PRINCIPLES AND METHODOLOGY OF INTERVENTION FOR STRUCTURAL RESTORATION

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ABSTRACT:

We use the term structural restoration for those interventions that are carried out on monuments in order to restore the bearing capacity of the whole or of parts that have structural problems. Most of the structural problems of the Acropolis monuments are due to the cracking and splintering of the marble caused by the rusting of the extensive iron reinforced elements that had been inserted during earlier interventions, especially during the restoration made by Balanos at the beginning of the 20th century, and from other causes too (explosions, displacements caused by earthquake, fires, and so on). In the course of the interventions parts of the monuments that were restored in the past – and, in some cases, sections that had not been restored before but which show the same signs of wear and breakage – are dismantled The articulated system of construction of classical building facilitates this sort of work. The dismantled pieces undergo conservation while on the ground. The old rusted metal reinforcements are removed. The fragments of the architectural members are then joined using titanium rods and a special cement based mortar. Where deemed necessary, missing parts of the members are filled in with new Pentelic marble so as to restore their original structural efficiency. When they have been repaired, the architectural members are set again on the monument and joined by means of titanium clamps and dowels that are consolidated in the ancient tenon holes and cuttings with an inorganic binding material.

1. INTRODUCTION

The works being carried out at present on the restoration on the Acropolis monuments have reached from 2000 their fullest development and greatest extent since their initiation: large restoration projects the Parthenon the Propylaia and the temple of Athena Nike. The Acropolis Restoration project is financed with funds from the Third Community Support Framework.

Figure 1. Acropolis of Athens. View from east. By S. Mavrommatis

The restoration of the Acropolis monuments is rescue work, in order to tackle the two kinds of serious problems of the monuments :

1. structural problems due to the cracking and splintering of the marble caused by the rusting of the extensive iron reinforced elements that had been inserted during earlier interventions and from other causes too (explosions, displacements caused by earthquake, fires, and so on).

2. deterioration of the surfaces problems due to the erosion of the marble surfaces on account of the effects of atmospheric pollution and other biological and natural factors. Gradually, during the course of the interventions other problems are also confronted. Architectural members of the monuments that had earlier been wrongly positioned were reset in their correct positions, and scattered architectural members, the original positions of which are now identified, are reset to the in their original places. Through interventions of this sort some of the structural and formal authenticity of the monuments is regained, the immediate result being the demonstration of their importance for scholarship with their inherent architectural worth and more generally their aesthetic and environmental values. In addition the monuments can be better comprehended by more of the visitors.

2. STRUCTURE OF THE ACROPOLIS MONUMENTS

Most important for the estimation of a monument's capacity for resistance and the interventions necessary is the knowledge of the way in which it was constructed and the evaluation of the actual structural damage. The monuments of the Acropolis are built of worked stones in the form of rectangular blocks or drums, without mortar, joined to each other with metal clamps and dowels. Although constructed of separate architectural members, their «dry masonry» joining has been done so accurately that in some cases the joins are imperceptible, giving the impression that the construction is continuous. The purpose of the clamps is to relieve tensile and shear forces when the friction restraint between the members is overtaken. The joining elements (horizontal- clamps, or vertical to the layers of stones- dowels) are made of iron, placed in specially cut tenon-holes or sockets and sheathed with cast lead. The clamps connect members in the same horizontal series and absorb chiefly the tensional forces, while the dowels connect members of successive courses and withstand shear forces. These connecting elements assure the total resistance of the construction, especially against seismic load or deformation due to various other disturbances (strong movements, foundation settlements, etc.). The lead supplies a mechanical continuity between clamp/dowel and stone; as a pliable material it absorbs part of the shock movement and force of an earthquake. Its main purpose, however, is to protect the iron of the joining elements from rusting by shielding them from the atmosphere.

Figure 2. The Parthenon. View from north - west.By S. Mavrommatis

3. STRUCTURAL AND SEISMIC WEAKENING OF THE MONUMENTS

It is well-known that the dimensioning of the structural elements of the monuments was determined on the basis of morphological criteria, without any preliminary structural calculation in the modern sense of the term. Even so, the excellent structural performance of the monuments in all the natural actions throughout the 2,500 years of their history shows that the mechanical features of the material they used were known to them and that the structural function of the bearing system had been estimated very close to the mark. It is notable that a great part of the damage we are obliged to face today is due not to the forces of nature, but to the activity of man. Much of the extensive damage to the monuments stems from interventions of the recent past that were intended to protect the monuments.

Figure 3. Section plan of the Parthenon. By M. Korres

The basic feature of the bearing system of the monuments is the presence of joins between the wall blocks. The joins are surfaces of discontinuity in the construction that undertake compressive and shear but not tensile stresses. These joins can open with a resulting concentration of compressive and shear stress along an edge. This fact can result in a non-linear behaviour of the bearing system.

