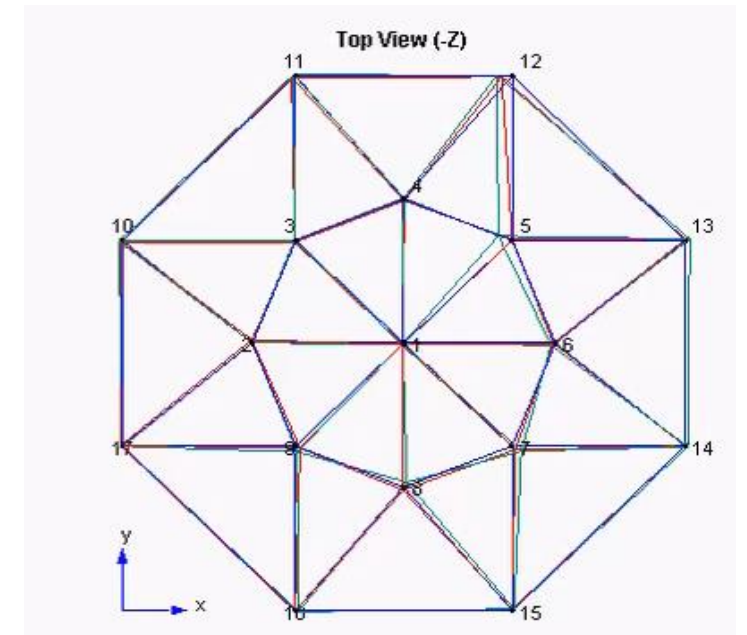
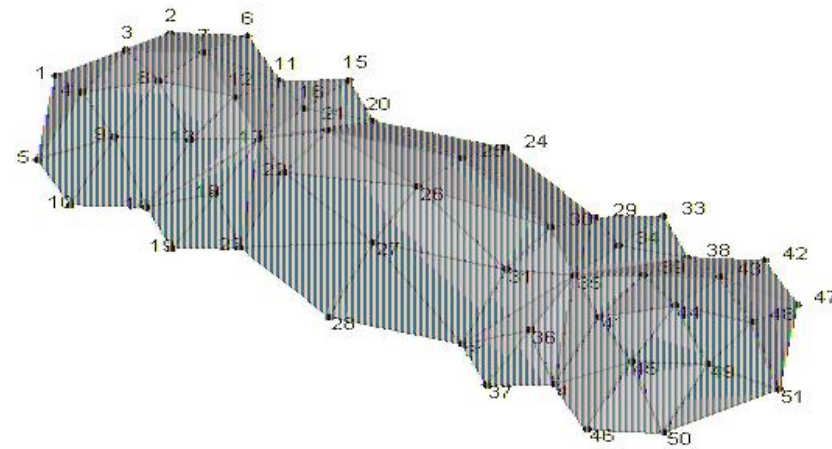
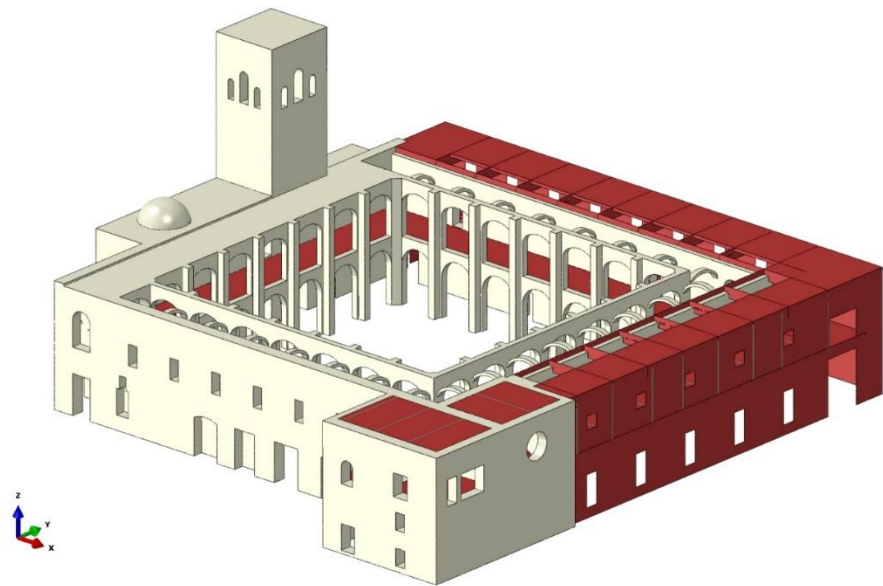
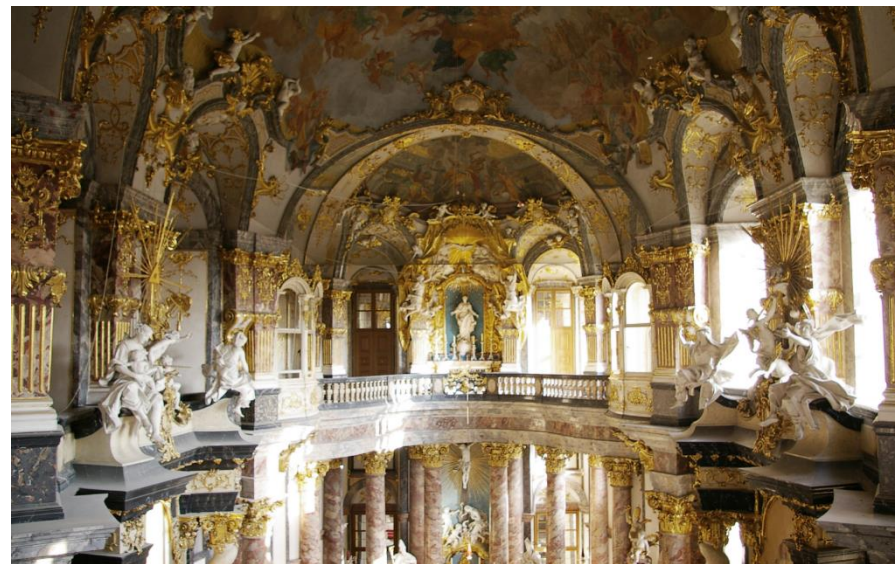


# IDENTIFICACIÓN DE DAÑO EN ESTRUCTURAS HISTÓRICAS MEDIANTE ANÁLISIS MODAL OPERACIONAL (OMA)

Víctor Compán Cardiel  
Escuela Técnica Superior de Arquitectura  
Universidad de Sevilla



**Monasterio de San Jerónimo.  
Sevilla**



**Capilla de la Residencia de  
Wurzburg. Alemania**



**Capilla de la Jura. Jerez de la  
Frontera**

# Líneas de Investigación

- Análisis Estructural de Edificaciones Históricas
  - Identificación de sus propiedades dinámicas.
    - Ensayos de vibración ambiental
    - Análisis modal operacional
  - Actualización de modelos de elementos finitos
  - Análisis avanzado de estructuras históricas.
    - Respuesta no-lineal.

## Casos de estudio

- Capilla de la Jura. Jerez de la Frontera
- Monasterio de San Jerónimo. Sevilla
- Capilla de la Residencia de Wurzburg. Alemania

# Capilla de la Jura. Jerez de la Frontera

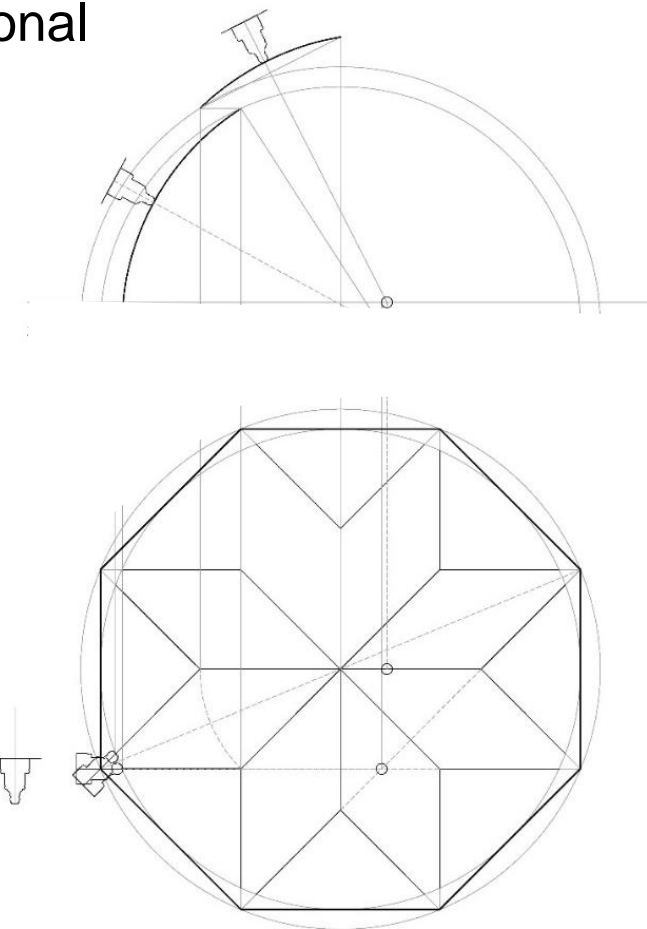


## Objetivos

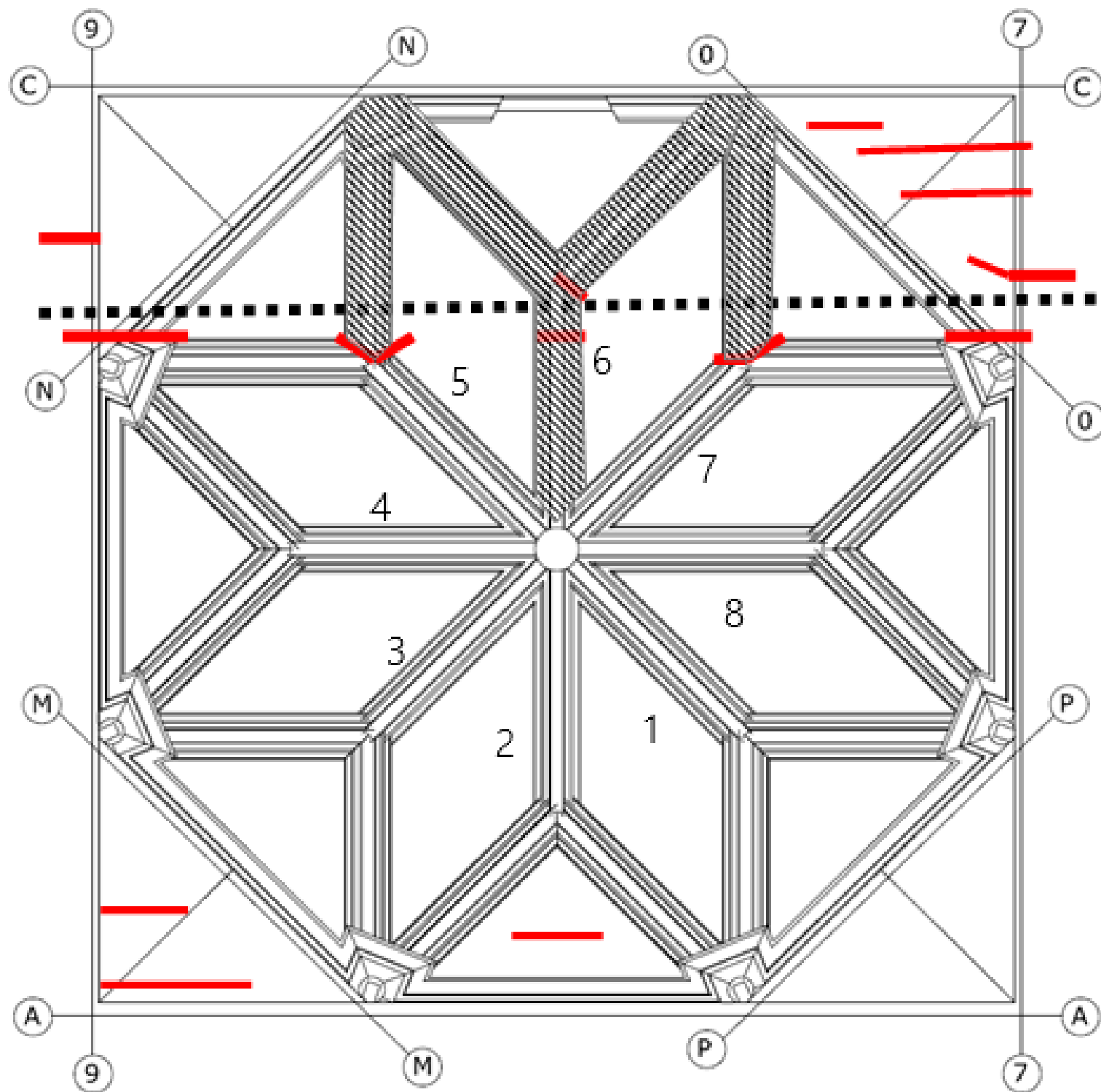
- Control estructural de la intervención
- Evaluación de la intervención

## Tools

- Modelo de Elementos Finitos
- Test de vibración ambiental
- Análisis modal operacional



# Capilla de la Jura. Jerez de la Frontera



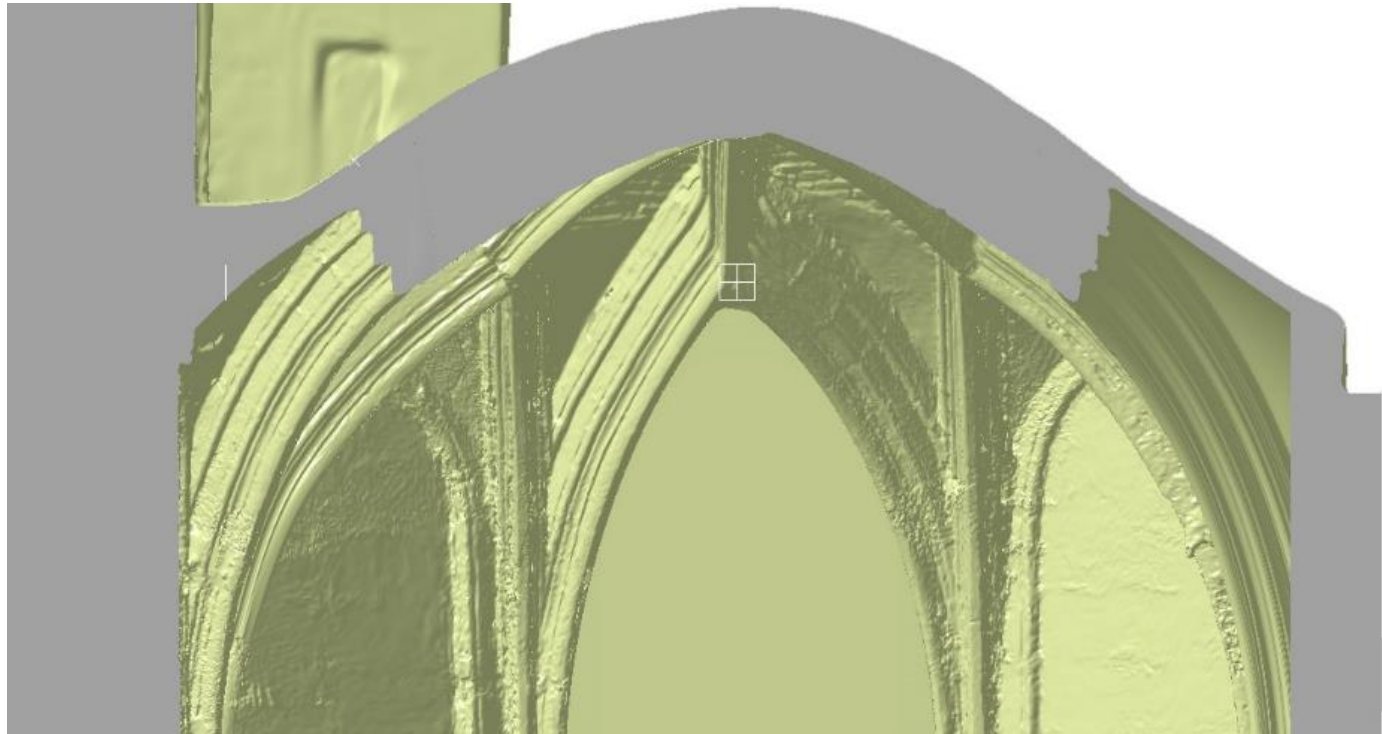
IDENTIFICACIÓN DE DAÑO EN ESTRUCTURAS HISTÓRICAS MEDIANTE ANÁLISIS MODAL OPERACIONAL (OMA)

