SEISMIC RESPONSE CONTROL OF RIGID BLOCK SYSTEMS BY USING TENDON SYSTEM: THE CASE OF GREEK COLUMNS

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ABSTRACT

Improving the seismic strength of historical monuments, representing world cultural heritage, is the issue widely discussed in the scientific community and, in addition, a challenging task. Any intervention of these monuments, indeed, must be reversible thereby to protect their historical value and preserve the originality and the uniqueness of itself. Despite the classical intervention, in the early years, the advanced methods are developing. Among others, the structural control, active, passive or semi-active, is taking hold. In this within, this paper presents and discusses the effectiveness to apply a Tendon System to improve seismic performance of Greek columns like the ones, for example, in Paestum (SA), Italy. In particular the work presents the main theoretical and experimental results obtained by small-scale models tested on a shaking table.

Key words: *Tendon System, Rigid Body, Dynamic Response, Greek Temple*

1. INTRODUCTION

Testimony of past classical stone architecture is present in Greek, Roman, Byzantine, Romanesque and Gothic monuments. The buildings, which remain nowadays, are only a few examples of the wide activity of this ancient culture, since many of them, characterized by high seismic vulnerability, have been located in areas of severe seismicity.

The ever present seismic threat to those monuments that have survived or been rebuilt has triggered an increasing interest of the scientific community in the

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conservation of these important historical structures. The difficulty to improve the seismic strength by preserving the cultural heritage is well known. Non-invasive strengthening methods are requested, since the uniqueness of the building must remain intact and any structural intervention must be essentially reversible to allow for a return to the original historic state, before intervention, at any time.

These are basic requirements within the international framework for the preservation and restoration of ancient buildings as stipulated in *The Athens Charter for the Restoration of Historic Monuments (1931)* and *The Venice Charter for the Conservation and Restoration of Monuments and Sites (1964)*.

This paper focuses on monuments of classical Greek architecture: the temples, which are not only common in Greece, but also in its colonies, like those of Magna Graecia in the southern Italian peninsula. Starting around the 8^{th} century B.C., these monuments were generally made of large structural stone elements that lie on top of each other without mortar, like drums in the case of columns [3].

This type of structures behaves as rigid-labile systems with unilateral constraints. In the case of the columns excited by seismic events, for example, the drums usually slide and/or rock, independently or in groups, with consequent permanent dislocations or even probable failure due to the overturning of the whole structure or one of its parts also for low seismic actions.

In the literature, both the questions of a rigid body resting on a moving rigid foundation and the seismic response of multi-drum columns has been studied in depth and several dynamic formulations for triggering conditions and dynamic motion have been proposed [4-5-6-7-10-11].

With regard to structural restorations, in the past, several types of interventions have been put in practice, such as strengthening, substitution or reconstruction of structural elements by means of masonry, reinforced concrete or steel, epoxy injection, connecting chains, or the introduction of an additional structural system able to fully resist the design seismic actions.

Despite these classical interventions, recently some new concepts are being developed, among others, structural control concepts, which can be active, semi-active or passive. One of these possibilities is the Tendon System [2]. The basic idea is to tie the loose stone blocks of a historical monument with tendons that run through their centres, but without continuous connections between tendons and stones (like grouting). Ideally, no pre-stressing is applied. Only during motions under earthquakes, forces develop in the tendons that limit these motions and prevent collapse. These forces can be controlled through special devices, like active hydraulic actuators or passive shape-memory alloy devices (SMA). Under regular loading conditions (dead load, wind, etc.), the historical state of stress is untouched. This system works particularly well in the case of a rigid body mechanism, like the one, which characterizes the Greek columns.

The tendon system can be removed any time easily, thereby returning the structure to its state before the intervention.

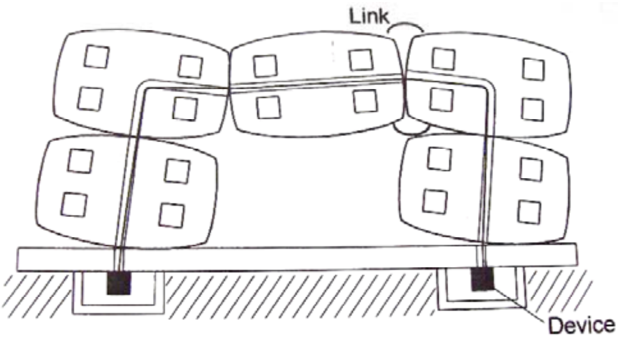

Fig.1 - Tendon System Concept [2]

A good example for an early and successful application of a Tendon System is the seismic upgrading of the Church of San Michele in Solofra, Italy.

