DRUMS' FRACTURE-THE EXAMPLE OF THE 6TH COLUMN OF PARTHENON'S PRONAOS

Marilena Mentzini
Structural Engineer, PHD, Ministry of Culture and Tourism, 6th Ephorate of Prehistorical and Classical Antiquities
197, Al.Ipsilantou str., 26110 Patra, Greece

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ABSTRACT

In the present paper an effort is attempted to record all the failure modes of columns' drums made from marble, under ordinary conditions or under dynamic actions and to reveal the reason as well as the mechanism of fractures. Therefore is studied thoroughly the influence of both the member's position as well as the different geological stratification of its material (the internal structure of the marble is characterized by imperfections and is of layered nature). The drums of the 6th column of Parthenon's Pronaos are used here as an example. During this procedure some of the main failure's causes and mechanisms are reached. In this way the analysis yields satisfactory results that should be considered very carefully by the scientists working for the restoration projects.

INTRODUCTION, THEORETICAL CONSIDERATIONS, HISTORICAL EVIDENCE

The material used for the erection of the monuments of the Athenian Acropolis was Pentelic marble, well known as the constructive material of the classical period's masterpieces. Since the ancient quarries are nowadays exhausted, the needs of the restoration project (completions or even a few new members) are covered with the use of Dionysos marble. This marble (quarried from mountain Dionysos in Attica) has similar properties to the authentic one and therefore constitutes the experimental material for the study of the mechanical behavior of the ancient structural stone [1]. Until recently the data reported in literature vary between very broad limits. This scattering can be attributed to the different conditions under which the tests are performed but mainly to the anisotropy of Dionysos marble. There are three different anisotropy directions -parallel to the layers, along the width of the web and along its thickness. After a long series of direct tension and uniaxial compression tests, is concluded that the mechanical properties along the two of the anisotropy directions are very similar to each other. Thus this marble can be considered as a transversely isotropic material described with the aid of five elastic constants: two elastic moduli, in the plane of transverse isotropy and normal to it, two Poisson's ratios characterizing the lateral strain response in the plane of transverse isotropy to a tensile stress acting parallel and normal to it, and the shear modulus in the planes normal to the plane of isotropy. From these tests it was also concluded that the material appears to be slightly bimodular, i.e. its elastic moduli in tension and in compression are not exactly equal [2], [3], [4]. The combination of these mechanical characteristics with the special nature of the material composition (mainly calcite, small amounts of muscovite, sericite, quartz, chlorite and areas with imperfections) gives to members' possible fracture or cracks their complicated form.

The shape and the magnitude of the damages are also affected by the particular response of the drums due to the kind of destruction, their orientation as well as their role as structural members. As it is well known the catastrophic factors in general are of two types: natural and man –imposed. Among the natural factors stand the aging and as is already pointed out the special nature and the imperfections of the material, the decay from physico – chemical/biological action, freezing, seismic action etc. Man –imposed damages include fire, bombing, explosion, vandalism, the problems aroused by the previous restoration (thoughtless use of iron elements, which after oxidization expand making the beginning of a destructive process whereby the surrounding marble is fractured further) and even the effects of pollution.

Although marble is universally known as one of the hardest materials, many of the aforementioned factors could change the initial properties and its mechanical characteristics. The low thermal expansion coefficient of the marble is the reason of the intensive difference of the temperature versus the distance from the external surface. Therefore fire (or even thermal changes) affects the stone in a differentiate way related to the increment of the depth from the outer surface. Thermal fracture as observed simulates the geological phenomenon of exfoliation. In the case of local heating, the heated zone expands and in addition becomes bowed on the side of highest temperature. This process tends to detach the heated zone from the internal mass of the element, causing fracture of particular type. The heated zone as it tends to expand stresses its perimeter towards the surroundings, which sustains opposite resistance. The relief from the tension occurs either by the fracture of the resisting mass or by the tearing away of the detached zone because of bowing. The fracture's surface is complex; one part has a bowed form and approximately follows some isothermal surface while the rest has all the characteristics of a load fracture and it separates from the other forming clear edges. In any case variations of rock properties occur, such as the permeability and the ultrasonic wave velocity, strictly connected to the degree of fracturing of the marble. That is to say compression, tensile strength and deformability are influenced by the presence of cracks. A study of this damage allows to indicate the type and the position, not only of the wooden parts of the temple, but even of many stone parts, which are not preserved today [5], [6].

