# Study of the constructing materials, techniques and pathology symptoms of the stone bridge DeBosset in Kefalonia

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ABSTRACT: The stone Bridge DeBosset in Argostoli the capital of the island of Kefalonia, Greece, was firstly constructed in 1810, in order to connect the two opposite coasts of the Argostoli gulf (Argostoli – Drapano). It was considered to be one of the biggest above sea stone bridges of the Mediterranean basin at those times, with a total length of 750m. It is still in service, but serious problems have been appeared. The continuous contact with the sea water and waves, the different types of materials used for interventions, as well as the increased car circulation, have resulted in severe pathology symptoms to the materials and structure. Based on the analysis of the existing building materials, new repair materials were proposed so as to be compatible with the old ones, in terms of aesthetic harmonization and functionality in the structural system.

## 1 INTRODUCTION

### *1.1 Historical background*

The DeBosset bridge in Kefalonia, Greece, is a stone bridge of 750m length, see Fig. 1. It was firstly constructed in 1810, with wood, in order to connect above sea the capital of the island, Argostoli and the town of the opposite coast of the gulf, Drepano. Later on, in 1831, it was reconstructed with stones, keeping the same architectural structure with the earlier one, in order to be a bridge for pedestrians and wheeled vehicles. At those times, this bridge was considered to be a major construction project of the Greek land and one of the biggest above sea stone bridges of the Mediterranean basin. Today, it is considered to be a monument of high architectural and historical value. During the earthquake of 1953, the bridge structure was seriously damaged. After that the collapsed parts of the bridge were reconstructed by using reinforced concrete. Today, the bridge pavement is loaded on 16 stone arches of low height, see Fig. 2-3, from which only the 15 are still open. In the first two arches the authentic material has been kept, while in all others there are parts of stones and parts of concrete due to the repairing works of 1953.

Figure 1 : The DeBosset stone bridge.

Figure 2 : The first stone arch of DeBosset Bridge.

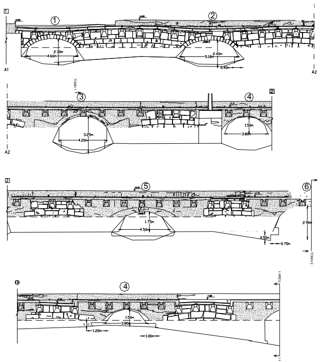

Figure 3 : The East façade of DeBosset Bridge, architectural design.

### *1.2 Aim and implementation of the project*

A large multidisciplinary project entitled "Study of the restoration and consolidation of the De-Bosset bridge in Argostoli, Kefalonia", started in 2004 under the responsibility of AUTH (Schientific Responsible: K. Pitilakis, Professor AUTH). The part concerning the study of building materials and techniques, the grade of deterioration was implemented by the Laboratory of Building Materials of AUTH. The architectural survey was also made by the Dr. Architect A. Alexiou.

## 2 STATE OF PRESERVATION

### *2.1 General issues*

The structure of the bridge confronts today a variety of crucial pathology symptoms that put the safety of the bridge under question. These symptoms refer to the static stability of the bridge, due to its problematic ground substructure (Rovithis et al, 2006), the low bearing capacity of the structure, as well as the severe corrosion that is presented in its building materials.

In this paper the deterioration forms of the structural materials is studied which are related to specific factors. These factors can be summarised to the continuous contact with the sea water and waves, the different types of materials that are found in the structure (stone, concrete), as well as the increased loads due to car circulation.

### *2.2 Pathology symptoms*

The Pathology symptoms were generally separated in two categories. Those which are found in the stone mass of the structure and these that are presented in the parts of reinforced concrete. Regarding the first type, the most important forms that were identified macroscopically are:

1) In the stone masonry arches the stones are completely unjoined. Due to deformations of the structural system and displacements happened in the past, the arches made with the shaped stones cannot be considered as monolithic structural member.

2) Cracks of stones, especially in those of smaller dimensions, of the upper structure, see Fig.4.

Figure 4: Crucks of stones.

3) Loss of mass, see Fig. 5 was observed in all stone types, but especially in those of the upper structure, due to alveolization mechanism.

Figure 5 : Loss of mass of stone of the upper structure of the bridge.

4) Crusts of brown or grey color, see Fig. 6. The brown ones are due to the sediments of dust in comparison with products of oxidizing and are presented mainly in stones with loss of mass, whereas the grey are probably due to air pollutants (car circulation), and are mainly found in the upper structure.

Figure 6 : Crust of grey color.

5) Products of biological growth in the form of green stains, or of a compact crust of black color, see Fig. 7. The latter form is presented in the materials that are directly in contact with the sea water, while the former one is depicted in all the structure.

Figure 7 : Products of biological growth in the form of black crust.