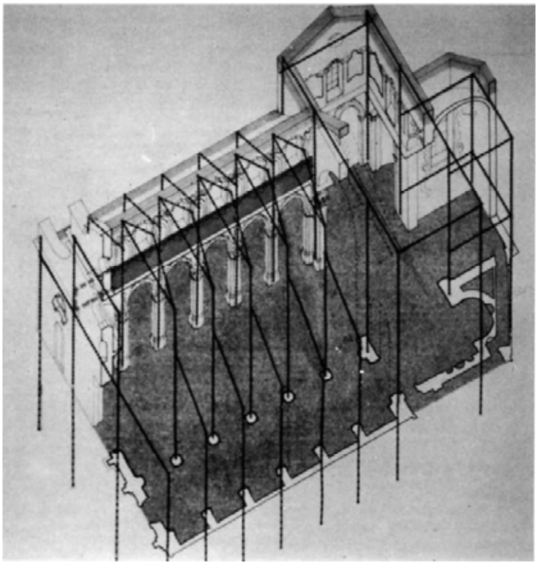

Fig.2 – Tendon System applied to the Church of San Michele in Solofra, Italy [9]

This provides integrity during an earthquake when cracks will form at both ends of the columns allowing them to rotate with the motion of a rigid roof on top. The tendons are not pre-stressed. Therefore, additional forces only develop during the motion and stay limited. There is no alteration of internal forces under regular loading conditions. Except for small holes that needed to be drilled into the columns, the original building fabric stayed untouched and remains in its historic original state. In this early application of the basic principle, the forces developing in the tendons during an earthquake are not controlled [9].

Tendons controlled by shape memory alloy (SMA) devices were used, instead, in the seismic retrofit of the historic bell tower of St. Giorgio in Trignano, Italy [1]. The tower, built in 1302, has a height of 18.50m and was heavily damaged by the 1996 Reggio Emilia Earthquake. In this case, the Tendon System consists of 4 steel tendons running through the four corners of the tower and anchored in the foundation. Four SMA devices have been located at the top of the tower to control the forces developing in each tendon.

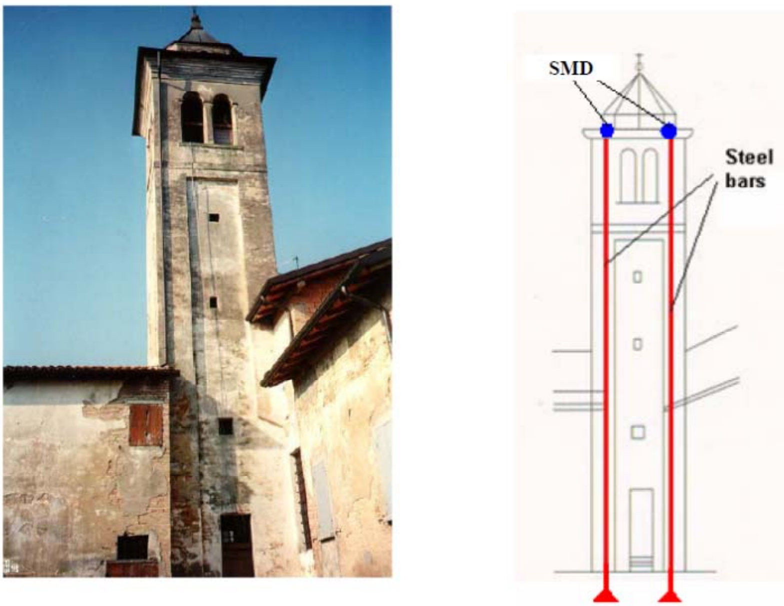

Fig.3 – Tendon System with SMA devices applied to the bell tower of St. Giorgio in Trignano, Italy[1].

