## Three-days workshop on Applications of BEM in Cultural Heritage and Structural Engineering Industry

# Numerical Modeling and System Identification of a Historic Masonry Structure in Historic Cairo using Dynamic Investigation Tests


MSc thesis by

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Under supervision of

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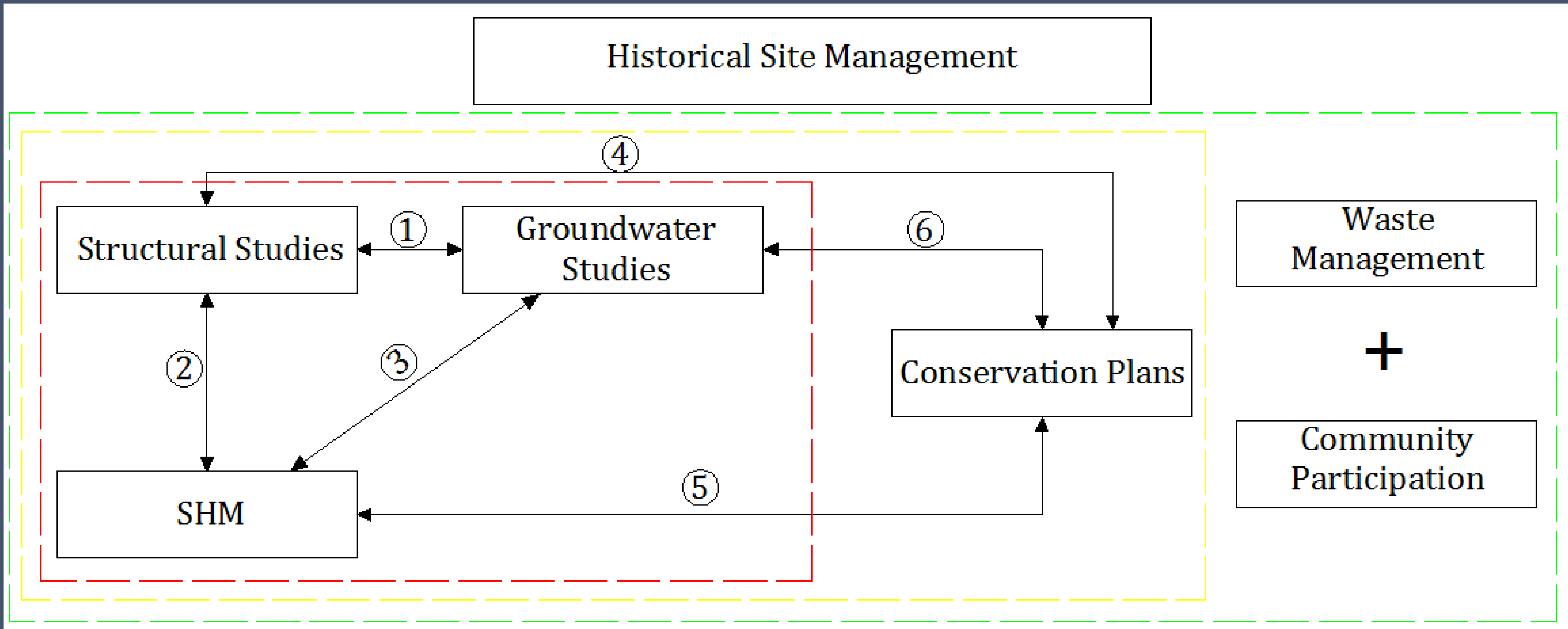
# Interdisciplinary approach for the management and conservation of UNESCO World Heritage Site of Historic Cairo. Application to Al-Ashraf Street

ICONIC project (ID: 30799)

# Contents

# ICONIC Project



# ICONIC Project

## T1: Site management

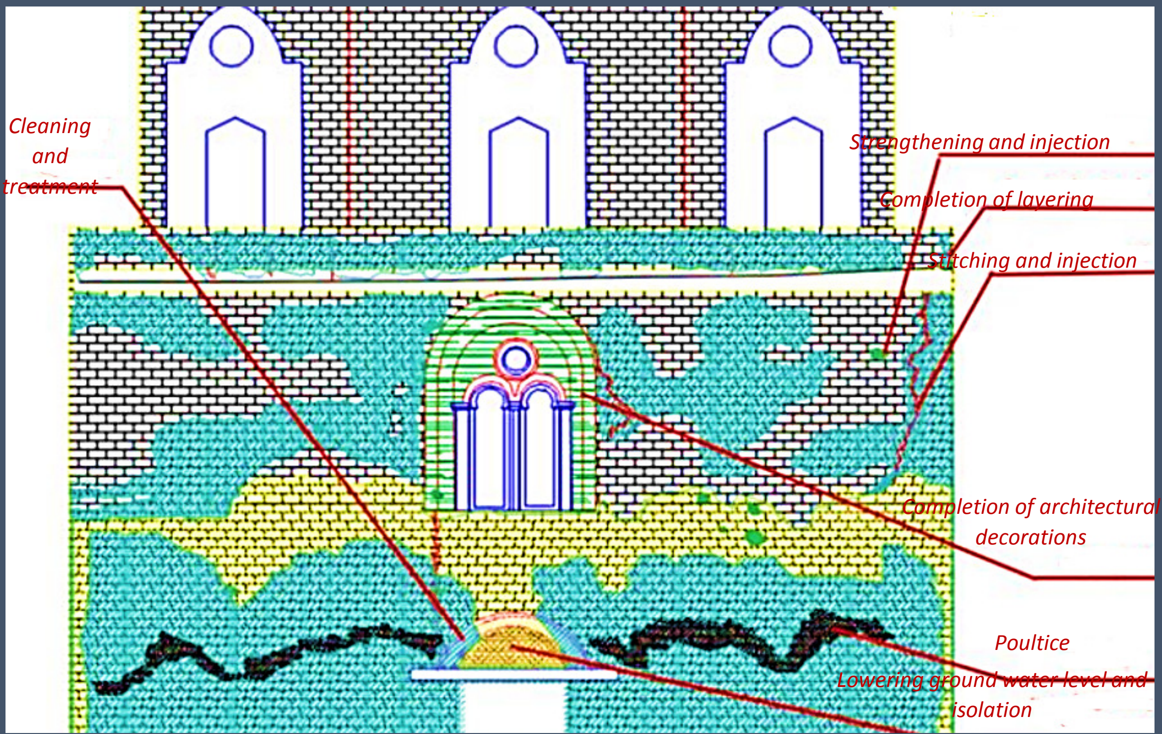
- Review and update GIS
- Waste management proposals
- Proposals for re-use of empty lands

## T2: Site archaeological conservation

- Documentation of site's historical structures with symptoms of damage
- Investigating causes of damage of site's historical structures
- Archaeological conservation and maintenance plans

# ICONIC Project

## T2: Site archaeological conservation




# ICONIC Project

T3: Structural assessment (territorial scale)

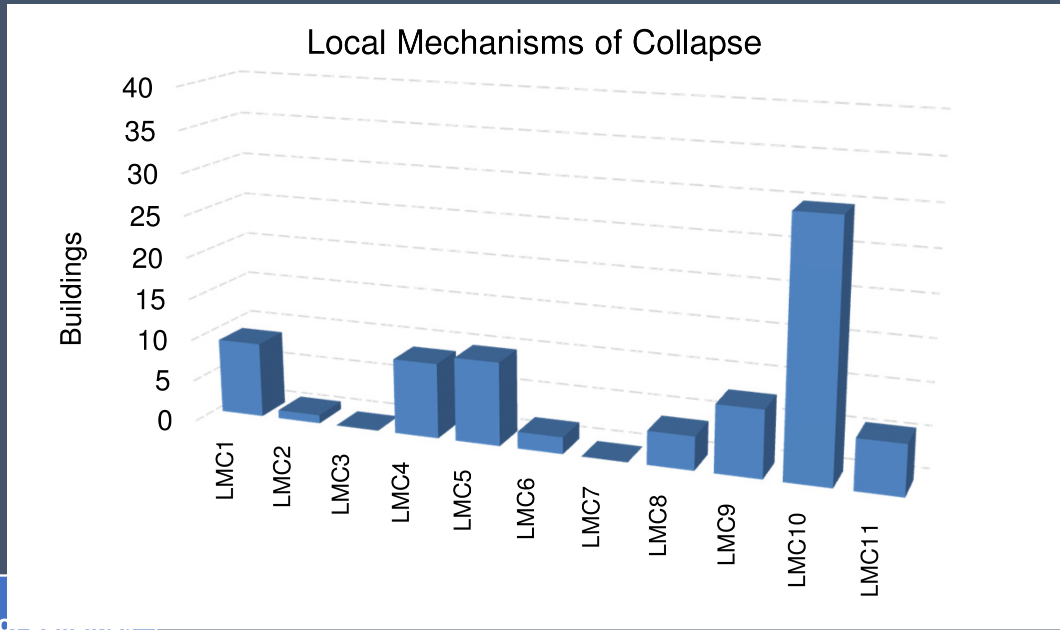
- On site survey and definition of typologies
- Identification of local mechanisms of collapse
- Implementation of fragility curves

T4: Structural assessment (single structure scale)

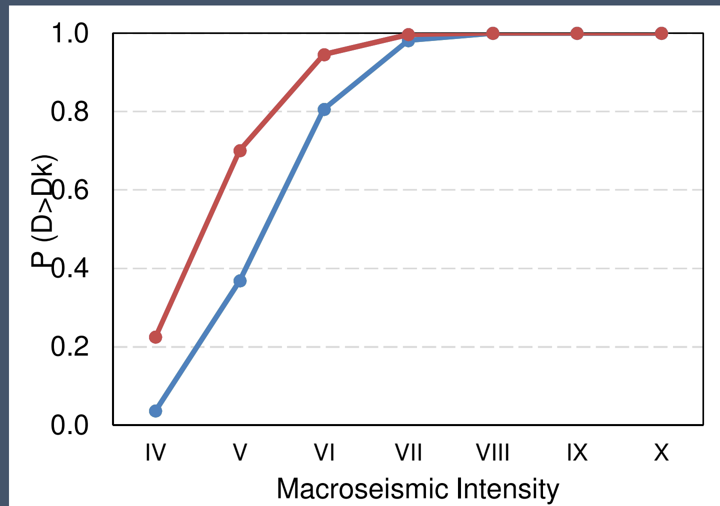
- Application to Fatima Khatun and Al-Ashraf Khalil Mausoleums

# ICONIC Project

## T3: Structural assessment (territorial scale)




| Local Mechanisms of Collapse | No. of Buildings |
|---|---|
| LMC1: Diagonal cracking in Unreinforced masonry walls | 9 |
| LMC2: Toe compression failure in Unreinforced masonry walls | 1 |
| LMC3: Bed-joint sliding in Unreinforced masonry walls | 0 |
| LMC4: Critical vertical crack between building parts | 9 |
| LMC5: Cracks around Wall Openings or at corners | 10 |
| LMC6: Outward Bulging of Walls | 2 |
| LMC7: Outward Detachment of Walls | 0 |
| LMC8: Pounding Cracks between Two Adjacent Buildings | 4 |
| LMC9: Excessive deflection of overhangs | 8 |
| LMC10: Deterioration of construction material and loss of parts | 30 |
| LMC11: Soft story formation | 6 |



