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ScienceDirect

Procedia Structural Integrity 2 (2016) 2921-2928



21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Fracture Mechanics in Ancient Egypt

B. M. El-Sehily*

Mechanical Engineering Department, Faculty of Engineering, Al-Azhar University, Nasr City, Cairo, Egypt

Abstract

Probably the first extensive investigation in the field of fracture mechanics was developed by the ancient Egyptian in the period before 3500 BC. The application of this knowledge from investigation on the exact splitting of rock using the fundamental techniques led to the production of many world famous monuments including the pyramids. A description is provided of the unfinished obelisk still lying in the quarries of Upper Egypt. Method of extraction including ancient fracture technique and erection of huge rock sections are presented. Some recent innovative experiments and their result that can be related to the ancient technology are discussed.

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Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: Ancient Egyptian; Ancient Technology; Ancient Fracture Mechanics; Rock Splitting; Obelisks

1. Introduction

The present study deals with fracture mechanics in ancient Egypt. It is based entirely upon the archaeological evidence in Egypt. The exploitation of richness of the country's natural resources such as rocks and wood were reflected in the wide range of techniques practiced by the Egyptian craft-man. Examples were pyramids, obelisks and statues. The great pyramid built for Khufu was constructed of more than two millions stone rocks, most weighting about two and a half tons, Casson (1965). Despite the weight magnitude, simplest implements were used with some of fundamental fracture mechanics techniques for rock splitting. Some of the methods used to split massive stone block in ancient Egypt are re-created here.

^{*} Corresponding author. Tel.: +2-100-667-3443. *E-mail address:* bmelsehily@hotmail.com

The quarry of huge of unfinished obelisk in Upper Egypt provides also an opportunity to study the fracture mechanics techniques used for production of obelisks. The obelisks were erected to the glory of the sun, Habachi (1906). The setting up of them were regarded as an act of admiration and thanksgiving in return for which the sun was expected to prolong the life of the Egyptians and make their names to flourish forever. If a high stone monument is desired, the obelisks of Egypt are the only practical form which is convenient for inscribing. Fig. 1 shows the finished obelisk that still stands in front of the Luxor temple, as four sided single piece of red granite rock with a high polish and beautiful decoration, standing upright, gradually tapering as it rises and terminating in a small pyramid. Most obelisks, especially the larger ones, are made of red granite. Fig. 2 describes the unfinished obelisk that is a piece of work that failed, not through any faults of the workers, but owing to an unexpected fissure in the rock. It still lies in its quarry in Upper Egypt, detached on all except lower side. If it had been extracted, it would have been 41.75 m height with a base about 4.2 m on each side. The total weight would have been 1168 tons. The objective of this study is to highlight the ancient fracture mechanics techniques used by ancient Egyptians. A description of the huge unfinished obelisk lying in its quarry shows how the ancient engineers extracted and erected obelisks at that time. The present work gives an analysis of how rocks split using the fundamental techniques of fracture mechanics. Experiments and their results related to the ancient technology are discussed.



Fig. 1 The finished obelisk



Fig. 2 The unfinished obelisk

2. Ancient method

It is fortunate that, so many different examples of the method of the old workmen have been discovered, where the action of ancient wedges and chisels, showing how easily the granite could be fractured. From Fig. 3, it can be seen that inscriptions of wedge gab marks where a block has been removed. Wedge gaps can be seen at the edges of fracture

plane in straight lines all over the quarries. They have cavities driven usually from the top downwards, but some may be seen which have acted horizontally and some even from below. It has been expected that the wedges themselves were of wood and made to expand by wetting them to exert their pressure to the interior surfaces of wedge gaps. It must be inquired into the nature of the tools with which the wedge gaps were cut. Choice of tools must be experienced more than five thousand years ago by ancient Egyptians. Generally, ancient men for many centuries relied on stone and wood as materials for their tools. The hammer is the oldest tool of all indeed. It is old as man himself. Hundreds of thousands of years were required to develop it from the rude hammer stone without a shaft, to the handled hammer. Near the ancient quarry, it can be seen that some of greenish-black stone balls round the obelisk, some whole and some broken, known as dolerite, having been shaped in geological ages in the Egyptian eastern desert. As described in Fig. 4, these balls which are harder than granite measure from 15 to 25 cm in diameter, their weights average 5 to 8 kg. Not only the faces of the monuments were dressed by means of these balls, but that balls were used as a hammer tool of the quarrymen for cutting out large monuments from the rock. This can be asserted by the fact that the wear on the balls is not even over the whole surface, but appears in patches, showing that they were used in one position until the working surface had become flat, and then changed to another position. To create the wedges

gaps, such dolerite balls were uses as a hammer while the sharp pieces of dolerite stone that resulted from broken balls

may be used as chisels.



