IAMON Workshop
10 July 2024

Application of a Tendon System to Protect Classical Columns against Earthquakes

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Classical monuments

- The columns are composed of drums, which are placed one on top of the other without mortar.
- Drums are allowed to rock and slide during earthquakes. Horizontal forces are transmitted mainly through friction.
- Highly nonlinear and complicated seismic response → Special analysis methods are needed.

Seismic vulnerability

- **In general**

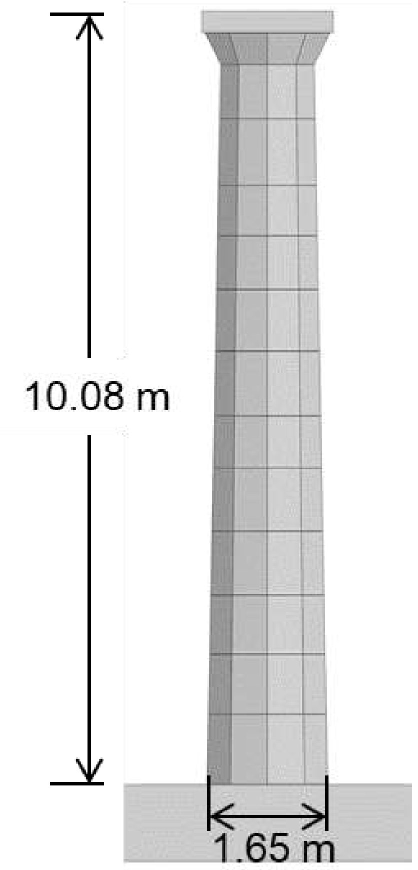
  In their intact condition, classical monuments can survive very strong earthquakes.

- **Proof**

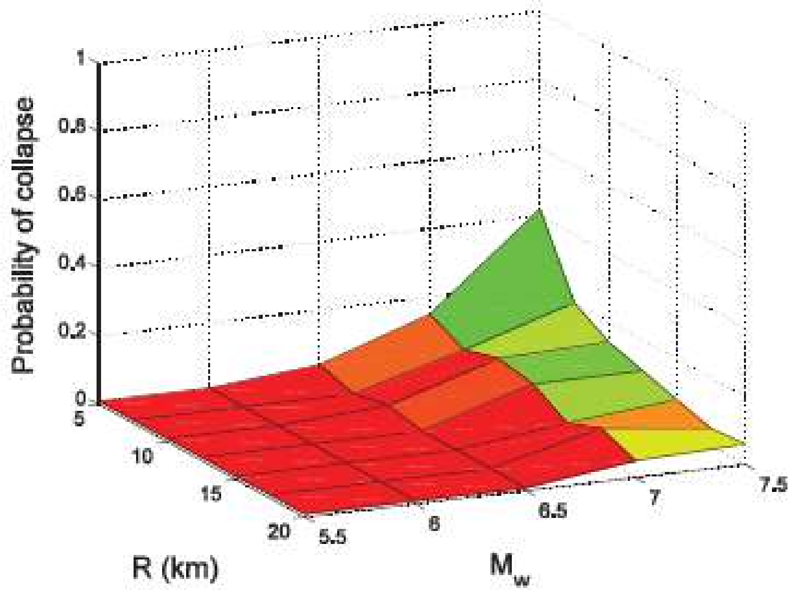
  Many classical monuments are still standing, after 2500 years from their construction, in seismically prone areas (Greece, Italy, Turkey, etc.)

- **Note**

  However, many others have collapsed!



Vulnerability of a column of Parthenon to 3500 artificial near-fault ground motions



(Psycharis *et al.*, 2013)

Application to the Temple of Pythios Apollo on the Acropolis of Rhodes

- Construction: 3^{rd}-2^{nd} century BC.
- Major restoration works took place during the Italian governance on the island (1938).
- Today, the monument is in bad condition due to the deterioration of the ancient material (porous stone of rather 'poor' quality) and the materials used in the Italian restoration (reinforced concrete).
- The monument will be restored with completely new material for the columns (of similar quality with the ancient one).

