THE STRUCTURAL BEHAVIOUR OF THE PYRAMID OF CHEPHREN

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1. INTRODUCTION

This paper deals with the result of studies, researches and close inspections of the Chephren's Pyramid carried out in co-operation with the Egyptian Supreme council of antiquities, with the contribution of the Italian Co-operation of the Ministry of Foreign Affairs, in order to detect the cause of damage and decay, which can be reduced to three categories: antropic alterations, natural weathering, seismic effects.

2. DESCRIPTION OF THE PYRAMID

The Pyramid (Fig. 1) has been built by the Pharaoh Chephren, who was the fourth king of the IV Dynasty (2620-2480 bc.), during the so-called "Old Kingdom". Nearby the Pyramid, Chephren erected also its valley building and mortuary temple, connected with the Sphinx that is thought to be a portrait of the King. The Pyramid has a square basis oriented in such a way to face with each one of its sides one the cardinal points; its original height was of 143.55 mt., and therefore about 3 meters lower that the Great Pyramid (Cheope's Pyramid). The present height of the monument is about 136.39 mt., being missing the very top portion including the capstone. Owing to its position on somewhat higher ground, Chephren's Pyramid creates the illusion of being taller than the Great Pyramid. Formerly each side of the monument measured 215.71 mt.; if faces slope at an angle of 52°20' as so they rise more steeply than the faces of the Great Pyramid that is a little higher but has the sides considerably larger.
For the construction of the body of the Second Pyramid, blocks of limestone and sandstone were used. For the casing instead, the stone employed were Tura limestone for the upper remnant, and red granite for the lower. Also the capstone, which has now disappeared, may also have been made of granite.

Fig. 1

Fig. 2

The dimensions of the blocks of limestone and sandstone composing the body of the Pyramid are variable between 55 and 110 cm in height and 50 and 150 cm as horizontal dimensions. The blocks of the tura limestone casing have dimensions of 45?65 cm in height and show a larger variability in length being present pieces from 13?15 to 180 cm.

3. THE CLIMBING OF THE PYRAMID

In October 1992 during a strong earthquake that hits the Cairo area, serious damage were produced in all the city and some fragments of stones fell down from the Pyramid.
That has been the start of the program of Co-operation between the Egypt and Italy.
After two years of researches of documents and studies on the seismic behaviour of the Pyramid, between 17 and 20 November 1994 a climbing and a close survey of the Chephren Pyramid have been carried out accordingly with the relevant Working Plan (Fig. 2). The overall operation has also included the shooting of a tape recorded TV Scientific Documentary, illustrating the different phases of the operation.
The inspection was essential to examine the actual conditions of the monument, with particular regard to the arrangement, state of conservation and stability of the blocks. Prof. G. Croci, Responsible of the Program of the Italian Ministry of Foreign Affairs and Eng. M. Biritognolo expert structural engineer have been part of the team.
The inspection has shown that the Pyramid is characterised by three main zones (Fig. 3):

UPPER ZONE. This zone is extended along the slope for about 50 meters and maintains the tura-limestone original casing.
The original very top part (about 7 meters in height) of the Pyramid is now missing and the monument ends at the actual top in a platform of about 4 meters of size.
The casing appears to be deteriorated in different way depending on the orientation of each face; the most deteriorated parts are those facing South and West, where the action of the thermal variations were added to the effect of the wind.
In the North and East faces the deterioration of the limestone is less visible and on the North face some kind of microorganism which affect the surface are creating a rougher surface.
The Tura limestone composing the casing appears to be of good quality even if some heterogeneities in the material are evident.