# ICONIC Project

T5: SHM

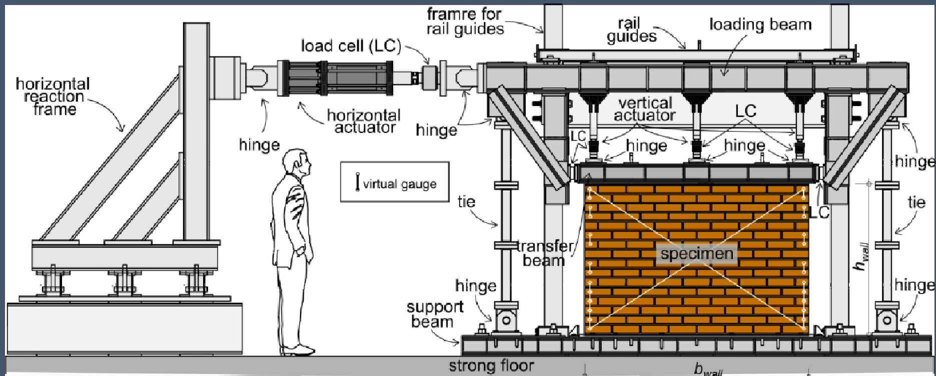
- Static and dynamic monitoring systems
- Continuous processing and evaluation of the systems
- Continuous correlation between the systems

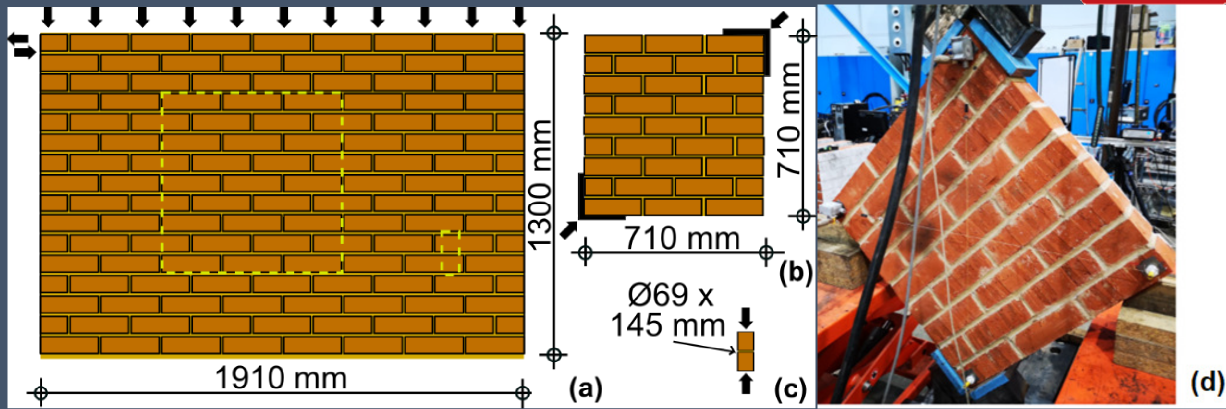
T6: Experimental campaign

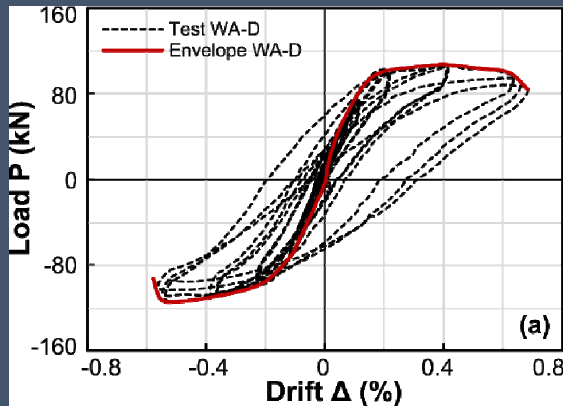
- Testing 2 specimens replicating original dry condition
- Testing 2 specimens replicating damp condition
- Testing 2 specimens replicating strengthened condition

# ICONIC Project

## T6: Experimental campaign



# ICONIC Project

T7: Groundwater

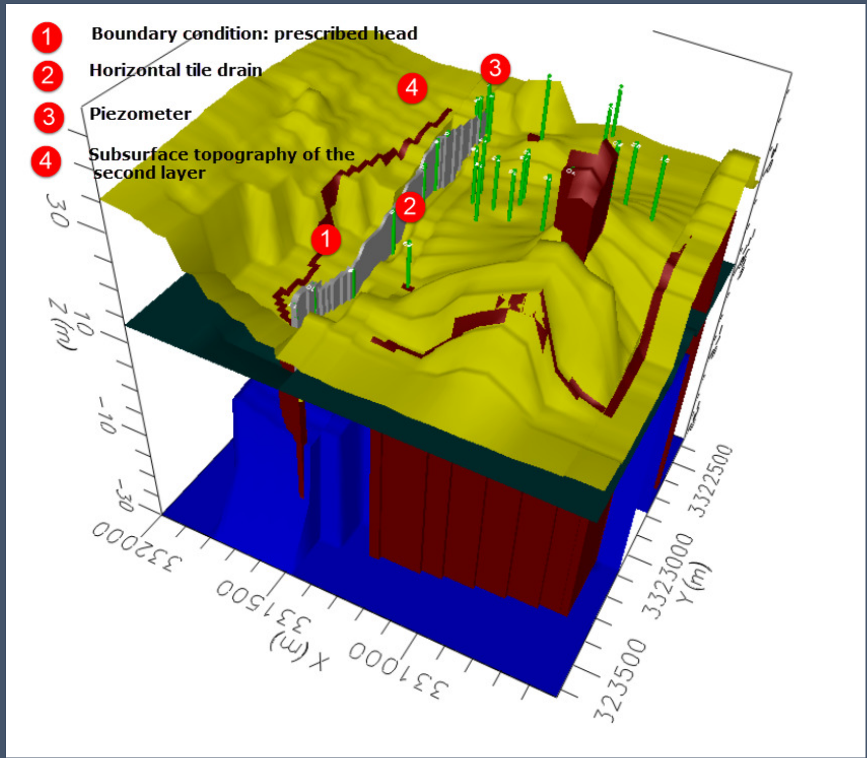
- Studying topography and geology of the street
- Hydro geochemical study of water
- Groundwater modelling

T8: Interdisciplinary approach

- Site management guidelines
- Site conservation guidelines

# ICONIC Project

T7: Groundwater




The proposed tile drain location along Al-Ashraf street in3D

# Fatima Khatun Mausoleum

- Scope
  - Characterization of construction materials
  - Creating 3D numerical model
  - Dynamic identification tests
  - Numerical model updating
  - Seismic analysis

# Fatima Khatun Mausoleum

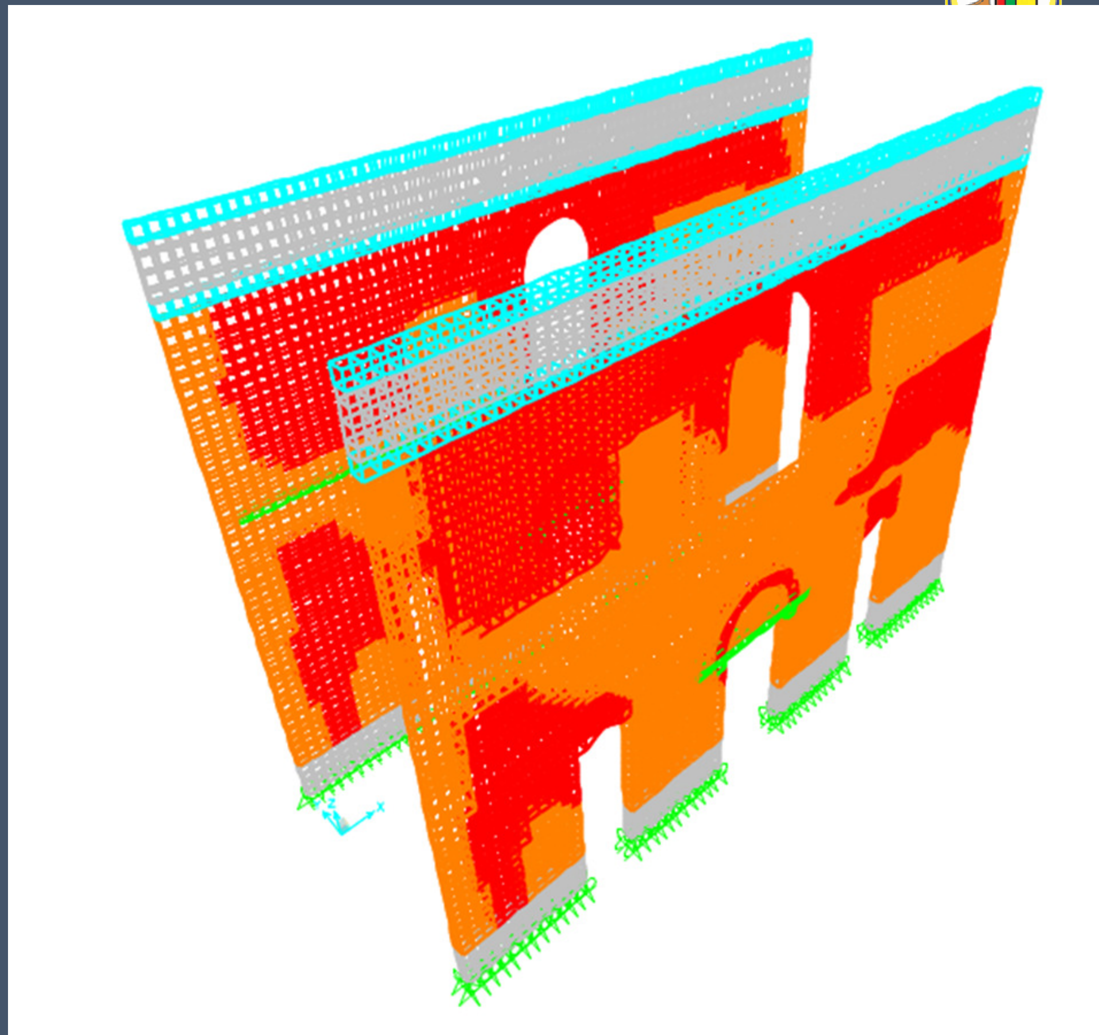
- Historical background
  - Located at Al-Ashraf street
  - Built in year 1284
- Resources
  - Visual Inspection
  - Old documents
  - Megawra conservation studies

