IAMON Workshop
Seismic response of column and colonnade:
The role of vertical connectors

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Seismic performance evaluation of the Roman Temple of Évora in Portugal

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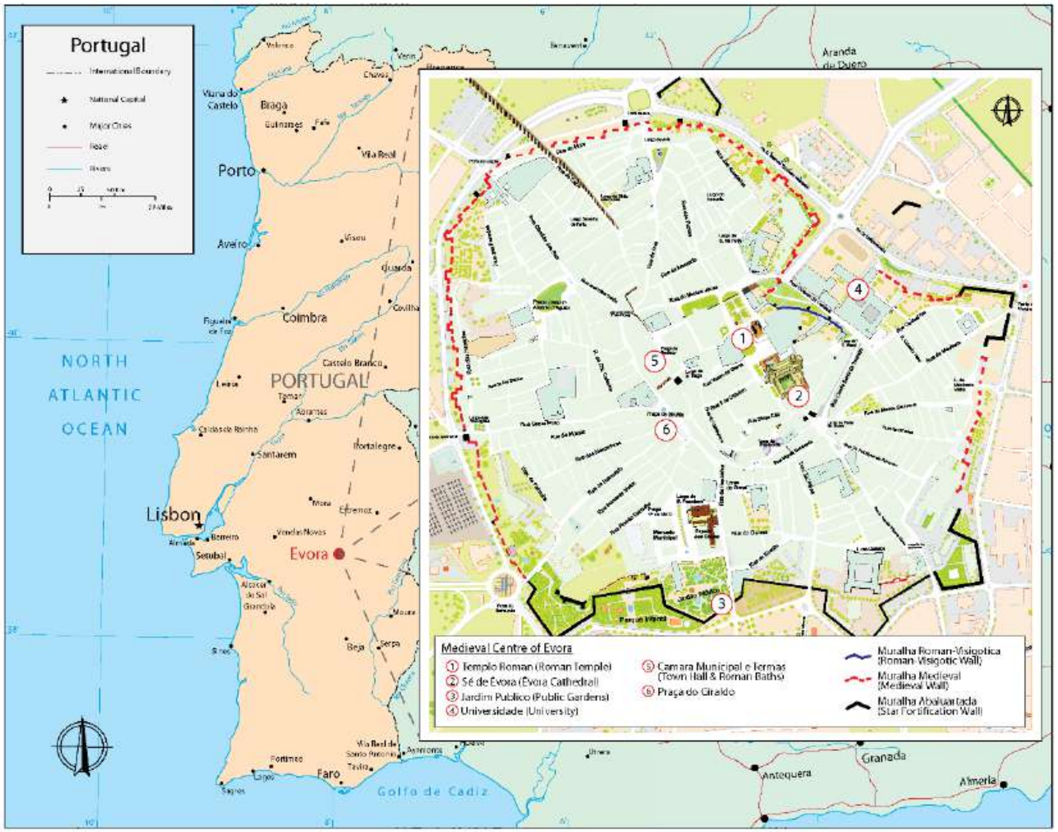
Contents

1. Introduction and history

THE CITY OF ÉVORA, PORTUGAL

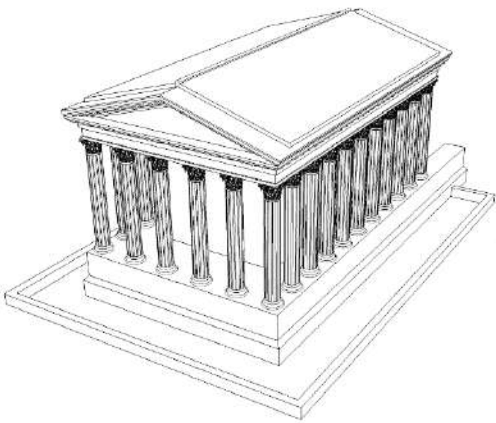
- The historic centre of Évora was designated as a **UNESCO World Heritage Site** in 1986



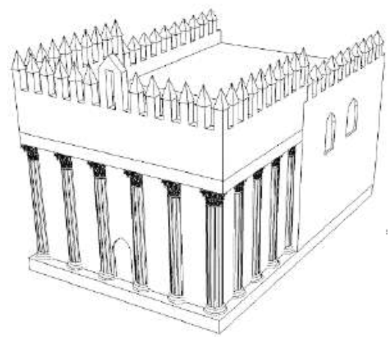
ROMAN TEMPLE OF ÉVORA

Roman temple of Évora

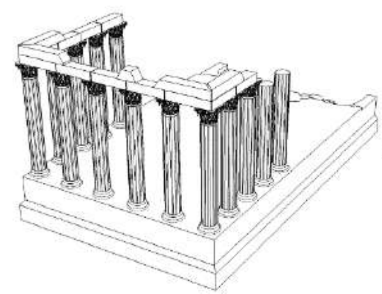
- Constructed in the first century AD (dedicated to the cult of Emperor Augustus)
- Southern entrance and roof destroyed during the Visigothic invasion in 584
- Has undergone numerous changes along time (e.g. public slaughterhouse)
- Medieval additions were removed in 1872
- **Structure's re-use** is the primary reason for its survival to the present day