A numerical feasibility study related to the Tendon System concept was performed at University of Kassel, Germany, in cooperation with Middle East Technical University and Atatürk University in Turkey The study was carried out on one of the most important historical buildings in Turkey, the old Double Minaret Madrasah in Erzurum dating from the Seljuk period (1230 – 1300). This study emphasizes not only again the feasibility of Tendon Systems for seismic protection of high-valued historic structures, but in particular the need for the development of validated numerical models to design these systems properly [8].

This paper describes the tendon control strategy in the case of Greek columns. In particular, the drums of the columns have been considered as held together through single cables running through the vertical axis, from the bottom to the top. On the top, the cables are connected to devices, which could control the axial tensile force and hence, provide a compressive pre-stress to the column to counteract seismic actions. The seismic behaviour of such a column is herein presented and described with analytical formulations. The theoretical results are compared with preliminary dynamic experiments carried out on small-scale models with a shaking table.

2. DYNAMIC BEHAVIOUR OF RIGID BLOCKS CONTROLLED BY TENDONS

The seismic response of a multi-drum Greek column retrofitted with a Tendon System has been herein theoretically analyzed by considering the model represented in figure 4. In particular, for the considered model, seismic control is obtained by means of an elastic spring, which allows for a constant pre-stressing force *N* along the height of the column.

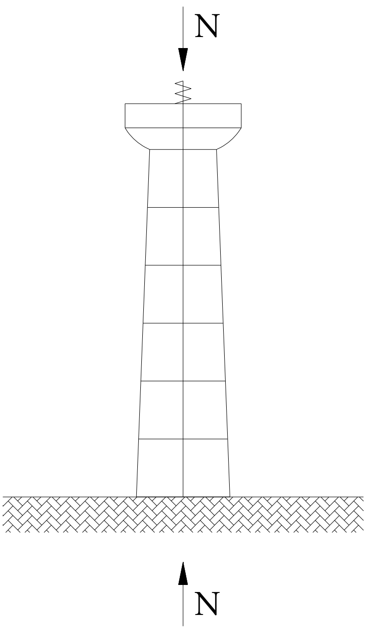

Fig. 4 – Tendon System applied to a Greek column [12]

The seismic response of this rigid block system can be easily analyzed by extending the formulations by Sinopoli [10] and Housner [4], respectively for sliding and overturning mechanisms. Herein, the effect of the Tendon System is represented by a vertical load as follows in the figure 5.

The system under investigation considers a symmetric rigid body with mass *m* and moment of inertia *I*. The rigid body is represented as a rectangular block of width *2B* and height *2H*. In general, there is no restriction on the shape of the body when considering a slide or free-flight mode, but in this formulation, symmetry about a vertical axis passing through the mass centre is required when considering a rock or slide-rock mode. The distance between either corner in contact with the foundation and the mass centre is denoted by *R*, and the angle α represents the maximum angle through which the body can rotate pseudo-statically under gravity before it topples. The smaller ⍰, the larger the slenderness of the rigid block.

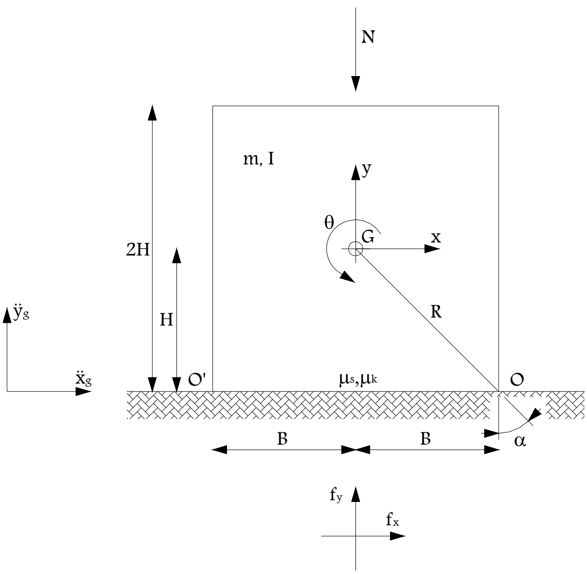

Fig. 5 – Scheme of a rigid body on a rigid ground constrained by vertical load [12]

Coulomb friction acts between the body and ground resulting in a force (f_x) that is a function of the normal reaction (f_y) and the relative velocity of the points in contact with the foundation. The coefficient of static friction is denoted as μ_s and the coefficient of kinetic friction as μ_k.