The basic corrosion types that are found in the concrete parts of the bridge are detachments of covering of the reinforcement. Pieces of the reinforcement are totally exposed to the severe marine atmospheric conditions, a fact that leads to their complete decay, see Fig. 8. The reinforcement is completely oxidized, while its cross-section is being diminished. As it was expected the concrete elements dated from the decade of ’50, present serious problems of delamination. The oxidize products produce stains and discolorization to the materials. The check with phenolphthalein indicator, showed that the concrete mass is completely carbonated and of course the presence of salts is obvious.

Figure 8 : Exposition and decay of the reinforcement of the concrete elements.

## 3 CONSTRUCTION TECHNIQUES AND MATERIALS

### *3.1 Construction Techniques*

During the construction of the stone mass of the bridge, there was not any use of bonding material. The stones were very well chiseled and were perfectly put in contact, without need of any mortar as a cohesion system. During the repair works of 50's, parts of the masonry were jointed externally with a cement-mortar of grey color, see Fig. 9.

Figure 9 : The absence of joints in the stone structure. The external cement-joints of the repair works.

In the height of the arch's keystones there are embossed ornaments (stone made in their authentic form and of concrete in the reconstruction areas). Their width is about 40cm and are placed with a between distance of 1m, see fig. 10. In the two sides of the asphalt road there concrete parapets of 40cm height, which present a severe decay. The cross section of a typical stone arch is given in Fig. 9.

### *3.2 Building materials' analysis*

In order for the analysis of the building materials of the structure to be made, there were taken 24 samples of materials, from different places and of different types. The samples referred to 17 stones that were taken in pieces or in the form of cores, four samples of concrete and three samples of the reinforcement. All these were substituted to a series of test, according to the holistic methodology that is followed in the Laboratory of Building Materials, A.U.T.H.

Regarding the samples of stones and concrete, all samples were shaped and put into a series of tests in order to define their physico-mechanical and microstructural characteristics. The methods of analysis were: determination of porosity, apparent specific gravity, compressive strength, dynamic modulus of elasticity, concentration in soluble salts, microscopical observation. The samples of the reinforcement were substituted to microscopical analysis, determination of yield point and of the decrease of steel rod diameter.

### *3.3 Results from the analysis of the samples of stones*

The shaped stones of the structure are mainly of dimensions 0,80x1,00m and in some parts of 0,30x0,50m. From the macroscopic observation of the stones of the DeBosset Bridge, as well as from their analysis, there was concluded that there are two general categories of stones that have been used in the structure. The first one refers to a white calcitic stone, while the second to a brown-yellowish sandstone.

The calcitic stone, see Fig. 10, is of biogenic origin and presents color alterations, while it contains crystals of different size (rough or micro-crystallic), which are mainly calcitic (in a smaller proportion there are silicious as well).


Figure 10 : Sample 16. In situ, macroscopic, microscopic and photo taken by polarized microscope.

From the analysis of the mechanical properties of the stones it is concluded that there is a high spreading of the values, due to the different degree of corrosion of each sample, see Table 1. The highest values are for the core samples (Samples C15-C17), with a compressive strength of about 48MPa and a dynamic modulus of elasticity of 73GPa. These values are considered to be the most representative, since they come from the inner side of the structure. The rest samples, which were taken from the surface of corroded stones, present lower values of compressive strength (5,62-27,3MPa). Regarding the porosity and apparent specific gravity of the samples there is also a spreading in the values (Porosity: 0,28-4,41%, Ap. Spec. gravity: 3,441-2,455), which is also due to the pathology of the samples (microcracks, discontinuities of the structure). The determination of soluble salts (method HPLC) showed an extremely high concentration of salts in the inner as well in the outer surface of the samples. The values are 101,3-4565 mgr/lt for $Cl^{-}$ and 10,1-312,5 mgr/lt for $SO_4^{2-}$. The highest concentration of salts were given for the sample that is in touch with the concrete part of the bridge.

Table 1 : Results from the physico-mechanical analysis of the samples of calcitic stones

| **Sample** | **Porosity** | **Ap. Spec. gravity** | **Dyn. Modulus of Elasticity** | **Compressive strength** |
|---|---|---|---|---|
| | **%** | | **GPa** | **MPα** |
| 3 | 1.66 | 2.615 | 38.59 | 8.46 |
| 4 | 1,55 | 2,715 | 88,72 | 27,3 |
| 6 | 0.54 | 2.767 | 23.48 | 8.28 |
| 7 | 0.94 | 2.774 | 80.30 | 13.32 |
| 8 | 0.28 | 3.441 | - | - |
| 9 | 0.53 | 2.698 | 39.96 | 5.62 |
| 12 | 6,45 | 2,285 | 49,51 | 9,21 |
| 14 | 1,23 | 2,916 | 12,17 | 14,25 |
| C15 | 1.98 | 2.674 | 76,42 | 48.15 |
| C16 | 2,63 | 2,844 | 74,06 | Splitting tensile strength: 2,28 |
| C17 | 4,41 | 2,455 | 70,31 | 47,45 |

As far as the sandstone is concerned, see Fig. 11, it is of high concentration of clastics of silicious origin, of circular shape and of size 300-900μm. In their conjunction there are a lot of voids.