Fig. 3 Inscriptions of wedge gaps



Fig. 4 Dolerite balls

Fig. 5 describes that, the ancient method used for granite splitting is still using nowadays by Egyptian craft men. They were making, with a steel chisel, a series of small holes along the line where fracture plane is required. Inserting steel chisels in such holes, and giving them in turns up and down the line moderately hard blows with a sledgehammer weighting about 6 kg, the desired granite block fractured. In the clearance of the obelisk some hundreds of large blocks had to be broken by this means. In ancient time granite is so hard that the Egyptian's copper and bronze chisels could scarcely make a dent in it. Dolerite chisel that mentioned above had to be used to create wedge gab in the rock. This may be done by a frictional process, i.e. to and fro motion between sharp dolerite chisels and gap walls, with the aid

of sand as abrasive material. Wooden wedges then fitted into the wedge gaps; soaked with water, the wood expanding and by applying moderately hard blows on the wooden wedges in turn, up and down the wedge line, the granite rock split.



Fig. 5 Series of small holes along the line of fracture plane with inserted steel chisel

Having reduced the granite until it was suitable for extracting an obelisk, and before dressing the surface in any way, they began to make the perimeter of the obelisk. This may have been measured out by cords stretched over the rough surface. The next step was to render the surface flat. This was done by bruising with the balls of dolerite. For the detachment of the two sides of the obelisk, i.e. making trenches, the dolerite balls were used by being struck with force. In the structure of the trench interior, there are no any marks of wedges or chisels. In Fig. 6, it is obvious to see a series of parallel, vertical cuts. A further feature of the trench is that is no corners where everything is rounded. These peculiarities are seen, not only in the obelisk trench, but in the pits within the trench. The only tools which could produce this effect are the dolerite balls which are already mentioned. The trench and pits were therefore not cut out, but rather bashed out.



Fig. 6 Trench Interior round unfinished obelisk

Had the obelisk proved to be flawless, the lower side would have been detached from the parent rock. It can be assumed that the obelisk was completely detached, perhaps by inserting expanding material, i.e. wood and water, in one of the obelisk longitudinal trench while leaving the opposite trench side free from wedges. This means that one of the longitudinal trenches will be used as wedge gab for detaching the obelisk bottom from the parent rock. In the same quarry there is an area which seems originally to have been the bed of a small obelisk. It probably detached from the parent rock by the mentioned method, i.e. swelling wedges in one of its trenches while using many dolerite balls as a hammer in a synchronized manner. The obelisk then is lying on its packing surrounded by the trench, but detached from the parent rock. So, it can be transferred by sliding it out on a wettable mud which may be used as a lubricant. The erection of the obelisk on its pedestal was made by using a ramp of sand raising up gradually to a chamber

containing sand. Such chamber was built around the location where the obelisk was to stand. The obelisk was dragged on the ramp to the top of the chamber where the obelisk base was positioned into the middle of the chamber top. Lowering the obelisk in the steep angle was done by removing the sand from a small hole near the chamber bottom. The obelisk was then pulled upright using ropes fixed near its tip.

3. Experimental work and results

An experiment has been carried out to simulate the method used to split rock in ancient Egypt. It should be mentioned here that such simulation has been made to study rock splitting in the first stages of the obelisk clearance, where some hundreds of large blocks had to be broken to clear the upper side of the obelisk in the quarry. A red granite block specimen of 100x100x200 mm has been selected from quarry of unfinished obelisk. Two gaps similar in shape to the wedge cavity found in the quarry of unfinished obelisk were made on each side of the granite block specimen except the bottom as schematically shown in Fig. 7. All wedges gaps have been aligned on the same line for outlining the fracture plane. Wedges from special kind of Egyptian wood called "Sunt" were cut to shrink by interference fit inside the wedge gaps. The granite block specimen without & with fitted wooden wedges are illustrated in Fig. 8. Such kind of wood has been selected from different kinds of Egyptian wood. It has a good strength and good swelling in water relative to other Egyptian woods. It should be noted here that an experiment has been carried out to calculate the swelling rate and swelling time of wooden wedges where a block of dry wooden specimen 7.1x13.25x35.75 mm in x_0 , y_0 and z_0 directions has been immersed in water. The height of dry wooden specimen, i.e. z_0 direction was selected to be parallel to the cellulose micro-fibers of wood.