Displacements of the mass relative to the foundation are denoted by $x(t)$ and $y(t)$, as measured from the original at rest position of the mass centre. Angular rotations are denoted by $\theta(t)$, positive in counter-clockwise direction. Displacements of either corner in contact with the foundation are denoted respectively by $x_O(t)$, $y_O(t)$ and $x_{O'}(t)$, $y_{O'}(t)$. The motion of the ground can be described by two values of acceleration, $\ddot{x}_g$ and $\ddot{y}_g$.

The starting conditions and the equations of motion can be represented by considering the dimensionless ratio ν*=N/W* between the vertical force *N* and the block weight. In particular, it can be verified that for small values of rotation θ, during the rocking motion, the point *O* doesn't slide only, if:

$$\left(B - H\mu_s\right)\dot{\theta}^2(t) \geq \frac{g}{4\left(H^2 + B^2\right)}\left[3BH - \mu_s\left(B^2 + 4H^2\right) - 4\mu_s\nu\left(B^2 + H^2\right)\right] \qquad (1)$$

This relation shows that a vertical downward force, imposed by a Tendon System, yields a stabilization of the rigid body against its possible motions.

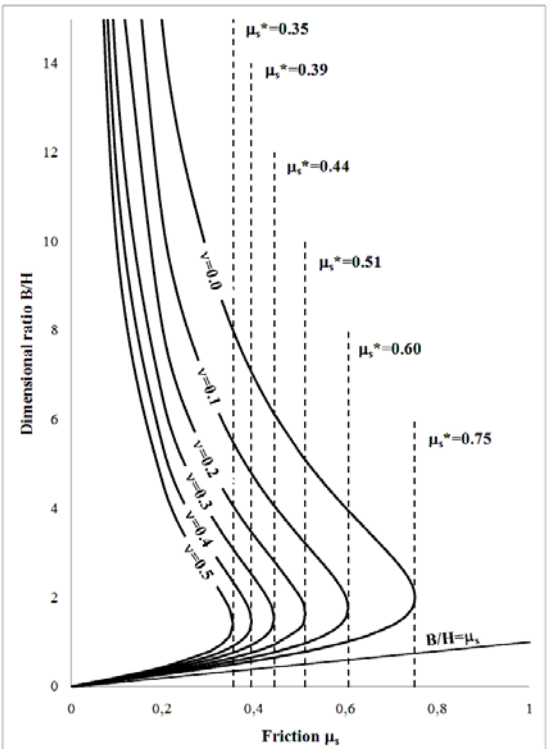

Fig. 6 - Effect of vertical load in preventing sliding of the rigid body [12]

Figure 6 shows the values of dimensionless ratios (*B/H*) of a rigid body for which sliding occurs or not. For each value of the vertical action ν a minimum value μ_s* can be determined for which sliding does not occur. In particular, for *B/H* ≥ μ_s and $\mu_s > \mu_s*(\nu)$, the sliding of a rigid body is always prevented, while, for *B/H* ≥ μ_s and $\mu_s \leq \mu_s*(\nu)$, the sliding is prevented only for particular values of the ratio *B/H*, as shown in the Table 1.

Table 1 – Values of ratio B/H for which sliding occurs under varying ν [12]