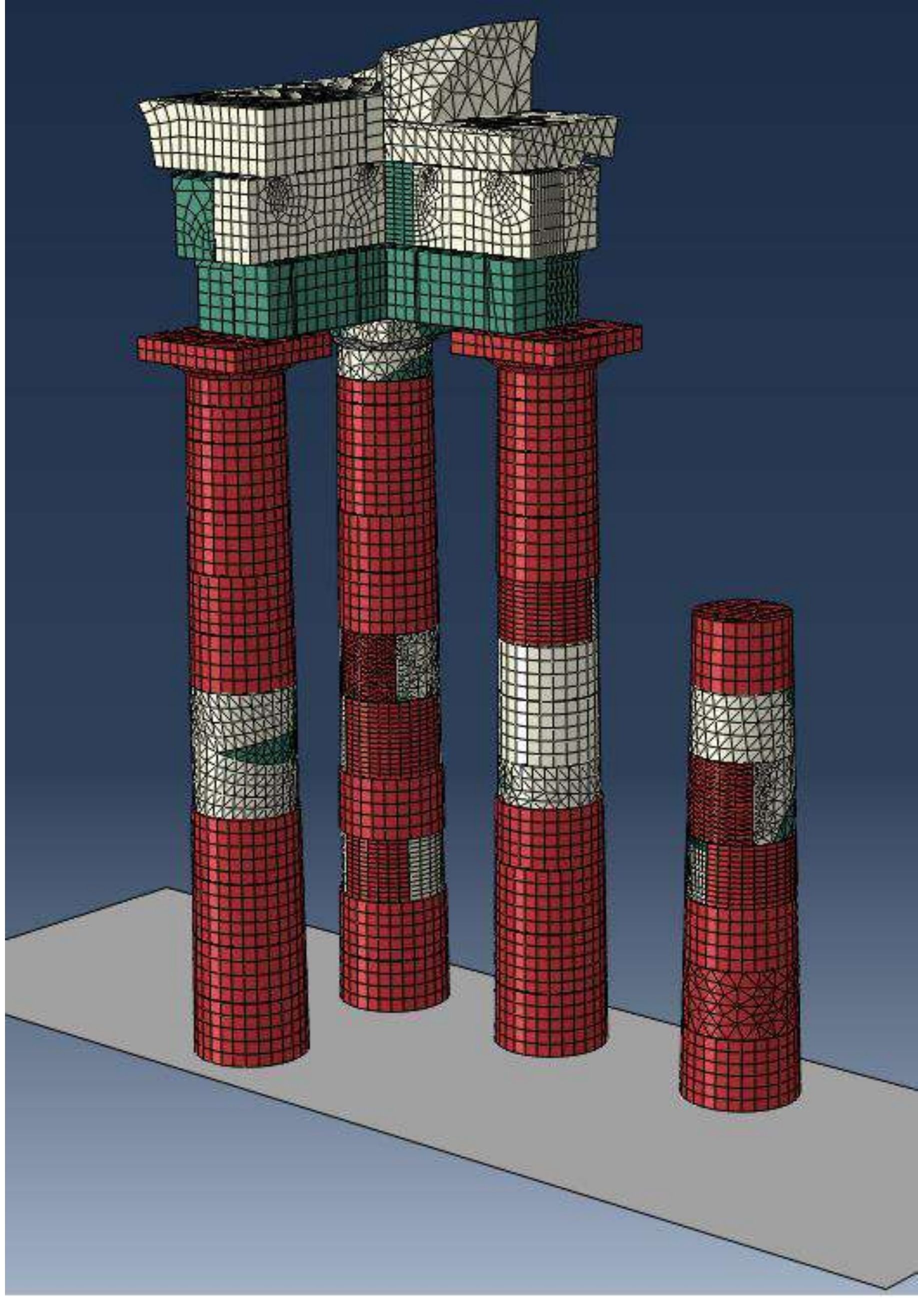
Previous Results

Research program:

"Examination of the structural response of the Temple of Pythios Apollo in Rhodes Island under probable seismic excitations and recommendations for its restoration"