# The Initial Model

- Geometry

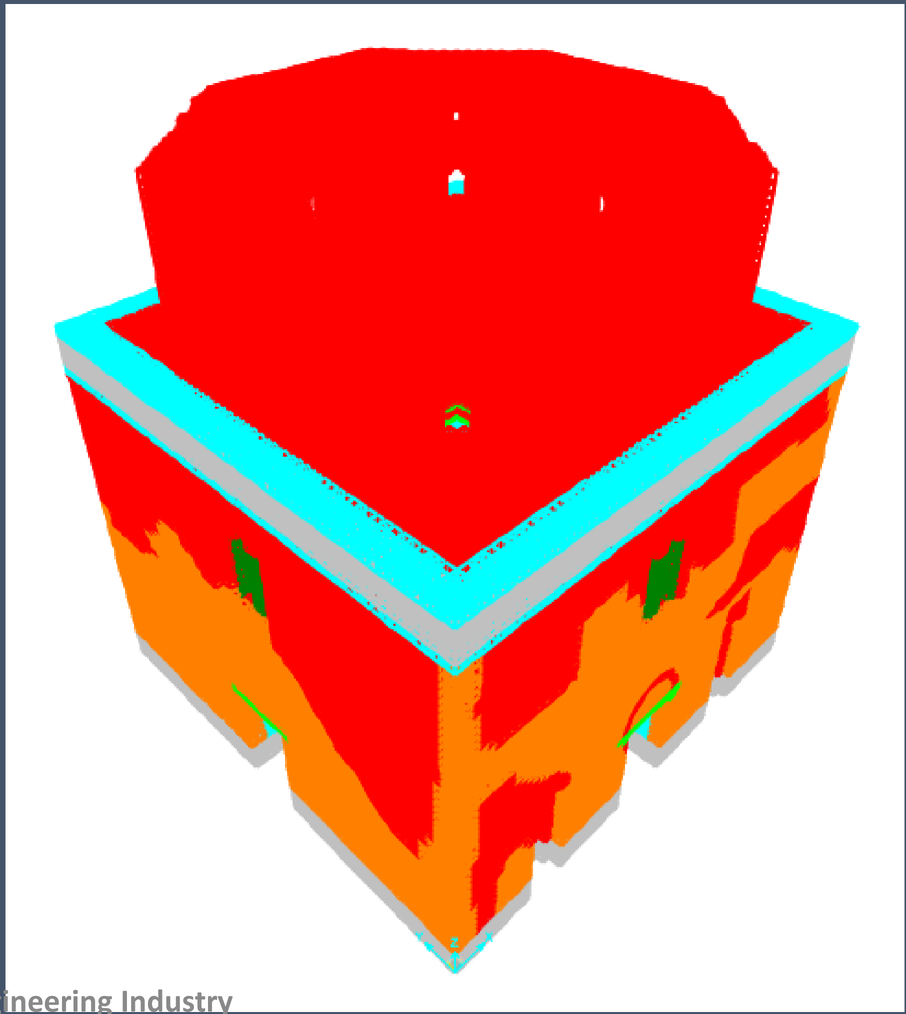
  Macro modeling using solid elements

Creating Sections → 2D Elevations → Extruding to Solids



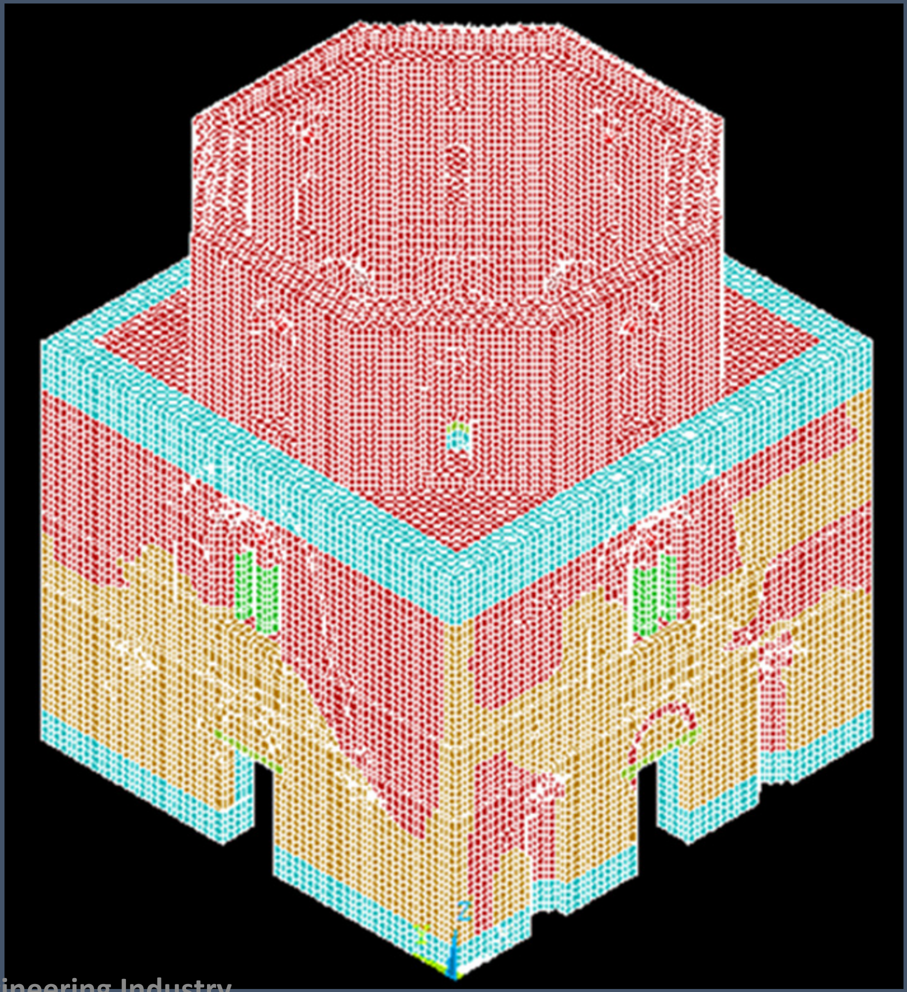
# The Initial Model

- SAP2000 model



# The Initial Model

- ANSYS model



# The Initial Model

- Material review

| Parameter | Masonry Type | FEMA 356 | Eurocode 6 | Italian 617 | ECP 204 |
|---|---|---|---|---|---|
| Specific gravity | Limestones | - | - | $\gamma_{avg} = 2.14$ | $\gamma_{light} = 1.76 - 2.16$<br>$\gamma_{med.} = 2.16 - 2.56$<br>$\gamma_{dense} > 2.56$ |
| | Solid Bricks | - | - | $\gamma_{avg} = 1.835$ | $\gamma_{min} = 1.6$ |
| Masonry compressive strength (MPa) | Limestones | $Good = 8$<br>$Fair = 5.3$<br>$Poor = 2.7$ | $f_{\mathrm{m}} = 0.45 \times f_b^{0.85} \times 1.25$ | $f_m = 2.6 - 3.8$ | - |
| | Solid Bricks | | $f_m = 0.75 \times f_b^{0.85} \times 1.25$ | $f_m = 2.4 - 4$ | - |
| Young's Modulus (MPa) | Limestones | $E = 550 \times f_m$ | $E = 1000 \times f_m$ | $E = 1500 - 1980$ | - |
| | Solid Bricks | | | $E = 1200 - 1800$ | - |
| Shear Modulus | Limestones | $G = 0.4 \times E$ | $G = 0.4 \times E$ | $G = \frac{1}{3} \times E$ | - |
| | Solid Bricks | | | | |

# The Initial Model

- Material testing

# The Initial Model

- Material testing

| Parameter | Specific Gravity | | | Compressive strength (MPa) | | | |
|---|---|---|---|---|---|---|---|
| Masonry Type | Limestones | Old Bricks | New Bricks | Limestones (Cubes) | Limestones (Cylinders) | Old Bricks (Cubes) | New Bricks (Cubes) |
| Sample 1 | 1.99 | 1.1 | 1.73 | 15.5 | 10.1 | 3.26 | 19.4 |
| Sample 2 | 2.05 | 1.07 | - | 20.5 | 10.5 | 7.65 | 13.3 |
| Sample 3 | 2.09 | - | - | 15.4 | 11.1 | 2.94 | 14.6 |
| Sample 4 | 2.02 | - | - | - | - | 6.2 | - |
| Sample 5 | 2.02 | - | - | - | - | 7.15 | - |
| Sample 6 | - | - | - | - | - | 5.67 | - |
| **Average** | 2.034 | 1.085 | 1.73 | 17.15 | 10.54 | 5.48 | 15.75 |
| **Normalised** | - | | | 14.58 | 11.59 | 4.66 | 13.39 |
| $f_m$ | - | | | 5.5 | 4.5 | 3.5 | 8.5 |

