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DOWEL ACTION OF TITANIUM BARS CONNECTING MARBLE FRAGMENTS AT DIFFERENT ANGLES

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Abstract

Very often, marble elements belonging to ancient monuments, such as those of the classical Greek antiquity, are fragmented in many pieces. In order to be repaired, those fragments need to be connected again. The connection of marble fragments with dowels and bars is the main mechanism for undertaking the applied shear and traction forces. This paper presents the results of tests that were performed to gain evidence concerning the dowel action of titanium bars connecting marble fragments. The parameters investigated were: the diameter of the bars and the angle between a plane perpendicular to the dowel longitudinal axis and the marble surface. In a previous programme the effect of the size of the cover was investigated as well. Main aims of the testing program were to determine the failure mode and to evaluate the dowel shear strength as a function of the angle between dowel and marble surface.

Key Words

Dowel, marble, titanium, shear

Notation

d_b: Nominal bar diameter
D_u: Maximum mobilized shear resistance
τ_u: Shear strength of dowel
d_u: Shear displacement corresponding to D_u

1 Introduction

Titanium is quite extensively used in the conservation works of the monuments at the Athens Acropolis. The commercially pure titanium was selected both for its resistance to all types of corrosion and for its physicochemical compatibility with the marble.
Threaded titanium bars, installed in drilled holes and connected with the marble by means of a white cement mortar, have been used up to now, to connect pieces of

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fractured architectural members. In those applications, in which titanium bars are subjected to tension, the connections are designed in a way to exclude failure of the connected marble pieces. The relevant design method (Zambas 1988, Zambas 1992) is supported by experimental evidence.

There are, however, numerous applications, in which the marble to titanium connection is subjected to shear. For this type of loading, neither experimental evidence nor a design method was, until recently, available. As a first step, in order to provide relevant experimental evidence, an experimental program was carried out at the Laboratory of Reinforced Concrete, NTUA. Threaded titanium bars were installed in drilled holes in Dionysos marble and they were subjected to shear up to failure. Various parameters were investigated, namely the diameter of the titanium bars, their cover and the direction of loading (against the strong or the weak direction of marble's anisotropy) (Vintzileou and Papadopoulos 2001). In this research, the longitudinal axis of the titanium dowels was always perpendicular to the marble surface.

However, an angle of 90° between dowel and marble represents only one of the many possibilities that may occur in praxis. Indeed, as in case of the multi-fragmented beams (architraves) of the western part of the Parthenon, the fragments may have various angles or, it might be impossible to insert dowels with a direction perpendicular to each fractured surface (Figure 1). It became necessary to study the effect of the angle between a dowel and a marble surface.

In this paper, the main experimental findings of this program are presented and commented. In a future work, formulae will be proposed for the calculation of the maximum shear force carried by the titanium to marble connection.