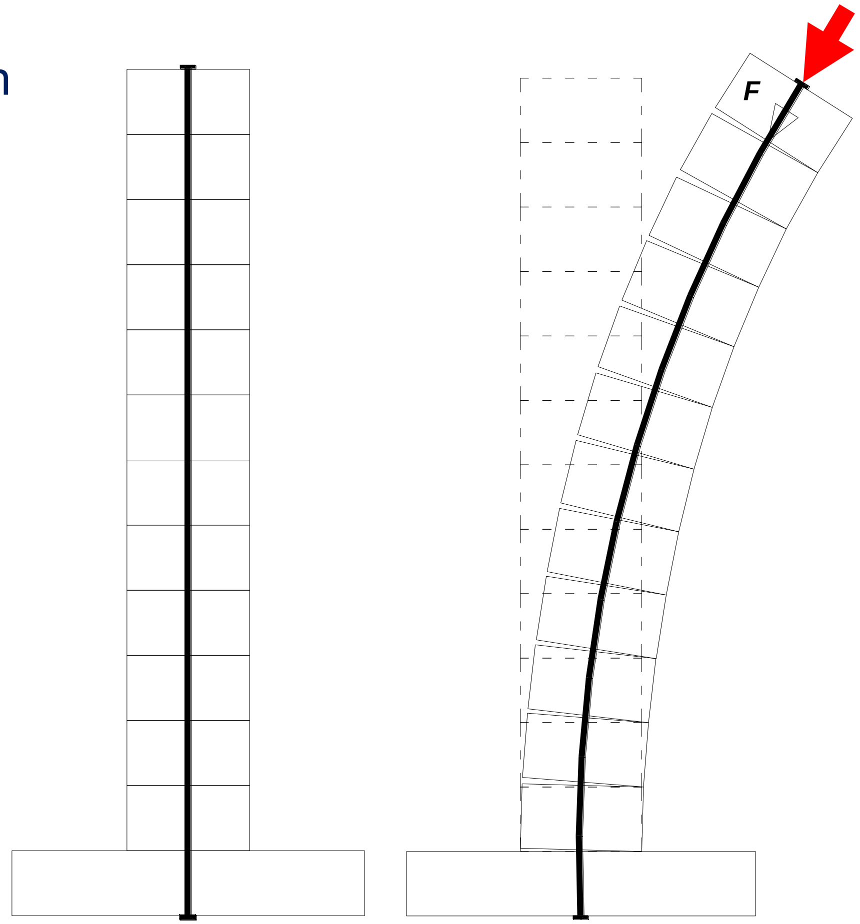
- Seismic response to 6 examined earthquakes scaled for 500 years Return period (PGA=0.5 g):
  - Collapse of the free-standing column in 3 out of the 6 examined records
  - Collapse of the three connected columns in 1 out of the 6 examined records
- Even when the structure does not collapse, it experiences large deformations and significant residual drum dislocations, which can affect its stability to aftershocks and future earthquakes

⇨ Need to take measures to enhance seismic stability



The innovative “tendon system”