Classical monuments as Parthenon constitute a structural system with special characteristics: symmetrical arrangement of the vertical bearing elements (i.e. the columns), frame function through the entablature, diaphragm function through the marble peripheral ceiling, an absolutely rigid core –the cella. The form and the stability of the structure is reached by a simple but perfect contact between the members, the lack of connecting mortar, the development of friction bond instead and the use of horizontal (clamps) and vertical (dowels) metallic joints that resist tensile and shear forces. Thus a complex construction is formed and the dynamic response is governed by the sliding and the rocking of the individual stones, independently or in groups. Therefore, it is quite different than the response of "typical" structures. The complexity of the seismic behavior is dominated by the fact that the structure continuously shifts from one mode (the term mode is used here to denote different patterns of the rocking response) of vibration to another; different joints are opened and different poles of rotation apply for each mode. During rocking, the pole of rotation of each drum may move from one point to its diametrical opposite. This transition produces impact phenomena among adjacent members and energy dissipation, causing a sudden decrease in the angular velocities. The vulnerability of classical monuments mainly depends on two factors, the predominant period of the ground motion and the size of the structure. Thus low-frequency earthquakes are more dangerous and they are characterized by intensive rocking of the columns, as opposed to high–frequency ones, where significant sliding of the drums occurs, especially on the upper part of the structure, while rocking is restricted to small values. Furthermore, bulkier structures are more stable than smaller ones with the same aspect ratio of dimensions [7]. A numerical modeling study of a single column of Pronaos using the earthquake's records of Calamata, Aigion, Bucharest etc. lead to various modes of motions, such as rocking, rotation of the drums around a vertical axis ("twisting of the column") -increasing gradually from the basis to the capital or even rocking at the lower part, instead of the upper one which is moving as a single block [8]. The previous analyses show that cracks at drums do not seem dangerous to the stability of the structure, as long as they do not form wedges, the possible sliding of which produces loss of contact between adjacent members. Of course in addition even the common cracks may become dangerous, since they may wide open after a number of dynamic actions.

In the course of this research the drums of the 6th column of Parthenon's Pronaos are used as case study. This particular column has been chosen because it is the only one of the temple which has the marks of all the kinds of destruction that the monument has undergone through the centuries: earthquakes, fires, bombing and explosion [9], [10], [11]. It still stood all these years in the same original place and twice (by N.Balanos in the eve of the 20th century and nowadays by Acropolis Restoration Service) was restored almost without the use of new marble (completions) [12]. More specifically the first serious damage in the monument caused by the great earthquake of 426 B.C., but the vast destruction came at 267 A.D., by a German tribe –the Erouli- who burned the place down. The fire soon extended to the wooden parts (roof, doors, etc.) attacked the internal surface of the Pronaos' drums. During the siege of the Acropolis by the Morosini's Venetians (1687 A.D.) an explosion blew up three of the four walls of the cella, six columns on the south, eight ones on the north and the remains of Pronaos collapsed except the 6th column.
The drums have been subjected -one by one- to a thorough in situ observation of their failure. The cracks, the movements and the deformations are investigated, recorded and classified. In this way it is examined the possibility of foreseeing the kind of fractures provoked under ordinary conditions as well as under different unfavorable actions by knowing the layer's direction. Taking into account these results as well as the interaction of the members' position, its function as a structural one and its orientation it is attempted to evaluate the seriousness of the problem in order to take the appropriate measurements to avoid or mediate a possible failure. Finally we could trace or confirm the history of the monument through its pathology.