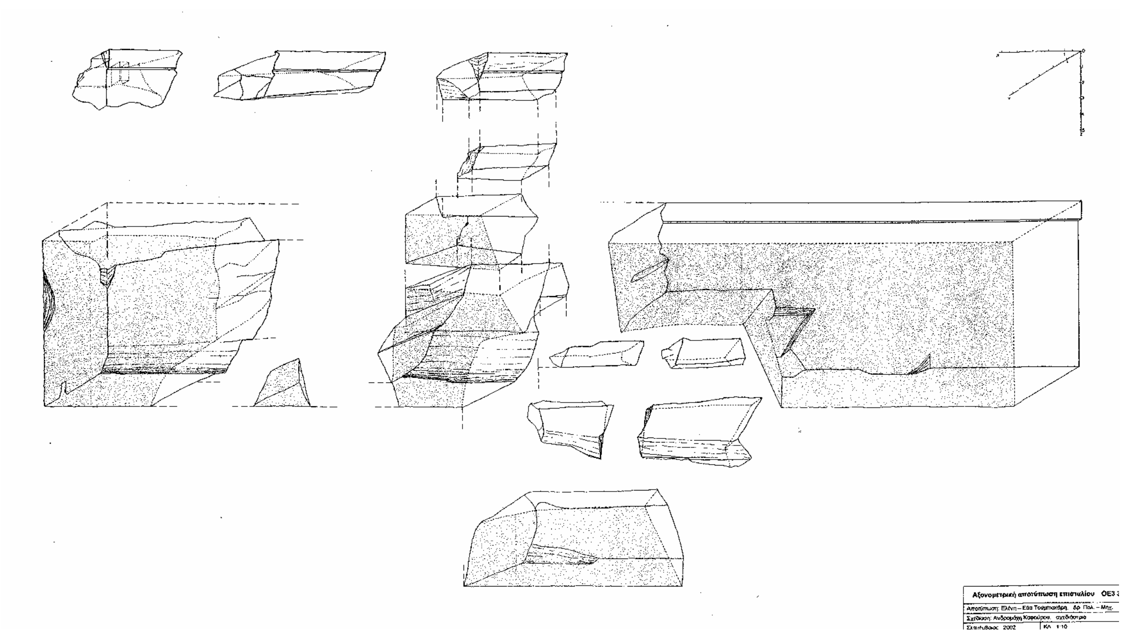

Figure 1 Example of multi-fragmented marble element: architrave OE3.3 of the western part (Opisthodomos) of the Parthenon (measured by E.-E. Toumbakari, drawn by E.-E. Toumbakari and A.Kafourou) (Toumbakari 2002)

2 Experimental

2.1 Materials

2.1.1 Dionysos marble

Pentelic marble is the basic material of the Acropolis monuments. However, since the quarries of Penteli were closed for environmental reasons, marble from Dionysos mountain, near Penteli, is used in restoration works. Dionysos marble was selected because its physical and mechanical properties are similar to those of the remarkably durable Pentelic marble (Zambas 1988).

According to tests carried out at the National Technical University of Athens (Vardoulakis and Kourkoulis 1997, Vardoulakis et al 2000), the compressive strength of Dionysos marble is equal to 83 N/mm^2 and 70 N/mm^2 in its strong and weak direction respectively. Its strength in direct tension is equal to 8.7 N/mm^2 in the strong direction of the marble. The available data regarding the tensile strength of the marble in its weak direction are not considered to be reliable. The Poisson's ratio is equal to 0.33 in both directions.

2.1.2 Titanium

Titanium bars, threaded along their whole length, are used to provide continuity between the fractured pieces of the architectural members.

Commercially pure titanium (Grade 2, in accordance with ASTM B348) was selected because of its high resistance to all types of corrosion, as well as for its physical and mechanical properties that render it suitable for joining together pieces of the original marble. In fact, the Poisson's ratio of titanium (=0.32) is practically equal to that of the marble. In addition, titanium exhibits a low coefficient of thermal expansion (=9x10^{-6} grad^{-1}), sufficient (but not excessively high) mechanical strength and high elongation at failure (20%÷22%). The yield strength of titanium is equal to 300 N/mm^2, whereas its tensile strength is equal to 420 N/mm^2.

2.1.3 Cement mortar

As mentioned previously, titanium bars are inserted into drilled holes and connected to the marble by means of white cement mortar. To this purpose, white Portland cement is used. The mechanical properties of the mortar were measured on conventional 40x40x160 [mm] specimens. Its mean compressive strength at 28 days was equal to 12.1 N/mm^2, whereas its tensile strength (in flexure) was equal to 0.96 N/mm^2.

2.2 Experimental procedures

2.2.1 The specimen

Eight pieces of Dionysos marble were used for testing in the strong direction of the marble. All pieces were free of macroscopic discontinuities and imperfections. The cross section of the marble pieces was initially rectangular, with dimensions ranging from 23 x 25 cm^2 to 28 x 30 cm^2. On the one side of the rectangle, a triangular piece of marble was cut, to materialize a surface inclined in relation to the dowel (Figure 2). Three inclination values were selected: 30°, 45° and 60°. This value expresses the angle between a plane perpendicular to the dowel longitudinal axis and the marble surface. At the edge between the horizontal upper surface and the inclined one, holes were drilled to the marble, to accommodate titanium dowels (Figure 3).