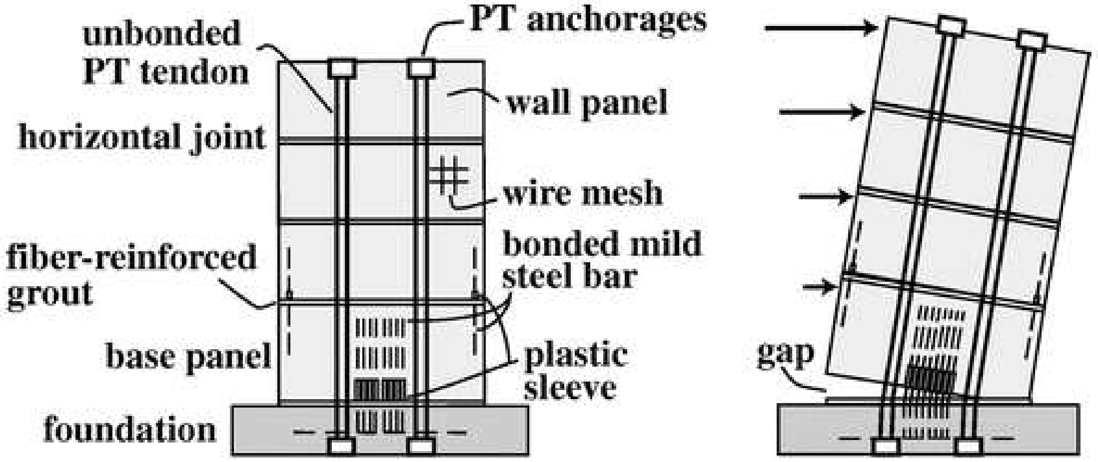
- The system consists of an unbonded steel tendon that passes through the drums of the column and is anchored at the foundation and at the top of the column.
- During the seismic response of the column, the tendon is elongated due to the rocking of the drums and, thus, it applies a restoring (compressive) force F to the column.
- The restoring force increases as the deformation of the column increases, leading to a “controlled rocking” system.
- In this way, the deformation of the column and the rocking of the drums is reduced and the collapse of the column is prevented.
- Advantages:
  - The tendons are not visible.
  - The intervention to the column is reversible, except of a small hole that has to be drilled at the center of the column.



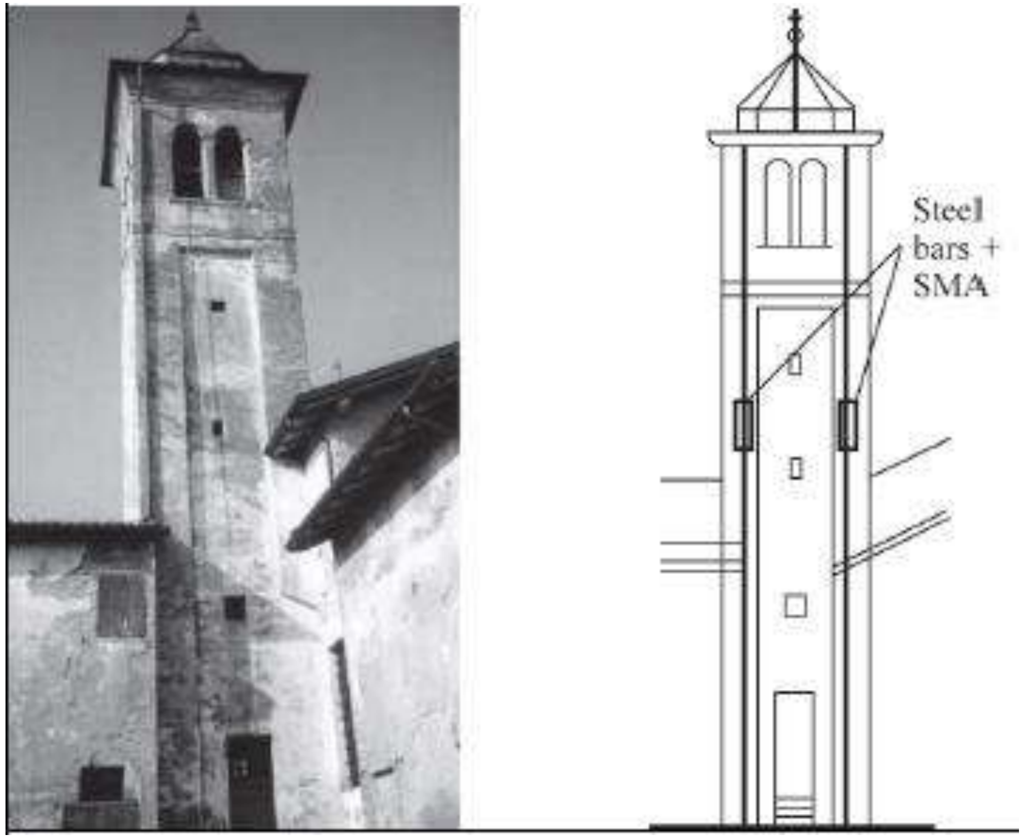
Other applications of tendons

Up today, tendons have been applied to several cases, like:

- Rocking piers of bridges
- Precast shear walls
- Historic masonry structures



Application of unbonded tendons to precast walls



Application of unbonded tendons to the bell tower of St George church at Trignano, Italy

Application to the restoration of Pythios Apollo

Research program:

"Investigation of the Seismic Behaviour and the Means of Improvement of the Seismic Response of the Restoration of the Temple of Pythios Apollo at the Ancient Acropolis of Rhodes"

Participants:

- Ministry of Culture
- Region of Southern Aegean
- National Technical University of Athens (Laboratory for Earthquake Engineering)

- Application of the "tendon system" to all columns of the monument.