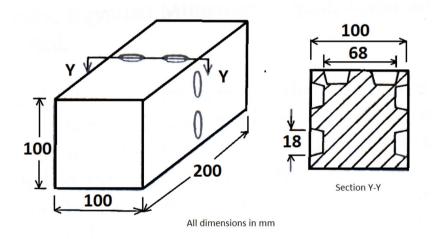


Fig. 7 Schematic diagram for granite block specimen

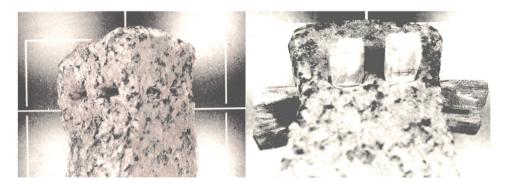


Fig. 8 Granite block specimen without & with fitted wooden wedges

The data of swelled wooden specimen were used to calculate swelling rate by normalizing tangential, radial, and longitudinal values of swelled wood by the respective values of dry wood specimen. Swelling data for such three principal directions of wooden specimen have been presented in Fig. 9. It can be seen that wood swelling increase with the corresponding increase in the time to reach approximately to constant values. Obviously, increases of swelling in x-direction are most dramatic in relation to the other directions.

The granite block having inserted wooden wedges were immersed in water to let wedges expand their pressure on the interior surface of wedge gaps. The swelling time of fitted wooden wedges in the granite block was taken as eight days. Such swelling time approximately represents double of the time which has been calculated to reach the maximum size of swelling wooden specimen. It should be noted here that wooden wedges have been fitted in the wedge gaps to be in the right position, i.e. the direction of maximum swelling, i.e. x-direction, could give maximum pressure on gap surfaces in the direction that is normal to the desired fracture plane. The next step was to brake the block of red granite into two pieces through the wedges line. Using a hammer of 300 grams to apply in turn moderately hard blows, up and down the wedges line, the red granite block specimen fractured. The fracture surface was passing through the wedges line as shown in Fig. 10.

4. Discussion

While the process of brittle fracture is highly complex when studied in detail, a number of general features can be recognized in the present study. The basic assumption of the brittle fracture in granite block specimen is that the material is permeated by an array of cracks distributed towards the fracture plane. These cracks grow and interact with one another under the action of applied tensile loads generated by the moderately hard blows on the swelled wedges along the wedge line. Geometry of the wedges and their distributions control the location of micro-crack growth and crack coalescence along the fracture plane. In homogeneous, crystalline rock such as granite which is a brittle material, crack nucleation occurs rapidly, Whittaker et al. (1992). Also due to the increased crack densities, rapid fracture should occur. This type of crack growth is concentrated at the advancing fracture tip in a pattern that cracks grow along the desired fracture plane.

The origin of brittle fracture mechanics can be traced to the work of Griffith (1920) on fracture of glass. Griffith first recognized the importance of pre-existing flaws in controlling the tensile strength of brittle materials. In this case, geometrically sharp cracks concentrate stresses at their tips to such a degree that local failure can occur at modest applied stress. The features of the fractured surface in granite block shows that the crack damage was mainly mode I in nature. In mode I loading the crack is subjected to a normal stress and the crack faces separate symmetrically with respect to the crack front resulting in displacements of the crack surfaces that are perpendicular to the crack plane. Under mode I loading, the fracture criterion is expressed as crack initiation taking place when the crack tip stress intensity factor, K_{I} , reaches the critical value, i.e., the mode I plane strain fracture toughness, K_{IC} , Broek (1991). It is well known that a higher value of K_{IC} means increased fracture resistance to crack extension [3]. For most rocks including red granite, the fracture toughness is much lower than those for metals, i.e. usually not more than 3 MPs \sqrt{m} , Whittaker et al. (1992).

According to mode I crack growth which characterizing the fracture plane of granite block specimen, cracks of various sizes are initiating at the edges of the wedge gaps. Since the wedge normal stress is tensile, it will tend to dilate neighboring cracks. For any given distance from wedge edges, there exist cracks at some angles that are most favorably oriented to be dilated towards the direction of desired fracture plane. The application of fracture mechanics to these cracks require knowledge of the mode I stress intensity factor for a crack with straight front which has received ample attention in the literature, Broek (1991).