Víctor Compán Cardiel

Malaga, 20 de mayo de 2016



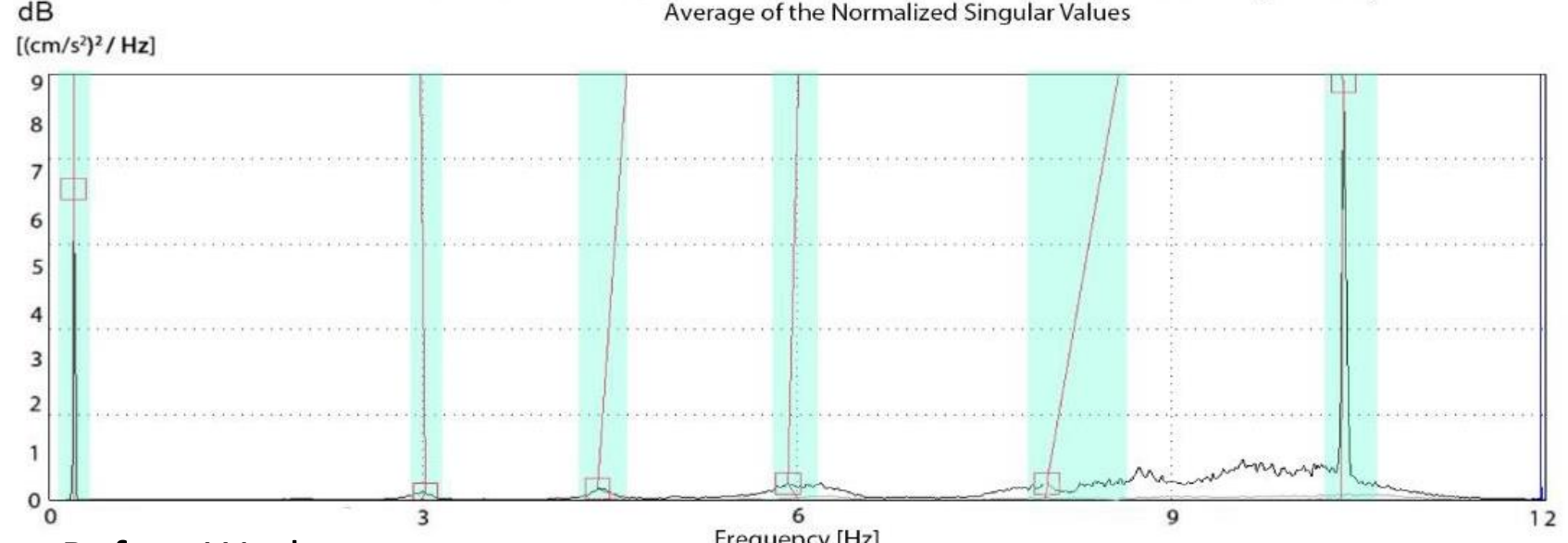
# Capilla de la Jura. Jerez de la Frontera



Levantamiento tridimensional. Fotogrametría

## Enhanced Frequency Domain Decomposition (EFDD)

Average of the Normalized Singular Values



Before Works

### Cursor Values

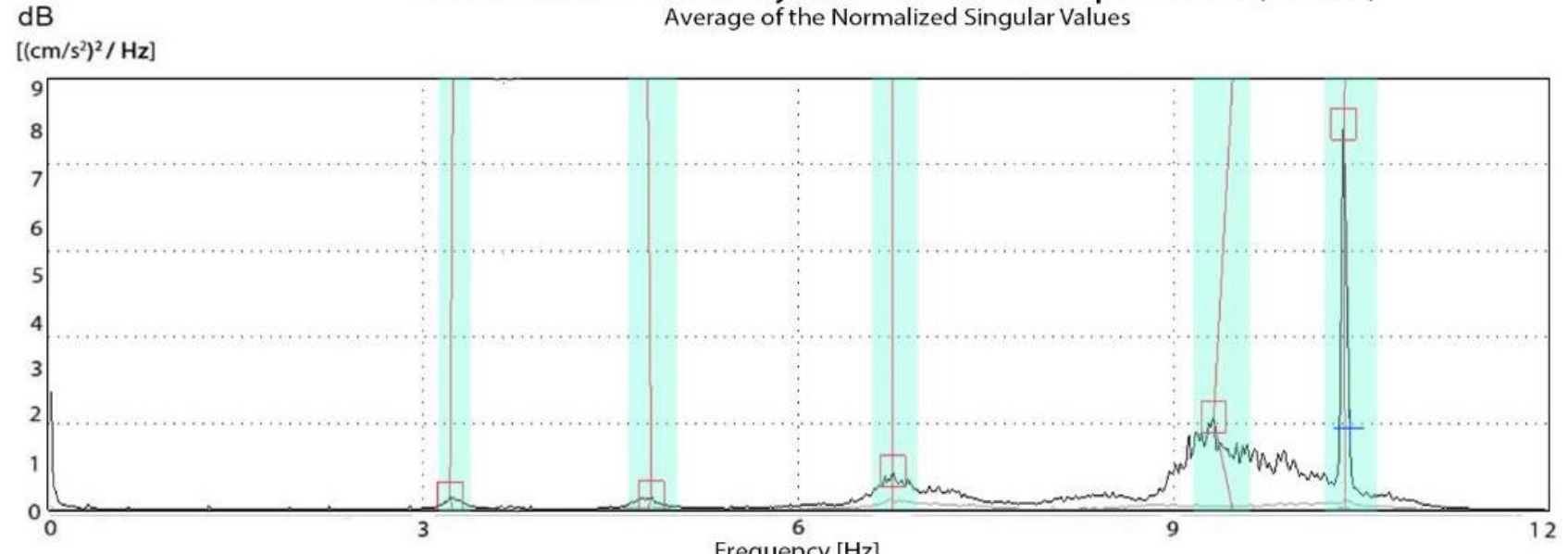
Frequency = 12 Hz  
SVD Line = 1

### Indicators

- Estimated Mode
- Modal Domain

## Enhanced Frequency Domain Decomposition (EFDD)

Average of the Normalized Singular Values



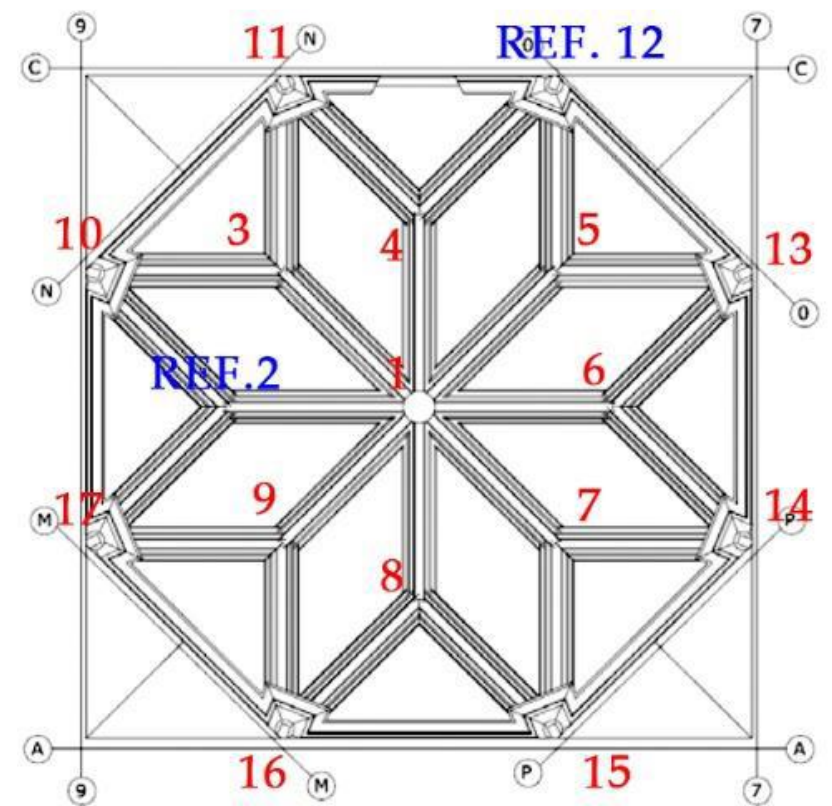
After works

### Cursor Values

Frequency = 12 Hz  
SVD Line = 1

### Indicators

- Estimated Mode
- Modal Domain

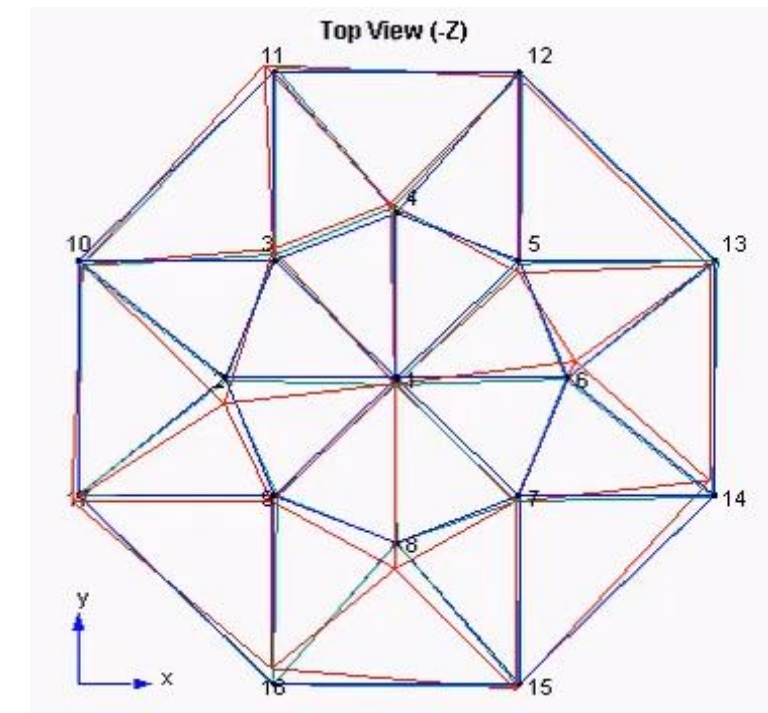
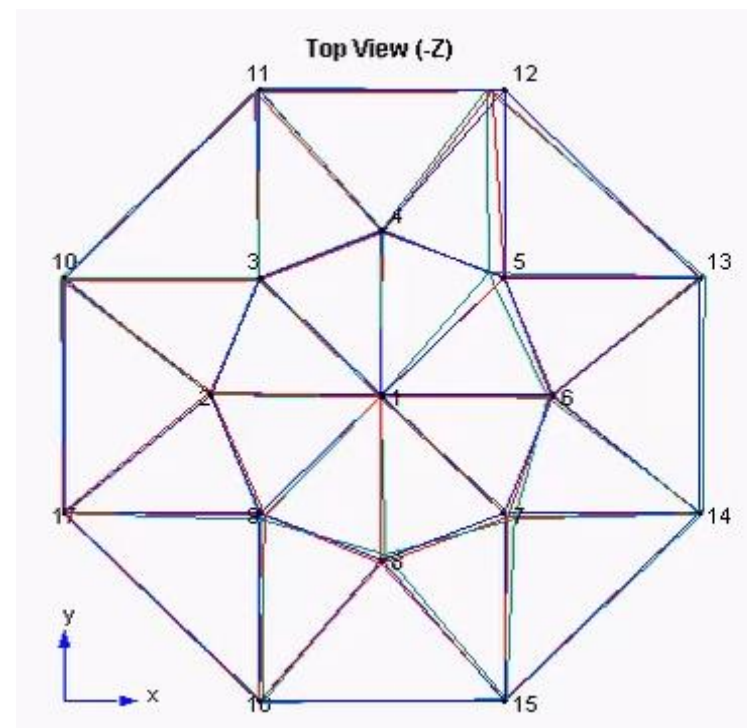
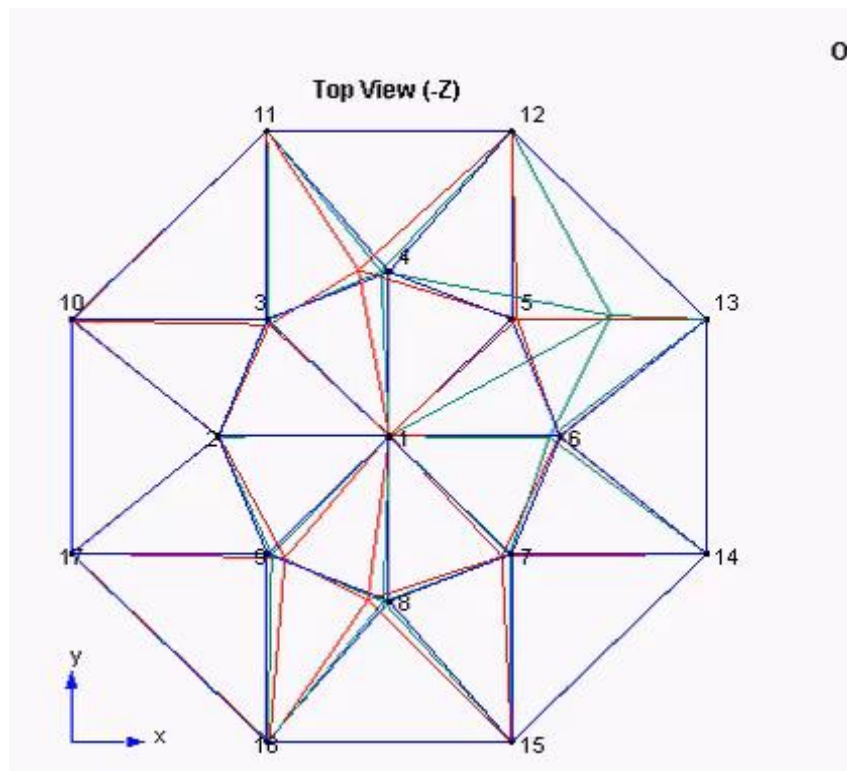


## OMA Technique

**Table 1.** Results of the experimental modal analysis tests before the works.

	EFDD		SSI		MAC
	f [Hz]	$\xi$ (%)	f [Hz]	$\xi$ (%)	
<b>Mode 1</b>	0.198	3.643	0.201 (1.49)	4.621	0.88
<b>Mode 2</b>	2.977	2.753	2.995 (0.66)	3.003	0.98
<b>Mode 3</b>	4.598	1.168	4.417 (3.93)	2.350	0.91
<b>Mode 4</b>	6.007	1.843	6.001 (0.10)	4.164	0.89
<b>Mode 5</b>	8.029	0.733	7.828 (2.50)	2.840	0.85
<b>Mode 6</b>	10.38	0.275	10.38 (0.00)	0.951	0.98

The percentage in brackets indicates the relative error taking as a reference the results of the EFDD method



## OMA Technique

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The percentage in brackets indicates the relative error taking as a reference the results of the EFDD method

**Table 2.** Results of the experimental modal analysis tests after the works.

	EFDD		SSI		MAC
	f [Hz]	$\xi$ (%)	f [Hz]	$\xi$ (%)	
<b>Mode 1</b>	-	-	-	-	-
<b>Mode 2</b>	3.238	2.030	3.240 (0.06)	3.336	0.99
<b>Mode 3</b>	4.776	0.960	4.772 (0.08)	2.588	0.87
<b>Mode 4</b>	7.205	0.772	7.240 (0.48)	4.823	0.85
<b>Mode 5</b>	9.010	1.794	8.967 (0.47)	3.822	0.81
<b>Mode 6</b>	10.38	0.127	10.38 (0.00)	0.409	0.99

The percentage in brackets indicates the relative error taking as a reference the results of the EFDD method