# The Initial Model

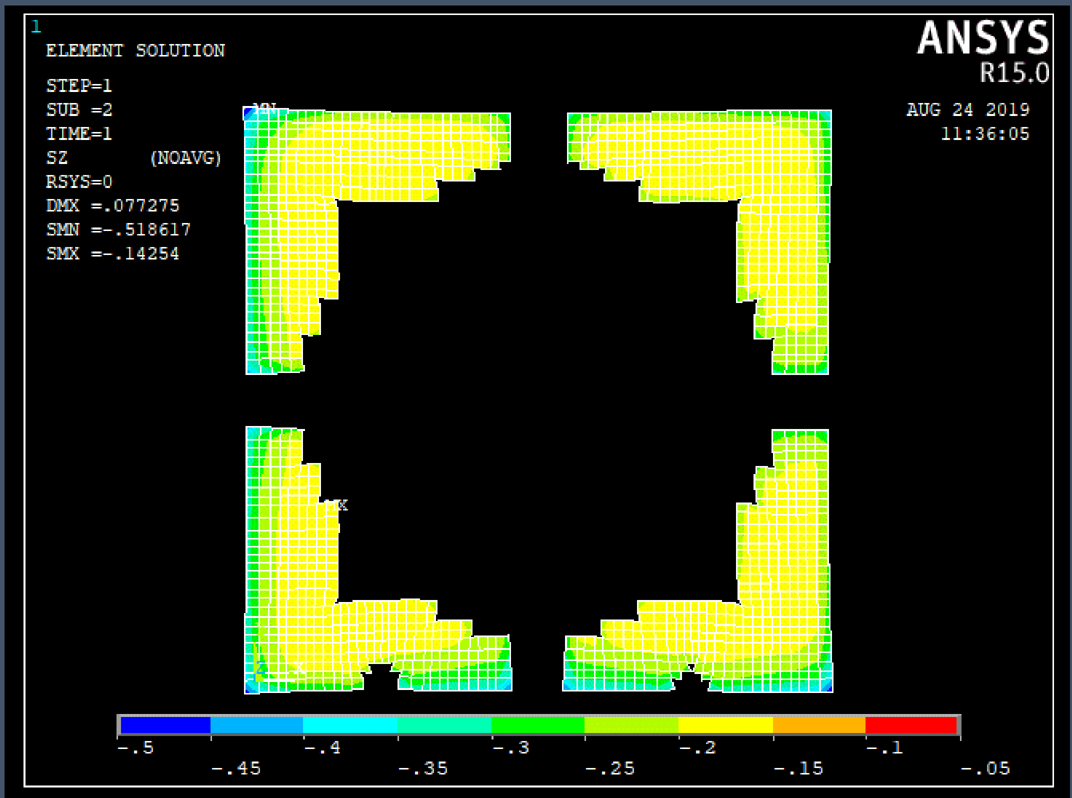
- Selected material properties

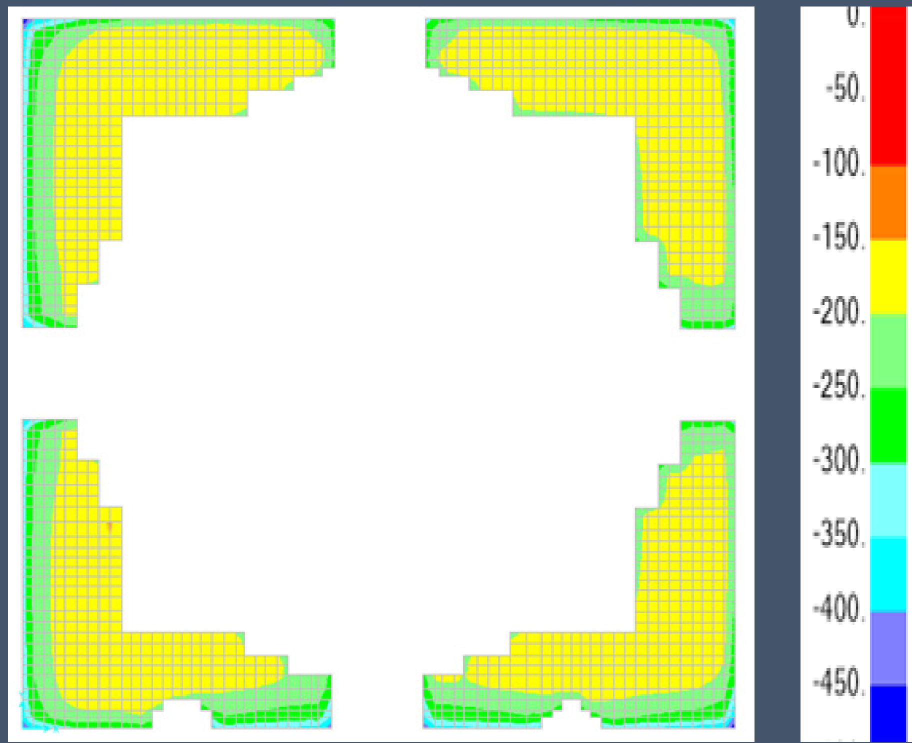
| Masonry Type | Limestones | Old Bricks | New Bricks | Timber |
|---|---|---|---|---|
| Specific gravity | 2.034 | 1.1* | 1.73 | 0.54 |
| Compressive strength (MPa) | 5.5 | 3.5 | 8.5 | - |
| Young's Modulus (MPa) $E = \mathbf{300} \times f_m$ | 1650 | 1050 | 2550 | 2450 |
| Poisson's ratio | 0.25 | 0.25 | 0.25 | 0.35 |

- Inputs
  - $E = 300 \times f_m$
  - $\upsilon = 0.25$
  - Foundation is hinged to ground
  - Attached school is not modeled

# The Initial Model

- Gravity analysis
  - Overall weight of the structure (14,400 kN)
  - Stresses on foundation level (Max stress = **0.52 MPa** in the corner)



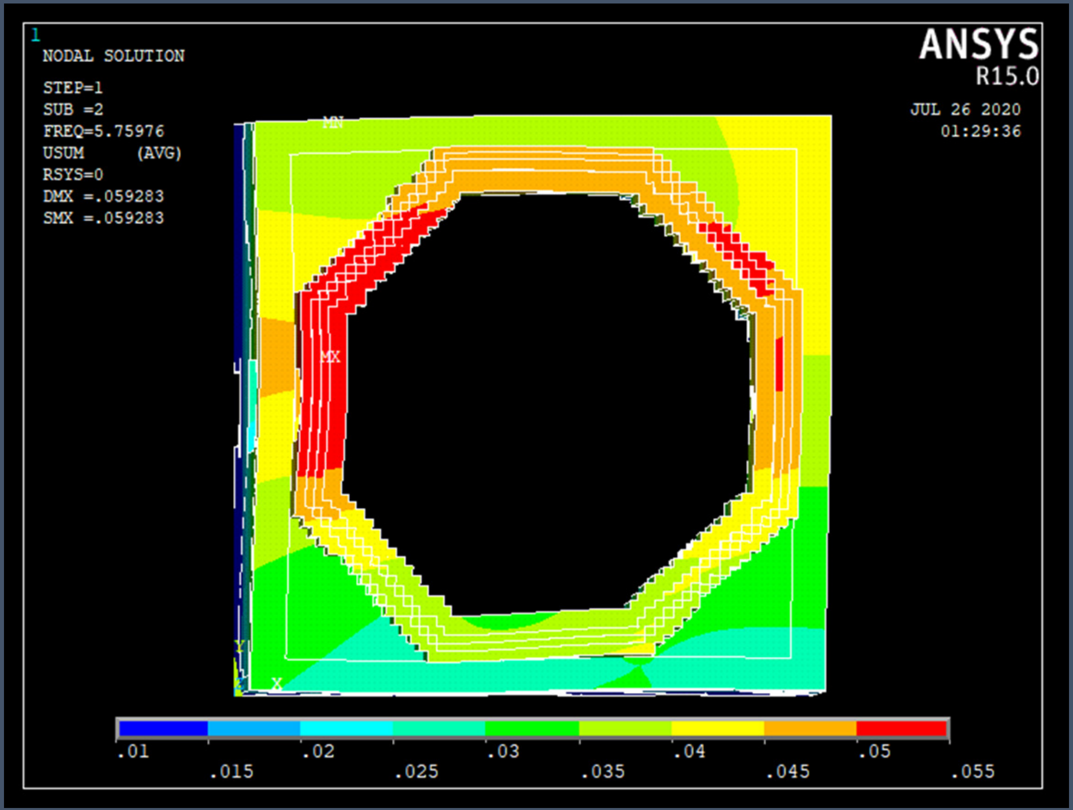
# The Initial Model

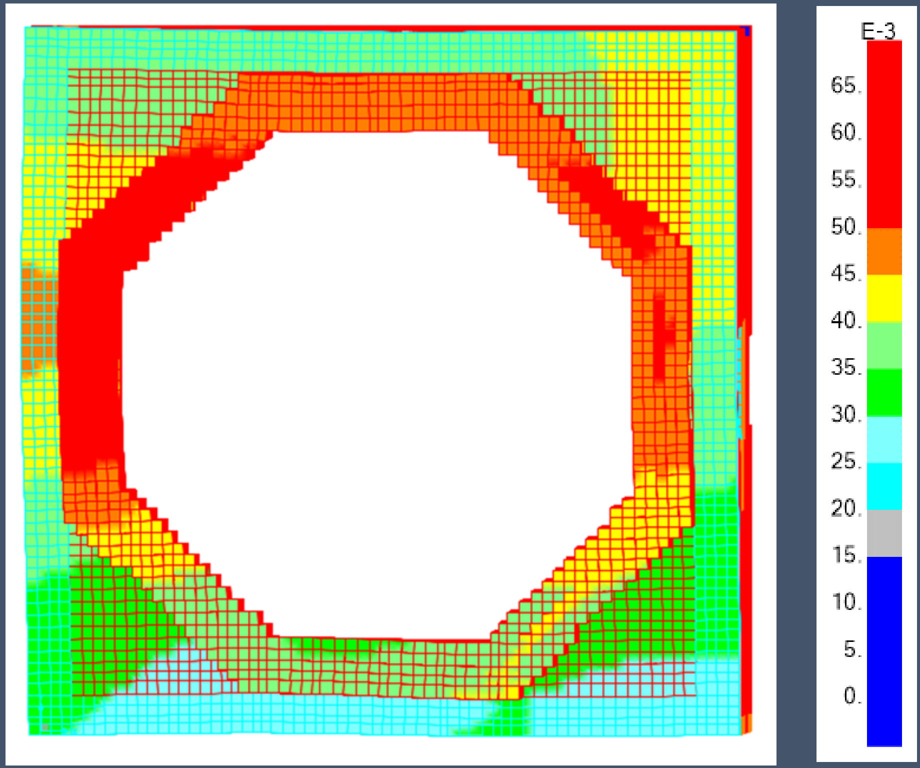
- Modal analysis

| Mode Name | SAP2000 (Hz) | ANSYS (Hz) | Difference (%) | Participation mass ratio | | |
|---|---|---|---|---|---|---|
| | | | | X direction | Y direction | Rotation Z |
| Wall Bending | 5.3262 | 5.3207 | 0.103% | 0.003 | 0 | 0 |
| Translational X | 5.7653 | 5.7598 | 0.095% | **0.62** | 0.05 | 0 |
| Translational Y | 5.8710 | 5.8653 | 0.096% | 0.055 | **0.62** | 0.002 |
| Corner Bending | 6.4885 | 6.4877 | 0.012% | 0.006 | 0.008 | 0 |
| Torsion | 8.9883 | 8.9817 | 0.073% | 0.001 | 0.001 | **0.73** |