Figure 11 : Sample 21. In situ, macroscopic, microscopic and photo taken by polarized microscope.

From the analysis of the mechanical properties of the sandstones it is concluded that there is not such a spreading of values as was presented in the calcitic stones, see Table 2. The values of the compressive strength are in between 7,09-11,50MPa, while the dynamic modulus of elasticity is of 22,32-30,95 GPa. The porosity is 9,28 – 21,18 %, while the apparent specific gravity is 1,701-2,371. The spreading in the values is once more related with the pathology of the microstructure of the samples. Regarding the determination of soluble salts, is high again, with the concentration of $Cl^-$ to be among 189,2-1063,8 mgr/l and of $SO_4^{2-}$ 19,6-318,6 mgr/lt.

Table 2 : Results from the physico-mechanical analysis of the samples of sandstones

| Sample | Porosity<br>% | Ap. Spec. gravity | Dyn. Modulus of Elasticity<br>GPa | Compressive strength<br>MPα |
|---|---|---|---|---|
| 5 | 11,48 | 2,113 | - | 8.46 |
| 10 | 21,18 | 1,701 | 24,21 | 27,3 |
| 11 | 16,42 | 2,087 | 30,95 | 8.28 |
| 13 | 10,23 | 2,036 | - | 13.32 |
| C20 | 9,28 | 2,371 | 22,32 | - |
| C21 | 16,77 | 1,858 | 23,89 | 5.62 |

### *3.4 Results from the analysis of the samples of concrete*

The old concrete seems to be of old technology. Based on the microscopic analysis of the concrete samples, lime and fine crushed ceramic materials have been used as additions to the concrete mixture. This possibly implies an effort made to enhance durability of concrete by benefiting from pozzolanic reaction of traditional in Greece pozzolanic materials. A lot of lime lumps have been detected microscopically, see Fig. 12. The covering of steel reinforcement ranges from 1,5 to 2,5cm.

Figure 12 : Calcitic lump in a concrete sample (C19). Microscopic photo.

As it was prescribed previously, the concrete cannot protect the reinforcement, since it is in high depth carbonated. The concentration of chlorines in combination with the PH value of concrete (PH≈9), are much more above the crucial value for the protection of steel. This is obvious in the places where the detachment of concrete leaves the steel in a complete decay.

The concrete's compressive strength is low, about 8MPα in shaped cube samples taken from concrete parapets and 18MPα in the core samples taken from the concrete slab that is forming the road level, see Table 3. The Dynamic modulus of Elasticity (with sonometer) is about 22-42GPa, values that correspond to 8.5-20GPa respectively of the Static Modulus of Elasticity. Due to the high concentration in soluble salts ($Cl^-$:0,7-2,4%p.w., $SO_4^{2}$: 0,1-1,8%p.w.), and the high level of corrosion of the reinforcement, the bearing capacity of the concrete regarding its mechanical properties is low. It corresponds to the category C8/10, which is extremely low for a reinforced concrete construction. The vicinity of the concrete with the authentic stones of the structure is certainly the source of sulfates transfering, which have corroded the stoney mass of the structure.

Table 3 : Results from the physico-mechanical analysis of the samples of concrete

| Sample | Porosity<br>% | Ap. Spec. gravity | Dyn. Modulus of Elasticity<br>GPa | Compressive strength<br>MPα |
|---|---|---|---|---|
| 1 | 7,73 | 2,248 | 35,33 | 7,19 |
| 2 | 6,15 | 2,327 | 22,22 | 6,56 |
| C18 | 3,52 | 2,676 | 39,18 | 17,13 |
| C19 | 4,09 | 2,473 | 42,61 | 19,98 |

### *3.5 Results from the analysis of the samples of the reinforcement*

The reduction of the diameter of the steel bars which are embedded in the concrete, is about 31.0-54.6%, with a reduce of weight about 46,98-91,70%, see Table 4. The yield point stress that has been experientially determinated in two samples of the best preserved sample is about 396-431MPα and it is near to the category S400 that corresponds to a 420MPα, see Table 5.