## OMA Technique

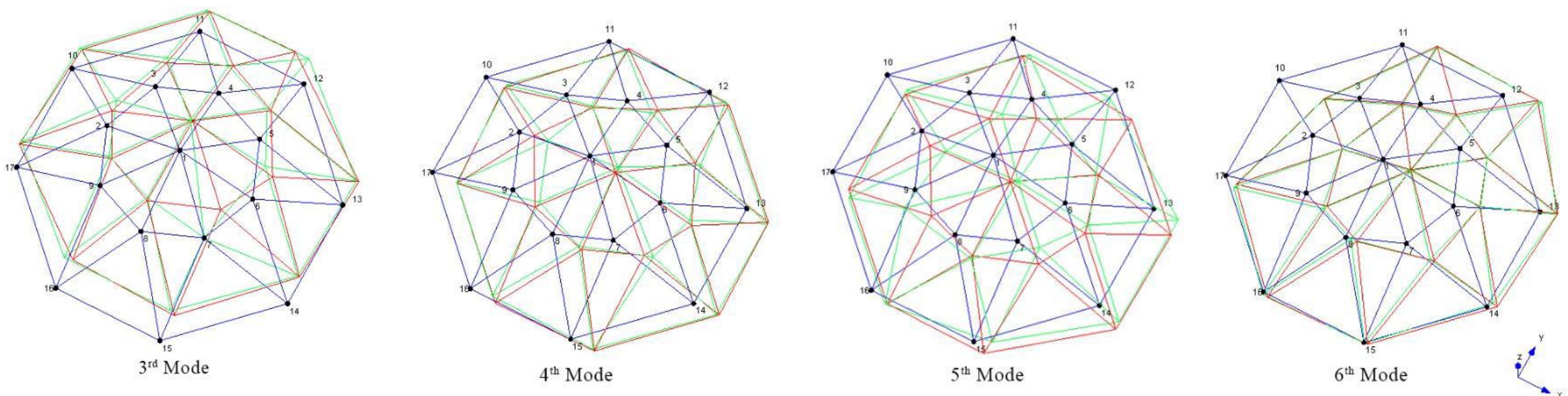
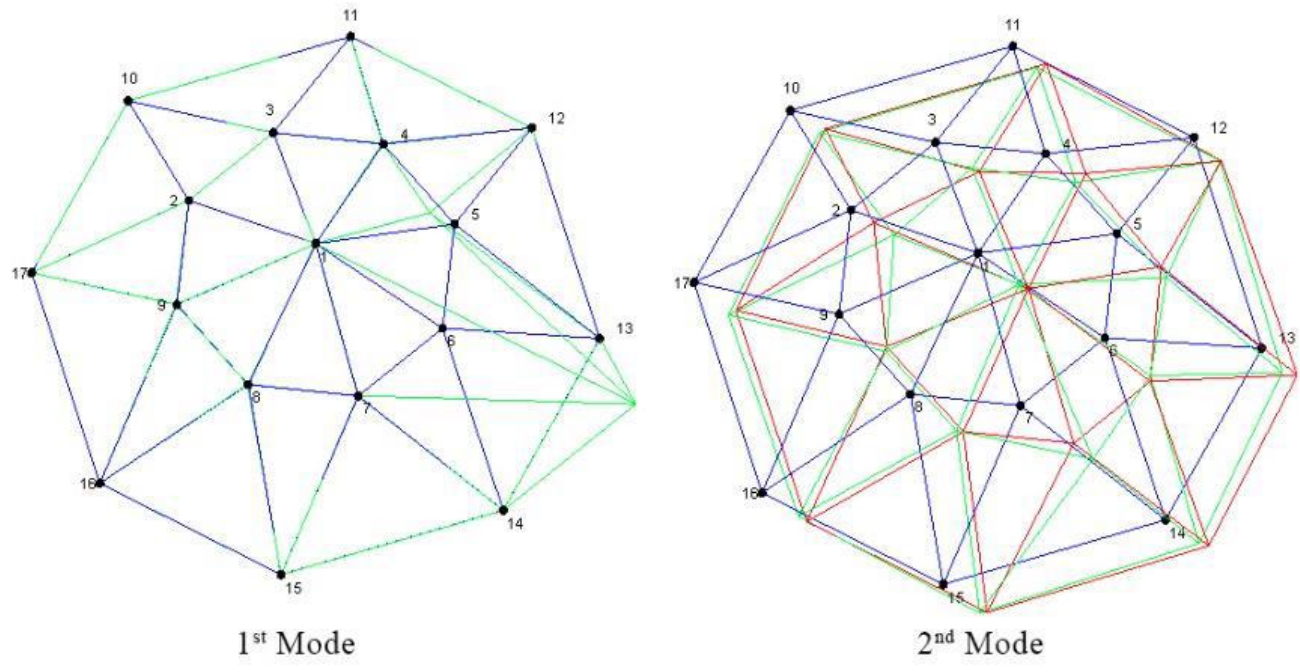


# Capilla de la Jura. Jerez de la Frontera

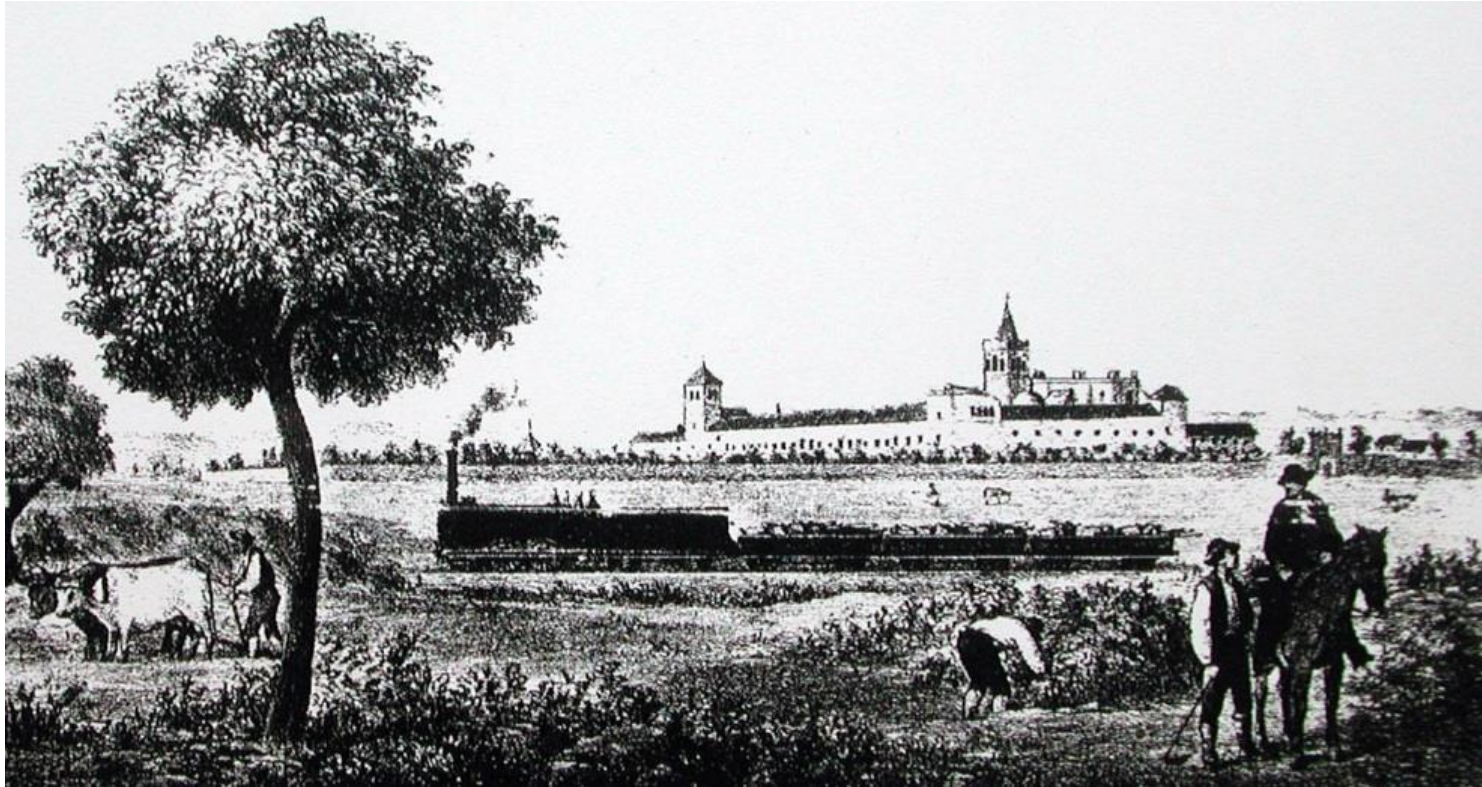
**Table 3.** Comparison of modal results.

	Natural Frequency [EFDD-Hz]		% Dif.
	Before works	After works	
<b>Mode 1</b>	0.198	-	-
<b>Mode 2</b>	2.977	3.238	+8.76
<b>Mode 3</b>	4.598	4.776	+3.85
<b>Mode 4</b>	6.007	7.205	+19.94
<b>Mode 5</b>	8.029	9.010	+12.21
<b>Mode 6</b>	10.38	10.38	+0.00

■ Undeformed geometry     
 ■ Before works     
 ■ After works



Evaluación de la intervención estructural



## Objetivos

- Análisis del estado actual de la estructura
- Establece una medición de referencia para futuras intervenciones

## Herramientas

- Modelo de Elementos Finitos
- Test de Vibración Ambiental
- OMA
- Actualización de MEF
- Análisis Estructural



# Monasterio de San Jerónimo. Sevilla



- Tower
- Church\_disappeared
- Main Cloister
- East Cloister\_disap.
- Printing Press\_disap.
  
- Two Floors
- One Floor

Monasterio de San Jerónimo



Galería Alta

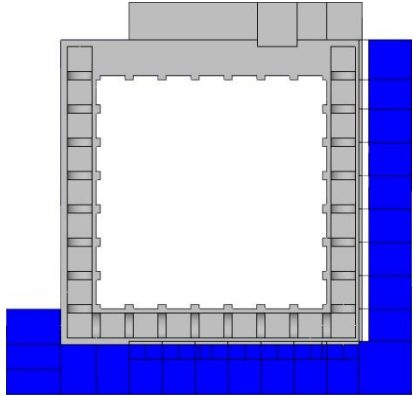


Claustro principal



Imagen de la Torre

# Monasterio de San Jerónimo. Sevilla



Civic center project



Proyecto del Centro Cívico

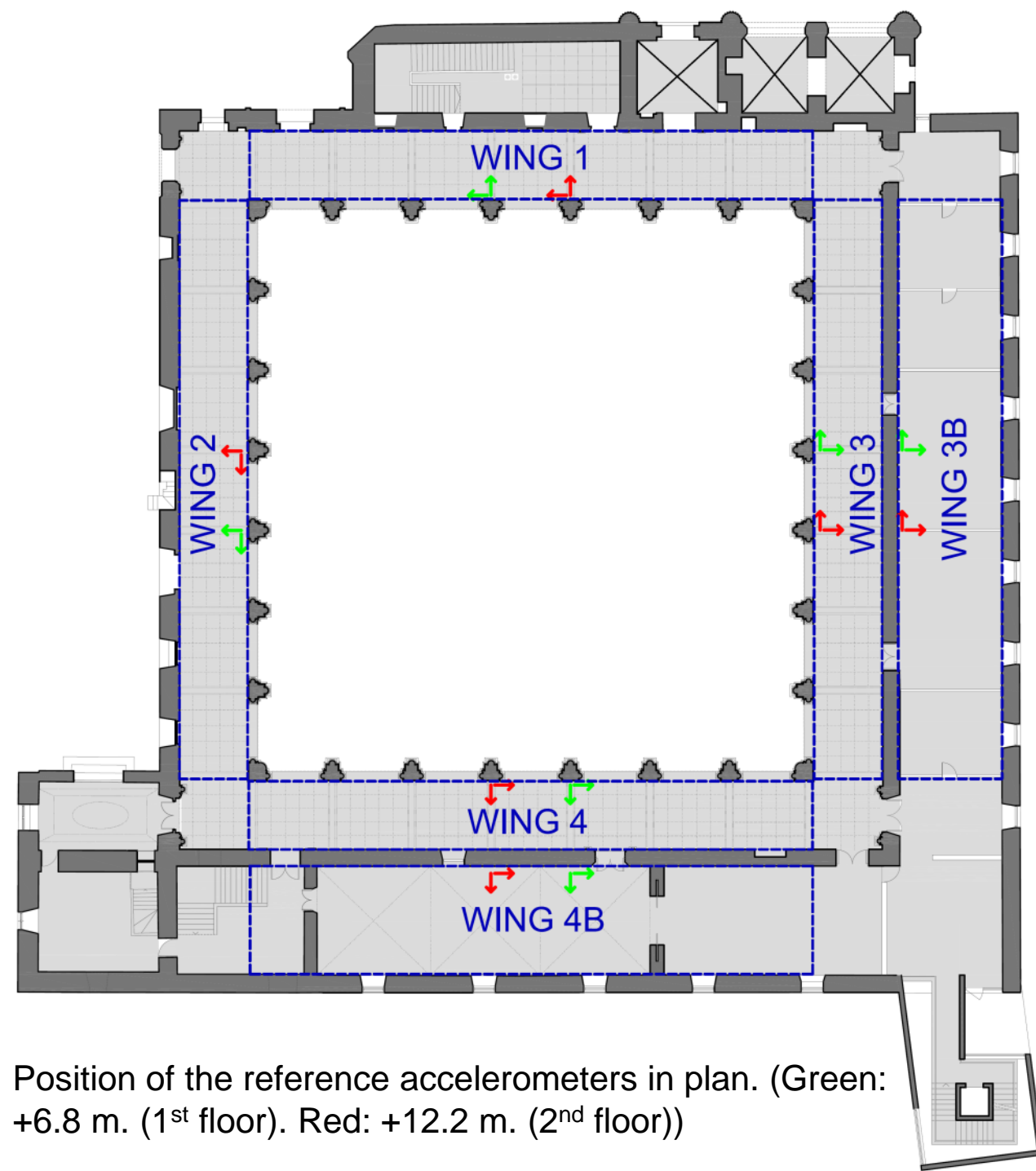


Grietas entre las bóvedas y los muros perimetrales. Ala Este



Grietas verticales en pilar de esquina.

# Monasterio de San Jerónimo. Sevilla



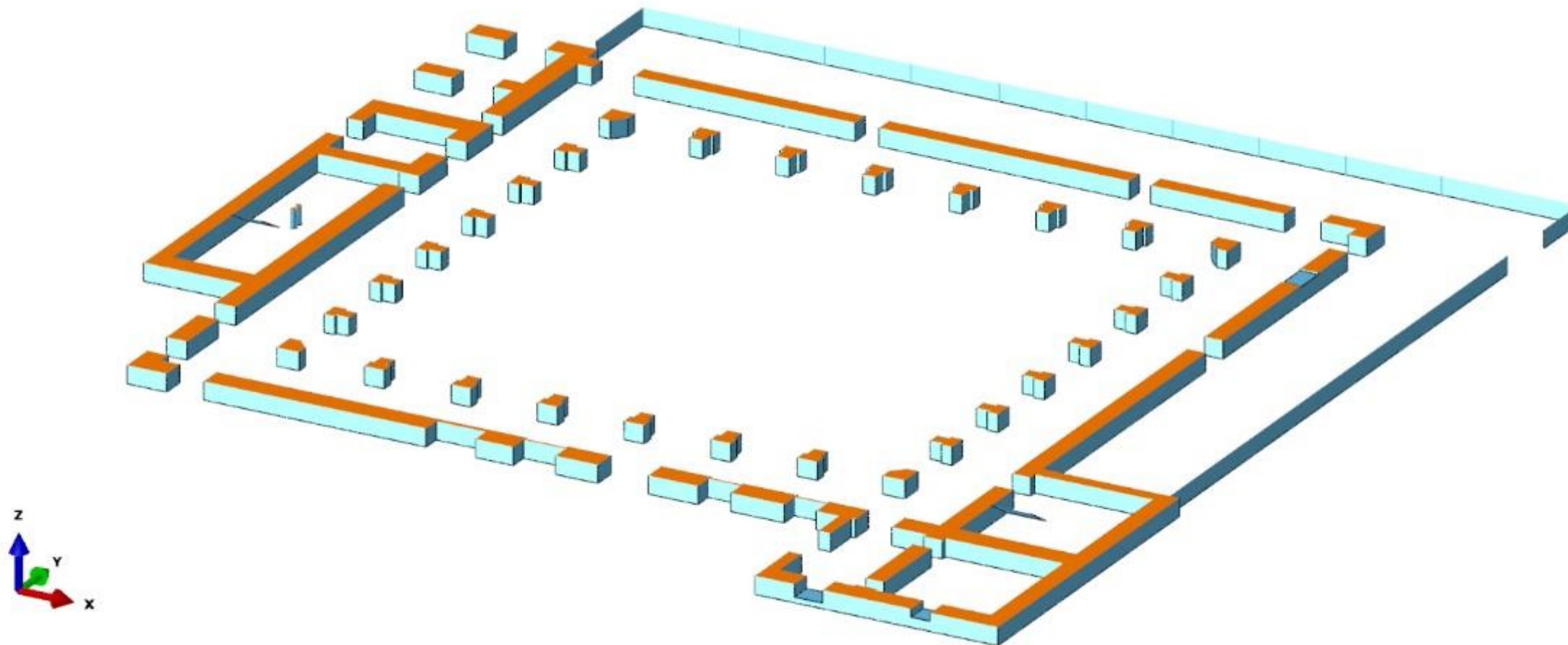
Position of the reference accelerometers in plan. (Green: +6.8 m. (1<sup>st</sup> floor). Red: +12.2 m. (2<sup>nd</sup> floor))