# The Initial Model

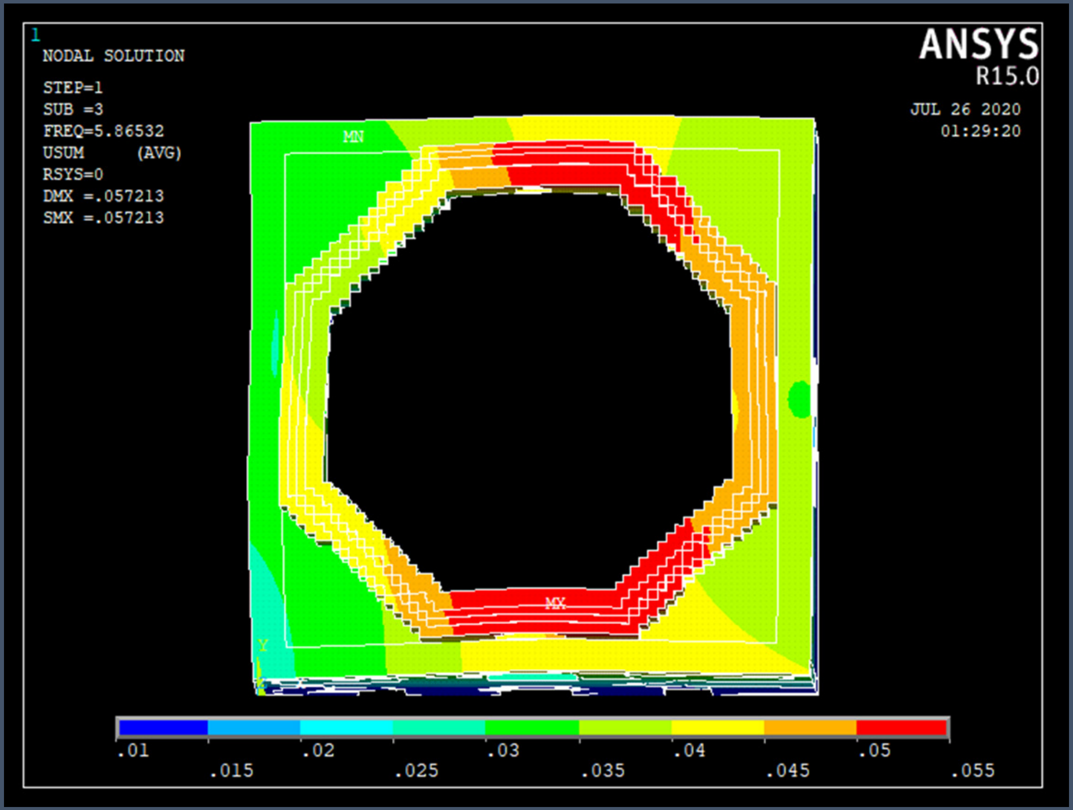
- Modal analysis

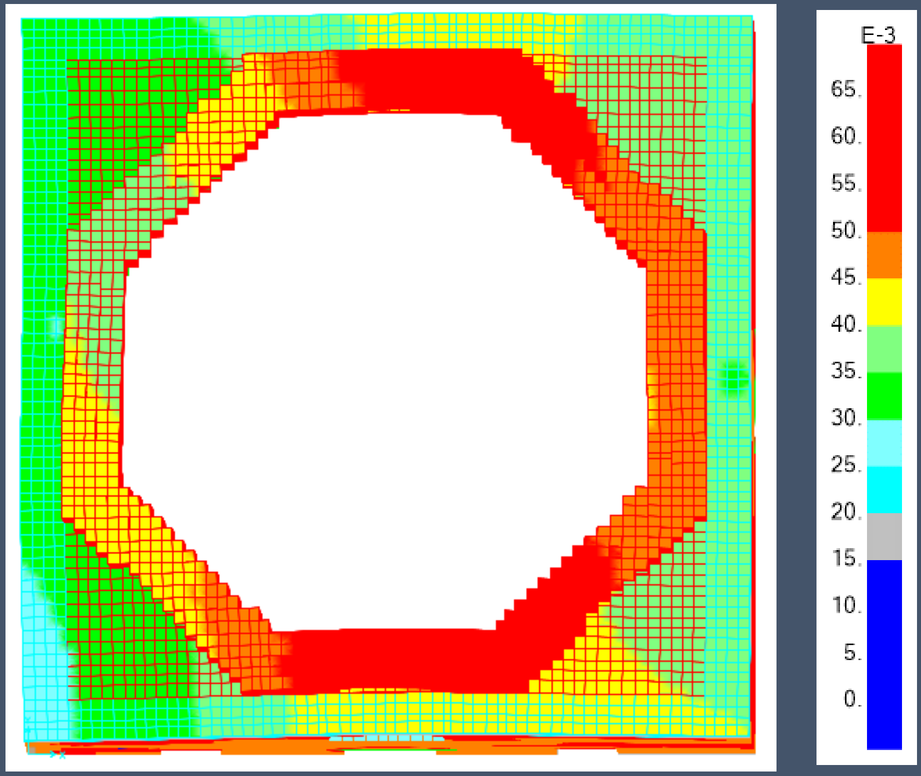


# The Initial Model

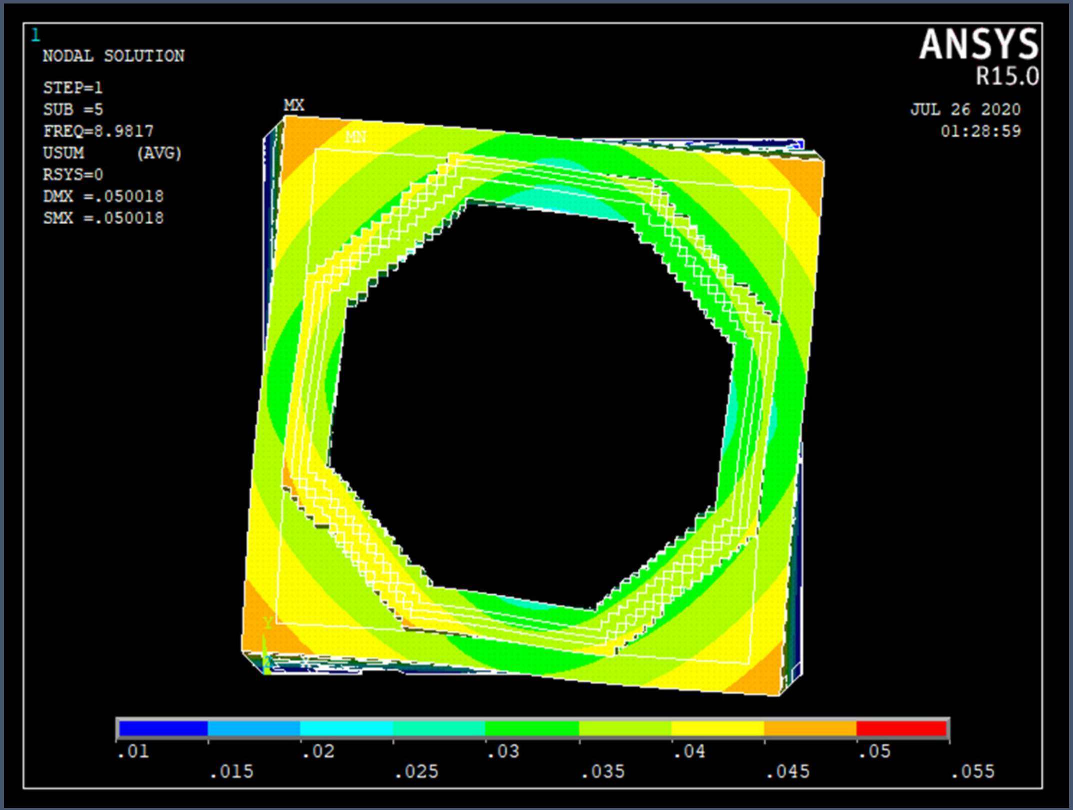
- Modal analysis

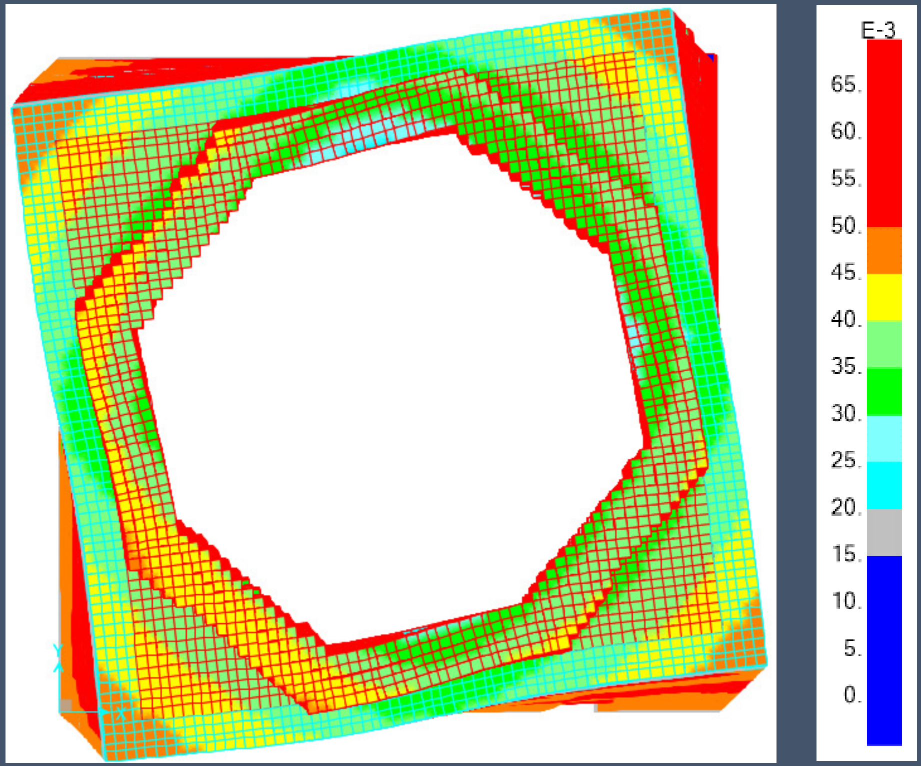


# The Initial Model

- Modal analysis



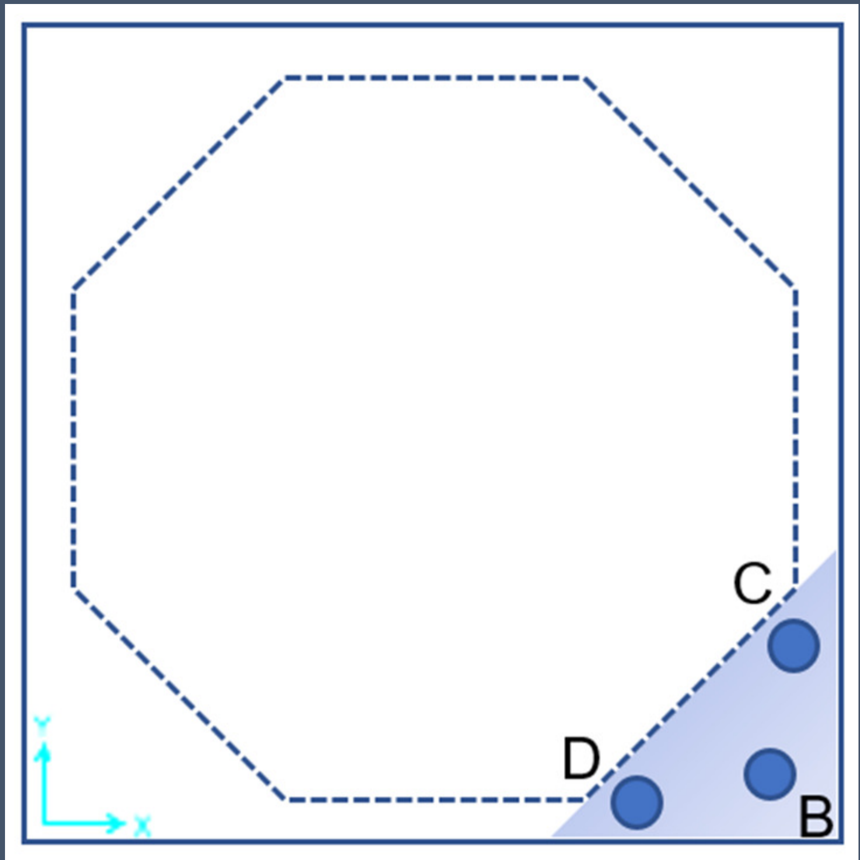



# Dynamic Investigation

- Experimental setup

# Dynamic Investigation

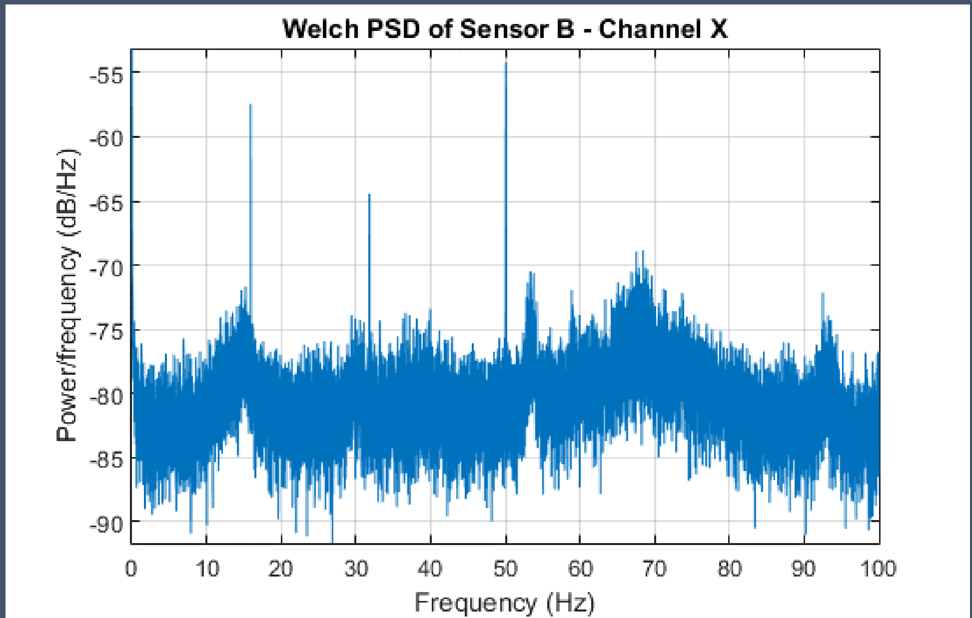
- Experimental setup

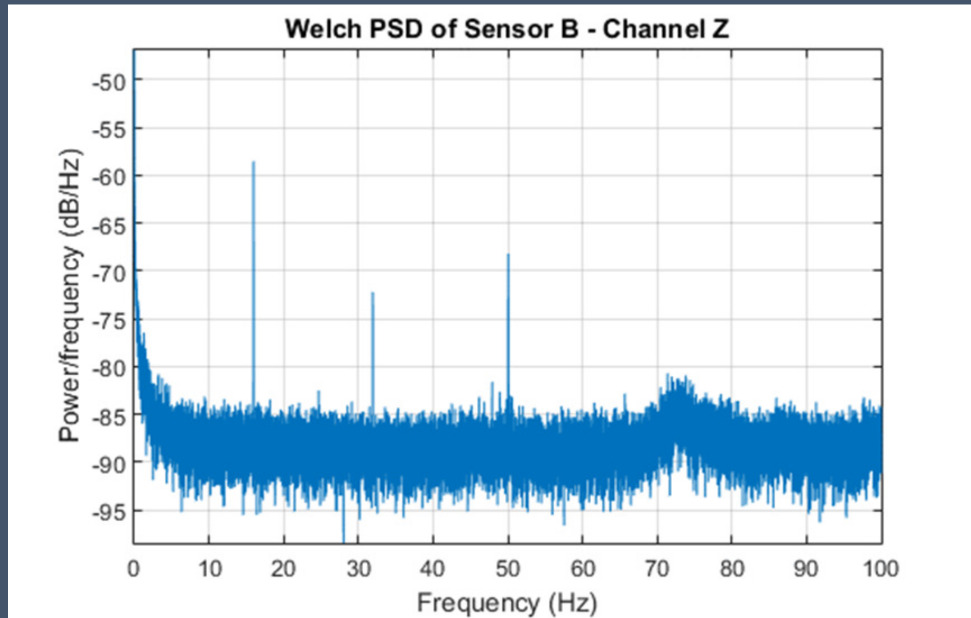