1st century AD



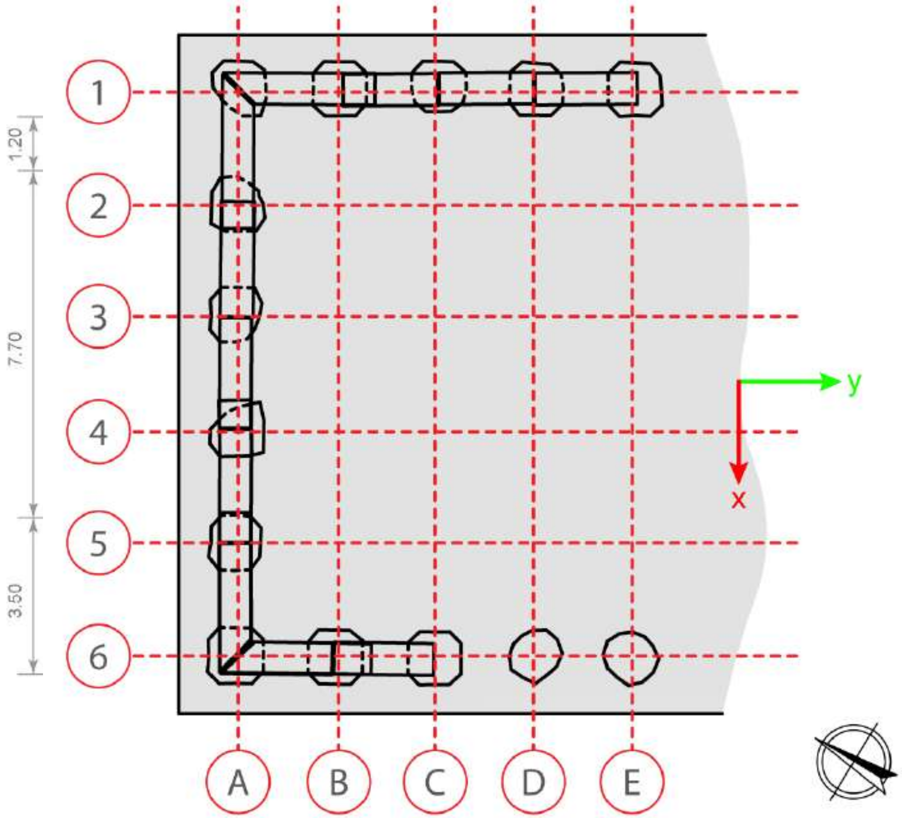
14th century



19th century

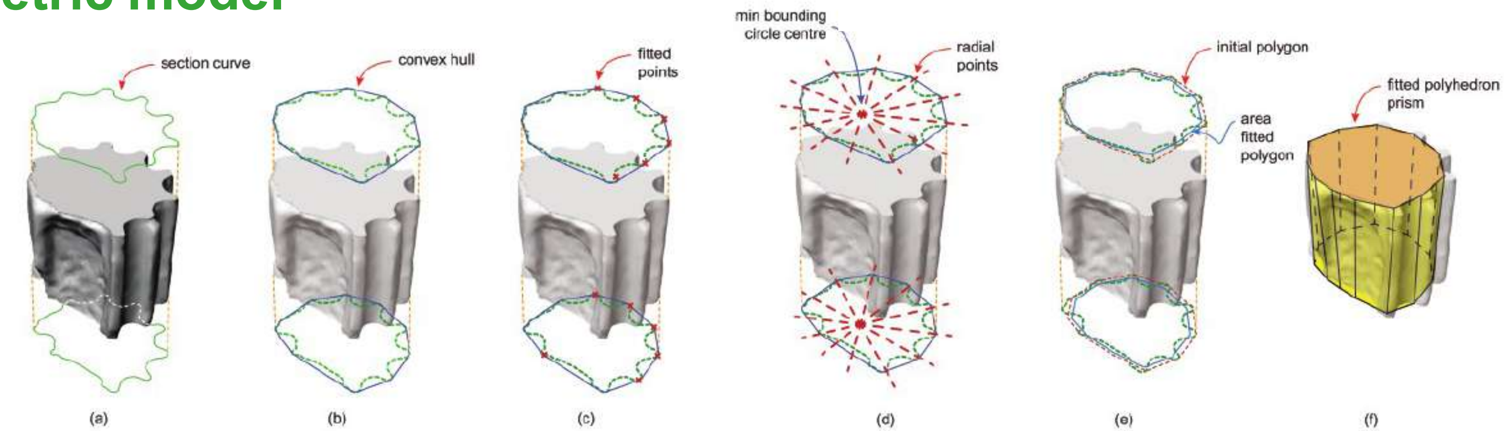
Description of the Structure

- A hexastyle (having a six column portico) periptical Roman temple
- Today fourteen columns remain
- Twelve support the remaining architrave blocks and are 7.77 m high
- Two are freestanding and are 6.77 m high
- Columns are composed of marble bases and capitals with granite drums which were once covered with plaster
- Podium is 3.5 to 4.3 m high, 15 m wide and 25 m long

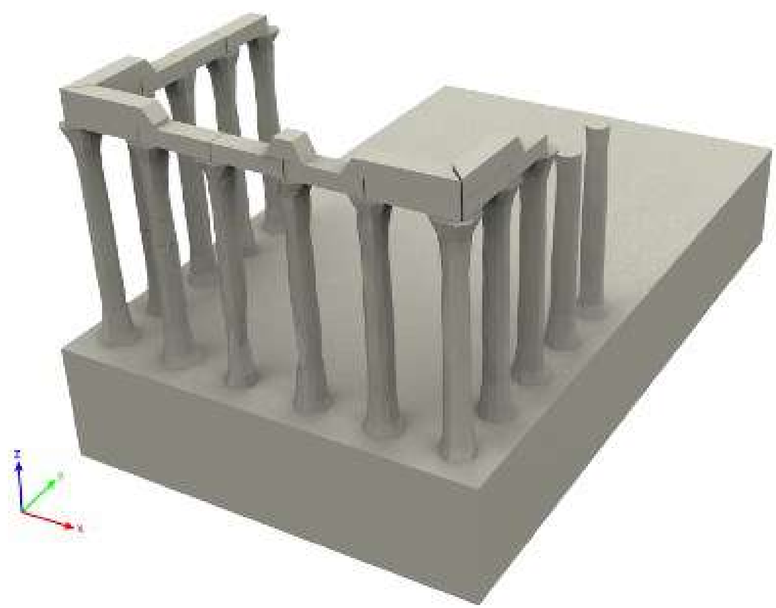


2. Modelling and analysis

Geometric model



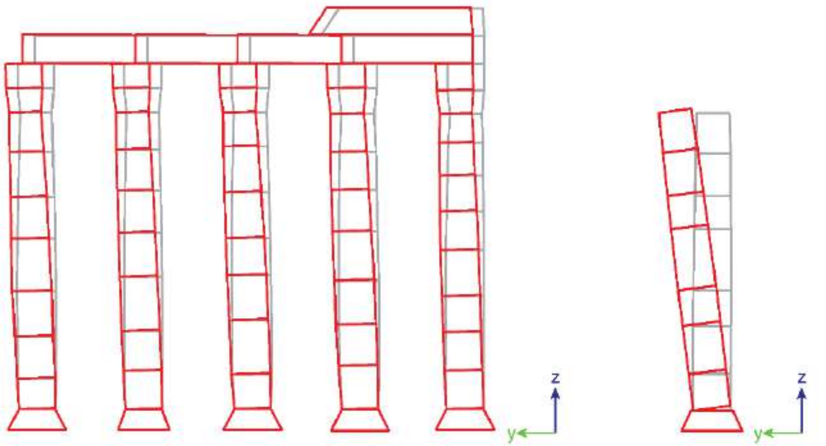
(a) 3D Scan Mesh Model



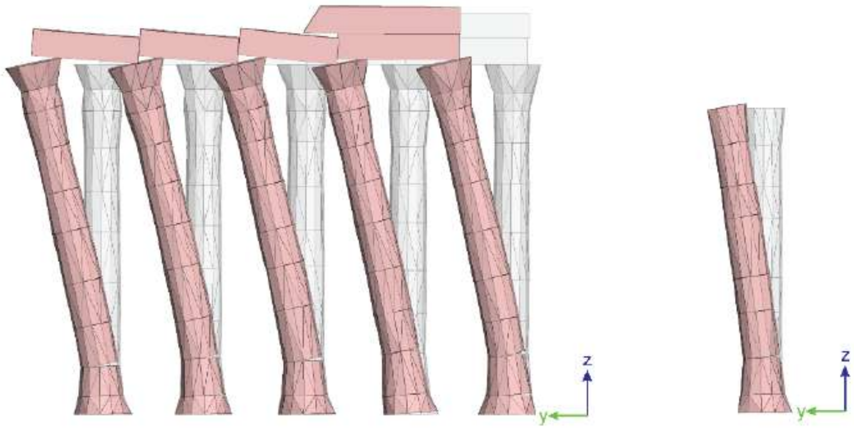
(b) Simplified 3D Block Model

Main results of limit analysis and pushover analysis

- ❑ Failure is initiated through rotation of upper portions of the columns about the second block at the bottom
- ❑ Blocks rock and fail as a large group rather than as individual blocks or smaller isolated groups



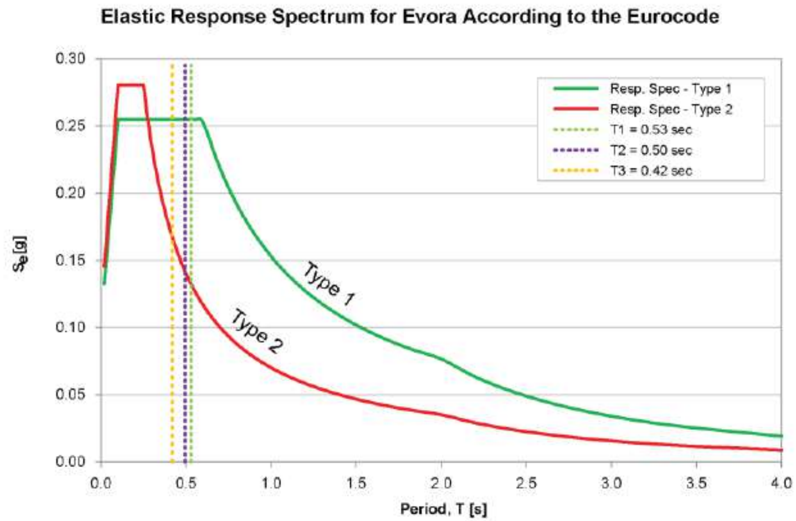
(a) East facade (α = 0.097) (b) Column D6 (α = 0.130)