GENERAL MODES	WINGS	SSI (F)	EFDD (F)	% DIF.	MAC
1	1, 3	2,01	2,01	0,00	0,99
2	1, 3, 3B, 4, 4B	3	3,04	1,32	0,97
3	1, 2, 4, 4B	3,51	3,57	1,68	0,99
4	2, 3, 3B	4,36	4,34	0,46	0,98
5	2, 4, 4B	4,75	4,71	0,85	0,96
6	3, 4	6,25	6,35	1,57	0,85

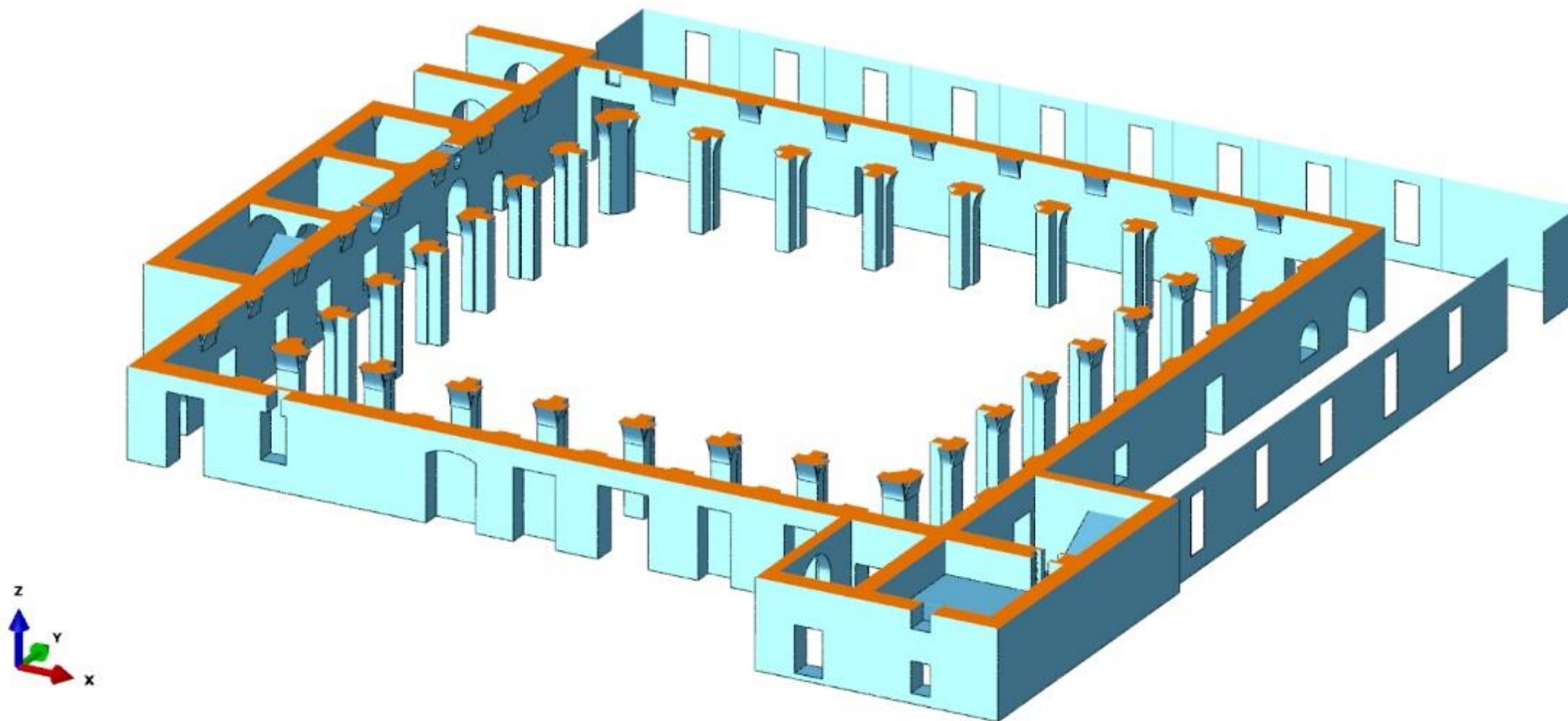
  

LOCAL MODES	WING	SSI (F)	EFDD (F)	% DIF.	MAC
1b	2	2,32	2,33	0,43	0,99
2b	2	3,34	3,35	0,30	0,98
3b	4	5,15	5,08	1,38	0,86
4b	3	7,22	7,17	0,70	0,85

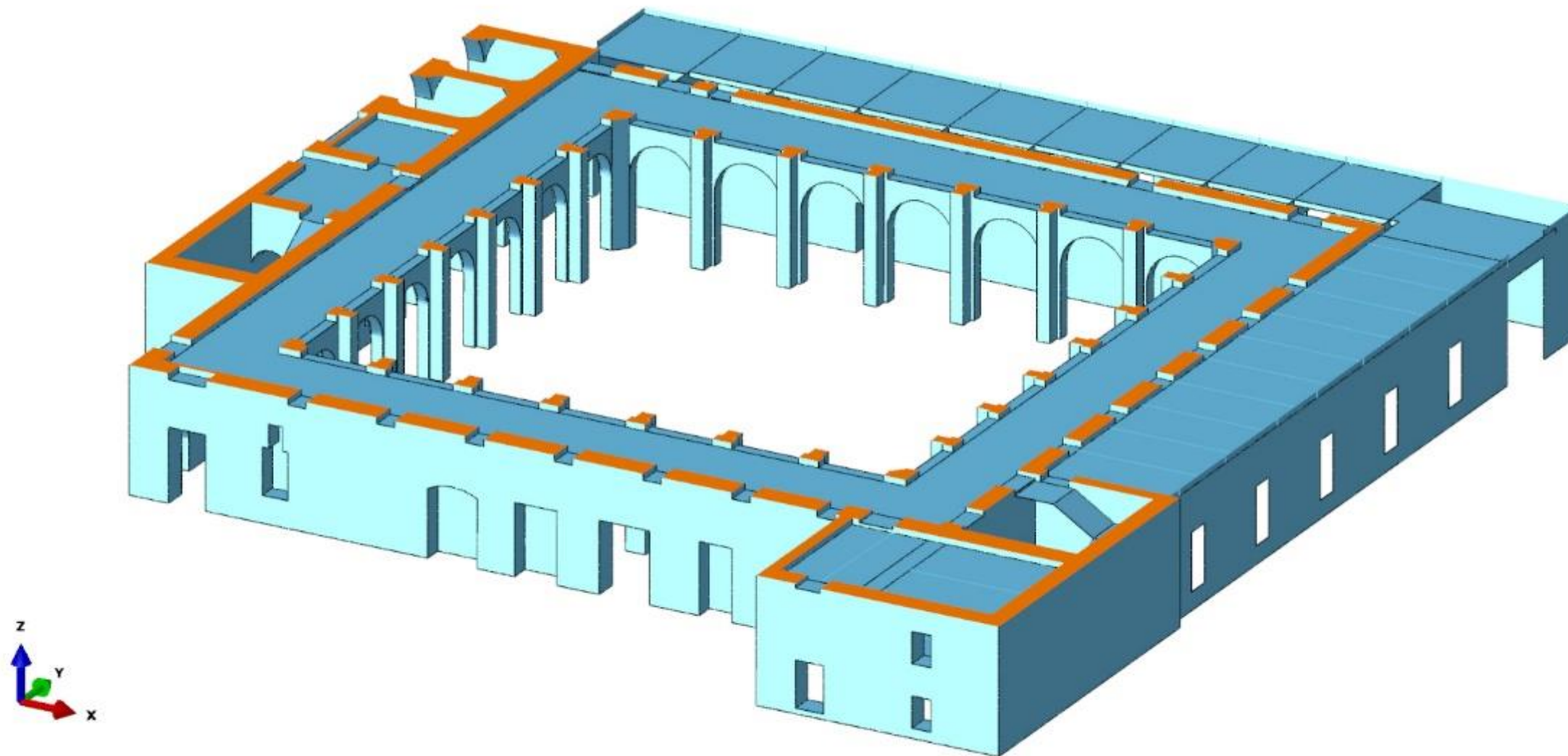
## OMA Technique



Finite Element Model

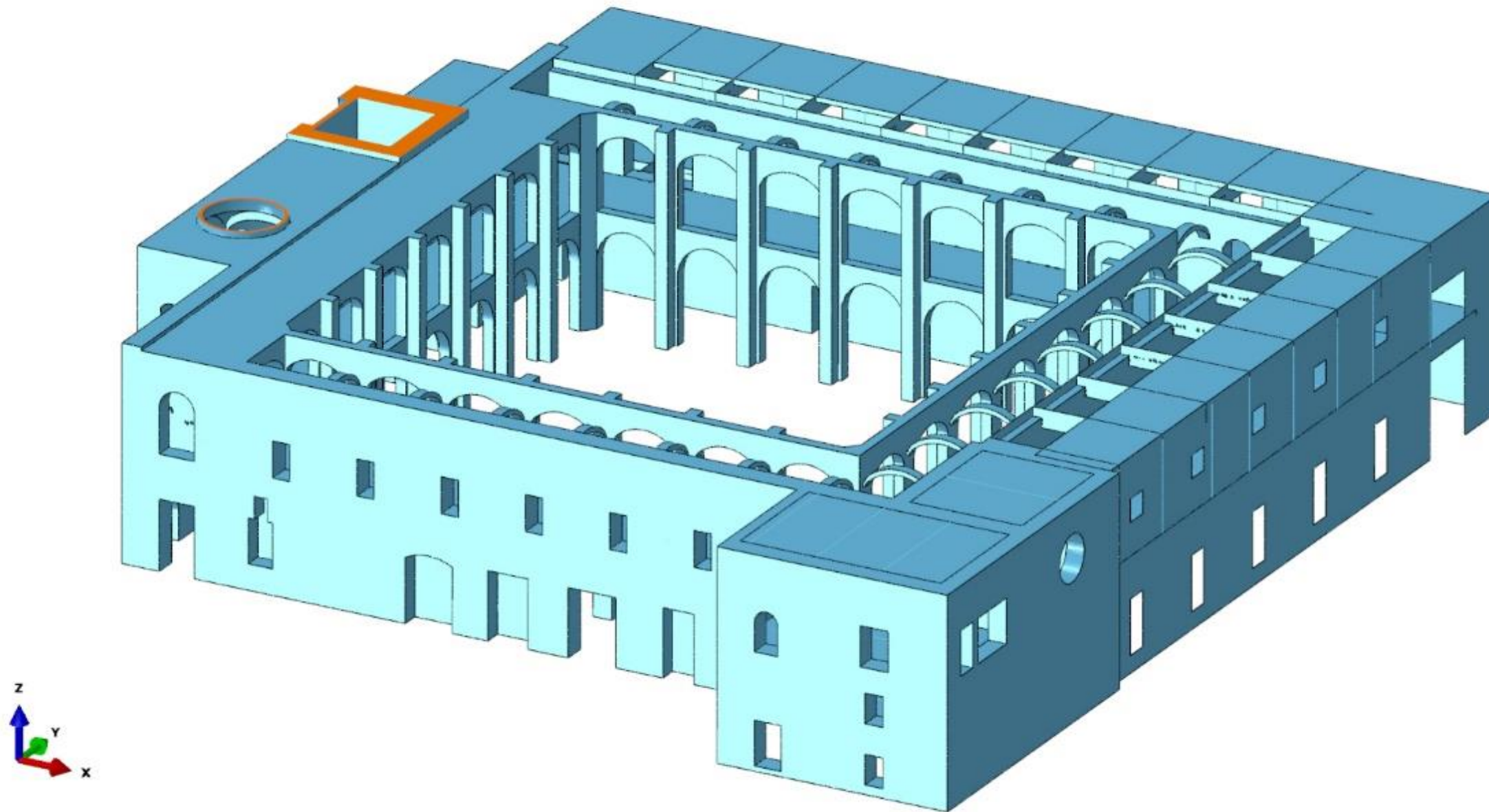


Finite Element Model

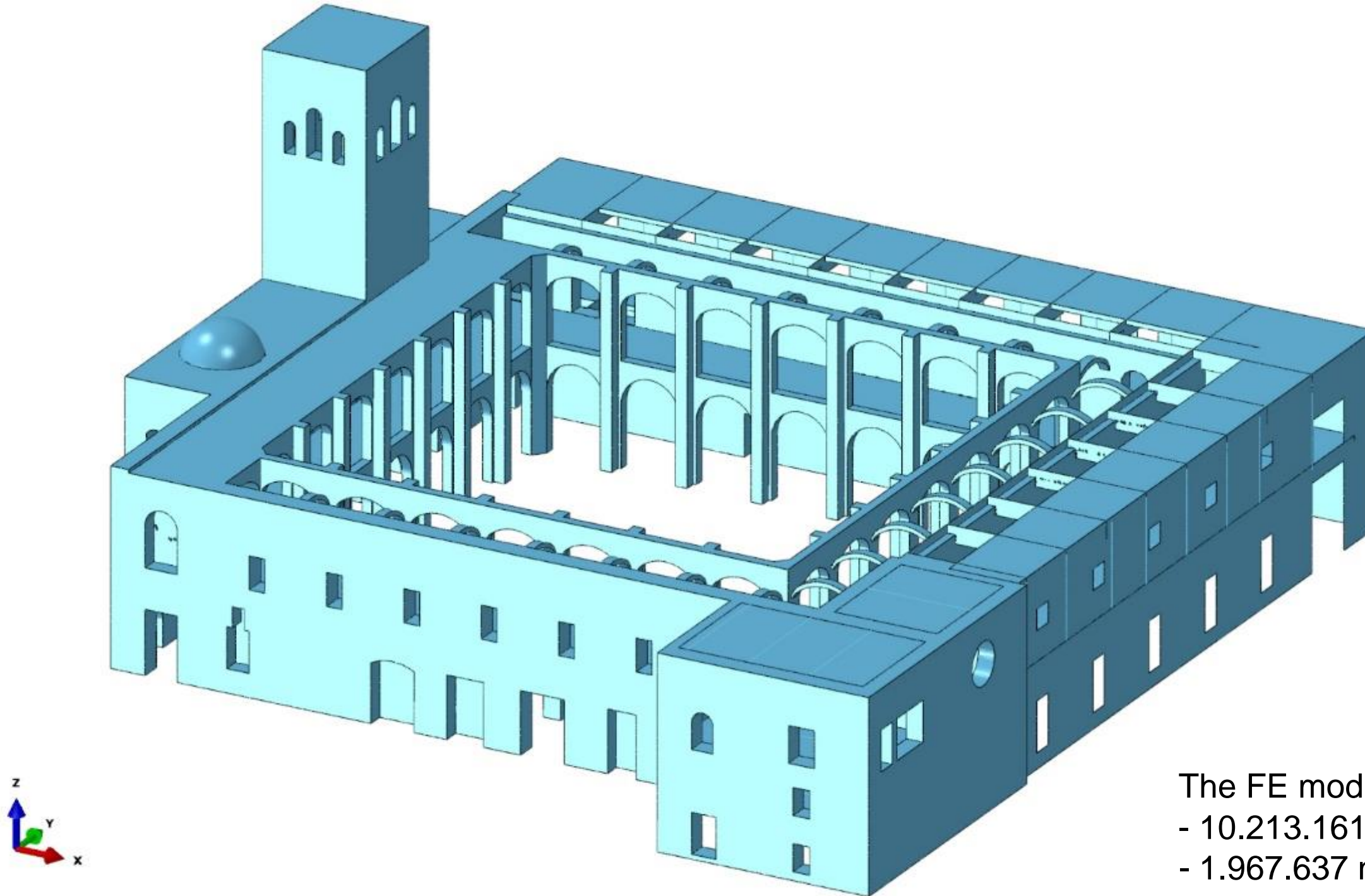


Finite Element Model





Finite Element Model



The FE model is composed by:

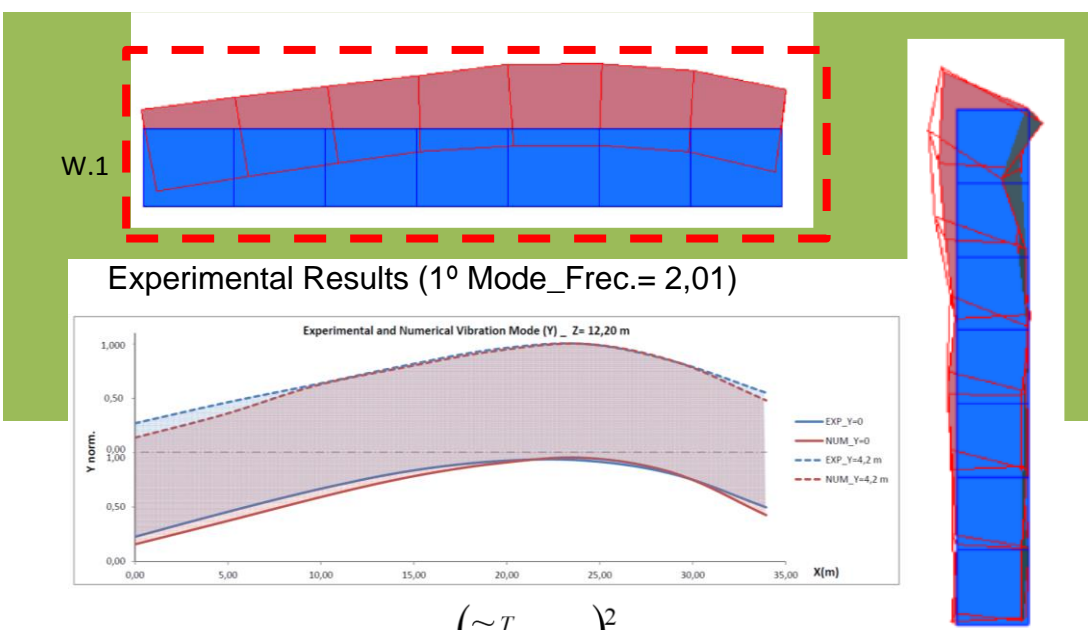
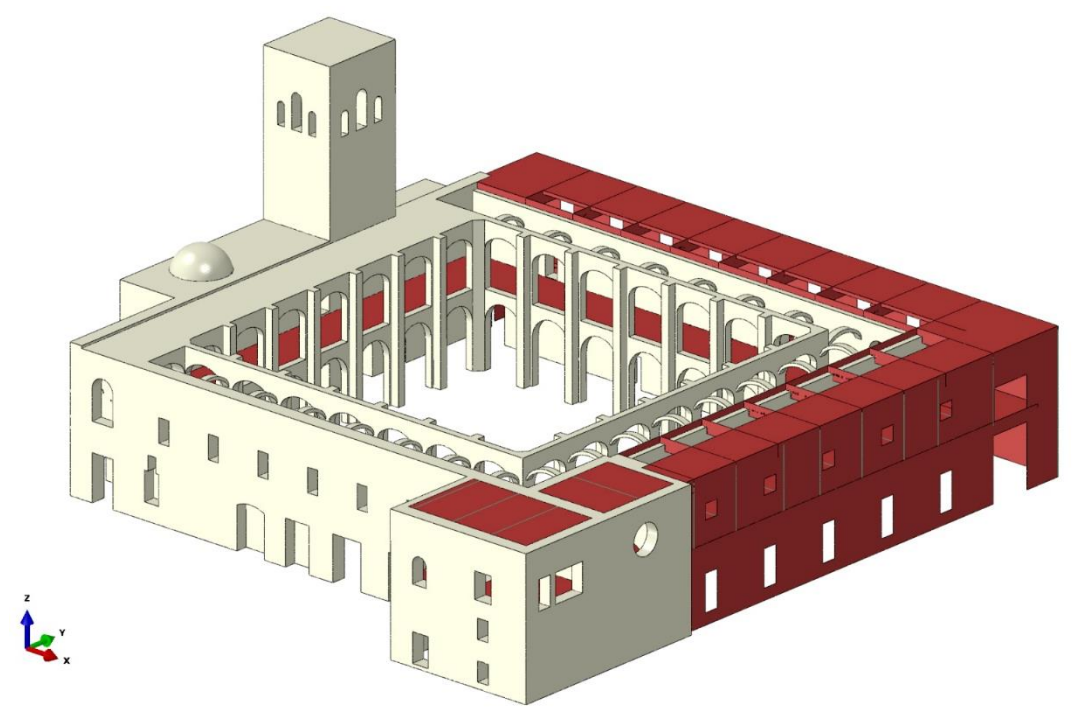
- 10.213.161 elements
- 1.967.637 nodes
- 6.113.772 degrees of freedom

Finite Element Model

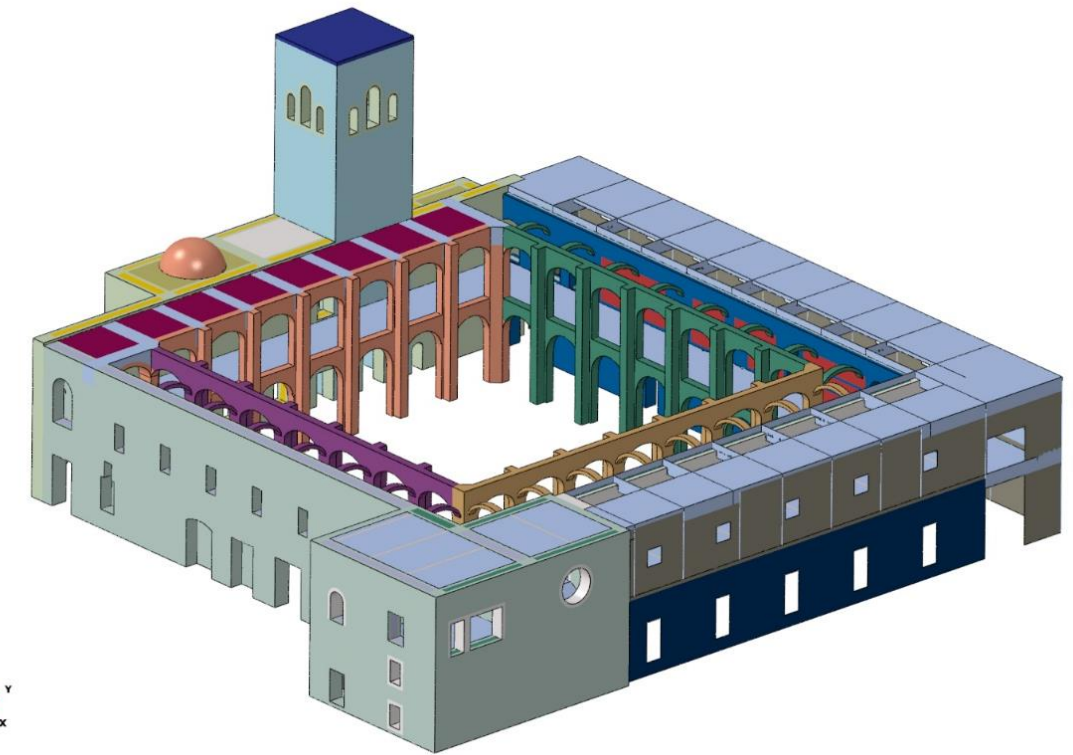
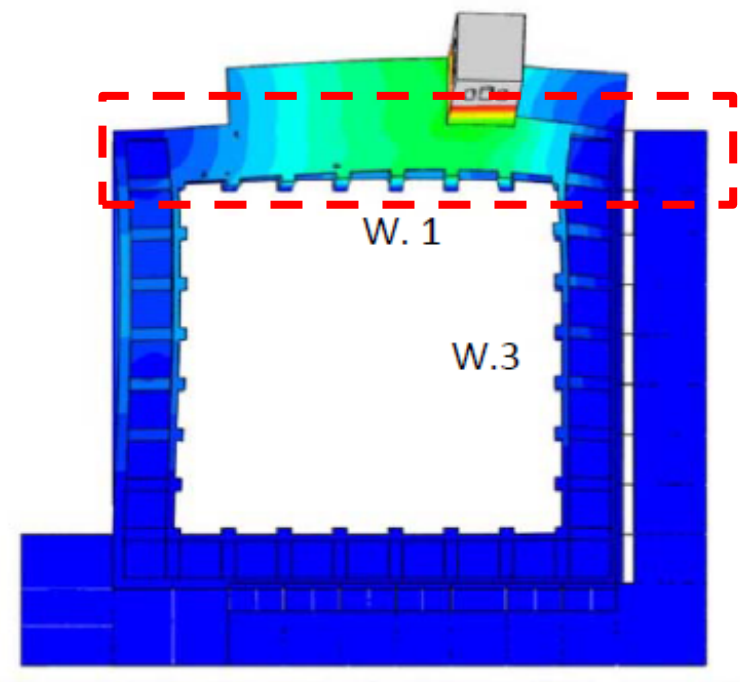
# Monasterio de San Jerónimo. Sevilla

Mechanical properties of materials in the updated Finite Element Model								
	Masonry				Filling Vaults	Filling Walls	Conc.	Steel
	E1	E2	E3	E4				
Density (Kg/m <sup>3</sup> )	1800	1800	1800	1800	500	1500	2500	7850
Young's modulus (MPa)	<b>950</b>	<b>1000</b>	<b>700</b>	<b>750</b>	500	500	23000	210000
Poisson Coefficient	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3

GENERAL MODES	WINGS	BEFORE UPDATING PROCESS			AFTER UPDATING PROCESS		
		F.E.M.	EXP. M.*	% DIF.	Up. F.E.M.	EXP. M.*	% DIF.
1	1, 3	2,2	2,01	9,45	1,93	2,01	3,98
2	1, 3, 3B, 4, 4B	3,5	3	16,67	3,13	3	4,33
3	1, 2, 4, 4B	4,42	3,72	18,82	3,69	3,72	0,81
4	2, 3, 3B	5,29	4,36	21,33	4,6	4,36	5,5
5	2, 4, 4B	5,73	4,75	20,63	4,74	4,75	0,21
6	3, 4	7,7	6,25	23,20	6,39	6,25	2,24



$$MAC_{j,K} (1^{\circ} \text{ mode}) = \frac{(\tilde{\varphi}_j^T \cdot \varphi_k)^2}{(\tilde{\varphi}_j^T \cdot \tilde{\varphi}_j) \cdot (\varphi_k^T \cdot \varphi_k)} = 0.991$$

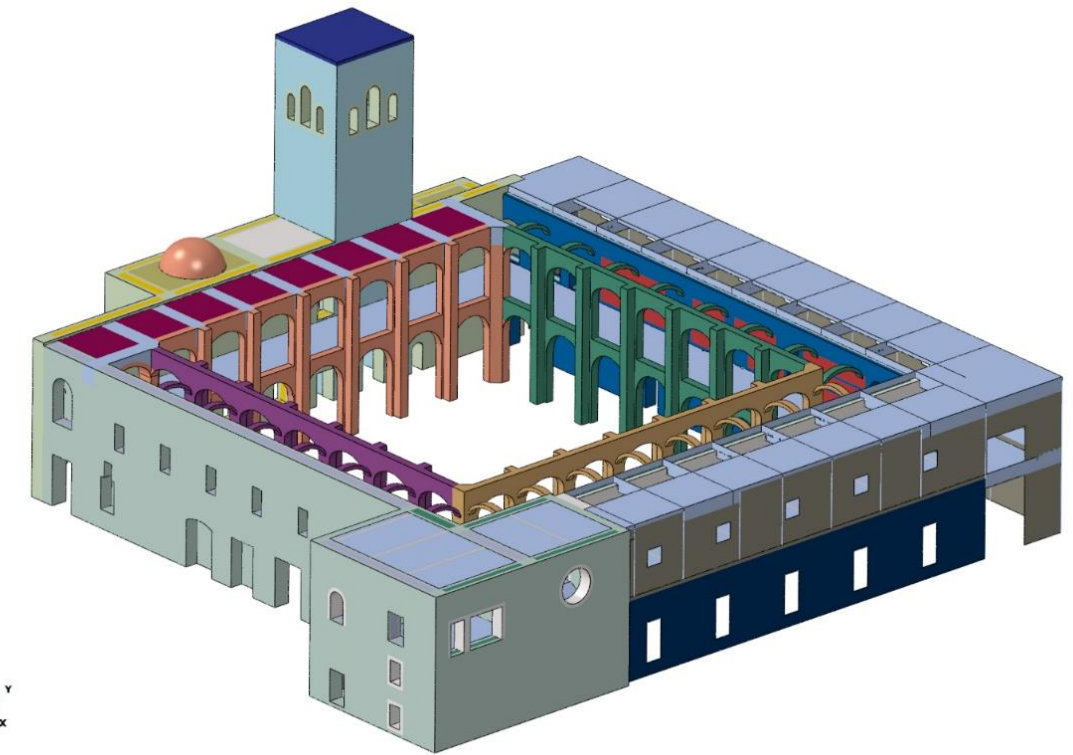
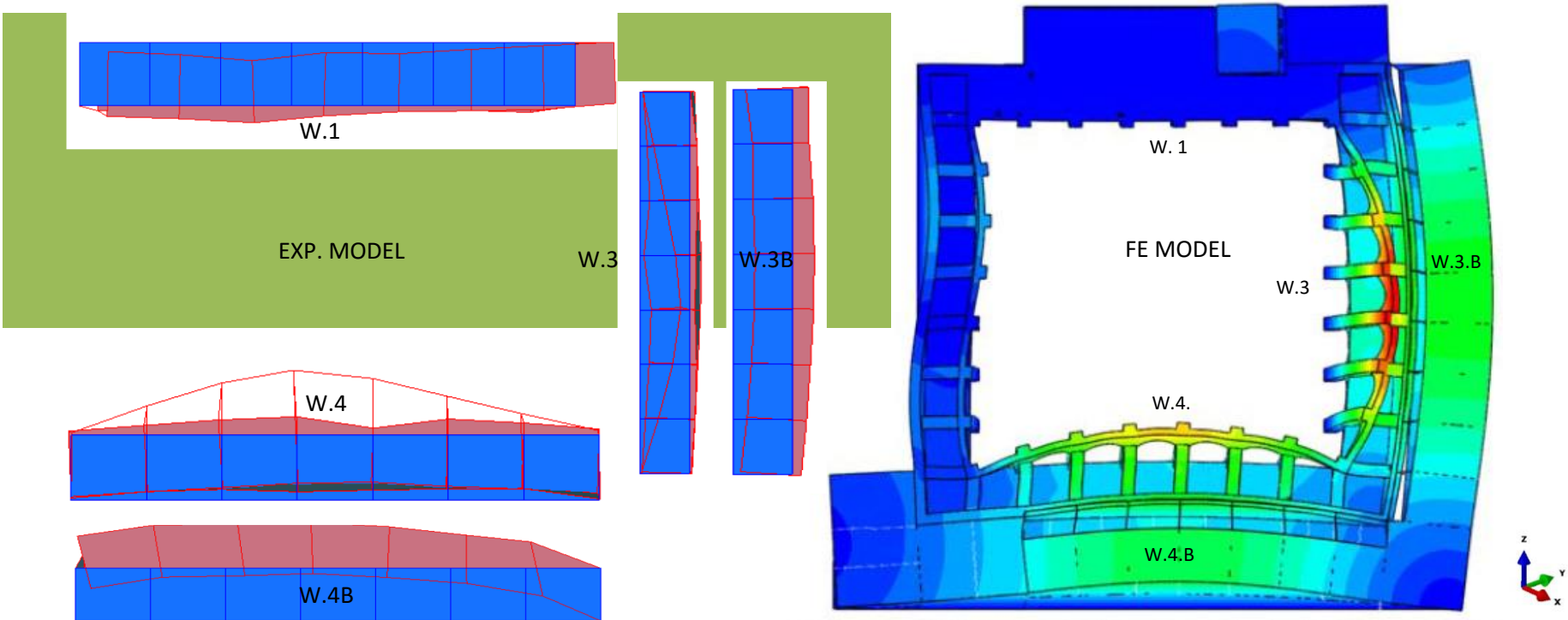
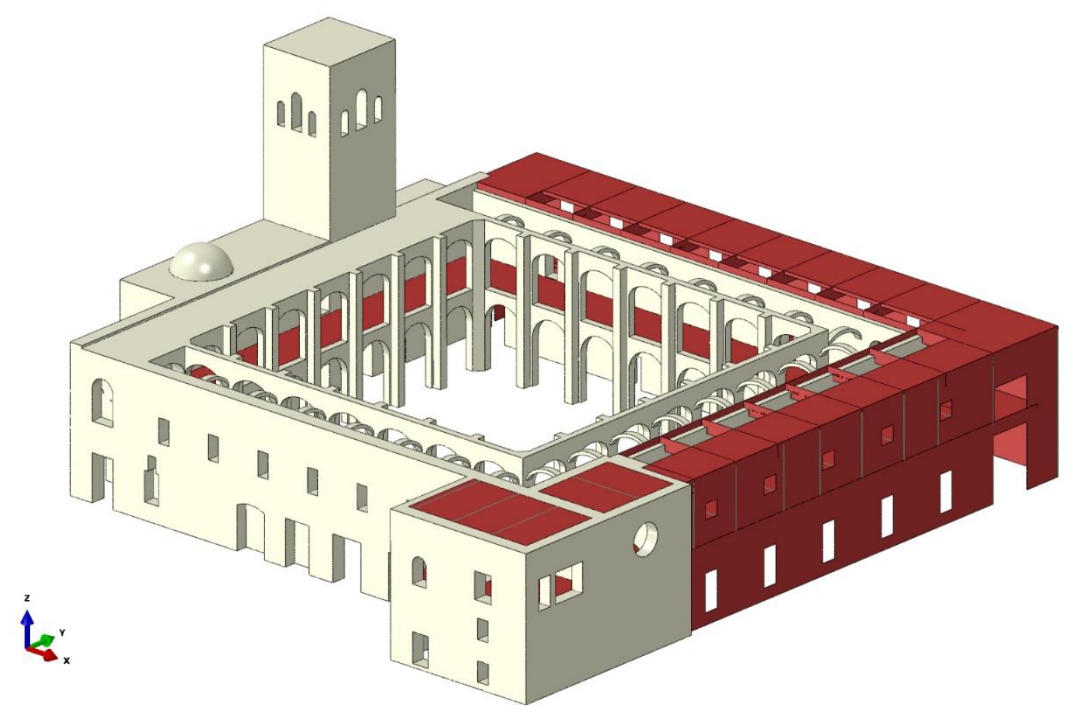