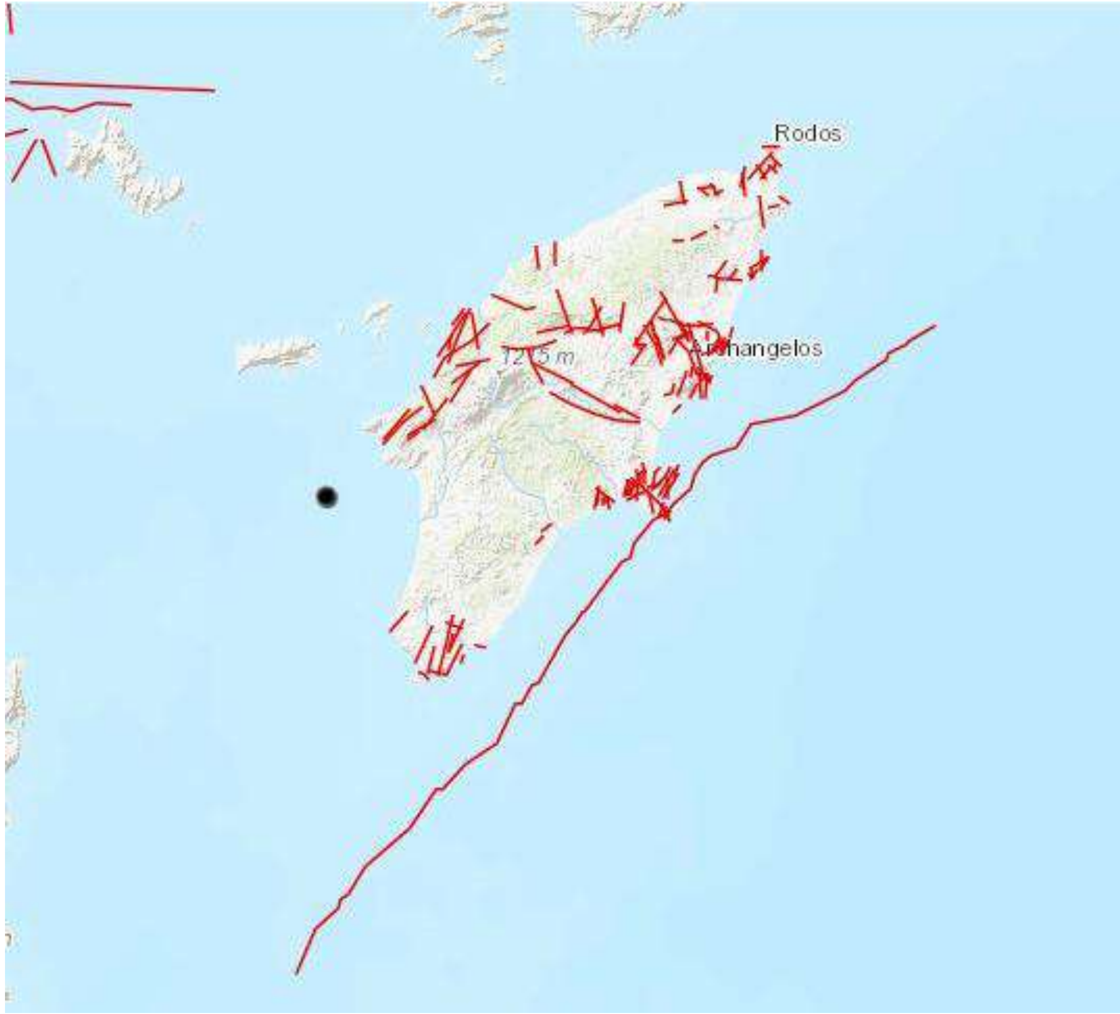
  Note: The columns of the restoration will be made of new material.