(a) East facade (α = 0.107) (b) Column D6 (α = 0.146)

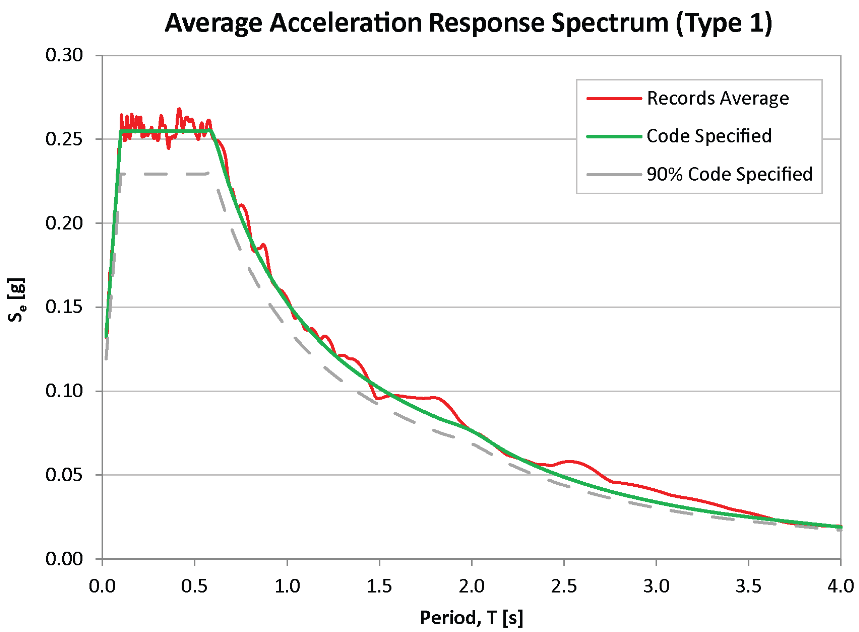
Incremental Dynamic Analysis

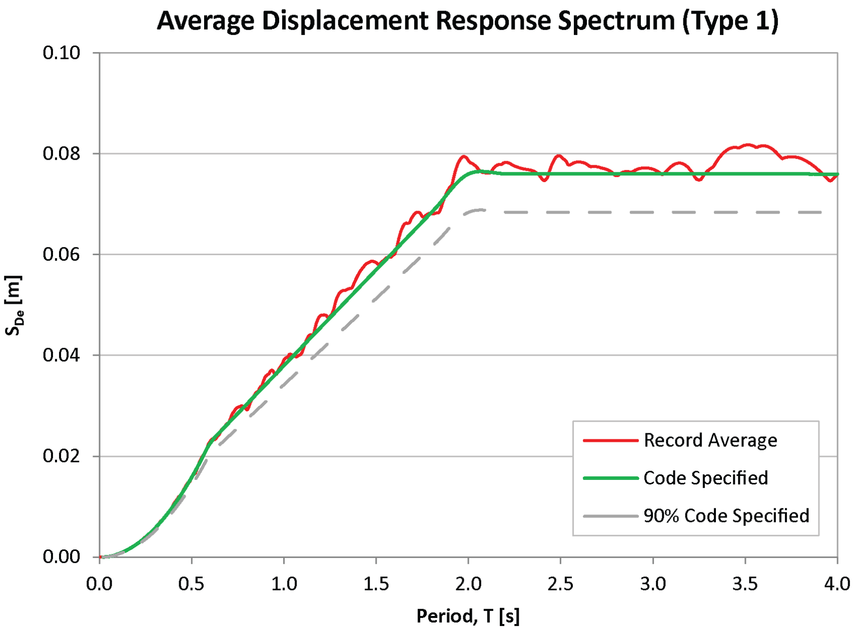
- Response of rigid block assemblage to dynamic excitation is highly complex and non-linear
- Discrete element model of the structure, composed of 156 rigid blocks and 155 contacts
- Response of the structure is evaluated over a range of input excitation intensities (until a factor of seven)
- Two types of earthquake as prescribed by EC8 are considered:
  - Type 1 (far field) with a PGA of 0.10g and a duration of 36 sec
  - Type 2 (near field) with a PGA of 0.11g and a duration of 14 sec
- For each EQ, three records are used



Incremental Dynamic Analysis

- Generation of code-compatible artificial accelerograms

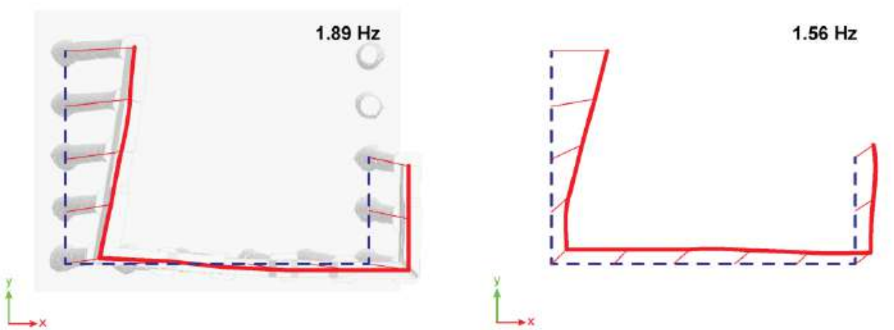




Dynamic Identification and Calibration of Model

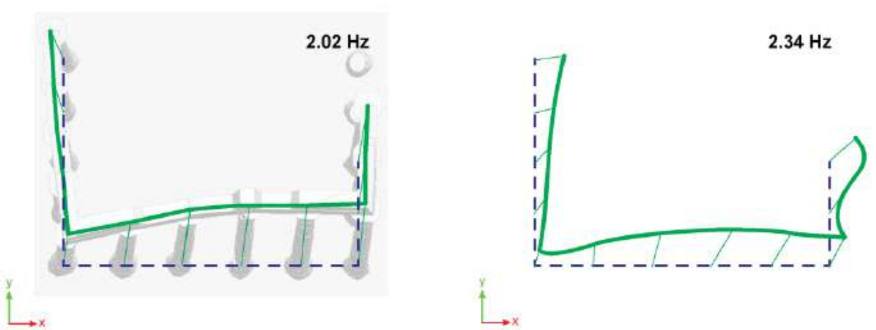
- Dynamic identification technique was used to obtain the frequencies and vibration modes (many local modes)
- This information was used to calibrate the numerical discrete element model
- The free-standing columns were calibrated against the experimental results by changing the joint normal stiffness
- The calibrated value of normal stiffness was then applied to the entire model

Mode Shape and Frequencies for First Global Mode of Vibration



(a) Numerical Results (b) Experimental Results

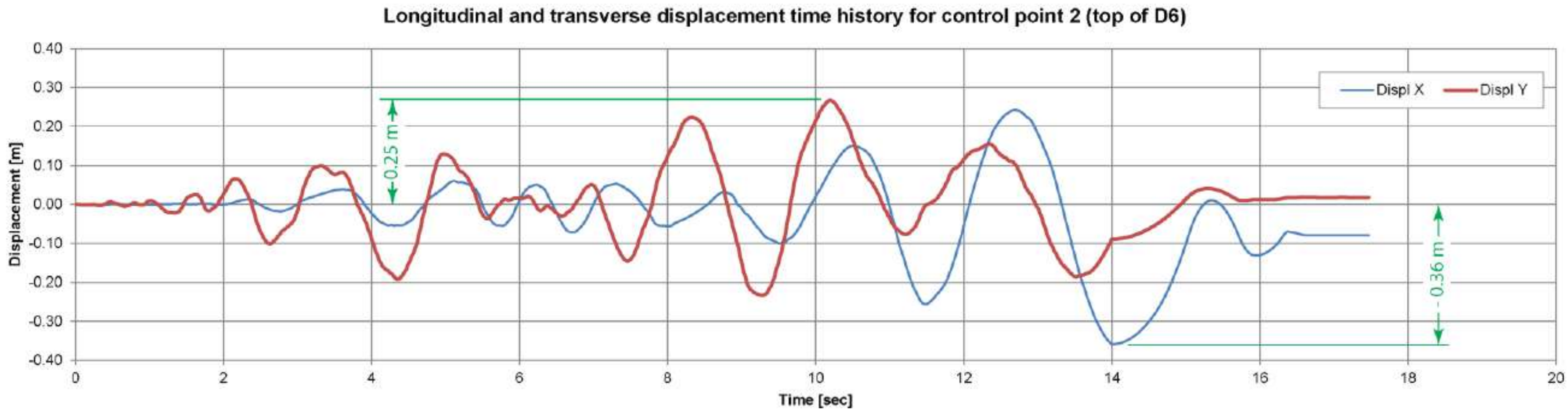
Mode Shape and Frequencies for Second Global Mode of Vibration