# Dynamic Investigation

- Signal processing

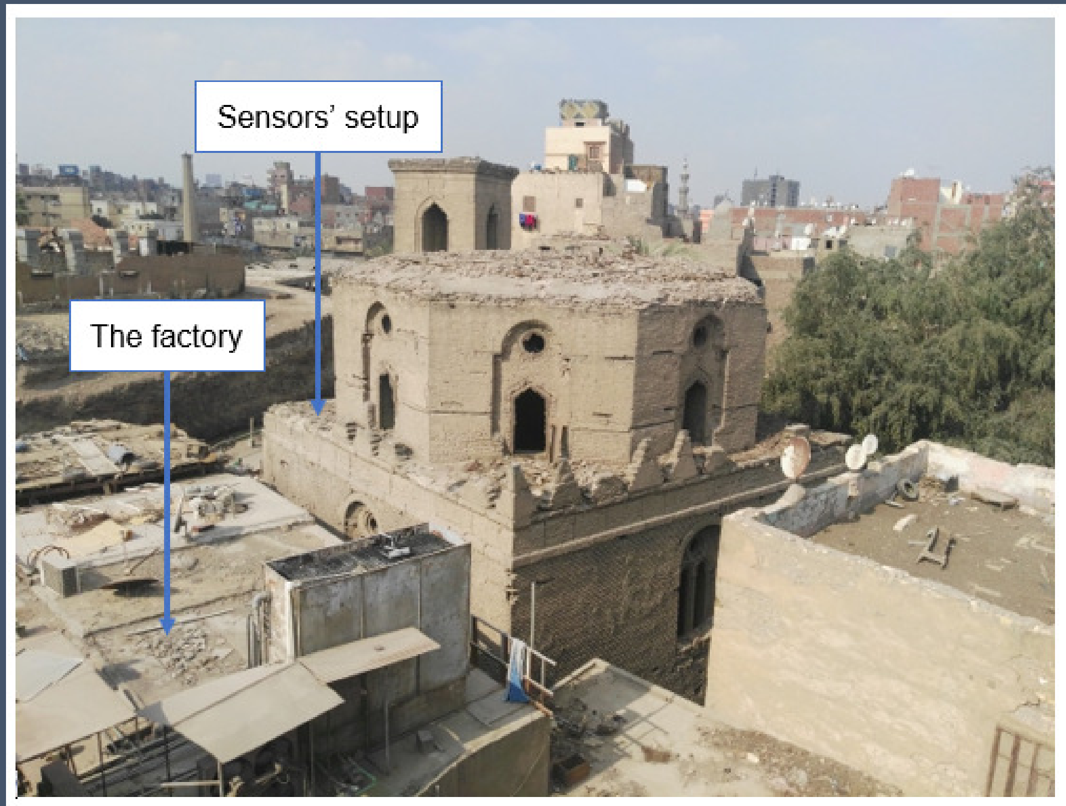
  - Peak picking method (In frequency domain)
  - Welch estimator using default values (pwelch function in MATLAB)



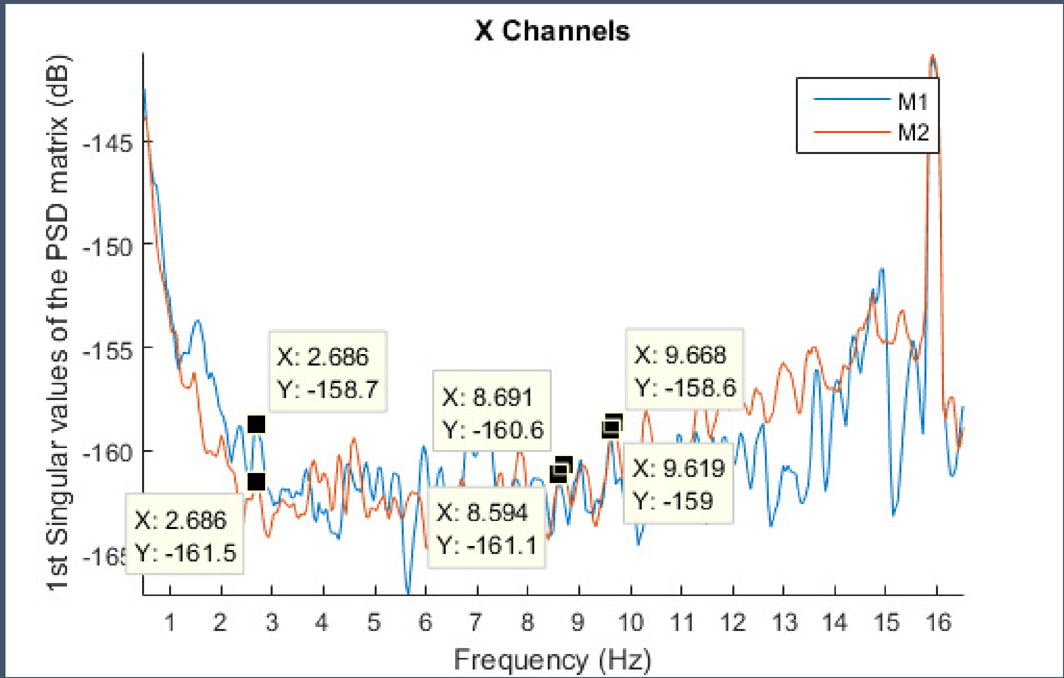
# Dynamic Investigation

- Signal processing
  - Harmonic excitations
  - Verified by ARTeMIS Modal software



# Dynamic Investigation

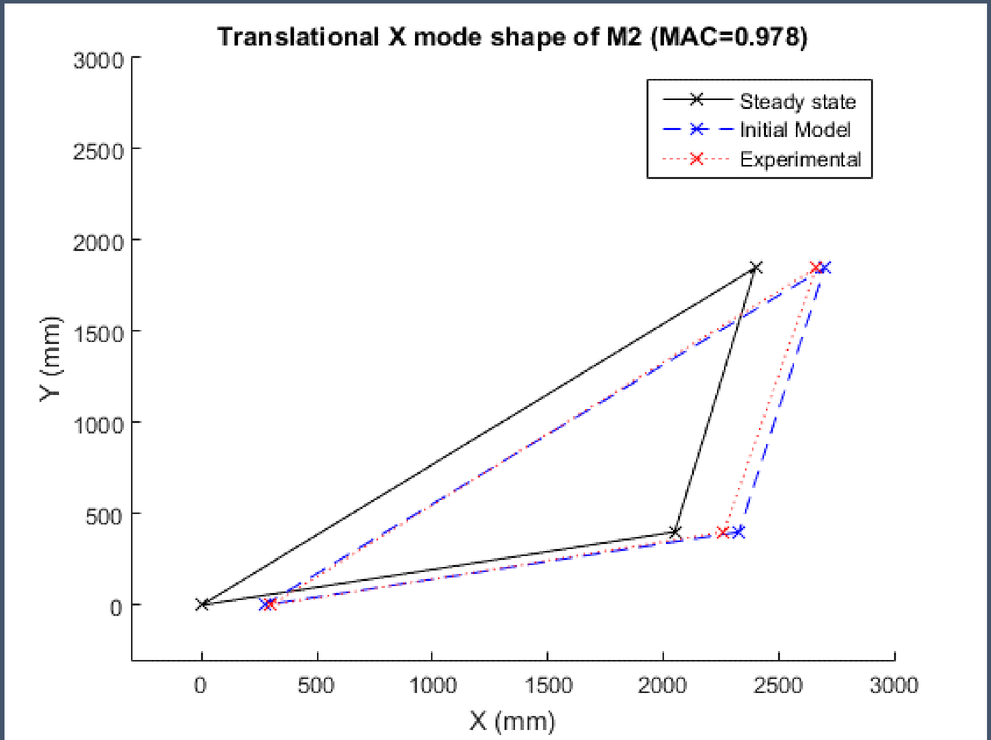
- Signal processing
  - Window size is **20 sec**
  - Each direction is separated
  - Measurements comparison