μ_s	Range of values for B/H											
	ν=0.0		ν=0.1		ν=0.2		ν=0.3		ν=0.4		ν=0.5	
	≤	≥	≤	≥	≤	≥	≤	≥	≤	≥	≤	≥
0,100	0,13	29,9	0,15	21,3	0,16	16,5	0,18	13,5	0,19	11,3	0,20	9,80
0,200	0,27	14,7	0,30	10,4	0,33	8,00	0,37	6,45	0,40	5,37	0,44	4,56
0,300	0,42	9,58	0,47	6,67	0,53	5,02	0,60	3,95	0,68	3,17	0,78	2,55
0,354	0,50	7,98	0,57	5,49	0,66	4,06	0,76	3,09	0,92	2,35	1,41	1,41
0,393	0,57	7,07	0,66	4,80	0,77	3,47	0,93	2,54	1,47	1,47	-	-
0,400	0,58	6,92	0,67	4,69	0,79	3,38	0,97	2,44	-	-	-	-
0,443	0,65	6,11	0,77	4,06	0,95	2,81	1,54	1,54	-	-	-	-
0,500	0,76	5,24	0,94	3,35	1,33	2,00	-	-	-	-	-	-
0,510	0,79	5,09	0,97	3,22	1,63	1,63	-	-	-	-	-	-
0,600	1,00	4,00	1,57	2,00	-	-	-	-	-	-	-	-
0,604	1,01	3,95	1,77	1,77	-	-	-	-	-	-	-	-
0,700	1,37	2,91	-	-	-	-	-	-	-	-	-	-
0,750	2,00	2,00	-	-	-	-	-	-	-	-	-	-

The analysis of results shows that, by increasing the vertical action, the regions where dry friction is not sufficient to prevent sliding reduces: the larger *N*, the smaller the friction necessary to prevent sliding.

With regard to the overturning mechanism, the rigid block will overturn when the base acceleration $|\ddot{x}_g| > g\cdot\alpha$ and acts for a sufficient length of time t_1 [2]. In particular, overturning occurs when the total virtual work done by the inertia forces is just equal to the potential energy accumulated passing from $\theta=0$ to $\theta=\alpha$. This condition can be written in the case of vertical action N due to a tendon as:

$$\cosh\left(p\cdot\sqrt{1+\nu}\cdot t_1\right)=1+\frac{1+\nu}{2\frac{\ddot{x}_g}{g\alpha}\left(\frac{\ddot{x}_g}{g\alpha(1+\nu)}-1\right)} \tag{2}$$

In the latter equation the frequency parameter *p* defined as $p^2=mgR/I_O$. The formulation allows the evaluation of time t_1 necessary for overturning by varying the vertical load ν, having represented the ground acceleration in terms of *g* and slenderness α

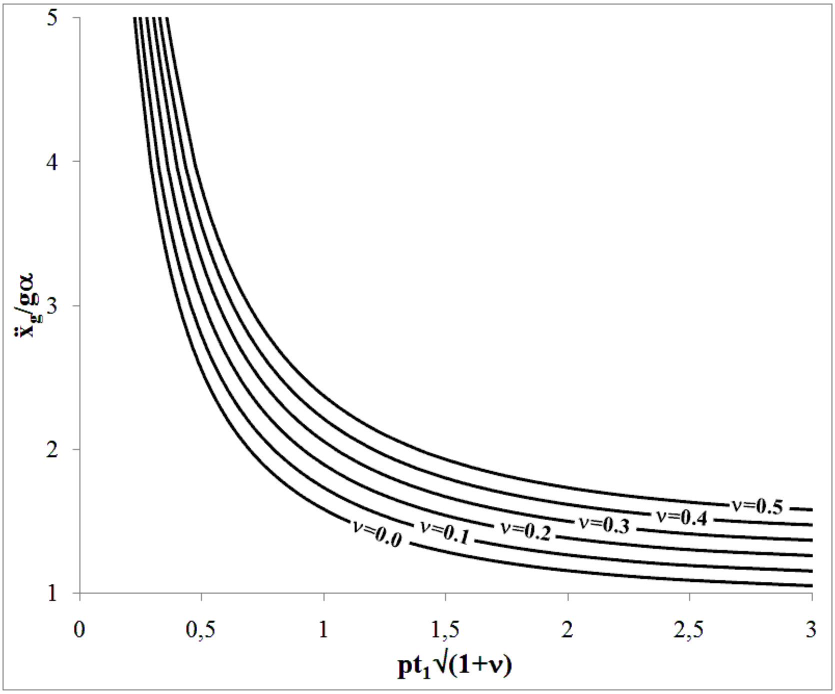

Fig. 7 - Effect of vertical load in preventing overturning of the rigid body [12]

Figure 7 shows that the bigger the vertical force, the longer the time for overturning. The smallest value for t_1 corresponds to the case $\nu=0$ [4], that is just the case of a column not being retrofitted by a Tendon System

These analytical results show in principle the effectiveness of a Tendon System to control the dynamic motions of rigid blocks.