(a) Numerical Results (b) Experimental Results

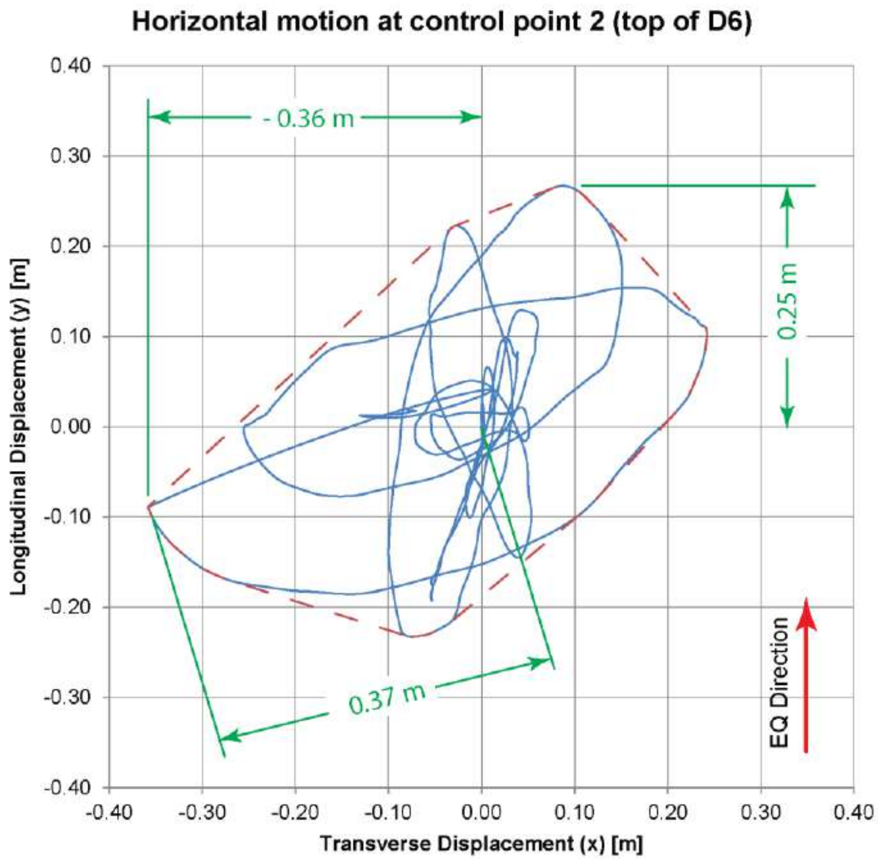
Time History Response of Free-Standing Column

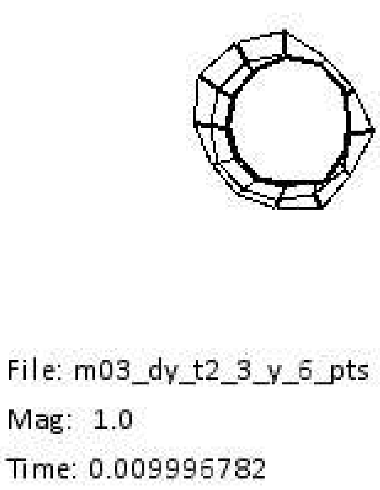
- Example shows applied earthquake in <u>longitudinal (y) direction</u> and displacements (x and y) at the tip of free-standing column D6
- Excitations in the longitudinal (y) direction, BUT maximum response in the transverse (x) direction
- Out-of-plane displacements as a significant part of the response (planar 2D analysis is not enough)



Time History Response of Free-Standing Column

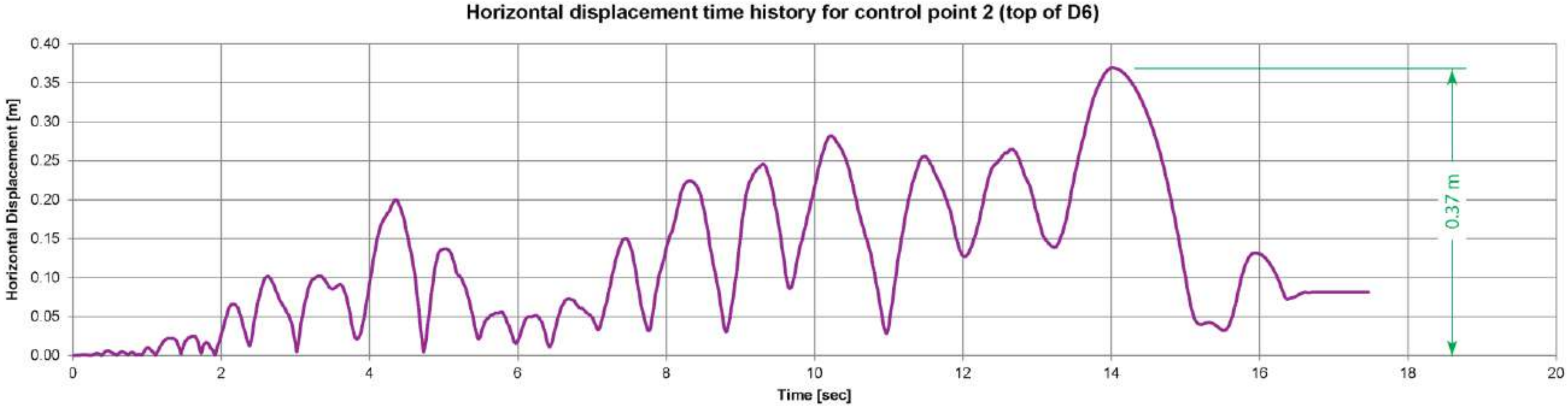
- This behaviour can be better observed by looking at the top view:

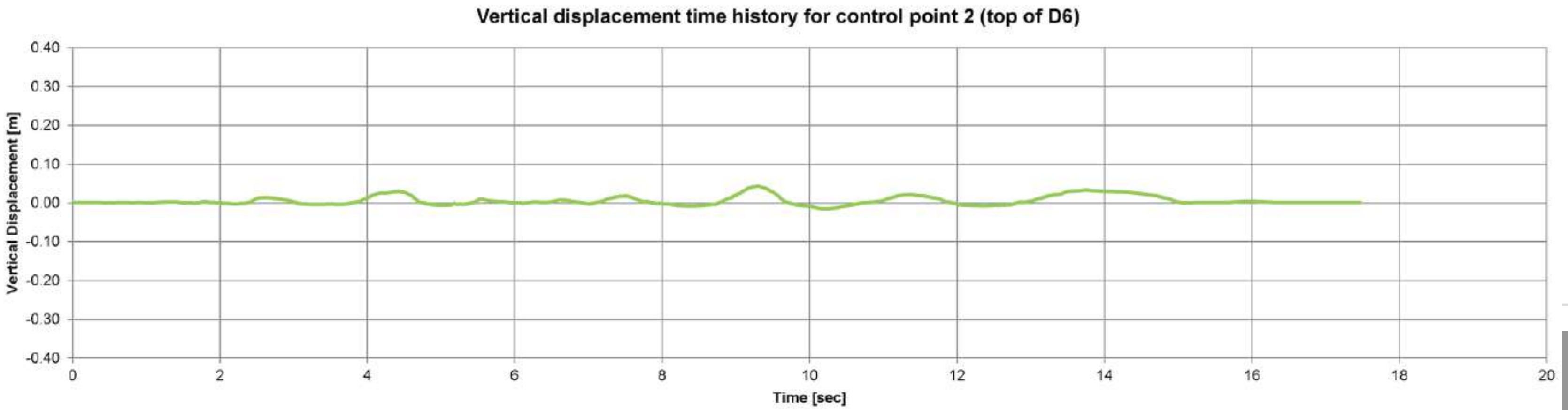




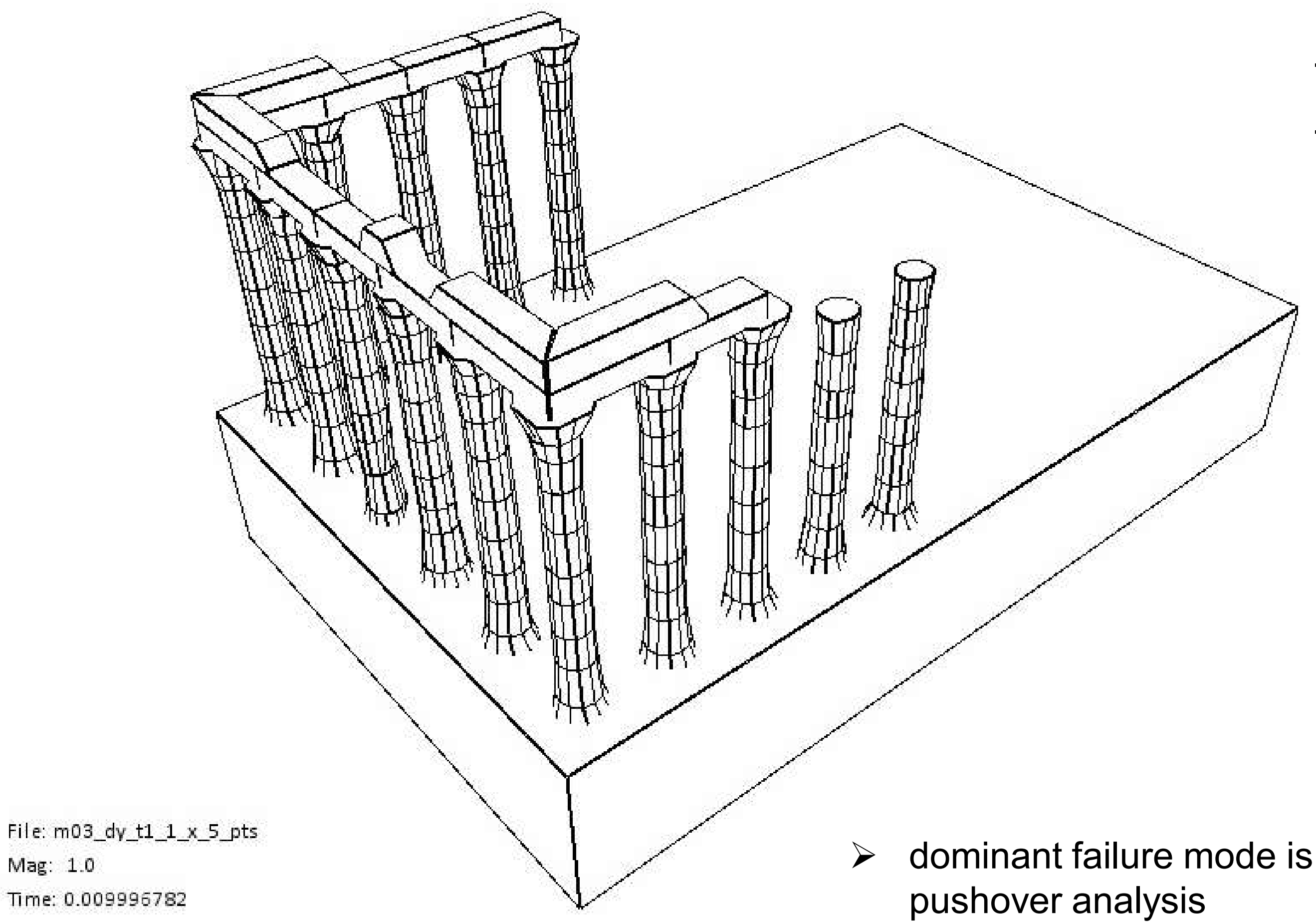
Time History Response of Free-Standing Column

- Most significant displacement is in horizontal direction. Vertical movement is very limited since there is no vertical excitation





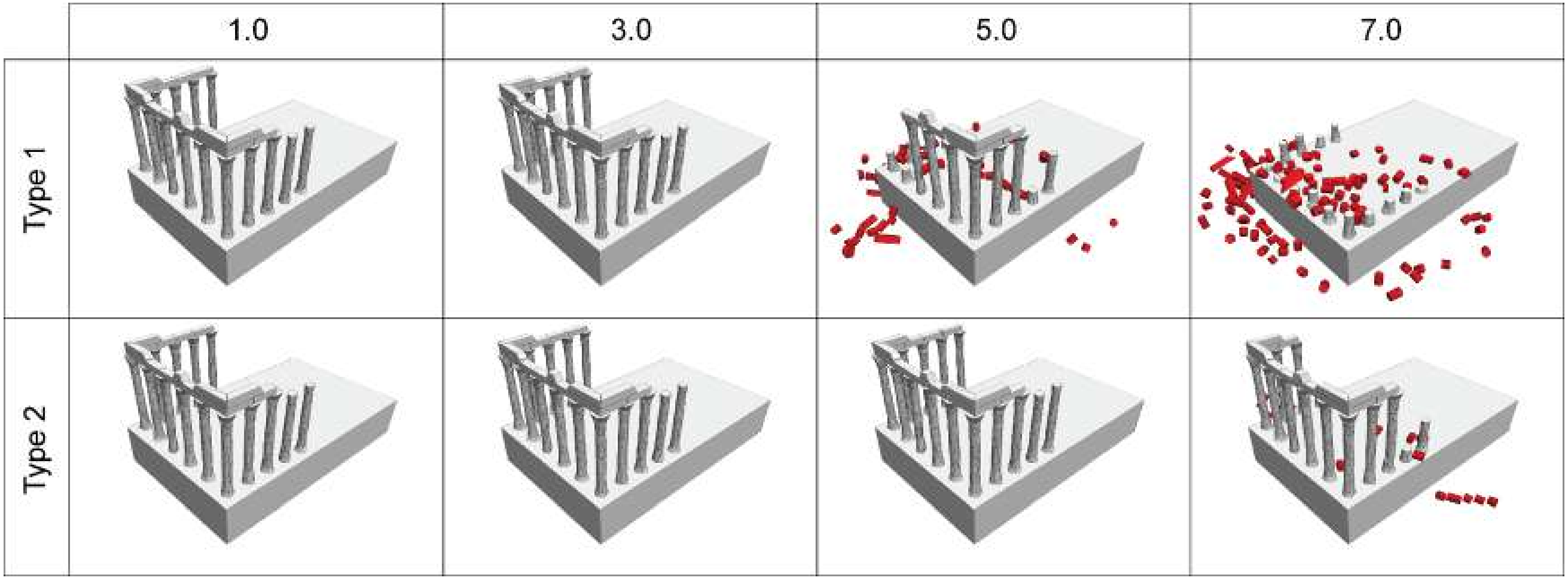
Typical Response of the Entire Structure



- Type1 accelerogram
- Direction y
- Scale factor 5

➢ dominant failure mode is consistent with limit and pushover analysis
(rotation of columns about the first or second base block)