The diameter of holes was by 4mm larger than the diameter of the dowel. The distance of consecutive holes was large enough to avoid overlapping of marble cones in case of cone failure. The depth of holes was equal to 10 times the dowel diameter. The holes were cleaned from dust before the insertion of titanium dowels.

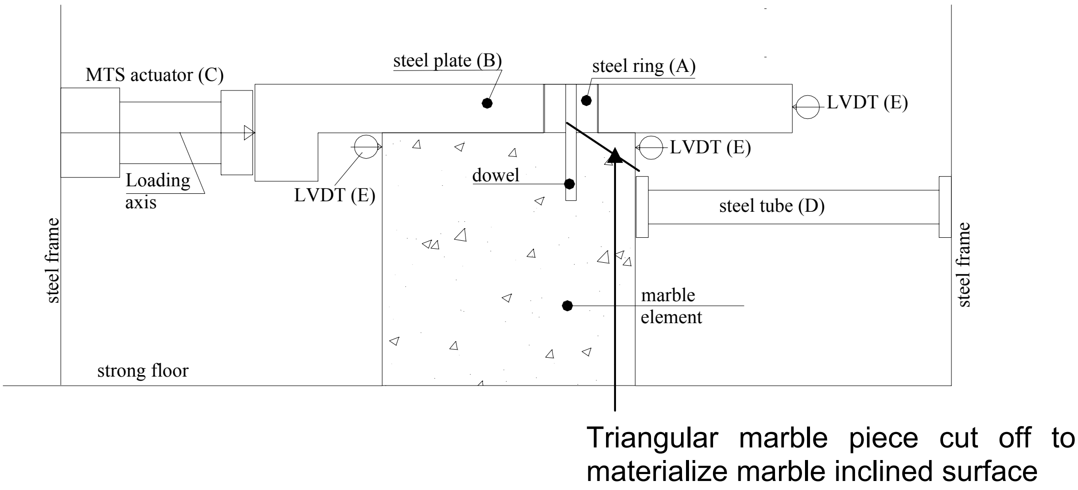

Figure 2 Test arrangement

Threaded titanium bars with a diameter of 8mm, 12mm or 16mm were used to form the dowels. Each piece was of a length equal to 10 times the bar diameter (equal to their embedment length) plus 100mm (equal to their protruding length). Cement mortar was poured into each hole and the respective dowel was pushed-in by hand. All tests were carried out more than 28 days after the application of dowels, to allow for sufficient hardening and strength gaining of the mortar.

Figure 3 Marble specimen during testing. On the right, the angle between the marble surface and the dowel (which is inside the rigid slab) is visible.

2.2.2 Experimental setup

Figure 2 also shows the set up used for testing the dowels: The specimen was placed horizontally on the strong floor of the Laboratory. A steel ring (A) was surrounding the dowel under testing. Subsequently, a steel plate (B), having a hole of diameter by 2mm larger than the external diameter of the ring was placed on the specimen. Gradually increasing displacements were applied by an MTS hydraulic actuator (C), with maximum capacity of 500 KN, to the steel plate. The longitudinal axis of the actuator coincided with the surface of the marble element, to avoid eccentric loading of the dowels. The reaction was transmitted to one of the strong steel frames of the Laboratory by means of two horizontal steel tubes (D). The distance of the two tubes was large enough to avoid any parasitic loading of the marble at the vicinity of the dowel under testing. Three LVDTs (E) were used to record displacements of the steel plate and of the marble element during testing.

