldi (1963)

persons are needed here: In addition to the two operators, a helper has to open the knots that lock each pair of ropes (fig. 9) to gently transfer control to the operators.

They can then lower each portcullis independently, but also in one operation using a sophisticated rope configuration like in tests 25 or 40 (tab. 3). Operating such a configuration requires experience and great skill though, because control forces drop rapidly from one portcullis to the next. If such a configuration is not properly prepared and executed, the last portcullis may not move.

Protective plates (e.g. made of copper) are absolutely needed to prevent the ropes from damaging the logs, a fact that was known in Cheops' time from earlier experience (fig. 9).

Loops around the logs can be used as rope brakes to fine-tune the mechanism. They must be used with care because they can reduce control forces drastically.

Lubrication with animal fat improves control and prevents screeching noise: The mechanism can be operated almost without a sound.

Now that we understand one of the key technologies of Cheops' time and with it, the sophistication of his scribe-engineers thanks to the antechamber, it does not mean that it has revealed all its secrets. Sooner or later one realizes that, this arrangement of portcullises does not provide any considerable measure of security against breaking into the burial chamber:

The N- and M-blocks are no obstacle at all because one can simply climb over them. Even the S-block is of little value here: Because granite is a very brittle material and the S-block covers only a small rim around the entrance to the chamber, a few precise blows with a hammer will (and actually did) provide an opening quickly with enough space to even take out an inner sarcophagus. Like the logs and ropes of the mechanism, any item from the chamber could then be moved over the portcullises, across the northern stone leaf and into the Great Gallery with ease. For an inner sarcophagus to overcome the stone leaf though, at least one corner of the leaf had to be removed. Interestingly, such a corner is missing.

When considering the advanced technical knowledge of the scribe-engineers, which the antechamber mechanism is just another proof of, it is not plausible to assume that they did not recognize this lack of security. But if it was not a security measure, which purpose did this mechanism serve?

A possible explanation could be that, it was ceremonial. They had just completed a technical feat without equal: the building of the greatest structure on Earth. Even today it is testimony to their technical prowess. Closing the burial chamber with a sophisticated application of one of their most important key technologies in a way that no one has done before would certainly do the importance of this moment justice and serve as a befitting final challenge to the extraordinary skills of Cheops' scribe-engineers.

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