Damage pattern for increasing PGA



Comparison of Analysis Methods

- Pushover and limit analysis provide **very similar results** both in terms of the value of seismic coefficient and predicted failure mechanism
- The **failure mechanism** observed through time history analyses is consistent with the response reported by the static methods. However, the **magnitude of the horizontal accelerations** needed to destabilise the system is much higher than that predicted by limit or pushover analysis *(static methods seem to underestimate the structure capacity)*
- This is due to phenomenon of **dynamic stability** takes into account inertial forces that counteract the destabilising gravitational forces
- Pushover and limit analysis indicate that the **free-standing columns** are less vulnerable to the action of horizontal forces. However, dynamic time history response shows that the free-standing columns are one of the first components of the structure to fail

3. Performance assessment

Damage Indicators

- Indicators are required in order to **quantify the level of damage** experienced by the structure during a simulation and **compare** the effect of different ground motions together
- Indicators are also a way of visualising the outcome of incremental dynamic analysis
- Definitions:

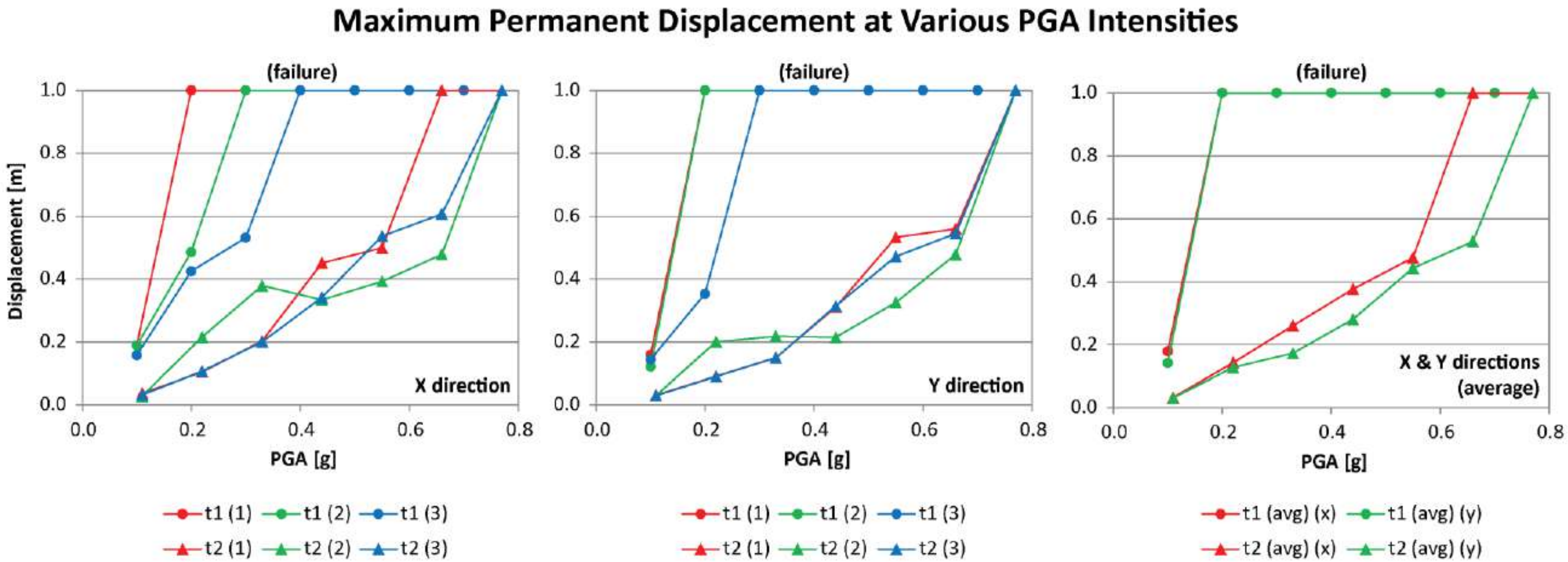
  Damage: represents any **inelastic deviation** (mostly in terms of displacements) from the initial state of the structure caused by the seismic action

  Failure: represents a **complete loss of stability**, be it for a single block or the entire structure

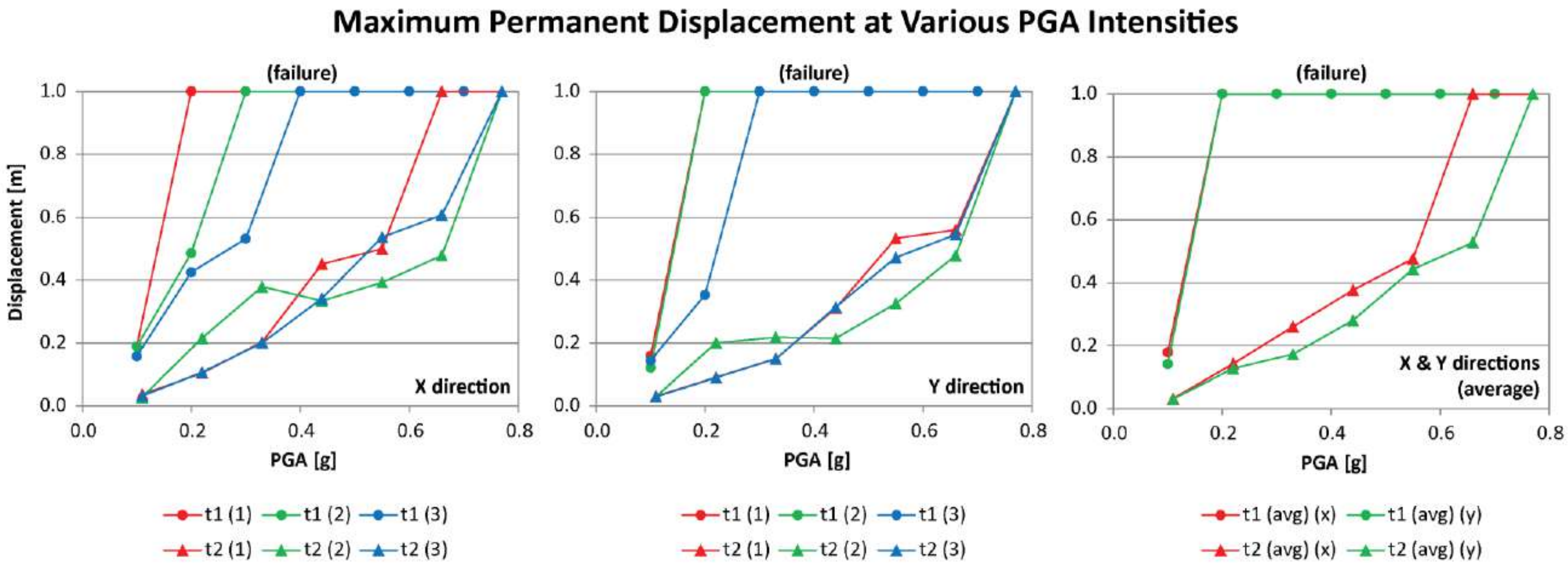
- Three damage indicators are investigated in the study:
  1. Maximum Permanent Displacement
  2. Percentage of Failed Blocks
  3. Percentage of Contact Area Loss

1) Max Permanent Displacement

- Is a measure of the **maximum residual displacement** at the end of the time history simulation
- Provides a reliable indicator of whether or not there has been any failure
- However, it cannot be used to quantify the magnitude of the failure