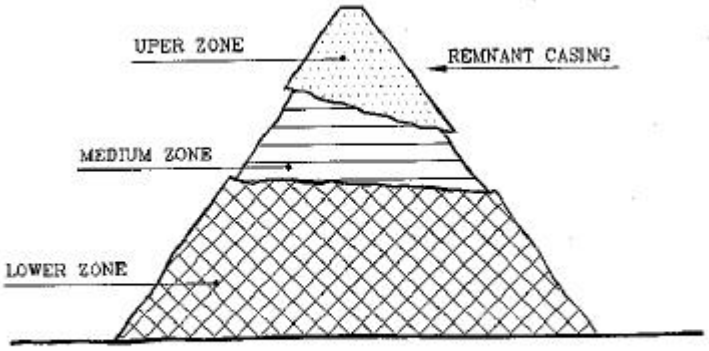

Fig. 3

The lower border of the casing is not regular as the missing portions are larger in the corners (festoon shaped border).
The reason of this configuration will be explained below. The casing blocks have a horizontal development, and their joints show an exceptional precision of working of the stone faces and contain very thin layers of mortar. The dimensions of the blocks are variable in length and height, as described in the previous paragraph and shown in Fig. 4.
A close examination of the casing faces have permitted to take note of the following aspects:

- some elements of the upper part of the casing moved themselves outward,
- some blocks over the top platform have twisted,
- the corners are deformed due to the movements of the blocks,
- the shape of the blocks composing the casing elements was worked out in such a way to improve the mutual linking (presence of dents).

LOWER ZONE: This zone is the biggest one, both in lateral dimensions and in height (about 90?100 mt.); it is characterised by a chaotic situation for what that concerns the texture of the block masonry. The entire casing is missing and the exposed masonry appears to be affected by an irregular lack of blocks, that in same zones put in evidence a deeper asportation of the material.
The stone blocks appear to be very deteriorated, especially in South and West sides. The masonry texture exposed by the lack of block shows that more little blocks compose the more external strata under the casing, and a dimensional half modulus of 55 cm. appears. Besides, the internal blocks are not only larger but also more regularly shaped. Also in this zone the dents pre-cut in the blocks in order to improve the positioning and mutual linking of the block are visible. In all this zone the removing of casing and missing of the more internal blocks are due to the anthropoid action, that started in the early periods after the construction of the monument, still in the Pharaonic Age.

Fig. 4

Fig. 5

MEDIUM ZONE: This zone, extended till to the lower border of the existing casing, is characterised by the absence not only of the casing (that is completely missing), but also of the backstones; the masonry texture visible is very regular. The dimensions of the blocks are 50?150 in length and width and 80?110 in height. The close observation has allowed to clarify that all the missing stratum of material (about 3 meters of thickness) has been removed by means of a systematic action of dismantling similar in many aspects to the quarrying techniques.

The stone blocks were put away starting from the actual lower border of the casing, as shown by the verticality of the border surface that have been cut using chisels (Fig. 4) After having removed the first rows of blocks it has been very easy to proceed to the dismantling of the other strata from the top to the bottom, not only of the casing but also of the rear elements. The cornice that appears now at the bottom of the medium zone is in reality nothing else that the last level of the utilised quarry.

The situation as described before individuates clearly different periods of removing of stones.

In fact in the medium zone they used pulley, inclined plains, etc., to lead down the blocks, and that happened mainly in the Islamic Age, when many blocks coming from the Pyramids were used for erecting of buildings (especially religious ones). The masonry stones appear to be better maintained; that is not related to a better quality but to a shorter period of exposition.

4. THE RESULTS OF THE STUDIES AND OF THE INSPECTION

The ascent of the Pyramid has allowed to immediately answering to the first two questions:

The main destruction of the Pyramid is due to having used the monument as a quarry. However, while in the earliest times this destruction has been brutal, without any organisation (lower zone), in the Middle Age the removal of the blocks has followed a precise rational program (middle zone), cutting a row of stones immediately below the present survived casing and realising some little walls and masonry pillars to sustain it (Fig. 4).

The pulling away started at the corners (festoon shaped border when it was easier) and the stability of the remanent blocks was ensured by means of supports made by bricks (some of them appear to be made also in recent time). In this way it has been possible to have not only geometrically perfect blocks, but also to limit the damage to the thermal effects (that are more sever on the surface facing south and west) to which also the action of the wind is added.