3 Results and discussion

3.1 Failure mode

In the first part of the experimental program (Vintzileou and Papadopoulos 2001) two failure modes were observed, depending on the cover of the dowels, as well as on the direction of loading. Both failure modes are schematically shown in Figure 4: Failure mode I consists in fracture of the dowel at the surface of the marble element, accompanied by limited in depth spalling of the marble. Failure mode II consists in the separation of a cone of marble. The angle of separation was approximately equal to 23°, whereas the depth of the cone was almost equal to 2c (c being the cover of the dowel). It was observed that failure mode I occurred to all dowels to which a cover equal to 6 times the bar diameter was provided. The same failure mode was observed also for a cover equal to 4 times the bar diameter, when the dowels were loaded against the strong direction of the marble. On the contrary, a cover equal to twice the dowel diameter led to a cone failure. The same holds true for dowels with a cover of 4 times the bar diameter, loaded against the weak direction of the marble.
In the present experimental program, care was taken to provide a cover equal or bigger than 6 times the bar diameter (in this case, the "cover" represents the length of the inclined surface). Nevertheless, it was observed that all failures belonged to mode II. There was however a differentiation related to the angle of inclination and to the diameter of the titanium bar. When the diameters are small (8mm and 12mm for all angles) or for small angles (30° for all diameters) failure mode II was accompanied with simultaneous failure of the dowel (Figure 5a). At bigger diameters (16mm) and steeper angles (45° but mostly 60°) failure mode II occurred sometimes without failure of the dowel, which, of course, was substantially deformed (Figure 5b).

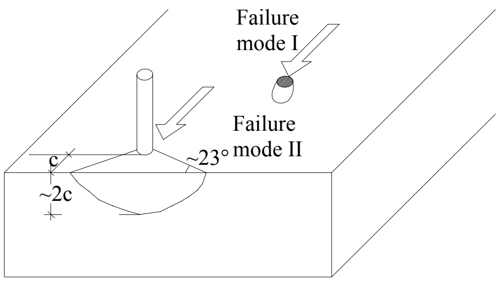

Figure 4 Modes of failure (schematic)

(a)

(b)

Figure 5 (a) Example of failure mode II with simultaneous failure of the dowel (D=12mm, inclination 45°) and (b) example of failure mode II without failure of the dowel (D=16mm, inclination 60°)

3.2 Shear force-shear displacement curves

In Figure 6, some shear force vs. shear displacement curves are presented. In the previous research, in which the dowels were always perpendicular to the marble surface, it was observed that, independently of the failure mode that occurred, there was a practically linear relationship between shear force and shear displacement up to approximately 80% of the maximum mobilized shear force. Then, a less steep curve followed up to failure. This is not, however, the case in the present research. As an example, the behavior of dowels with a diameter of 12mm is discussed.