IN FIELD ANALYSIS

Looking towards the 6th column of Parthenon's Pronaos it can be directly observe the thermal fractures stretch along its height and in which way they embrace the drums' surface in the SW area. As it clearly seems the fire's limits are connected to the place of the marble's carvings that determines the position of the wooden parts of the ancient diaphragms and thus it is concluded that the burn of the column came from the interior of the temple (Fig.1, 2). The extension of fire's trace all over a whole flute in the surface up to the 10th drum (drums' counting starts from the first one (drum) settled on the stylobate) is the effect of the remaining mortise (which implies a wooden holder) but also yields to the existence of the ancient south window of the east wall which is opened in this exact height and helped fire to spread (Fig.3). The beginning of the fragments' creation in this particular section due to the fire, judging from their bowed shape as it is already mentioned, but their evolution to clear, even bigger pieces, some of which have already fallen leaving their prints on the remaining fractured cross section, due to other reasons.

The most important of these reasons are the influence of the geological stratification and the results of dynamic actions. It is obvious that these two factors provoke failures also to the other –"external" part of the drums, but there it is easier to recognize them. However it is noteworthy the fact that even in a balance state there is always a concentration of the internal forces on the perimeter of each member. The conflict of two adjacent drums made of contrary material layers provokes the beginning or the evolution of fracture. To be also noted that sometimes there is a local change in the layer's direction, which may become serious when it is ending on the upper or the lower side of the drum and meets the geological stratification of the neighboring member. Yet when the material layers have the same direction, the cracks are easily transferred from one drum to the other, i.e. finally any conjunction all over the contact surface gives more or less unfavorable results (Fig 4-10, 22 pointed by a circle).

Figure 1:
The 6th column from NW

Figure 2: Start of the thermal fracture in the mortise's area

Figure 3

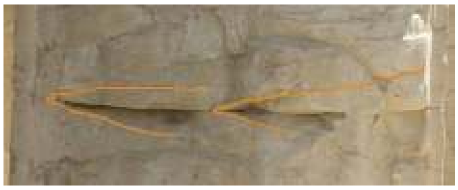


Figure 4

Figure 5

Figure 6: The fracture's limits follow the material layers

Figure 7: The upper drum of the depicted in Fig.6 has opposite geological stratification

Figure 8: The fracture's limits follow the material layers

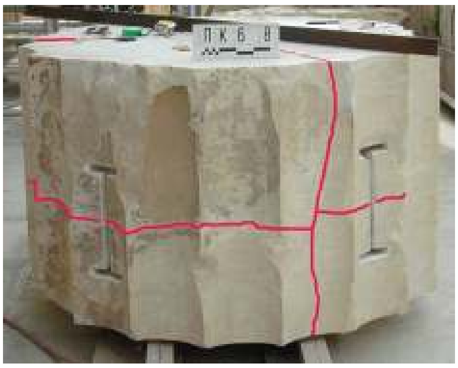


Figure 9: The resulting crack when a horizontal layer meets the main fracture's cross section

Figure 10: The continue of cracks within the layers

As far as it is concerning dynamic actions –in our case earthquake and explosion, drums may decline (raise themselves) from the horizontal state, while the rocking effect produces impact phenomena among adjacent members. The conflict damages particularly the edges of the contact area between them, which is linear and consist schematically an arc. The result produces fragments which usually form wedges and the presence of converging strata –as it pointed out before- make easier the start of the failure (Fig.5, 11).

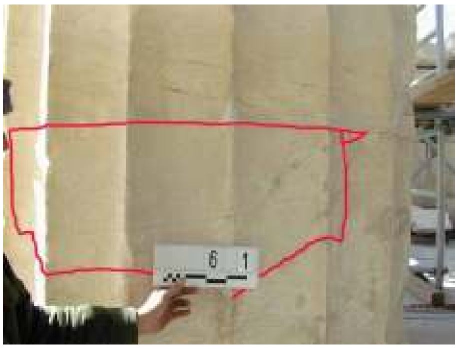


Figure 11: The right edge of the fragment coincides exactly with the conjunction of the layers on the upper side of the drum (see Fig.5)