Fig. 6 : Relative movements of the blocks in the corner of the Pyramid

The third problem has been more difficult to be explained; the mathematical models have finally helped very much to give a full satisfactory explanation of the seismic effect on the Pyramid.

The seismic action used for the analysis was that recorded by seismographs near the Pyramids during the earthquake of October 1992, furnished by the Italian National Institute of Geophysics.

The dynamic analysis in time-history gave the acceleration in relation to specific points; in particular the values reached at the points where the slippage between some blocks surveyed was detected. The maximum acceleration reaches values of (0.6?0.75) g, showing an amplification with respect to the ground of about 2?2.5.

On the basis of the above results, a local analysis was carried out to check whether the shear forces exceeded the friction strength and consequentially, sliding between blocks could be produced. The results of the analysis revealed that locally, and particularly in the upper zone where the vertical loads are lower, the shear forces, combined with a reduction of the vertical stresses during the earthquake, may exceed the friction strength causing permanent displacements (Fig. 5).

The sliding related to the various earthquakes may have produced, therefore, the observed permanent displacements; these, magnified by the effects of subsequent earthquakes, may well have led to unstable situations and ultimately to the falling of some upper blocks.

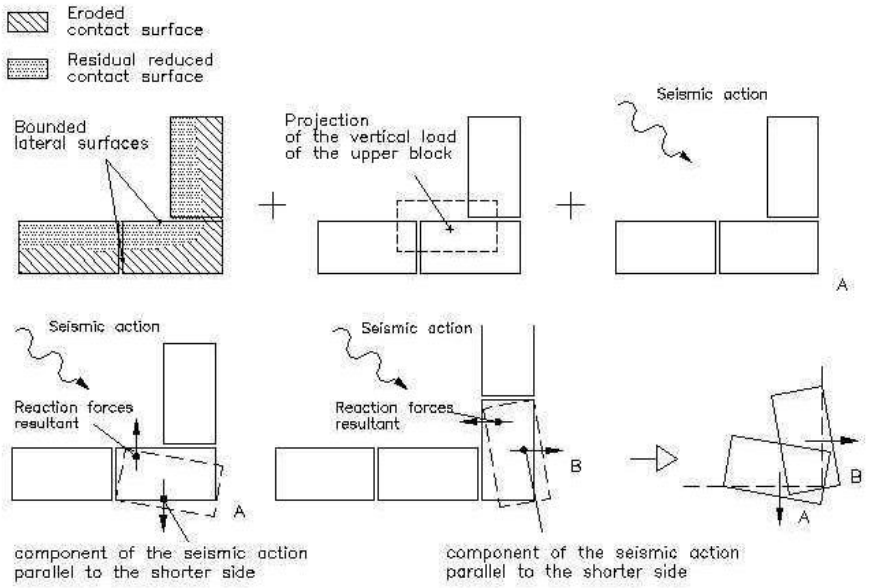

Fig. 7

The interpretation of the alternate displacements of the blocks that have been surveyed in the upper part of the corners is more complex (Fig. 6). This phenomenon can be explained by integrating the mathematical results with qualitative considerations, which regard the geometry of the blocks, the horizontal contact surface between them and the position of the applied loads (Fig. 7).

In particular it has to be observed that the wind deeply eroded the horizontal contact surface between the corner blocks, so that the latter are now reduced to an internal portion smaller than the original one, and that the load transmitted by a block to the underlying one is not applied in its barycentre, due to the wedged shape of the corner blocks.

It is astonishing, however, the Pyramids of Giza probably being the most studied monument in the world with thousands of books and papers written on the subject, that no one has ever paid attention to these relevant phenomena and studied them on the structural engineering point of view.

These phenomena contributed to the development, in each corner block, of an eccentricity of the centre of rotation with respect to the barycentre, in which seismic forces were applied creating twisting effects which have caused the observed alternate displacement (Fig. 6).

5 CONCLUSION

The results of the study have been of an exceptional interest contributing to better understand the behaviour of this astonishing moment. We want to express our gratitude to the Egyptian Authorities and the Italian co-operation that have allowed this work.