Due to high stresses near the crack tip, most materials exhibit some type of non-linearity prior to fracturing. The nonlinear behavior is usually due to plastic flow ahead of short cracks in metallic materials, Miller (1987) and to coalescence of micro-cracking in geological brittle materials, Whittaker et al. (1992). In general, most rocks such as granite, fracture in brittle manner rather than exhibit yielding, but most metallic alloys fail by yielding and seldom by brittle cracking. This distinct difference leads to a distinct fracture process manner. In rocks, the crack tip nonlinear process zone is caused by the initiation and propagation of the micro-cracks ahead of crack tip, Hoeka and Mrtinb (2014). Consequently, it is described as the crack tip micro-cracking zone or fracture process zone, which appears and behaves in an approximately similar way as the plastic zone in metals. However, there is no sound theoretical models available to fully describe the shape and size of the crack tip fracture process zone and it is often described by the approximate models developed to describe the plastic zone in metals. It may be reported here that, prior to macro-

crack propagation and just before the final failure of granite block specimen, fracture process zone is fully developed ahead of the wedge tips with sufficient sub-critical micro-crack growth.

Swelling of wooden wedges are of particular concern. Swelling occurs by the action of capillary spaces and the cell cavities until the fibers reach to the saturation point which is approximately equal to the moister content in equilibrium with 100% relative humidity. The tendency to swell with increase of water is greater in perpendicular direction than parallel to cellulose micro-fiber as shown in Fig. 9. On the other side, stresses develop between individual cell wall layers because water restrain the tissues. This and other morphological factors, such as difference in structure and composition of radial and tangential cell walls, are responsible for swelling anisotropy. So that, stresses can occur if the cell walls are prevented from taking place freely, i.e. swelling the fitted wedges in the granite block. This means, swelling will proceed from wooden wedges, so that there will be a good contact between wedges and the interior surfaces of wedge gaps in the granite block. The stress component that is normal to the desired fracture plane may be considered as the main stress component termed as wedge-normal stress. Such stress has the main driving force responsible for the crack growth. Finally, brittle rock often fails in tension, since the ultimate tensile strength of rock is much smaller than the compressive strength, Whittaker et al. (1992). So, tensile fractures are caused by wedge stress which is normal to the desired fracture plane.

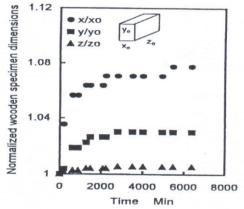


Fig.9 Variations of wooden wedge dimensions with time



Fig. 10 Fracture surface passing through the proposed fracture plane

5. Conclusion

Fracture mechanics in ancient Egypt including tools used and the manufacturing technology regarding the unfinished obelisk were briefly studied. It is shown that the splitting of red granite block is essentially a process of crack initiation and propagation. The wooden wedges apply a good contact pressure on the wedge surfaces. Surface tensile zone ahead of wedge edges are consequently induced. With the application of moderately blow loads, cracks extend rapidly towards the desired fracture plane. This means, rock fracturing in ancient Egypt involves a good contact pressure between wooden wedges and wedge cavities to initiate cracks due to a tensile fracture on the edges of wedge gaps and then propagating it deeply into the rock. Such rock fracturing refers to the complete physical separation of two face of the fracture surface due to excessive pressure resulted from moderately hard blows. Generally, cracks are stress concentrators when the rock is under tensile stress and are the sources of further fracture of the rock due to their coalescence. Obviously, it is recommended to carry out more research in this field in order to throw more light on fracture mechanics in ancient Egypt.

6. References

Casson, L., 1965. Great Ages of Man: Ancient Egypt Time Incorporated. New York, USA.

Habachi, L., 1906. The Obelisks of Egypt, Skyscrapers of the Past. Edited by Charles Scribner's Sons, New York, USA,

Whittaker, B. N., Sing R. N. and Sun G., 1992. Rock Fracture Mechanics: Principles, Design, and Applications. Amsterdam, New York, Elsevier. Griffith, A. A., 1920. The Phenomena of Rupture and Flow in Solids. Trans. R. Soc. London, A221, 163,

Broek, D., 1991. Elementary Engineering Fracture Mechanics. 4th edition, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Miller, K. J., 1987. The Behavior of Short Fatigue Cracks and Their Initiation, Part 1-A Review of Two Recent Books. Fatigue Fract. Engng. Mater. Struct. 10.

Hoek, E., Martin, C.D., 2014. Fracture Initiation and Propagation in Intact Rock – A review. Journal of Rock Mechanics and Geotechnical Engineering 6(4).