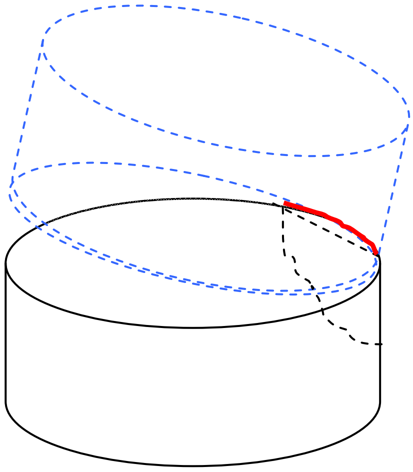


Figure 12: Genesis of the mechanism of fraction on the upper side (part) of the drum due to rocking (see Fig.11)

Figure 13: In the 2nd drum spots the penetrating break which separates the member in two pieces. The whole picture, together with the similar cut in the contact area to the next drum, implies a dynamic struck and gives its possible direction (see picture right above). It is easily to connect it with the explosion at 1687. In any case the fragments A, B, Γ and E are clearly due to the fire's effect, instead of Z and Δ which are antidiametrical and might became from rocking in the axis east –west as it appear also from the crash of the edges (see picture right below)

Dynamic actions provoked rocking, shifting or even twisting of the drums, which many times had lost their proper original seating. Although they have been already corrected by N.Balanos, the detailed observation succeeded to identify their movements as well as the direction of the phenomenon.

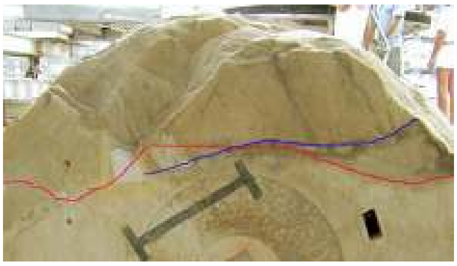


Figure 14: Two different positionings (due to movements after dynamic loadings) of the upper member of the drum left their traces upon its surface. The blue line indicates the reduced limits of the lower side on the next drum in its original place instead of the red line, which implies its rotation towards the south (see Fig.15)

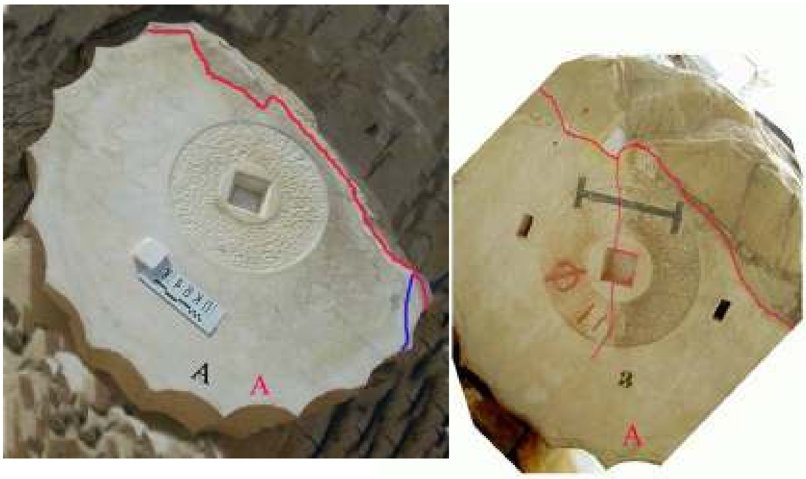


Figure 15: In left picture appears the reflection of the lower side of the next drum of the depicted one in Fig. 14, so in this way to reveal the coincidence of the outlines –right picture. With the letter A is symbolized the east for the drum in its original positioning and with A the real East. It is noteworthy that the beginning of the main crack of the drum in the right picture started from the point of the angular cut off on the surface which is also represents the boundary of the loading area from the upper member after the loss of