The existence of joins affects even more the behaviour of the monument when subjected to seismic force. The discontinuity - articulations determine the distribution of stresses such as the size and distribution of seismic force. The articulated elements of the monument (columns, pilasters, walls) can oscillate or they can slide, thus either absorbing the force, or concentrating these stresses at the ends of the blocks so that the edges break.

clamp dowel

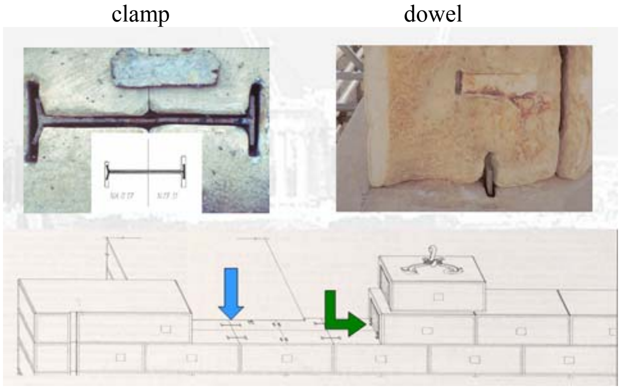

Figure 4. The way of construction of a marble wall

The seismic behaviour of the monuments is very complex without linear characteristics. The intricacy of the problem is intensified, not only by the number of joins, cracks, deformations, displacements and failure of the connecting elements. In recent years this has been studied in connection with the problems arising in the restoration of ancient monuments. On the basis of modern scientific knowledge it is not possible to create a really trustworthy simulated model of seismic behaviour for calculating the interventions.

The monument itself provides, however, many indications of its seismic behaviour as does the information stamped upon it over time: the deformations it has undergone during the long centuries of its history are of themselves the most significant source for its seismic behaviour. It is exceedingly important to evaluate the structural efficiency of the monument in its present state, taking into account the damage it has suffered. The monuments of the Acropolis, indeed, have shown excellent seismic resistance during the earthquakes that have struck Athens. Given this satisfactory seismic behaviour up to now, interventions are carried out with respect for the original structural system. The basic principle of planning interventions on the architectural members is the restoration of the bearing capacity of each member so that it can withstand the greatest possible load. In case of overload, the joining elements are planned to absorb the seismic force without damage to the marble.

The failure of earlier interventions on the Acropolis monuments is due chiefly to the use of ordinary iron for the connecting elements of the fragmentary architectural members or for strenghthening other members. Rusting and expansion of the iron elements caused the marble to break and architectural members to shift. The molten lead or cement plaster used in these earlier interventions to fill in gaps was not up to the excellent standard of ancient lead casting, while the hermetic connection of the architectural members in the ancient phase was not achieved in the restoration.

4. PRINCIPLES AND METHODOLOGY OF THE INTERVENTIONS

4.1. General methodology of the interventions

In cases where the damage is critical, dismantling of areas that have serious problems is inevitable. The dismantling is extended beyond the restored parts of the monuments into areas that have undamaged places here and there if serious damage has extended into these general areas as well. The rusted joining elements are removed and the filling material (cement plaster in the restored areas or, rarely, lead) taken out.

White cement and titanium reinforcements are used for the structural restoration of the stones. The reinforcements are threaded titanium rods which are inserted into holes in the marble mass and secured by an inorganic plaster made of white cement. The holes do not penetrate to the outer surfaces of the architectural members nor do they reach the coarsely worked interior surfaces, so that they are not visible. Fragments that do not belong together, that is that do not come from the same architectural member, are never joined together.

Where considered necessary, the missing parts of members are added in new marble so that they can regain their original structural self-efficiency. The required restorations in new marble are usually limited and the criterion for the decision is always the stability of the member and the monument and the structural and aesthetic self-autonomy of the areas being restored. The joining surface of the addition is cut so that it fits precisely the broken surface of the ancient piece. This is done by means of a pointing device. After it has been made, the additional piece is joined to the ancient marble likewise with a titanium rod and inorganic plaster.

Figure 5. Resetting of a architrave after its structural restoration

When the architectural members have been repaired, they are set again in their original positions or in positions where they had been placed during the previous restoration. They are connected with titanium clamps and dowels which are secured in the ancient clamp and dowel cuttings and sockets with inorganic plaster. During the re-setting of members, geometrical deformations of the area that was dismantled are parially corrected to the extent allowed by the remaining distortions of the members that were not dismantled, in order to achieve as much as possible the original form.

4.2. Principles of intervention for structural restoration

The Venice Charter forms the framework of principles accepted internationally in which are codified the requirements necessary for the restoration of monuments. Especially for the monuments of ancient Greek architecture and in the framework of studies for the restoration of the Acropolis monuments, additional principles were formulated especially for the monuments of this time.