Model Updating process

# Monasterio de San Jerónimo. Sevilla

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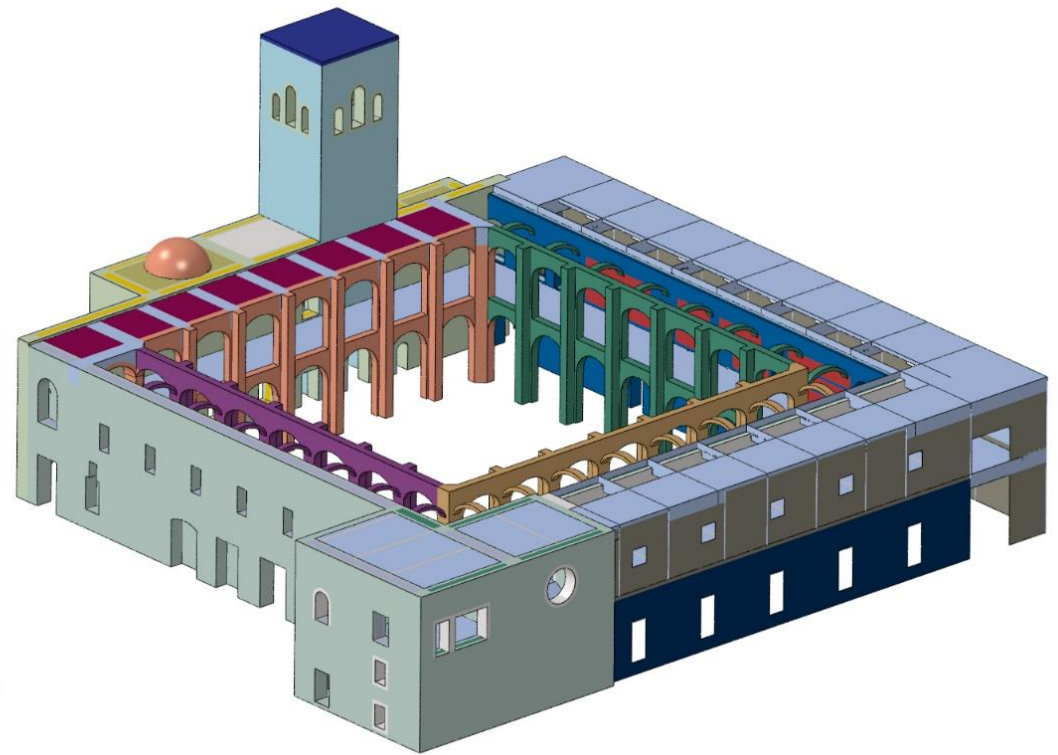
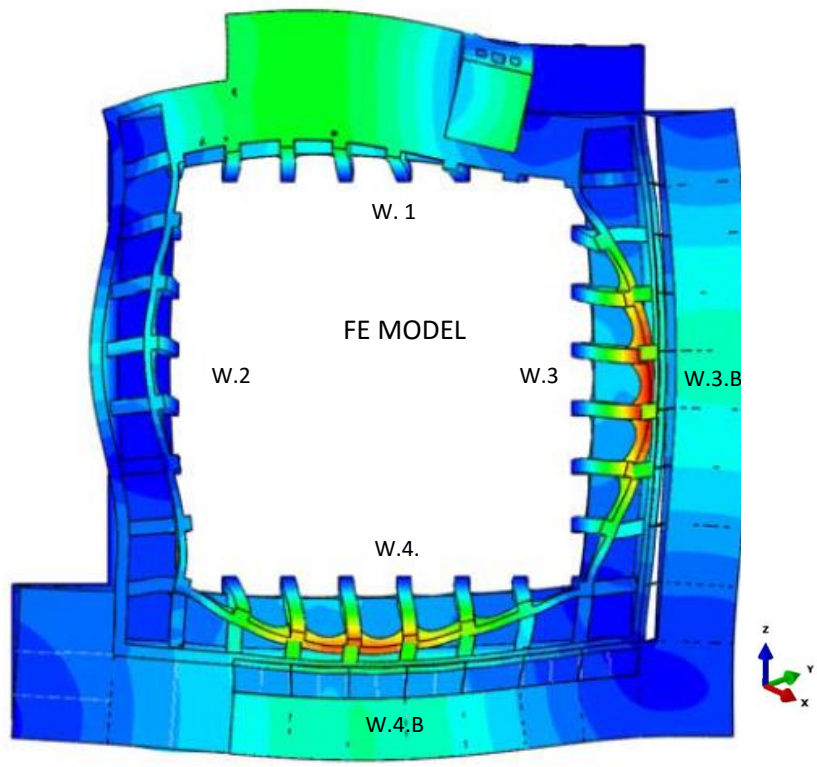
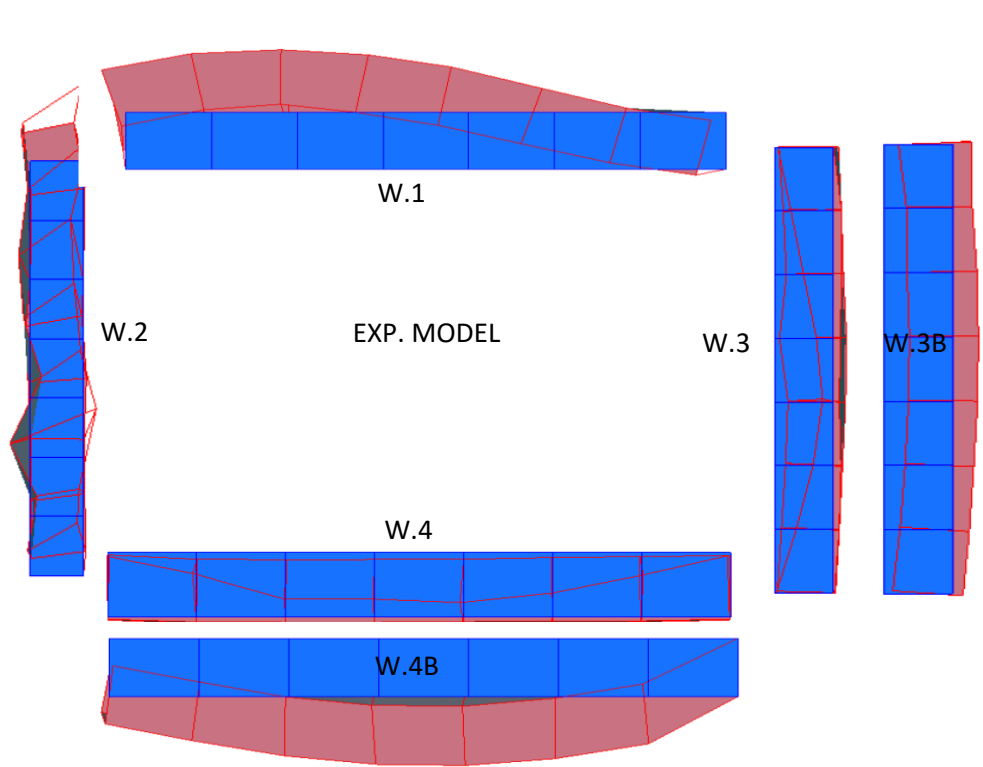
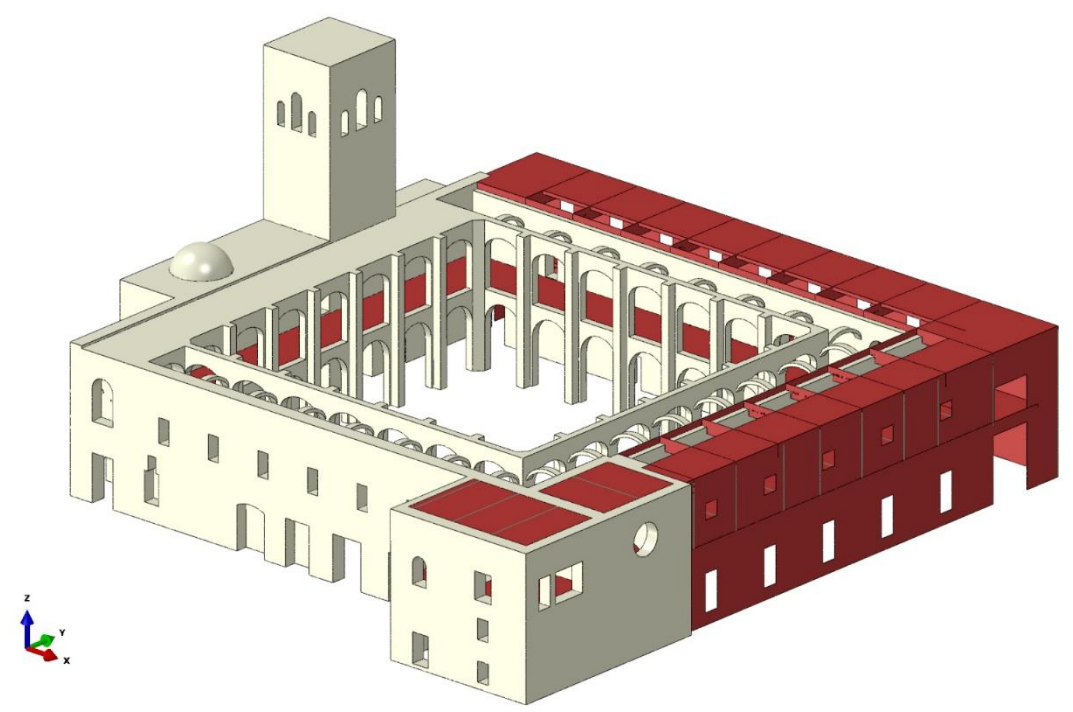


Model Updating process

# Monasterio de San Jerónimo. Sevilla

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GENERAL MODES	WINGS	BEFORE UPDATING PROCESS			AFTER UPDATING PROCESS		
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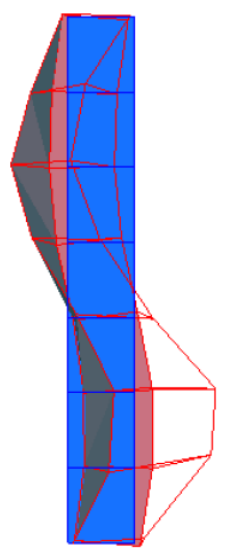
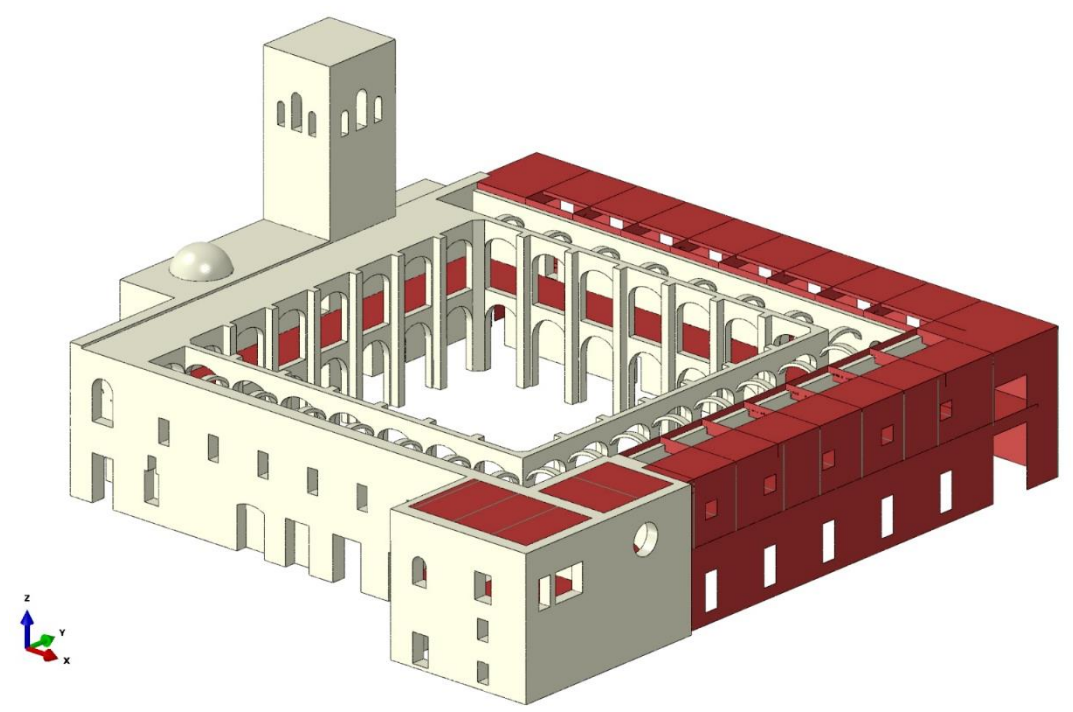


Model Updating process

# Monasterio de San Jerónimo. Sevilla

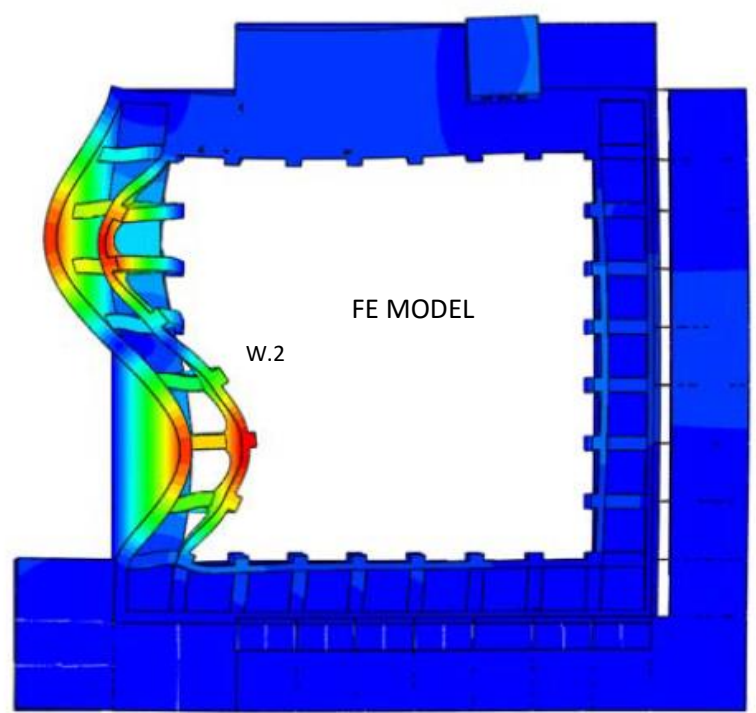
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Poisson Coefficient	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3

LOCAL MODES	WING	Up. F.E.M.	EXP. M.*	% DIF.	MAC
1b	2	2,27	2,32	2,16	0,996
2b	2	3,33	3,34	0,30	0,974
3b	4	5,1	5,15	0,97	0,782
4b	3	6,81	7,22	5,68	0,752