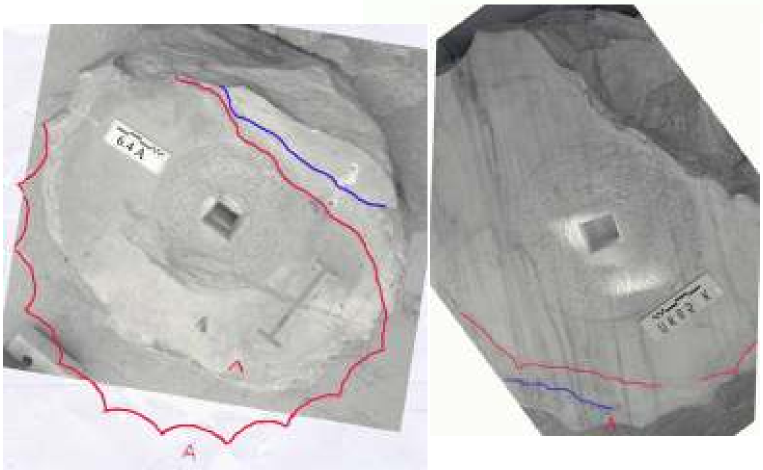
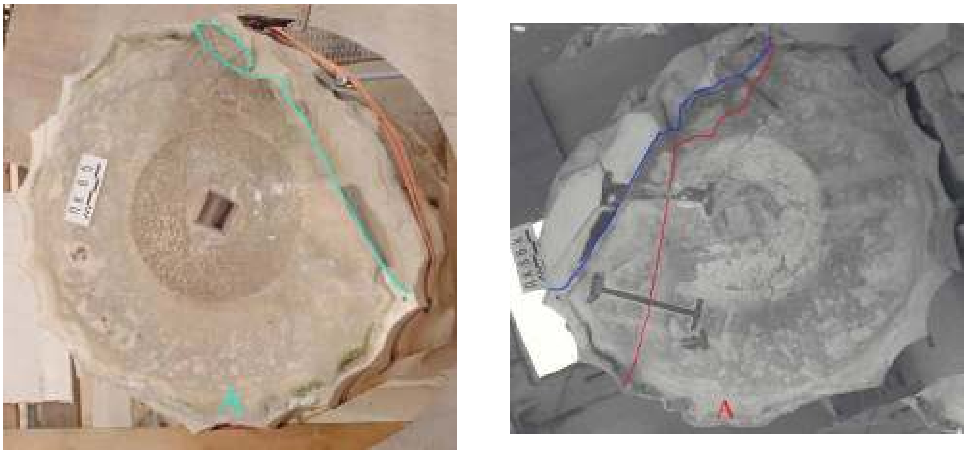


Figure 16: The cracks on the upper side of the 4th drum show the original and the relocated positioning of the 5th while they determine the limits of the missing part of the latter –left picture. The right picture is a reflection of the lower side of the 5th drum, where the marks of the 4th one are obvious.

Yet to be noted the start of the main crack on the surface of the 4th drum which coincides with the

The direction of the crack (left picture above) which is parallel to the missing front of the drum indicates also the direction of the rocking.



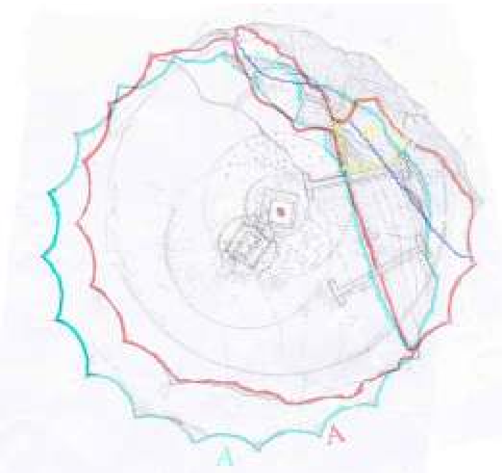


Figure 17: The comparison of the upper side of the 5th drum towards the lower side of the 6th one (pictures on the left and on the right above respectively) indicates the normal and the relocated positioning to each other. The former provoked to the latter the "blue" thin crack which represents the limits of its reduced surface, but also the red serious crack as the result of their conflict, when there were in a different relative connection than the original one (picture on the left). In the picture right above it also appears the crack due to iron's expansion, beginning from the clamps' head