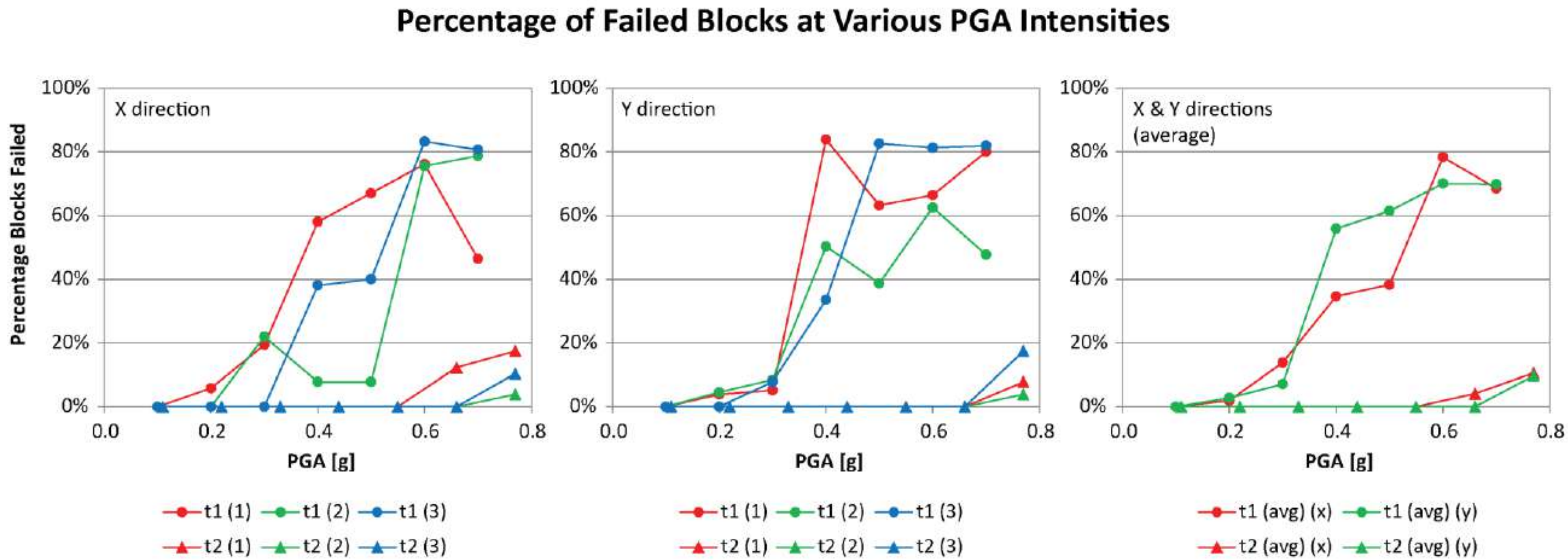
1) Max Permanent Displacement



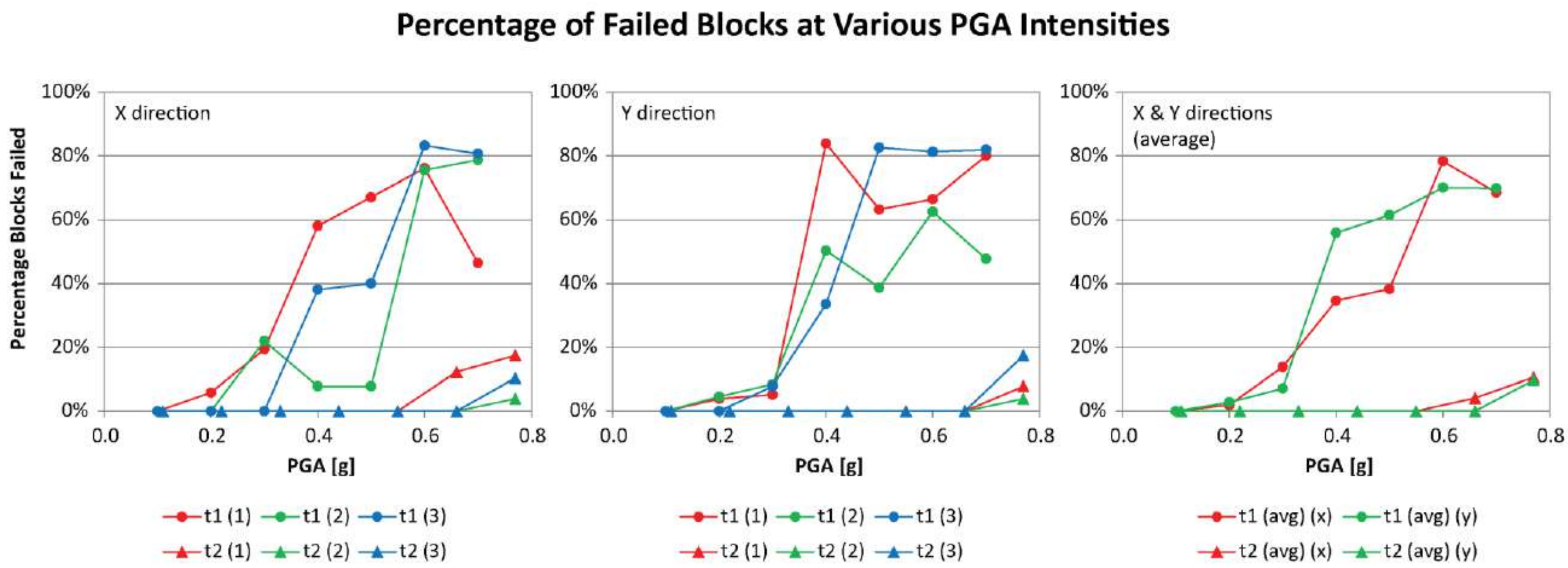
- Earthquakes type 1and type 2 produce very distinct responses
- Type 1 (far field) earthquakes produce the most extreme response
- Within each type of earthquake, average displacements are almost independent of the direction (max perman displa does not depend on the direction)

2) Percentage of Failed Blocks

- Provides a reliable measure to quantify failure
- Requires a robust definition of failure (location of the centroid)
- It cannot provide any useful information about degree of damage to the remaining blocks



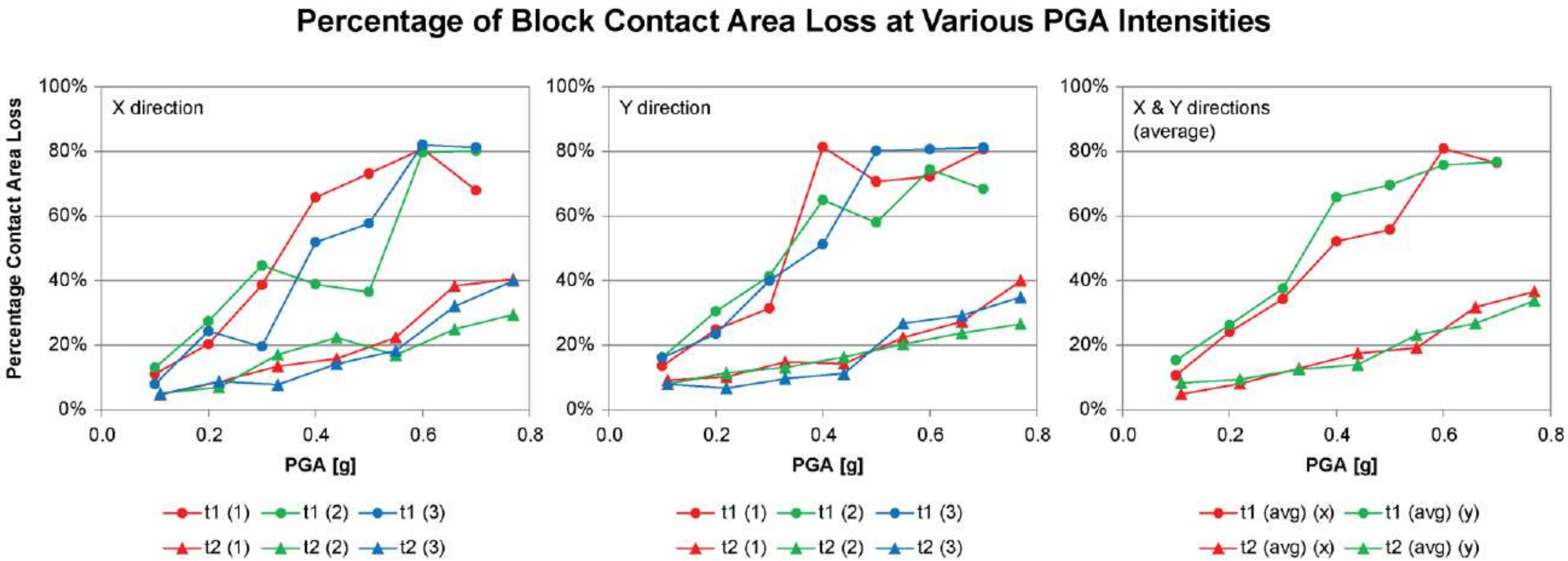
2) Percentage of Failed Blocks



- ❑ Results are globally consistent with the first indicator, i.e.
  - Clear difference between type 1 and type 2 responses
  - Type 1 earthquakes produce the most extreme response
  - Response almost independent from the earthquake direction