- The principle of reversibility of the interventions, that is, the possibility of returning the monument to the condition it was in prior to the intervention, so that all possibilities for information are preserved and so that any error in today's interventions can be corrected in a future intervention.
- Basic criterion of the interventions is respect for the authentic material, retention of structural autonomy of the architectural members and their original structural function. Retaining the structural system provides insurance in case of seismic activity against the danger of dissimilar behaviour in areas that are restored.

These principles lead to specific choices in the planning of structural interventions on the Acropolis monuments. Thus:
1. The principle of respect for the autonomy of the architectural members is applied so that the strength of the mended member is at most to that of the unharmed member. Thus, in joining fragments of members, we attempt to use as few as possible of the titanium reinforcements demanded by the structural study. Likewise the holes (sockets) for the rods are as small as possible so as to avoid damage to the ancient material. 2. For joining the members, an effort is made to use the ancient cuttings and cavities both for position and for size. In estimating the clamps, in borderline cases of damage the aim is for the connecting elements to fail rather than the ancient material.

4.3. Choice of materials

The materials used in restoration must be harmless and compatible with the authentic materials so that they do not cause damage in the future. Titanium is used as a connecting element for joining fragments of architectural members and for replacing rusted clamps and dowels. It is a relatively light metal, of satisfactory strength and with features (the coefficiant of thermal expansion and the modulus of elasticity) that allow it to work well with marble. The main characteristic for which it was chosen for connecting the members, however, is its excellent resistance to all forms of corrosion. The same requirements (to be harmless and compatible with the marble) are fulfilled also by the inorganic plaster with a white cement base, which is used as a glue for joining the fragments. The additions to the blocks are of Pentelic marble, from the Dionysos quarries.

Marble is in fact an entirely non-isotropic material because of its structural stratification. In calculating the strength of the join, the position of the structural strata within the marble mass must be taken into consideration.

During the past few years in our country, there has been considerable research on the material of the ancient monuments and on the question of which materials are suitable for their restoration. In the framework of the most recent research, tests were carried out at the Centre for Aeronautical Research and Technology in order to measure the tensional strength of the structural iron of the Parthenon. A characteristic feature of ancient structural iron is the alternating layers of soft iron and hard steel, which in combination with small inclusions of rust leads to a significant variation in the values of yield stress and breaking stress. In addition to brief samples, undamaged clamps were also examined, the strength and deformability of which turned out to be less than that of the samples.

The mechanical features of Pentelic marble were examined in the course of laboratory tests at the work-sites of the monuments and in the Durability of Materials Laboratory of the National Technical University of Athens. These tests have yielded the average values of compressive and tensile strength that are used in the calculations. Also studied during the course of recent laboratory tests was the reaction of marble under direct tension, uni-axial and tri-axial compression and three-point bending.

The behaviour of the parts reinforced by titanium has been studied in bending trials and pull-out tests. The behaviour of beams mended with titanium rods is also being studied in three-point bending tests. These tests are particularly important for the restoration of large bending members (beams, epistyles) . Similar tests have been carried out for the plaster with white cement base. These tests were conducted at the Public Works Research Centre, where the shear resistance of members mended with cement paste was measured on trial pieces in compression tests. Tests were run also to measure the tensile strength in bending on test pieces mended in the middle with cement paste.

4.4. Method of calculation the joining the fragments with titanium reinforcements

Structural restoration of architectural members is done by joining their fragments with titanium reinforcements and white cement. The reinforcements are calculated so as to take on tensile force in a direction at right angles to the surfaces of fracture. The basic criterion for calculating the reinforcements is that they can safely take on the functional loads and in a near limit situation the reinforcements in the joining should fail rather than the marble itself.

The architectural members are distinguished according to their load state: loaded by uniaxial compression such as the wall blocks; loaded by bend and shear forces as are the Doric column capitals; mainly bending members such as beams and epistyles. In calculating the joining it is possible to re-establish the original strength of the member. Particularly in the case of large bending members (beams, epistyles), this methodology leads to a redundantly large amount of reinforcement and as a result to a significant lack of the ancient material. In addition, the reinforcements yielded by these calculations cannot be placed in the ancient cross-sections of the members because of their special shape or damage and missing marble. The result of all these impediments is that the amount of reinforcing has to be reduced and its distribution in the marble changed. The end result is that the aim of restoring the original ancient strength of the member is not realised.