- Additional measures (titanium connections) are needed for the enhancement of the seismic stability of the superstructure (epistyles, the metopes and the pediment).

Investigation of the effectiveness of the “tendon system”

Selection of earthquake records for the analyses

- Take under consideration the large fault at the S-E side of the island:
  - Length: ~ 100 km
  - Estimated magnitude: $M_w \approx 7.5$
  - Distance from site: 12 km
  - Deterministic Seismic Hazard Analysis (reverse fault): PGA>0.65 g for T_R=500 years
- Criteria for selected seismic motions:
  - Magnitude: $6.0 \leq M_w \leq 8.5$
  - Distance from fault: 2 to 15 km
  - Ground category: 500 m/sec $\leq V_{S,30} \leq$ 900 m/sec
  - Scaling factor: $0.3 \leq SF \leq 3.0$
  - Pulse-like and non pulse-like records should be included in the sample



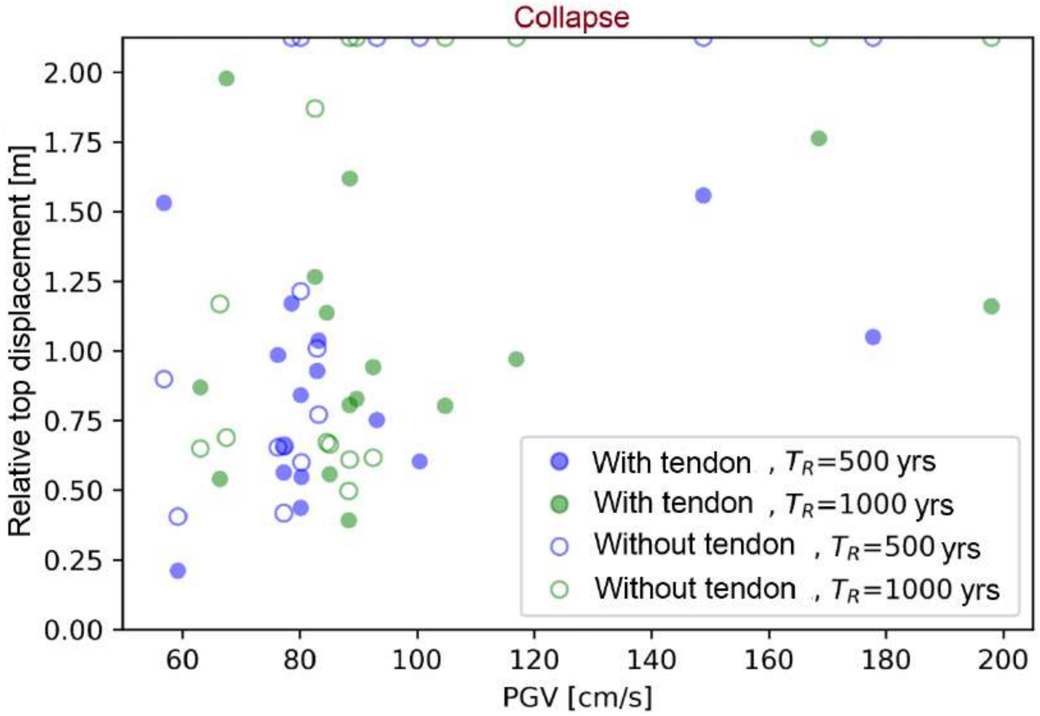
Investigation of the effectiveness of the "tendon system" (cont'd)