3. EXPERIMENTAL INVESTIGATION

The investigation has been carried out by means of a broad experimental campaign composed of eighty-two tests performed on small-scale models using a single degree of freedom shaking table at the University of Kassel. Two models have been investigated: one has two adjacent columns with an architrave on top (fig. 8) and the other is just a single column. Each column is made up of six drums and a capital, all made of gypsum and simply held together by gravity.

Both models have been tested in four configurations: without Tendon System and with Tendon System using three different values for the initial tensile force. Each has been exposed to several sinusoidal displacement histories with varying frequencies and amplitudes, and acceleration time histories recorded during the main shocks of two Italian earthquakes: *L'Aquila 2009* and *Irpinia 1980*.

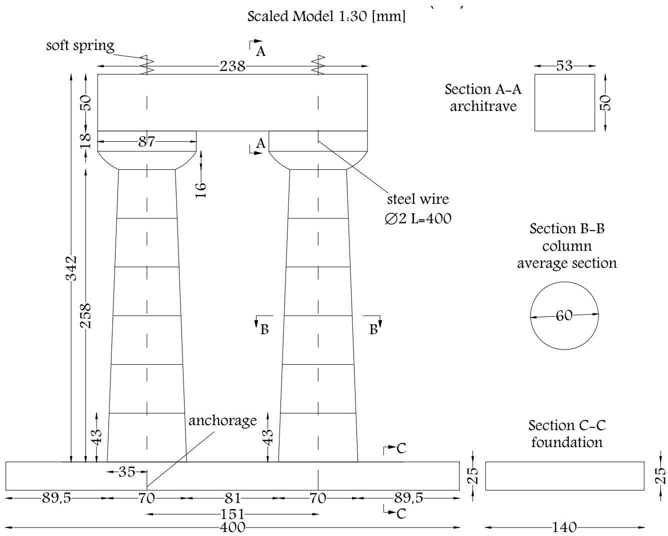

Figure 8 – Scale model representing columns of the Temple of Neptune in Paestum (SA), Italy [12]

The tendons, designed to pass through the centre of each drum, are anchored in the foundation and connected on the top by a soft spring, which serves as control device. The dynamic response of these rigid-body assemblies involves, primarily, the well-known sliding and rocking motions.

The tests were carried out considering kinematic similitude with fixed proportionality ratios for geometry and time scales. In particular, the models are characterized by a geometric scale ratio equal to 30, compatible with the weight capacity of the shaking table (5 kilograms).

The response of the models was measured with displacement transducers: the horizontal relative displacement between the shaking table and the top of the model itself, and the vertical displacements of each column (fig. 9).

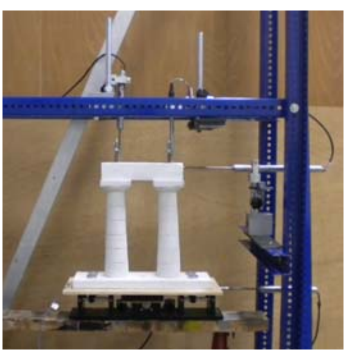

Figure 9 – Experimental set up at University of Kassel

The following shows the variation of the dynamic response of the model with two columns to a sinusoidal displacement with a frequency of *f=2Hz* and an amplitude of *a=1cm* for the four different configurations:

1) Without Tendon System;
2) With Tendon System and no initial pre-stress: $N_1=0$
3) With Tendon System and initial pre-stress: $N_2=6.75$ N
4) With Tendon System and initial pre-stress $N_3=13.50$ N

Pre-stressing and model weight *W = 16.34 N* lead to the following dimensionless ratios:

$$\nu_1 = \frac{2N_1}{W} = 0 \quad \nu_2 = \frac{2N_2}{W} = 0.83 \quad \nu_3 = \frac{2N_3}{W} = 1.65$$

In the tests without Tendon System (test no. 070), the model collapses almost immediately after 1 to 2 seconds. The maximum horizontal displacements of the architrave decrease with increasing initial pre-stress (Table 2).