W.2

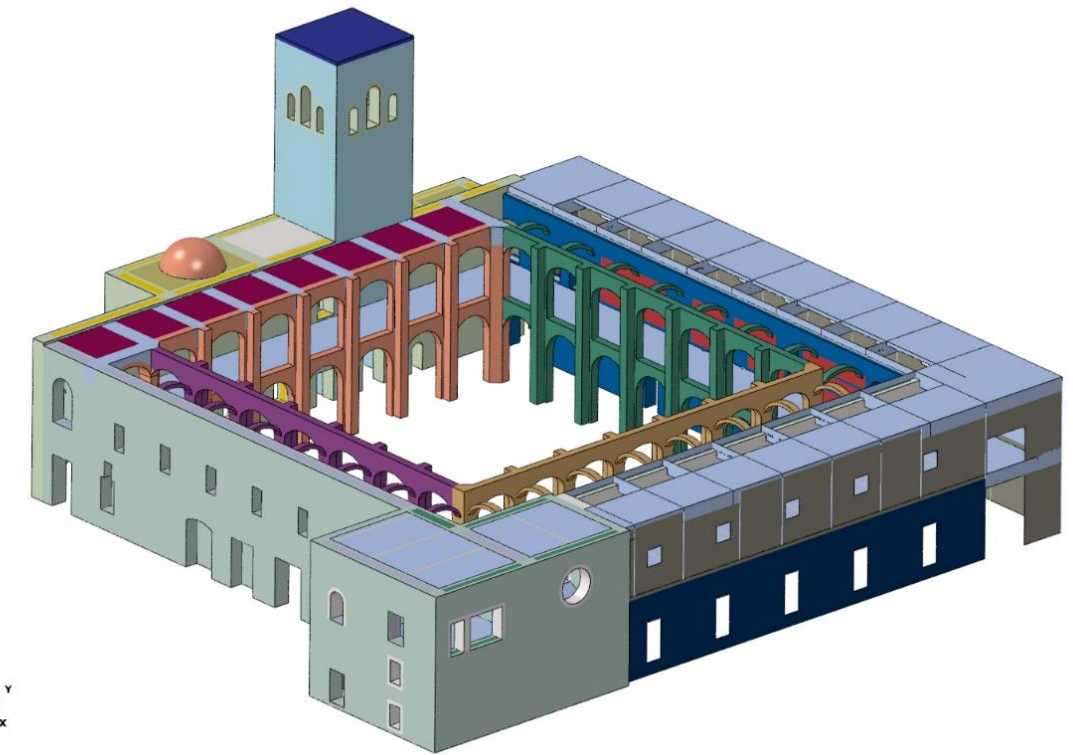
EXP. MODEL

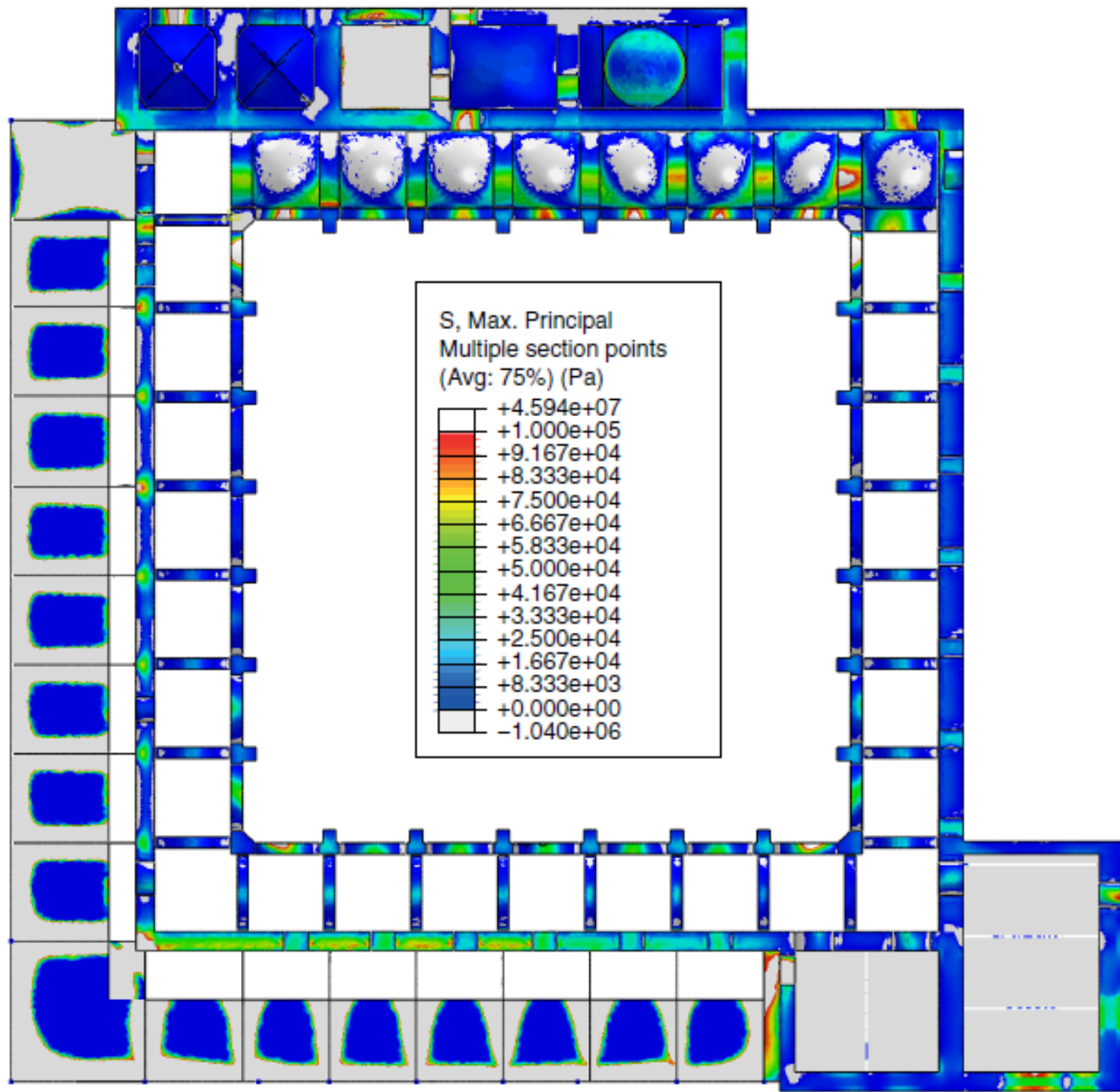


FE MODEL

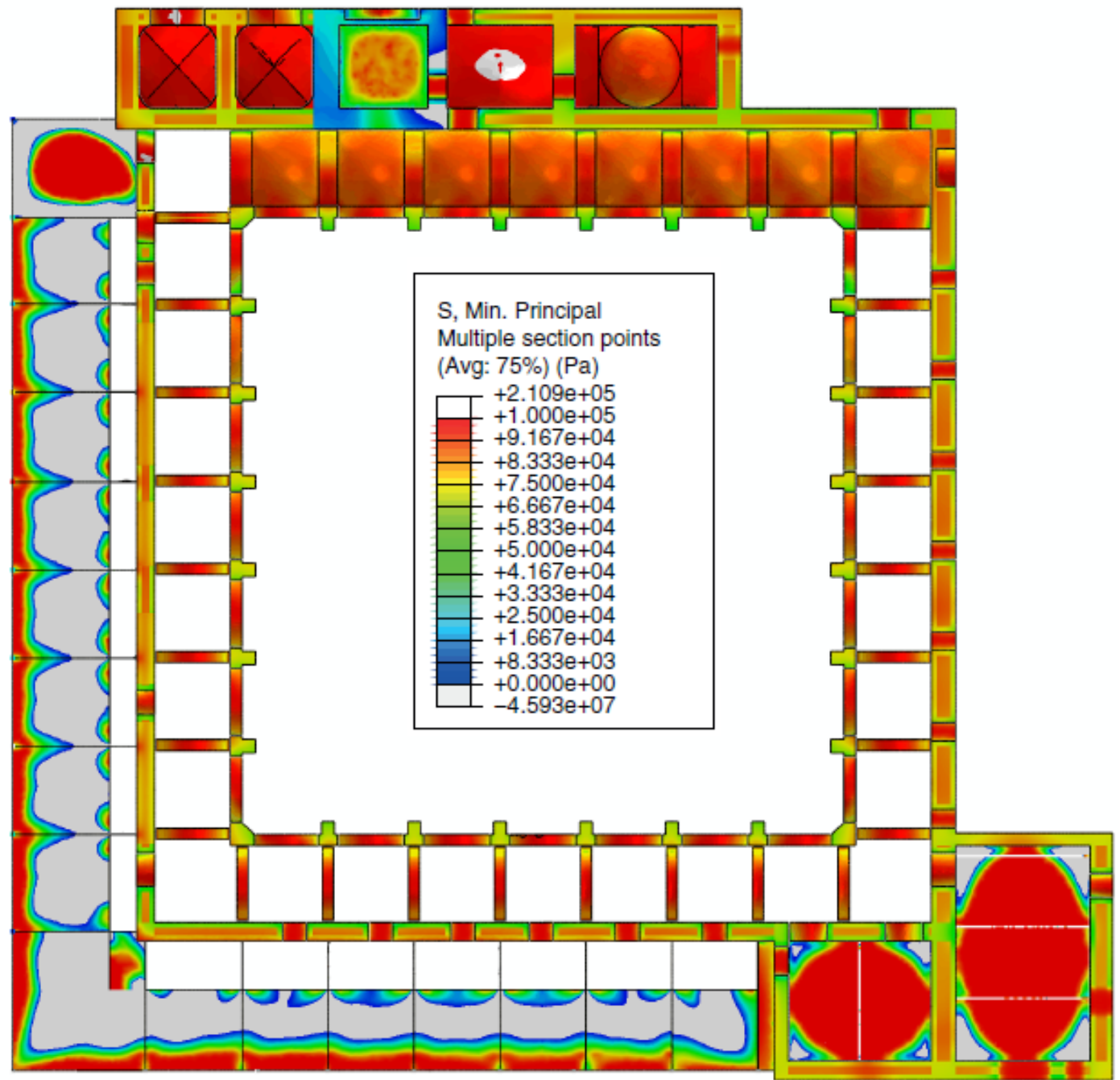
W.2

Model Updating process





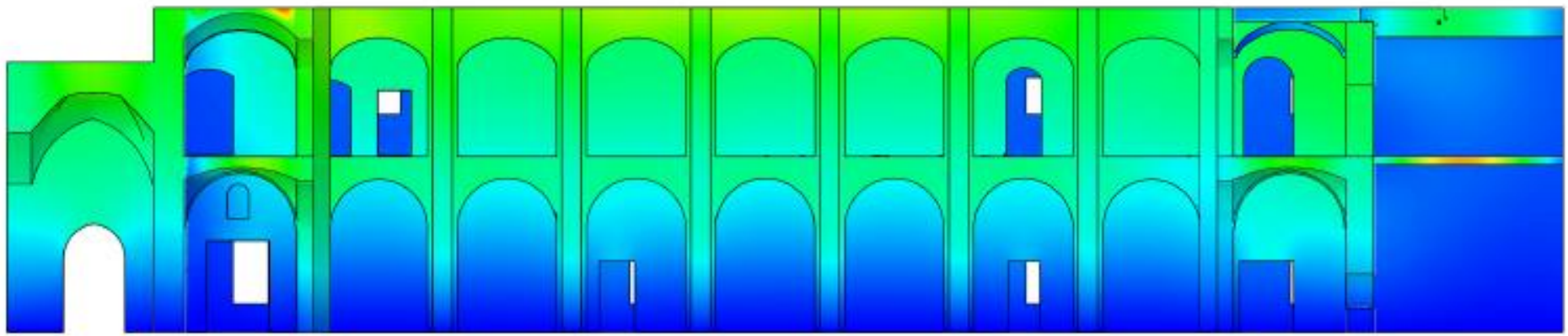
Tensile stresses



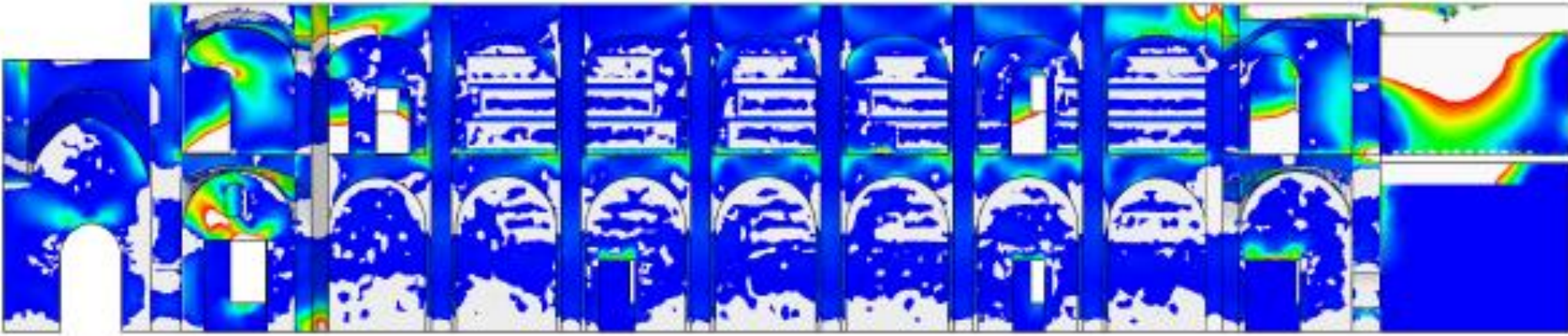
Compressive stresses

### Structural Analysis

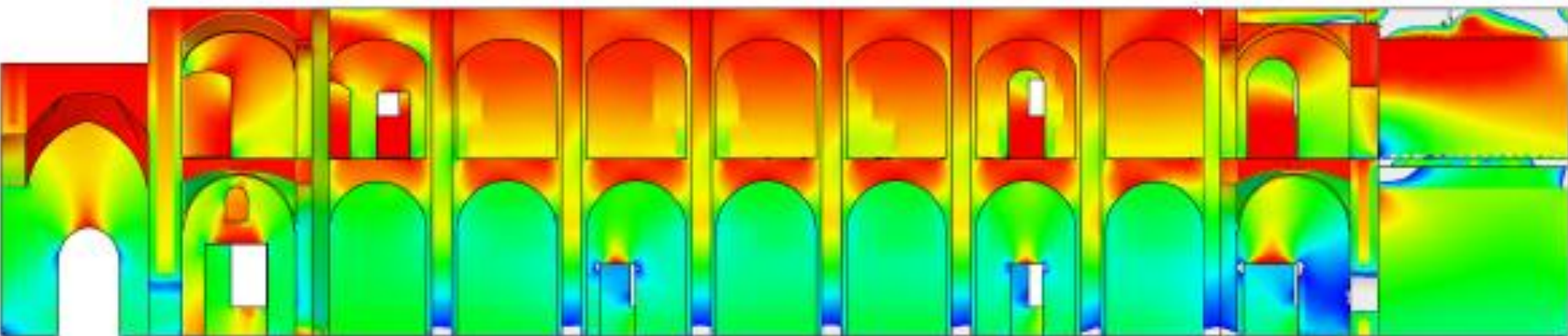
# Monasterio de San Jerónimo. Sevilla



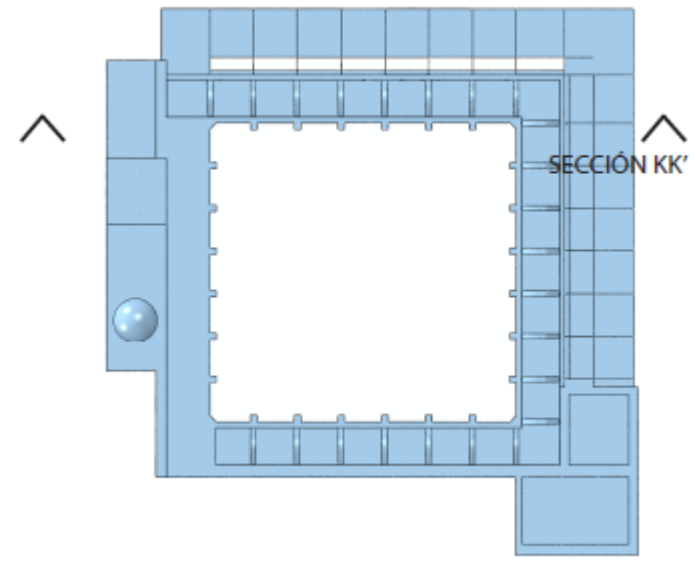
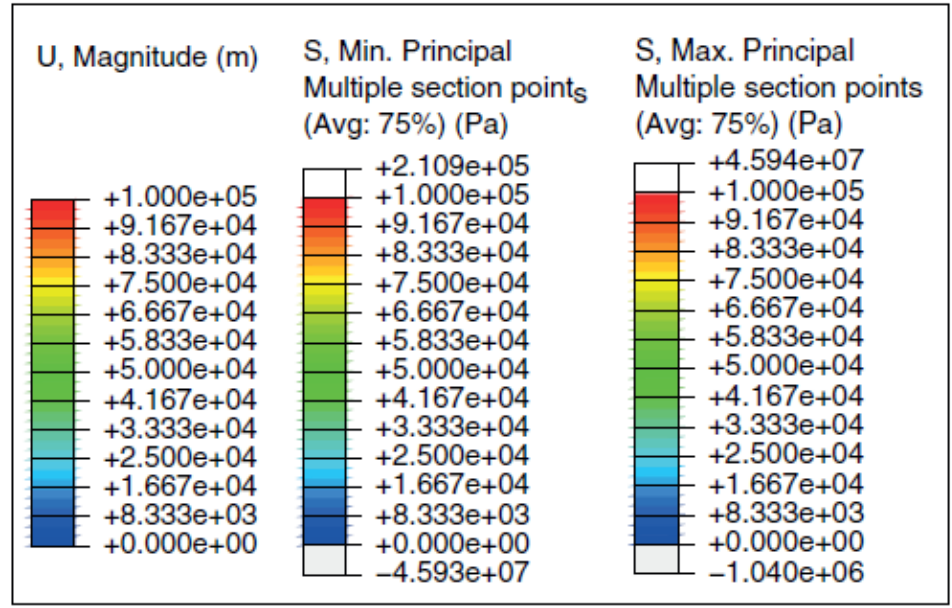
Vertical displacements