3) Percentage of Contact Area Loss

- Measures the changed state of block contacts at the end of the simulation
- Indirect measure of block displacement relative to one another
- Accounts for both **damage** (i.e. sliding and displacement) as well as **failure** (i.e. complete loss of contact by separation) - *no distinction can be made…*



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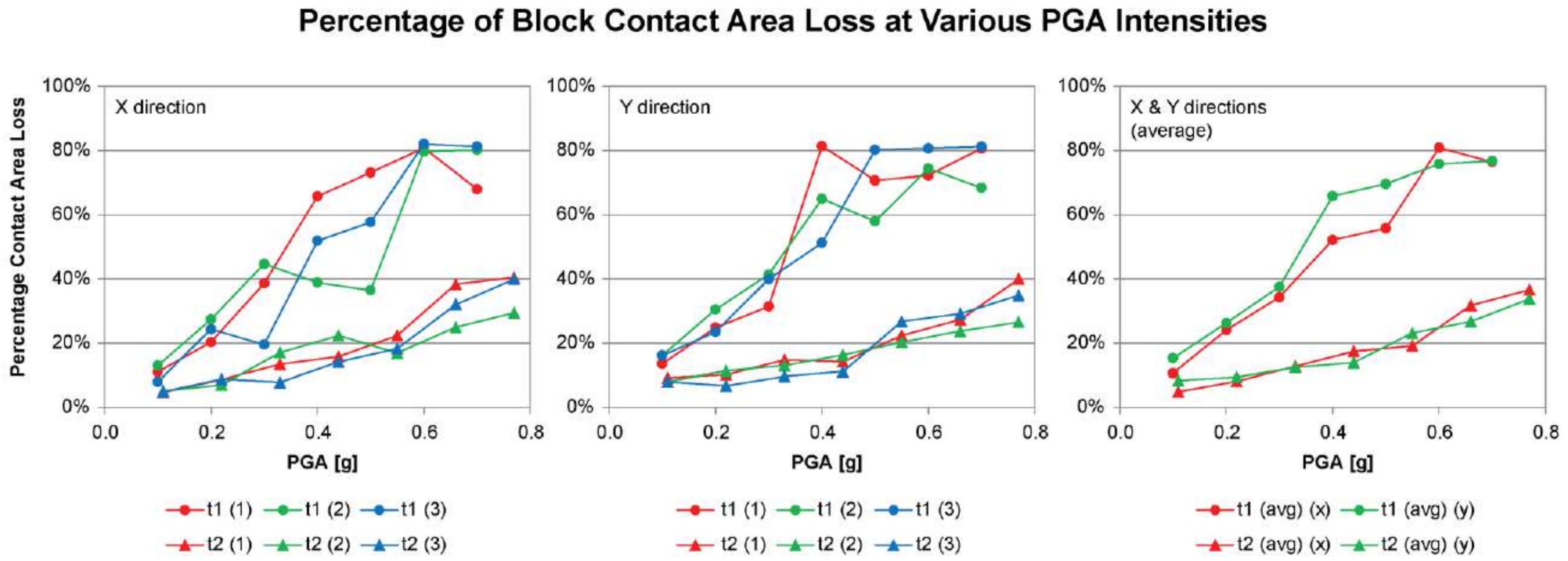
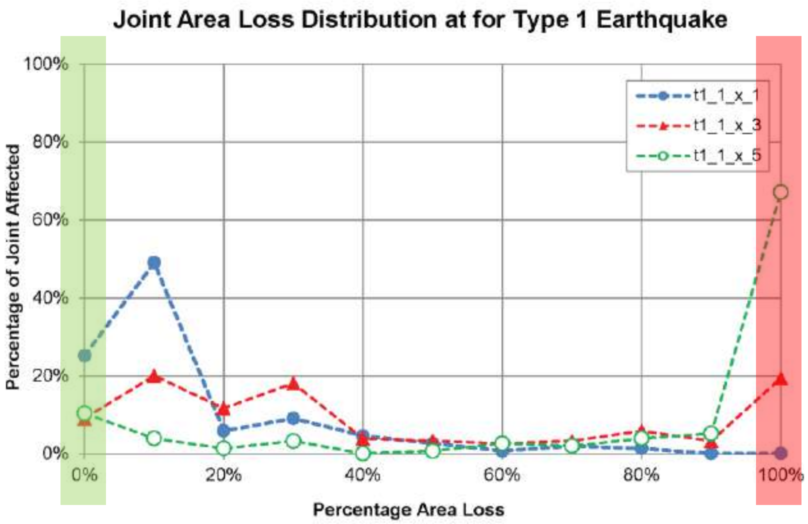
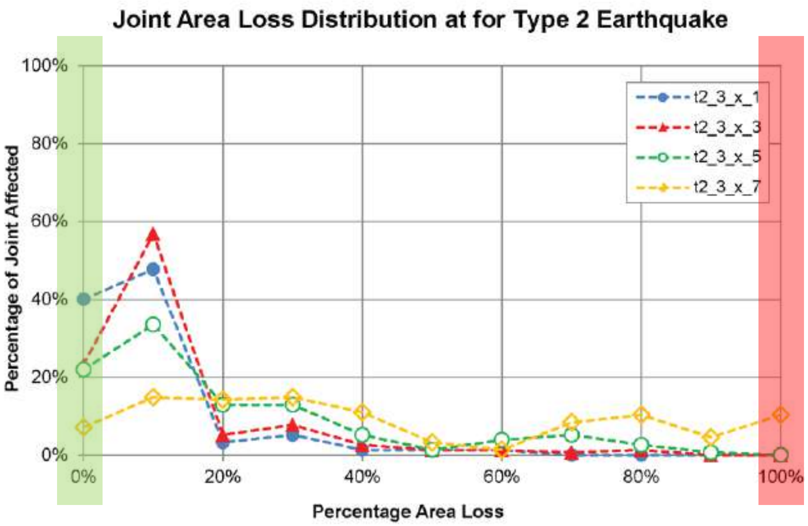


3) Percentage of Contact Area Loss

- One way to distinguish contact area loss due to damage and to failure is to compute the **frequency distribution of contact area loss** based on individual contacts
- Extremes on the x-axis correspond to the percentage of intact blocks on the left and the percentage of detached/failed blocks on the right
- Type 2 earthquake results show a gradual redistribution as ground acceleration intensity increases





4. Conclusions

Main Conclusions

- Limit and pushover analysis predict "correct" **failure pattern**, but underestimate the **capacity** of the structure
- **Non-linear incremental dynamic analysis** seems to be the only method to provide reliable results for the assessment of slender multi-drum structures
- At the **code-prescribed ground acceleration** levels, the structure will experience some damage (mainly due to the relative sliding of blocks), but **will not fail**.
- Type 1 earthquakes cause the most severe response due to two factors:
  - Type 1 **earthquake duration** is more than 2.5 times that of type 2, allowing accumulation of damage and displacement
  - Type 1 earthquakes are richer in higher periods (lower frequencies) and are more dangerous for multi-drum structures (at least this one)

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