Table 2 – Maximum horizontal displacements for the 2-column model with architrave under varying initial pre-stress [12].

	Test #026 N=0.00	Test #015 N=6.75 N	Test #004 N=13.50 N
Architrave	0.361 cm	0.304 cm	0.184 cm
Left column	0.054 cm	0.034 cm	0.026 cm
Right column	0.050 cm	0.034 cm	0.027 cm

A similar observation can be made regarding to the maximum vertical displacements of both the columns.

Results of all tests are reported in Figures 10 and 11, where the maximum displacements are plotted against the initial pre-stress.

The results clearly show the effectiveness of the Tendon System. It can be noted that an increasing initial pre-stress in the tendon yields a decreasing response in terms of displacement, but it also increases the stresses in the columns, which is not desirable. Already the tests without initial pre-stress showed stable behavior under all excitations.

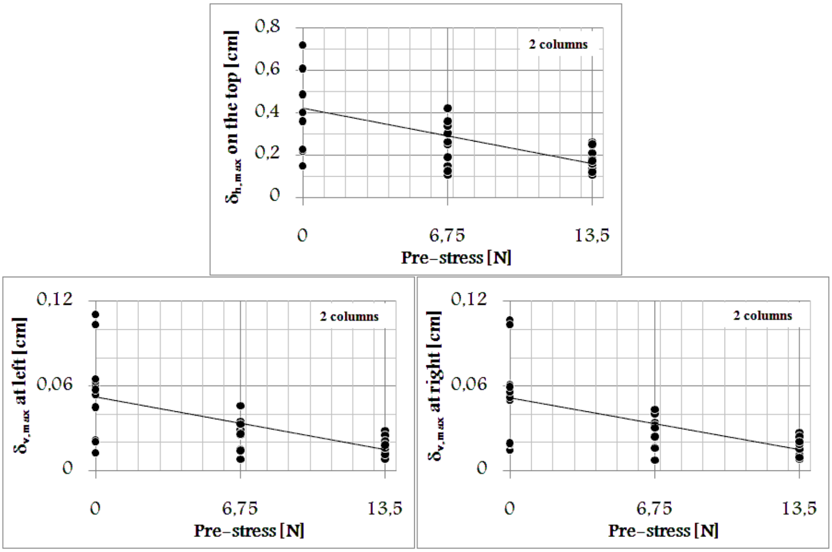

Fig. 10– Results of tests carried out on the model with 2 columns and architrave [12]

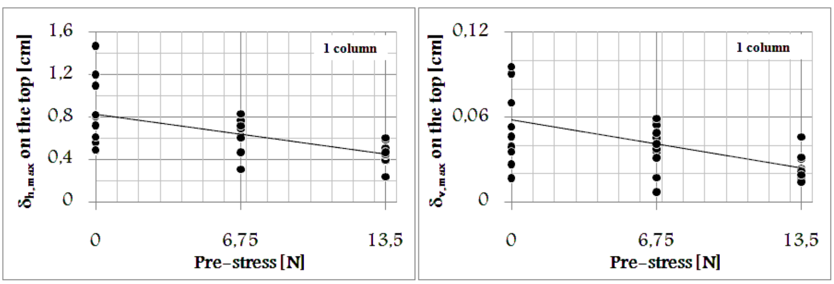

Fig. 11 – Results of tests carried out on the model with a single column [12]

4. CONCLUSIONS

This paper deals with the theoretical and experimental analysis of seismic retrofit of Greek columns by a Tendon System. This structural control concept is particularly suitable for retrofitting historic structures since it complies with basic requirements of the Athens and Venice *Charters for the Conservation and Restoration of Historic Monuments,* such as low interference and removability.

The dynamic behavior of a rigid block with vertical load has been considered as a basic model to describe the behavior of such systems analytically. This analysis has been confirmed in preliminary shaking table tests on scale models at the University of Kassel representing the columns of the Temple of Neptune at Paestum, Italy.

Whereas the columns without Tendon System will collapse even under moderate ground motions, no collapse was observed with the Tendon System in place, even without initial pre-stressing.

The obtained results clearly show the effectiveness of the control strategy presented here encouraging further in-depth studies for innovative applications of this system to monumental historic buildings.

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