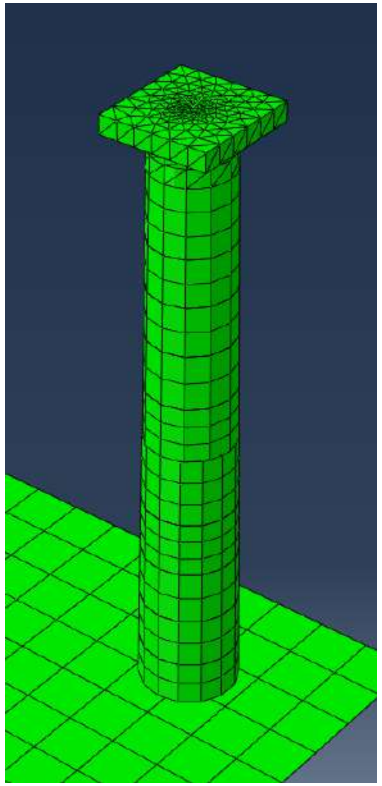
Analyses for a free-standing column

Preliminary analyses have been performed in ABAQUS to verify the effectiveness of the "tendon system" and to estimate the required tendon cross section area.

Results for 15 site-compatible earthquake records for T_R = 500 yrs and T_R = 1000 yrs:

- Column without tendon (open circles): collapse in 40% of the examined excitations.
- Column with a 7T15 tendon (solid circles): No collapse for all examined excitations.





Model in ABAQUS

Investigation of the effectiveness of the “tendon system” (cont’d)

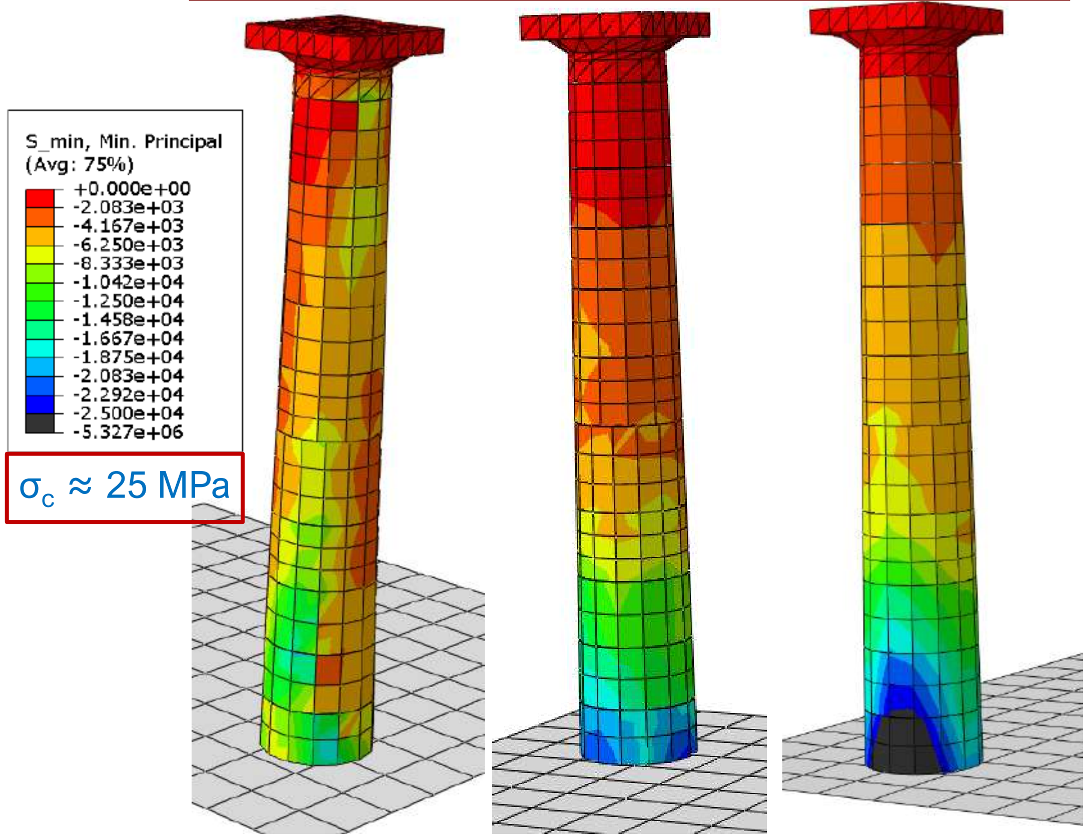
Analyses for a free-standing column – Investigation for large compressive stresses

The vertical restoring force, induced to the column by the tendon, produces compressive stresses at the column during the seismic motion, which might exceed the strength of the stone, especially at the base.