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Table 4 : Remove of steel rod rust by treatment with a specific solution HCl 10%p.w.

| Sample | Loss of Weight | | | Diameter reduction | | |
|---|---|---|---|---|---|---|
| | $W_0$ | $W_F$ | | $D_0$ | $D_F$ | |
| | gr | gr | % | cm | cm | % |
| 1 | 19.08 | 10.12 | 46.98 | 1.375 | 1.065 | 31.00 |
| 2 | 9.84 | 2.23 | 77.34 | 0.645 | 0.315 | 51.16 |
| 3 | 9.76 | 0.81 | 91.70 | 0.495 | 0.225 | 54.55 |

Table 5 : Results from the mechanical analysis of the samples of the reinforcement

| Sample | Diameter | Cross section f | Yield point load $P_\delta$ | Crushing load $P_0$ | Yield point stress $\sigma_\delta$ | Tensile stress $\sigma_0$ | Strain $\varepsilon_0$ |
|---|---|---|---|---|---|---|---|
| | mm | mm$^2$ | kp | kp | MPa | MPa | % |
| 3 | 6,0 | 28,26 | 1120 | 1350 | 396 | 477 | 26,5 |
| 4 | 5,7 | 25,50 | 1100 | 1250 | 431 | 490 | 28,1 |

## 4 CONSERVATION AND RESTORATION TECHNIQUES

### *4.1 General remarks*

According to all the results from the analysis of the structural system, building materials and deteriorating grade of the DeBosset bridge, it is obvious that the safety level of the structure, is extremely low. However, it is used everyday by the citizens of the two towns. This makes uncertain the static stability of the structure, regarding the international safety rules and codes. The main axis under which the whole restoration project was based, were (Pitilakis, K.D, 2006):

- The authentic parts of the bridge should be maintained and treated as of high historical and architectural value.
- The intervention should be effective regarding the strength level of the whole structure and its foundation, in order to be stable in future strains. The repair materials, should not create additional loads to the structure.
- The repair materials should be compatible with the authentic ones, in order not to create additional problems. In the parts that cement will be finally used, this should be of low concentration of sulfates, specific measures should be taken for the protection of concrete reinforcement.
- The interventions should strengthen the bearing system of the bridge, so as to ensure a monolithic and stable behavior of it, in order to fulfill all the safety rules for future earthquakes, since the island is in a high seismic zone.

### *4.2 Restoration methods*

The restoration methods that were proposed, regarding the building materials are, see Fig. 12 (Pitilakis, K.D, 2006):

- Cleaning of the bridge's masonry and consolidation of the stone elements with special jointing mortars. These mortars should be resistant as much as possible, to the severe climatic conditions of the area (high humidity, contact with sea waves), while being compatible with the authentic materials.
- Partial or total restoration of the stones in the places where there are detachments or loss of much, with new materials compatible with the old ones (physico-mechanical properties, aesthetic harmonization). Jointing with mortars.

- Restoration of the whole corpus of the bridge (where there is now concrete), with placing a layer of stones jointed with mortars (as described above). The concrete should then be cut in an adequate width. In this way the bridge would retain its authentic form by gaining uniformity.
- Strengthening of the main corpus of the body with lateral tendons that will be placed every 1-1.5m and which would retain the two facades of the bridge, increasing its mechanical capability in seismic loads. In parallel, increase of the bearing capacity of the bridge with the construction of small piles, that will be 30-50cm lower than the concrete slab of the road.
- Replacement of the concrete slab of the road, with a new one, reinforced and of small width. This slab should correlate in the best way with the structure and should be of low weight, so as not to create additional loads.
- Improvement of the ground conditions by protecting the foundations from corrosive action of sea waves (undermining).

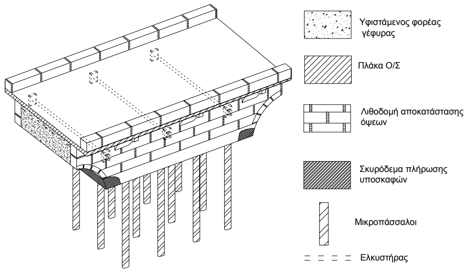


Figure 12 : Design of the bridge's corpus, after the interventions.

## 5 CONCLUSIONS

The DeBosset stone-Bridge in Kefalonia, is considered to be a structure of high architectural and historical value, not only for the cultural heritage of Greece but even for the Mediterranean basin. Its state of preservation is problematic due to the severe marine environment to which it is exposed. Based on the analysis of the residual bearing capacity, the severe corrosion damages of the concrete members and stone masonry deterioration it was concluded that the structure cannot confront the safety conditions for use as a road open to car circulation. In the restoration proposal that resulted from the study, the principles of maintaining the authentic character of the bridge is kept, whereas the structure will be consolidated and enforced for preventing future strains. The systematic study made during this project could constitute a modulus of studying stone bridges, by investigating their pathology symptoms, analyzing the building materials, structural system and proceeding to restoration methods, by which the original parts of the historic structure will be preserved..

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