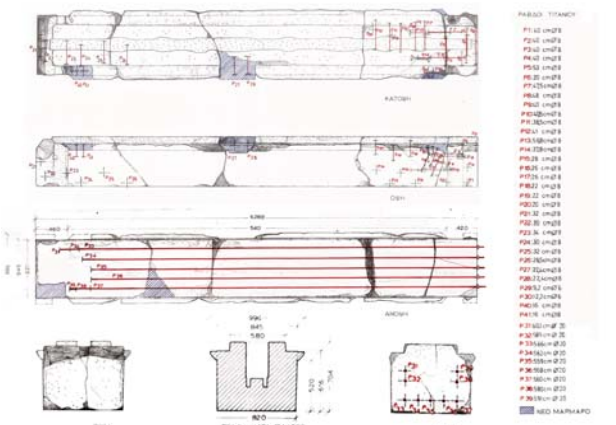

Figure 6. Structural restoration drawing of a marble beam. Study M. Ioannidou, V. Paschalidis

More realistic is the dimensioning of the bending members for the total action they are expected to undergo after their reconstruction. The actions include structural vertical loading and strong – seismic vertical and horizontal loads. Calculated also are the actions during transportation, storage and re-setting. Crucial for calculating the repairing are the stress features that develop on the surfaces of fracture. Analysis of the load state of the composite beam of marble-titanium is done by classical methods of structural analysis, whereas classification of stress is determined following the general principles of the strength of the materials. In order to check the strength of the join, developed stresses in the place of the mended crack are compared with the allowable stresses of the materials, compressive strength of the marble and tensile strength of the titanium. The functional stress of the titanium is kept below the yielding stress limit in order to avoid residual deformations. The amount of reinforcement needed, using this method, is indeed very small (1-2%) and as a result there is little damage to the ancient material.

Figure 7. Joining of fragments of a beam by means of titanium bars, at the specially designed table. By T. Tanoulas.

This method of calculating has been run on a calculation programme of Microsoft Excel. The programme enables us to register the characteristics of the members to be joined (dimensions, profiles of surface breaks, loads) and to calculate automatically the features of the load state of the profile (stress of marble and titanium) in different places, profiles and the number of titanium rods. This computer method has been checked also experimentally with excellent results.

During the joining of the beams fragments special care is taken so that the width of the join in the place where it is glued is as small as possible. The smallest possible amount of plaster is therefore applied. This is successful because the broken surface of the ancient piece is copied on the new marble (when an addition is made) and the fragments to be joined are strongly bound together during the process of joining and during the first stages of hardening of the plaster. Adhesion of the titanium to the plaster is improved by threading the rods.

Figure 8. Preparation for the joining of the beam fragments

Figure 9. Binding of the beam fragments after the joining

4.5. Joining architectural members with titanium clamps and dowels

The elements used for joining (clamps and dowels/rods) are designed to begin with in accordance with the positions and measurements of the cuttings and sockets in the ancient members. Respect for the original authenticity of the building, thus for the way in which the architectural members are joined, is demanded not only by a general requirement of respect for the monument, but also for structural reasons. The interventions are carried out on that part of the monument that has a problem, while the rest remains in its original condition. Whatever modification is made to the strength and stiffness (resistance to bend) of the bearing system in certain areas alone, will affect the behaviour of the monument in seismic stress with undesirable results for the whole of the bearing system. In designing the clamps and dowels, the aim is that the weaker element of the join be the metal clamp or dowel, so that in case of great stress the join can withstand permanent deformation and, if deemed necessary, there can be a new intervention, limited to replacing the metal clamps/dowels.

If the original socket is preserved, the double-T clamp is designed so as to have the greatest possible strength and ductility. These are determined by the bearing capacity of the marble in the area of the socket. The new titanium clamps have the same form as the ancient ones with reinforced transverse legs, whereas the long leg forms a long neck so as to prevent the failure of its significant deformation and thus significant absorption of force. If the cavity (socket) has been damaged, the smallest intervention on the ancient marble is made secure by opening two drill holes in the position of the transverse legs and by using Π-shaped clamps (letter Π of the Greek Alphabet). The same principle is applied to the design of the dowels (rods). To increase deformability of the dowels/clamps in situations of shear force, a space of 1-2 cm. is left in the area between the dowel/clamp and the socket. This is left free of cement plaster so that transverse deformation of the clamp/dowel is possible.

Figure 10. Different types of titanium clamps

5. CONCLUSION

The interventions on the Acropolis monuments are technical works, closely connected with research in various fields of knowledge.

The main characteristic of the Acropolis works is the interdisciplinary approach to the interventions and the special studies on the restoration of the monuments carried out prior to any intervention. They use traditional materials and techniques during the interventions directly on the monuments and at the same time modern technology during the study of the monuments, the organization of the work –sites, the restoration work, the management of documentation.

Particular emphasis is placed on documenting the condition of the monuments prior to each intervention and during the course of work with detailed graphic, photographic and cinematographic recording and the scholarly research that accompanies the project in all its phases.

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