Figure 18: The traces on the upper side of the 10th drum represent clearly the movement of the 11th over the lower member (left picture). Their relative position is exactly depicted through the application of the sides' plans which are in contact (right picture). This shift is also verified from Fig.19

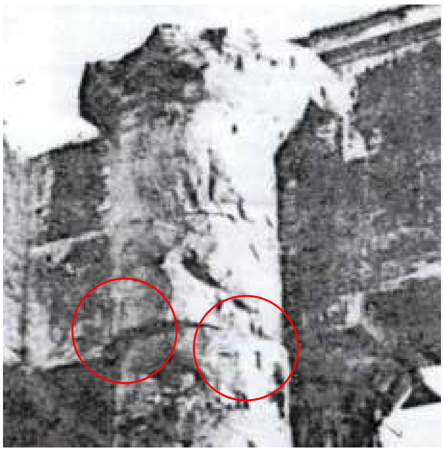


Figure 19: The relation between 11th and 10th drum before any restoration and nowadays. The left picture was taken by N.Balanos

The observation of both the cracks or/and the fracture's plans of adjacent drums helps to understand the magnitude and the direction of the dynamic actions. For example the certain position of the continuous crack which appears in the east and south surface of the two adjacent drums (Fig 20, 21) implies to a rocking versus the axis N.W. to S.E. i.e. to the same direction which follows the penetrating fracture (came probably from the explosion) in the lower 7th drum (Fig.22).

Figure 20: East façade of the 6th column –cracks over the height in the 8th and 9th drum

Figure 21: South façade of the 6th column –cracks over the height in the 8th and 9th drum

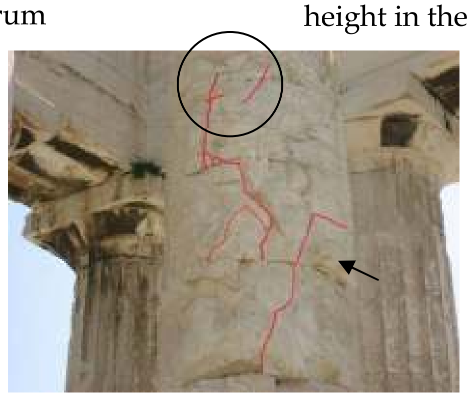


Figure 22: Northwest façade of the 6th column –the path of the cracks in the 7th, 8th and 9th

The aforementioned fracture is unified with the north limits of the fragment (type of wedge) near the lower side of the following 8^{th} drum (Fig.22 pointed by the arrow), which lay in the west and was created as a result of rocking versus the axis E. to W. This same phenomenon provoked the continuous crack from the 8^{th} to the 9^{th} drum (Fig.22 also) although it is not easily directly recognizable, because the topical deviation near the base of 8^{th} due to the combination of the thermal fraction and the geological stratification.

CONCLUSIONS

During this procedure some of the main causes and failure's mechanisms are reached. In this way the analysis yields satisfactory results that should be considered very carefully by the scientists working for the restoration projects.

As it pointed out the conflict of two adjacent drums made of contrary material layers provokes the beginning of fracture. Yet when the material layers have the same direction, the cracks are easily transferred from one drum to the other.

However, the most important conclusion is that an existed fracture and the consequent loss of mass at drums, which does not appear rather alarming or seems to comprise an immediate threaten to their stability or the stability of the structure, may become dangerous if not repaired and restored even with new marble if it's needed.

That occurs because in the edge of the remaining part of the drum during the rocking is being developed a severe stress field, which leads to the creation of cracks at the adjacent members; thus drastically deteriorating the bearing capacity and behavior under seismic loading of the entire structure.

Finally many of the historical evidence confirmed or clarified, such as in the present case the accurate direction of the explosion and the existence of the south window of the east wall.

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