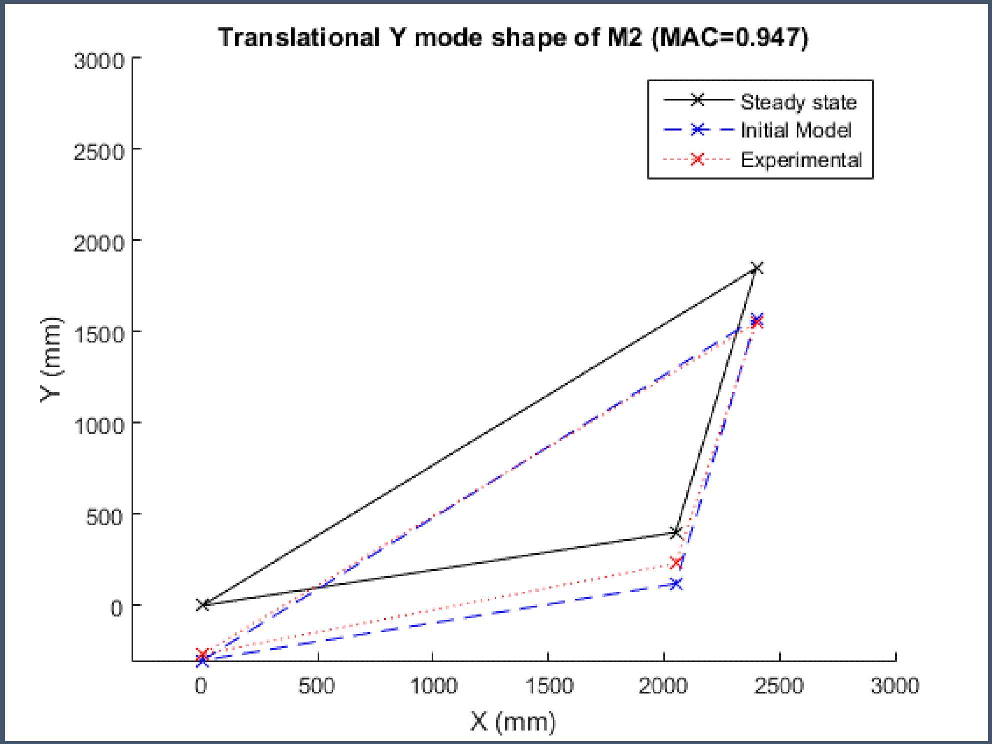


# Dynamic Investigation

- Signal processing

  Mode Shapes



# Dynamic Investigation

- Signal processing

Results

| Mode Name | Experimental frequency (Hz) | | | Initial model frequency (Hz) | MAC |
|---|---|---|---|---|---|
| | Selected | Min. | Max. | | |
| Translational X | 2.686 | 2.65 | 2.75 | 5.760 | 0.978 |
| Translational Y | 3.6 | 3.3 | 3.9 | 5.865 | 0.947 |
| Torsion | 9.65 | 8.5 | 10 | 8.982 | 0.254 |

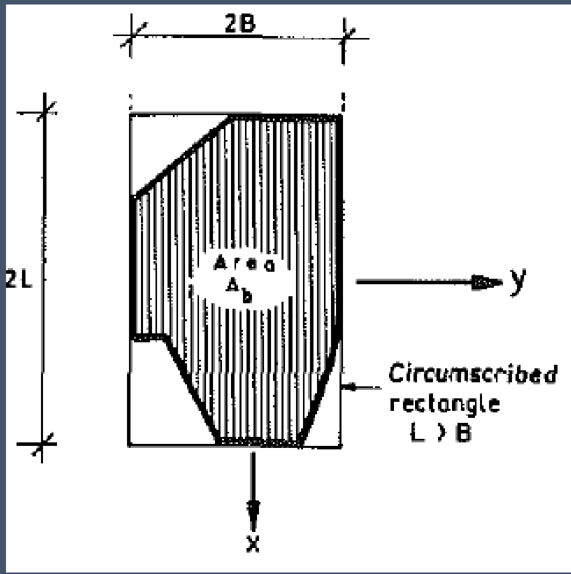
# Regression Analysis

- Soil modeling

  - Borehole No. 5 (Housing Ministry report)

  - Analysis by Assistant Professor Asmaa Hassan

| Formation | End depth (From normal land) |
|---|---|
| Fill (clayey silt and rock fragments) | 11 |
| Hard Silty clay, interlayers of rock ($q_u$>4) | 18 |
| Limestone/Sandstone, interlayers of silty clay | 30 |




- Applying Gazeta's equation using Winkler model (Site class E):

$$k_v = 685 \cong 700\ N/mm$$
$$k_h = 514 \cong 500\ N/mm$$

# Regression Analysis

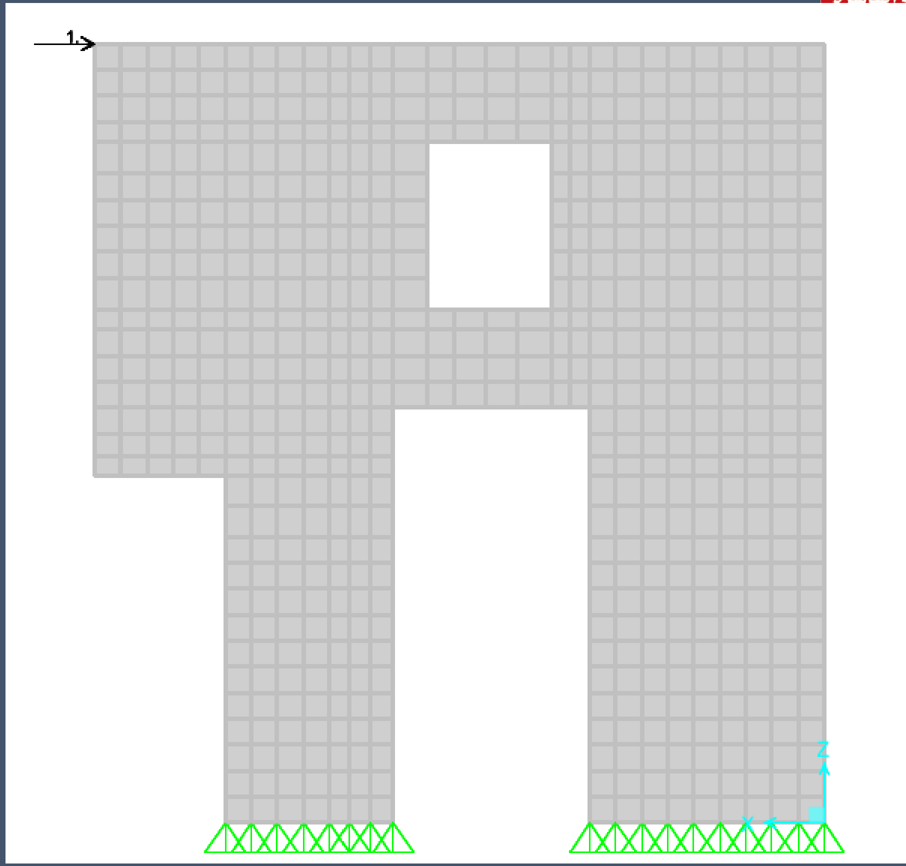
- Attached wall modeling

  - Contact length = 4 m

  - Linear springs model

$$k = \frac{F}{\Delta L} = \frac{1}{\Delta L}$$

$$k_w = 16{,}500\ N/mm$$



# Regression Analysis

- Strategy

$$X = \begin{bmatrix} E \\ \upsilon \\ k_v \\ k_h \\ k_w \end{bmatrix} \gg f(X) \gg M = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix}$$

- Get $f(X)$ using nonlinear fitting techniques
- Knowing $M$, solve for $X$ using a minimization algorithm

# Regression Analysis

- Neural network fitting (MATLAB app)

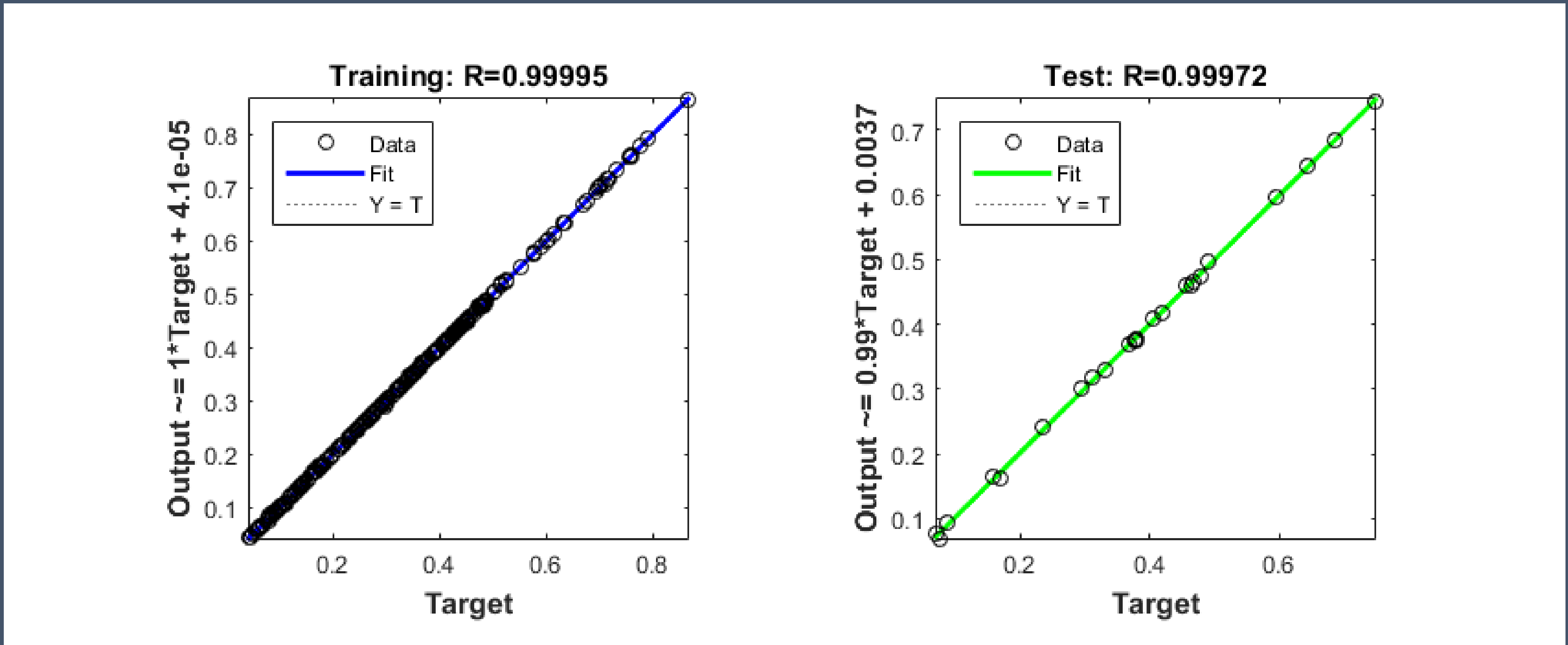
### Create dataset
- Input (5x50 Models)
- Output (5x50 Models)