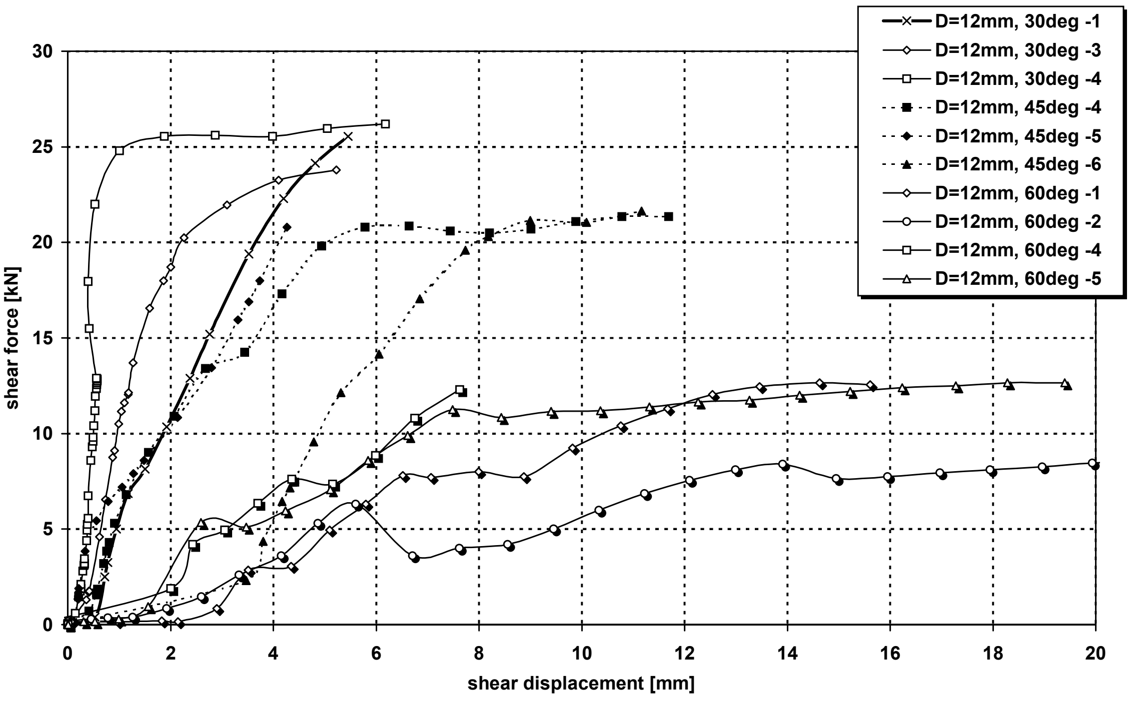

Figure 6 Shear force vs. shear displacement curves of the dowels with diameter 12mm at different angles

There is a clear grouping of the curves as a function of the angle of the marble surface. Expectedly, the steeper curves correspond to the smaller angle (30°). Then, an angle increase brings about a bigger inclination of the shear force – shear displacement curves. The very big deformations of the curves corresponding to a marble angle of 60° represent the deformations to which the dowels were subjected before failure (or before the test was stopped).
In several cases, an initial part of the curve was recorded, for which shear displacement was increasing without substantial increase of the mobilized shear resistance. This feature is attributed to the fact that this initial part of loading is governed by the characteristics of the cement mortar that lies between the dowel and the marble, which is much softer and less strong than the marble.

3.3 Results

In Table 1 the main test results are summarized and are compared with the relevant test results of Vintzileou and Papadopoulos (2001), obtained for titanium dowels perpendicular to the marble surface.

Table 1 Main test results

d_b	Angle [deg]	Specimen No	D_u [kN]	τ_u [MPa]	average τ_u [MPa]	d_u [mm]	Failure mode
8	0	10	9.94	198.8	213.90	4.77	I*
		11	9.94	198.8		8.59	
		12	12.21	244.2		3.73	
	30	II1	9.90	198.00	199.33	n.a.**	II
		II2	10.00	200.00		n.a.	
		II3	10.00	200.00		n.a.	
	45	VIII1	7.85	157.00	159.33	15.22	II
		VIII2	7.30	146.00		12.37	
		VIII3	8.75	175.00		18.31	
	60	III1	7.00	140.00	(140.00)	n.a.	II
12	0	22	22.89	202.57	204.16	8.91	I*
		23	23.39	206.99		8.24	
		24	22.93	202.92		5.75	
	30	F12IV1	25.55	226.11	221.68	5.46	II
		F12IV3	23.80	210.62		5.23	
		IV4F12	26.20	231.86		6.18	
		IV5	24.65	218.14		23.94	
	45	F12VI4	21.35	188.94	188.20	11.69	II
		F12VI5	20.80	184.07		4.26	
		F12VI6	21.65	191.59		11.16	
	60	F12VII1	12.65	111.95	109.18	14.63	II
		F12VII2	11.75	103.98		33.10	
		F12VII4	12.30	108.85		7.62	
		F12VII5	12.65	111.95		19.40	
16	0	not tested					I*
	30	I3	42.05	209.20	214.05	n.a.	II
		I4	44.00	218.91		n.a.	
	45	F16VI1	33.60	167.16	168.24	6.87	II
		F16VI2	34.05	169.40		23.16	
		F16VI3	33.80	168.16		6.87	
	60	F16V2	24.40	121.39	125.87	29.37	II
		F16V3	22.70	112.94		22.82	
		F16V4	28.80	143.28		35.69	

* Results obtained from Vintzileou and Papadopoulos (2001)
** Not reliable recording

It may also be observed that the values of shear displacement at failure are very scattered. In some cases, the failure was very sudden and, thus, the displacement at failure was not reliably recorded.

4 Conclusions

Regarding the dowel action of titanium bars connecting marble fragments at different angles, the following conclusions can be drawn:

1. When the angle between the dowel and the marble surface is different than 90°, a cone failure is always taking place.
2. The maximum mobilized shear resistance is substantially affected by the angle between the dowel and the marble surface. At very steep angles it may even drop to the half of the shear resistance corresponding to a dowel perpendicular to a marble surface.

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