The investigation shows:

- Large tendon cross sections are not preferable.
- Initial prestress of the tendon is rather detrimental (early yield of the tendon, large compressive stresses).
- Ideal scenario: The tendon remains elastic for small earthquakes (optimal displacement control) and yields for larger ones (prevention of large compressive stress).

Earthquake record for T_R = 1000 yrs × 1.75



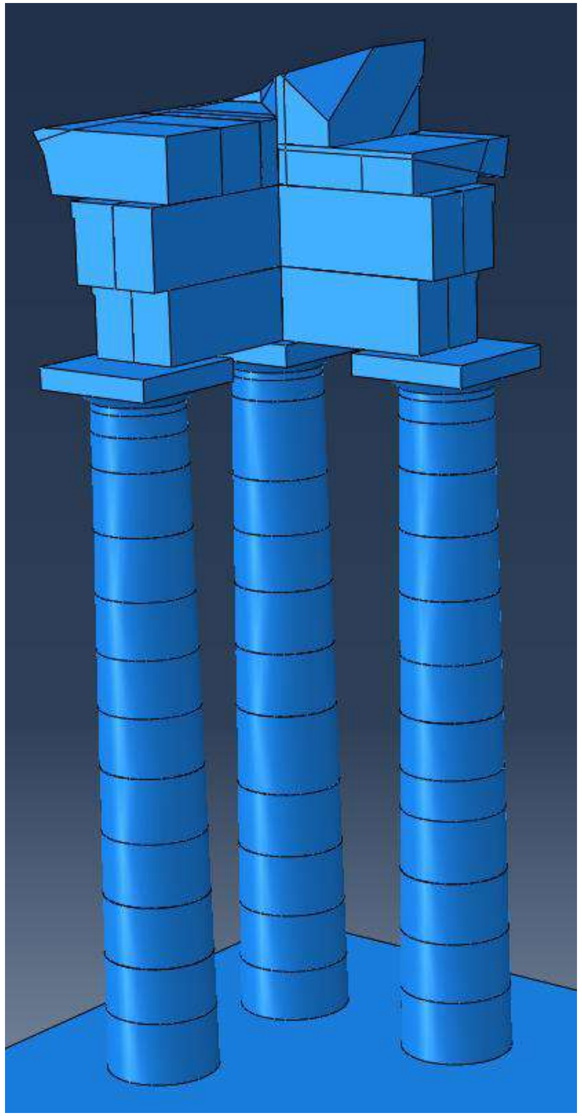
No tendon	Tendon 7T15	Tendon 12T15
	Tendon yields	Tendon elastic
σ_{min} < 20 MPa	σ_{min} < 25 MPa	σ_{min} > 25 MPa

Investigation of the effectiveness of the "tendon system" (cont'd)

Analyses for the whole monument

Preliminary analyses for the whole restoration (the final geometry of the entablature and the pediment has not been finalized yet) show that:

- For columns with tendons, the monument does not collapse under the examined earthquakes.
- Large horizontal accelerations develop in the superstructure. Therefore, strong connections (clamps and dowels) have to be applied at the joints of the superstructure to prevent collapse.
- Most critical connection: the ones between the capitals of the columns and the epistyles, due to the limited available area for dowels.



Conclusions

- An innovative “tendon system” is proposed for the enhancement of the seismic stability of classical columns.
- The proposed system results in the “controlled” rocking of the columns, showing promising properties, since:
  - With proper selection of the tendons, the collapse of the columns during strong earthquakes is prevented, while the structural integrity is maintained, and
  - With careful detailing and adequate connections at the joints, the superstructure can survive the increased seismic accelerations that develop.
- The application of the “tendon system” is a reversible and “hidden” intervention, as the tendons are not visible by the visitors.

  However, it requires the drilling of a small hole along the central axis of the columns, therefore it is conditioned to the approval of this intervention by the Authorities.