### Create the network
- Train (45 Models)
- Test (5 Models)

### Use the network
- Create database
- Sensitivity analysis
- Solve for $X$

# Regression Analysis

- Neural network regression



# Regression Analysis

- Neural network database ($20^3 = 8000$ model)

| ID | Input | | | | | Output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $E$ $(\times f_m)$ | $\upsilon$ | $k_v$ $(N/mm)$ | $k_h$ $(N/mm)$ | $k_w$ $(N/mm)$ | $f_1$ $(Hz)$ | $f_2$ $(Hz)$ | $f_3$ $(Hz)$ | $f_4$ $(Hz)$ | $f_5$ $(Hz)$ |
| 3994 | 581.1 | 0.25 | 700,000 | 500,000 | 194,564 | 7.209 | 7.367 | 7.986 | 9.022 | 12.532 |
| 3995 | 581.1 | 0.25 | 700,000 | 500,000 | 277,843 | 7.215 | 7.376 | 7.997 | 9.062 | 12.576 |
| 3996 | 581.1 | 0.25 | 700,000 | 500,000 | 396,768 | 7.220 | 7.383 | 8.006 | 9.100 | 12.618 |
| 3997 | 581.1 | 0.25 | 700,000 | 500,000 | 566,596 | 7.224 | 7.388 | 8.013 | 9.137 | 12.659 |
| 3998 | 581.1 | 0.25 | 700,000 | 500,000 | 809,115 | 7.228 | 7.392 | 8.018 | 9.174 | 12.700 |
| 3999 | 581.1 | 0.25 | 700,000 | 500,000 | 1,155,439 | 7.231 | 7.394 | 8.024 | 9.210 | 12.739 |
| 4000 | 581.1 | 0.25 | 700,000 | 500,000 | 1,650,000 | 7.234 | 7.395 | 8.028 | 9.244 | 12.779 |
| 4001 | 642.9 | 0.25 | 70 | 50 | 1,894 | 7.173 | 0.978 | 1.375 | 6.867 | 10.972 |
| 4002 | 642.9 | 0.25 | 70 | 50 | 2,705 | 7.155 | 0.946 | 1.473 | 6.878 | 11.011 |
| 4003 | 642.9 | 0.25 | 70 | 50 | 3,863 | 7.140 | 0.919 | 1.575 | 6.892 | 11.053 |
| 4004 | 642.9 | 0.25 | 70 | 50 | 5,517 | 7.126 | 0.895 | 1.681 | 6.909 | 11.098 |
| 4005 | 642.9 | 0.25 | 70 | 50 | 7,878 | 7.115 | 0.876 | 1.791 | 6.929 | 11.146 |
| 4006 | 642.9 | 0.25 | 70 | 50 | 11,250 | 7.105 | 0.861 | 1.904 | 6.951 | 11.197 |
| 4007 | 642.9 | 0.25 | 70 | 50 | 16,066 | 7.098 | 0.851 | 2.020 | 6.977 | 11.250 |

# Final Model

- Database filtration

| Mode Name | Frequency (Hz) | | |
|---|---|---|---|
| | Selected | Min. | Max. |
| Translational X | 2.686 | **2.65** | **2.75** |
| Translational Y | 3.6 | **3.3** | **3.9** |
| Torsion | 9.65 | **8.5** | **10** |

| ID | Input | | | | | Output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $E$ $(\times f_m)$ | $\upsilon$ | $k_v$ $(N/mm)$ | $k_h$ $(N/mm)$ | $k_w$ $(N/mm)$ | $f_1$ $(Hz)$ | $f_2$ $(Hz)$ | $f_3$ $(Hz)$ | $f_4$ $(Hz)$ | $f_5$ $(Hz)$ |
| 2556 | 395.4 | 0.25 | 973.3 | 695.2 | 396,768 | 5.637 | 2.679 | 3.604 | 5.922 | 9.382 |
| 2557 | 395.4 | 0.25 | 973.3 | 695.2 | 566,596 | 5.643 | 2.695 | 3.627 | 5.949 | 9.412 |
| 2558 | 395.4 | 0.25 | 973.3 | 695.2 | 809,115 | 5.649 | 2.711 | 3.646 | 5.976 | 9.441 |
| 2559 | 395.4 | 0.25 | 973.3 | 695.2 | 1,155,439 | 5.655 | 2.727 | 3.660 | 6.002 | 9.468 |
| 2560 | 395.4 | 0.25 | 973.3 | 695.2 | 1,650,000 | 5.660 | 2.743 | 3.668 | 6.027 | 9.492 |
| 2953 | 457.3 | 0.25 | 973.3 | 695.2 | 136,247 | 6.061 | 2.654 | 3.607 | 6.242 | 9.952 |
| 2954 | 457.3 | 0.25 | 973.3 | 695.2 | 194,564 | 6.067 | 2.665 | 3.652 | 6.271 | 9.992 |

# Final Model

- Updated parameters
  - $E = 400 \times f_m$
  - $\upsilon = 0.25$
  - $k_v = 1000\ N/mm$
  - $k_h = 700\ N/mm$
  - $k_w = 400{,}000\ N/mm$

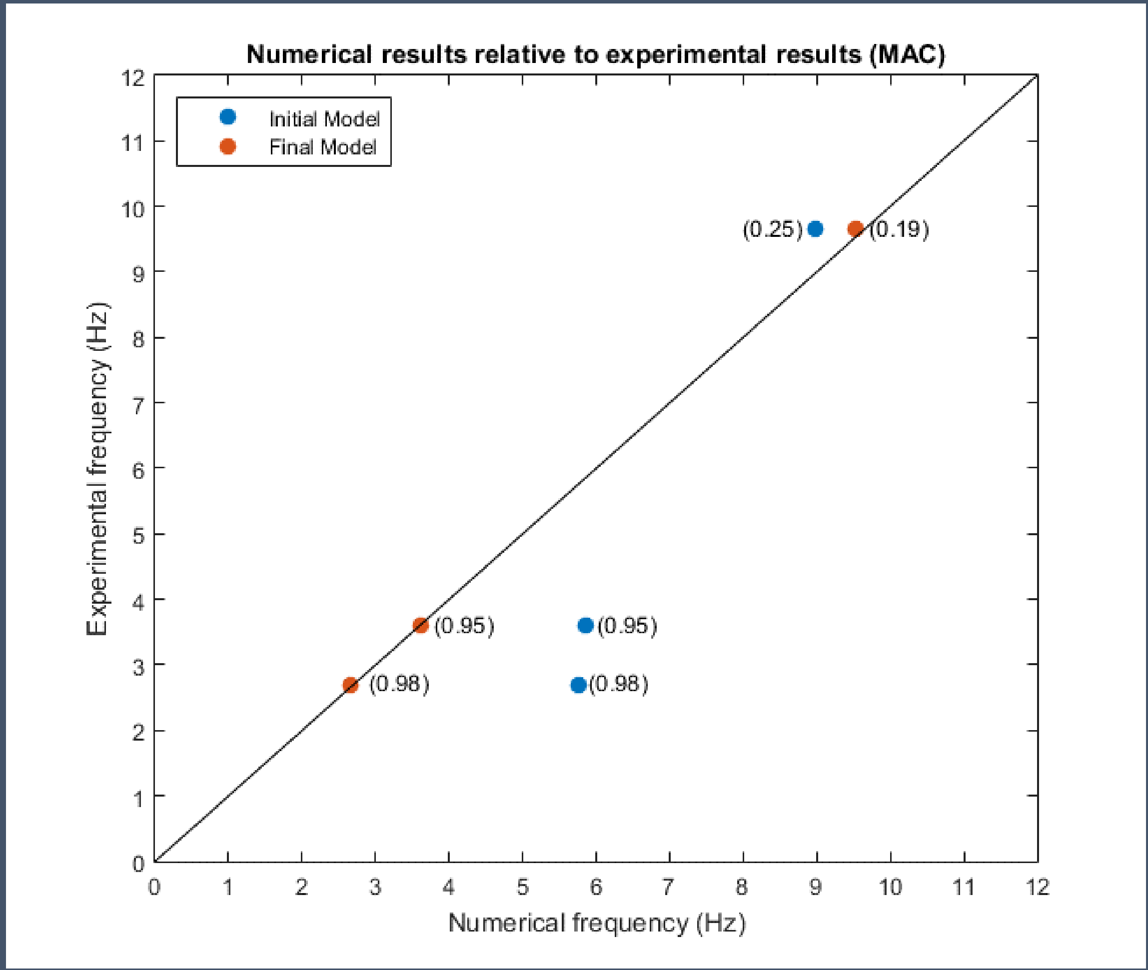
| Model | Input | | | | | Output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $E$ ($\times f_m$) | $\upsilon$ | $k_v$ ($N/mm$) | $k_h$ ($N/mm$) | $k_w$ ($N/mm$) | $f_1$ ($Hz$) | $f_2$ ($Hz$) | $f_3$ ($Hz$) | $f_4$ ($Hz$) | $f_5$ ($Hz$) |
| NN | 395.4 | 0.25 | 973.3 | 695.2 | 396,768 | 5.637 | 2.679 | 3.604 | 5.922 | 9.382 |
| ANSYS | 400 | 0.25 | 1,000 | 700 | 400,000 | 5.706 | 2.668 | 3.621 | 6.020 | 9.534 |
| Exp. | - | | | | | - | 2.686 | 3.6 | - | 9.65 |
| **Diff. (%)** | **-** | | | | | **-** | **-0.7%** | **0.6%** | **-** | **1.2%** |

# Final Model

Updated parameters

- $E = 400 \times f_m$
- $\upsilon = 0.25$
- $k_v = 1000\ N/mm$
- $k_h = 700\ N/mm$
- $k_w = 400{,}000\ N/mm$

- Expected parameters
  - $E = 300 \times f_m$
  - $\upsilon = 0.25$
  - $k_v = 700\ N/mm$
  - $k_h = 500\ N/mm$
  - $k_w = 16{,}500\ N/mm$



# Conclusion

- Modelling notes

  - $E_{stone} = 2200\ MPa, E_{old\ bricks} = 1400\ MPa, E_{new\ bricks} = 3400\ MPa$
  - Italian code provisions are conservative and acceptable
  - SSI is a governing parameter
  - Using horizontal soil stiffness as 10% of vertical soil stiffness is not always the case
  - The attached wall is inter-connected with other walls

- System identification notes

  - Taking several measurements at different times is useful during analysis
  - Vertical channels are important to detect soil vibrations
  - Sensors' setup was not enough to capture all mode shapes
  - Neural network fitting is an effective tool for model updating

# Conclusion

- Recommendations
  - Avoid harmonic excitations from neighboring environment
  - Problems associated with stiff structures during ambient vibrations

- Future work
  - Soil modeling effect on model updating
  - Seismic assessment
  - Dewatering effects
  - Structural health monitoring

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# THANK YOU!

Vielen Dank

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