Tensile stresses

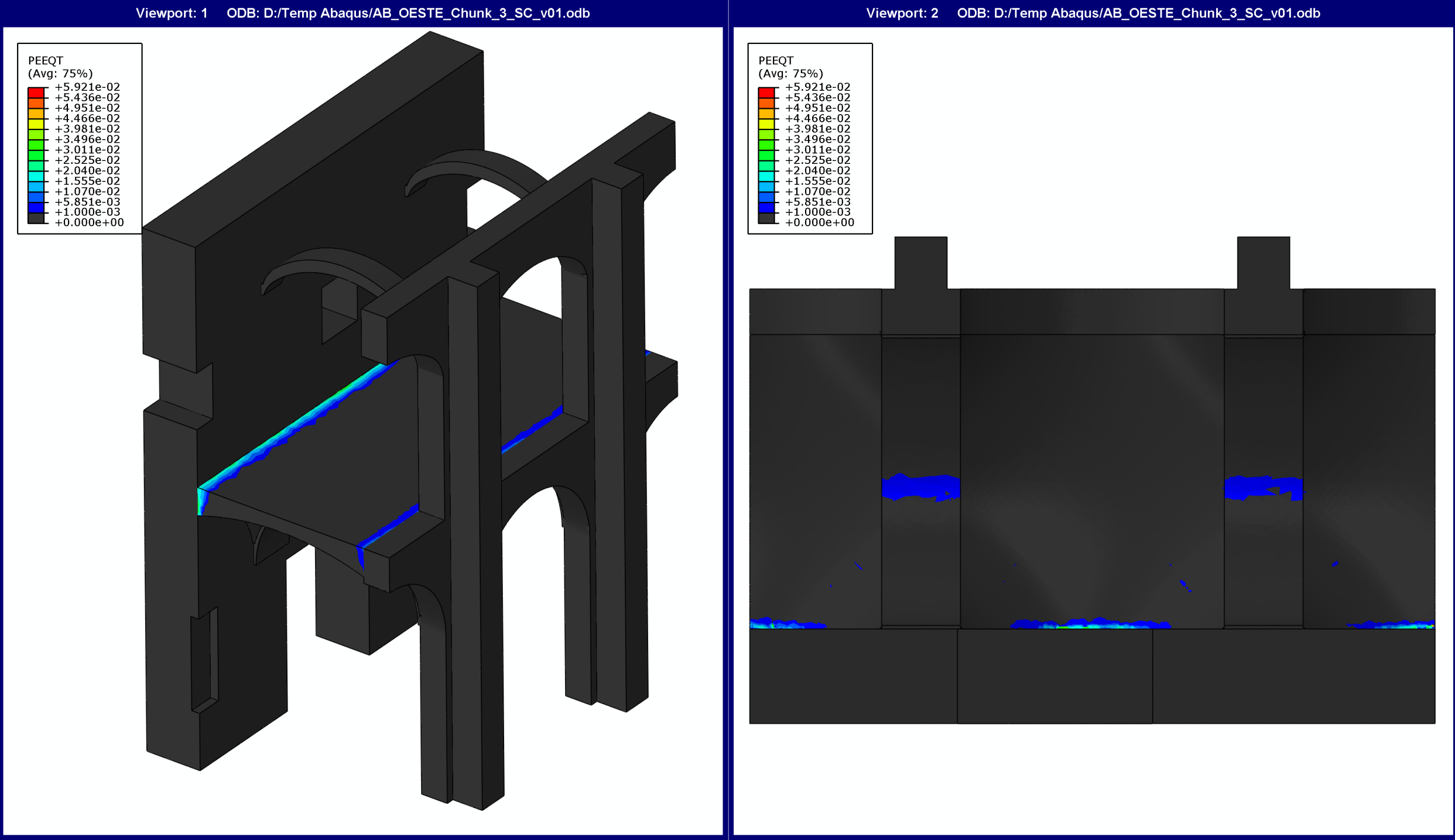


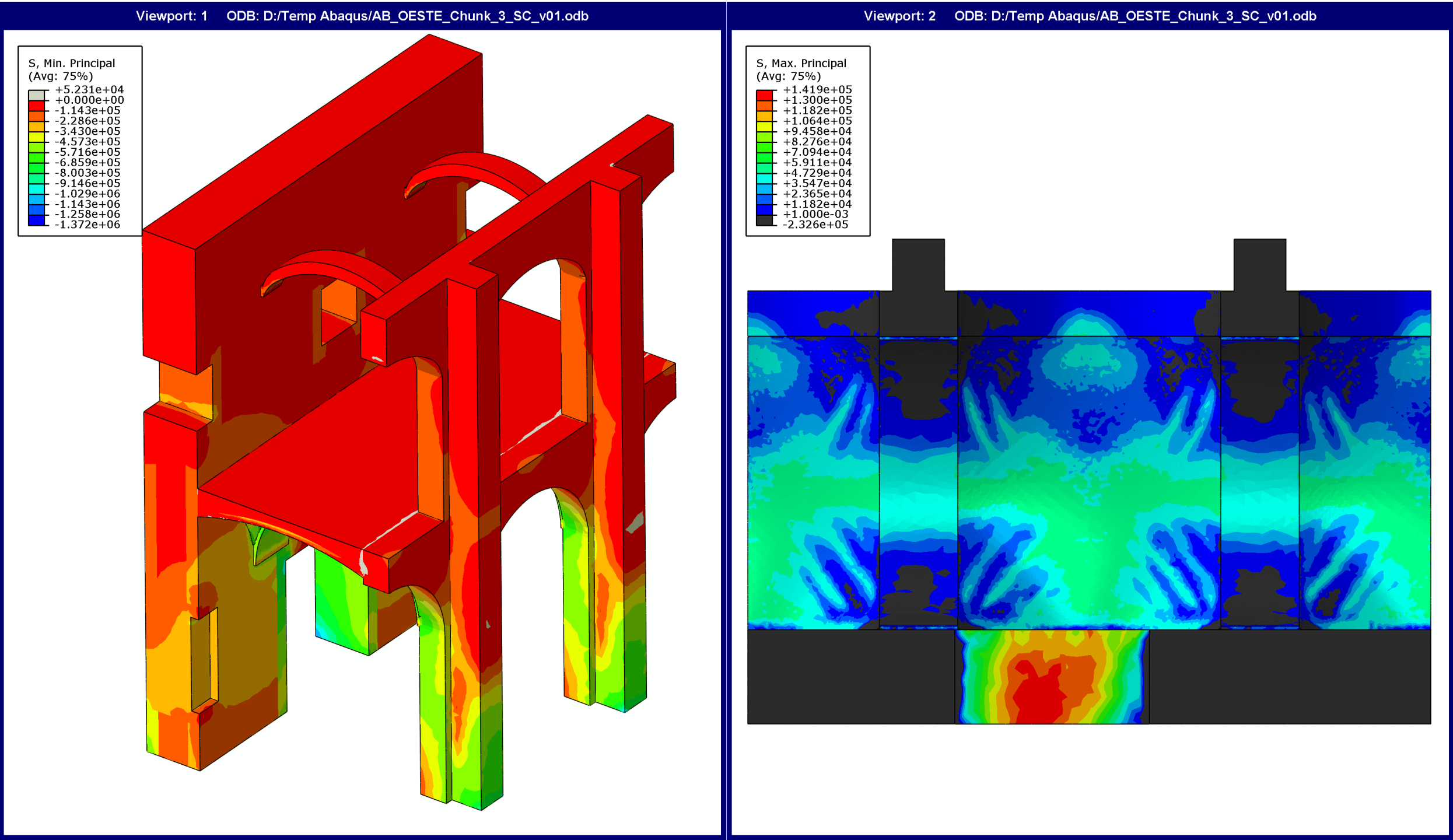
Compressive stresses



## Structural Analysis







# Capilla de la Residencia de Wurzburg. Alemania

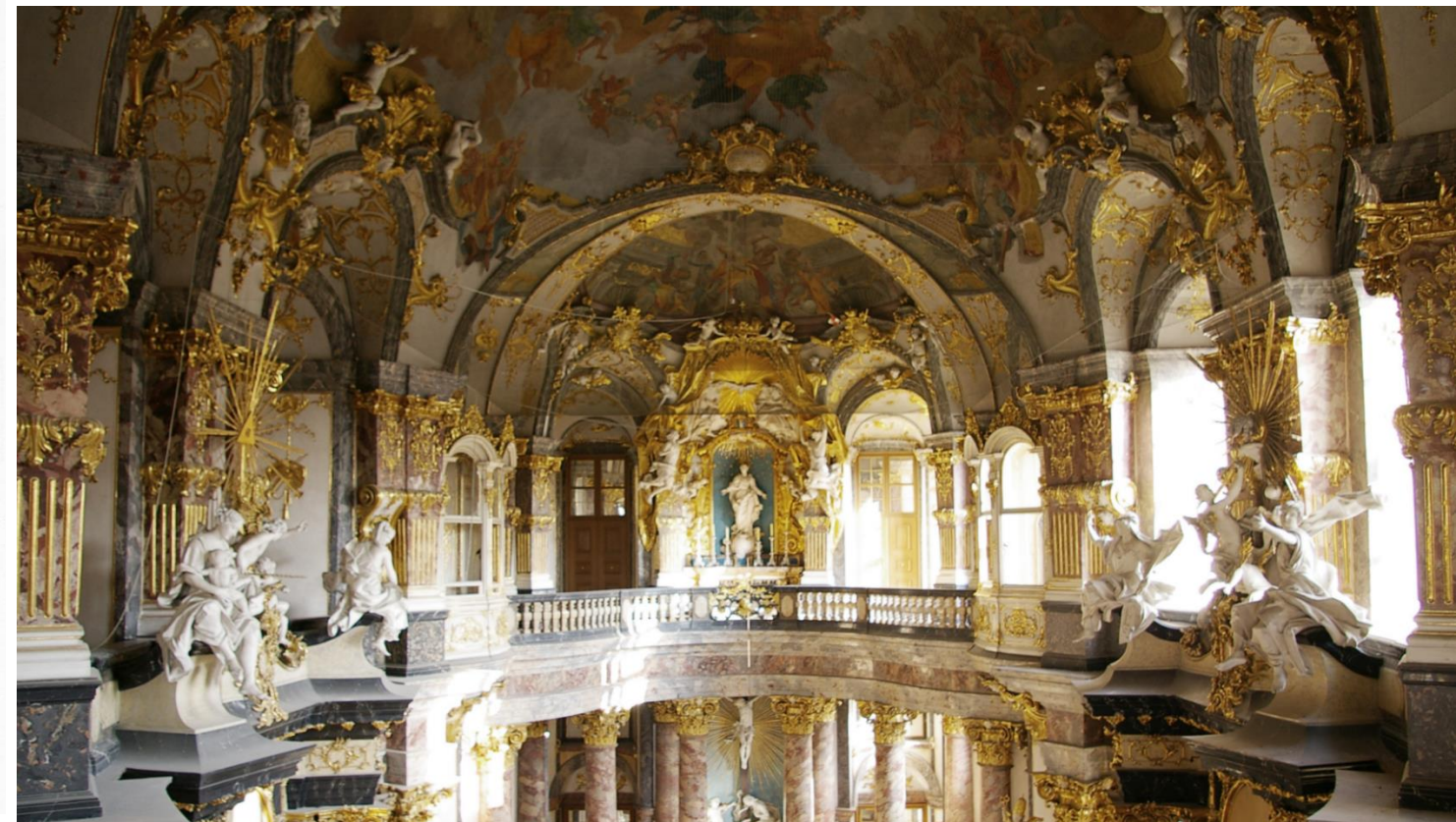
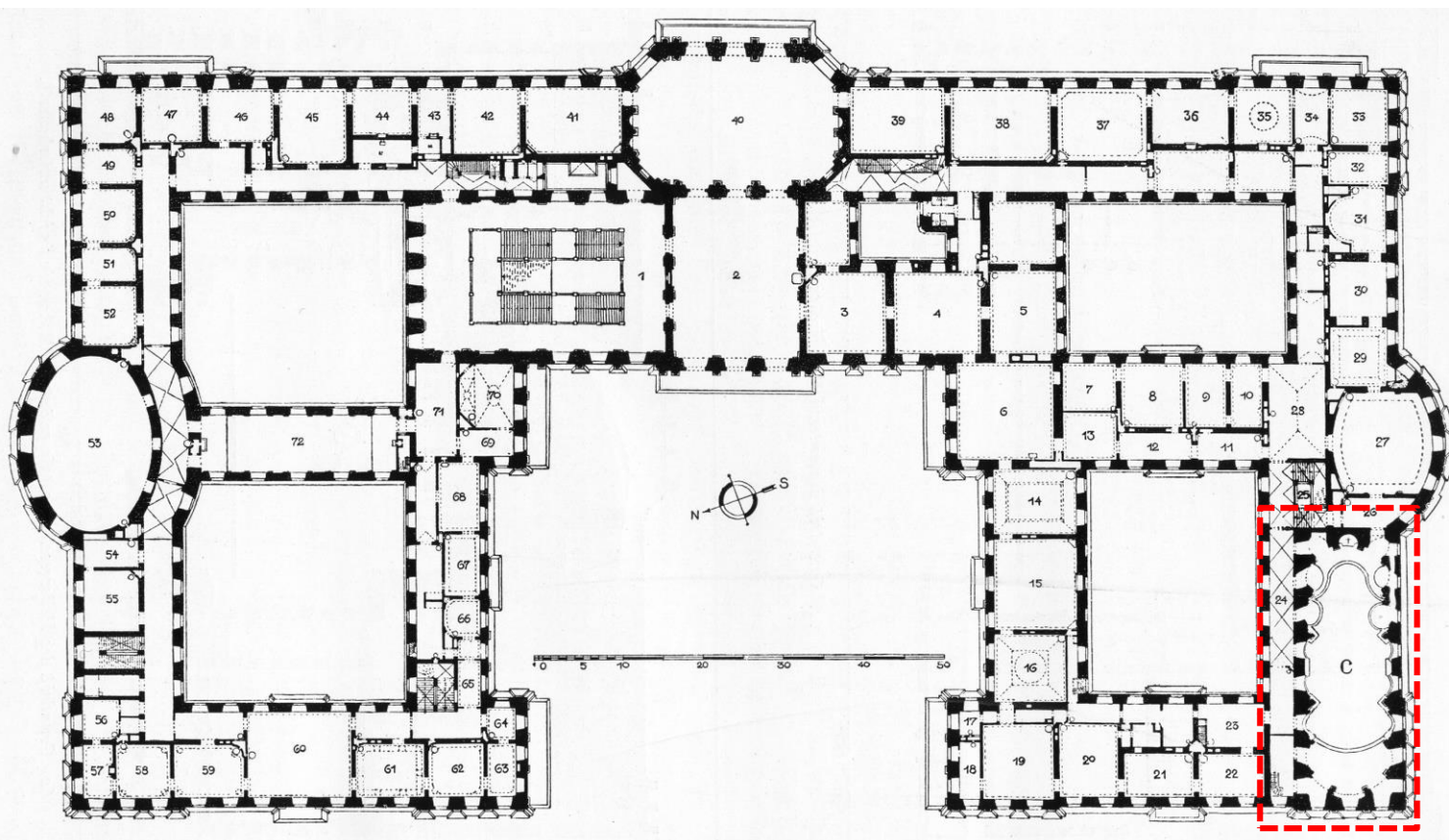


## Objectives

- Análisis estructural del estado actual y estudio de su seguridad.
- Establecer un estado de referencia para futuras intervenciones

## Herramientas

- Modelo de Elementos Finitos
- Test de Vibración Ambiental
- OMA
- Actualización de MEF
- Análisis Estructural



IDENTIFICACIÓN DE DAÑO EN ESTRUCTURAS HISTÓRICAS MEDIANTE ANÁLISIS MODAL OPERACIONAL (OMA)

Víctor Compán Cardiel

Malaga, 20 de mayo de 2016

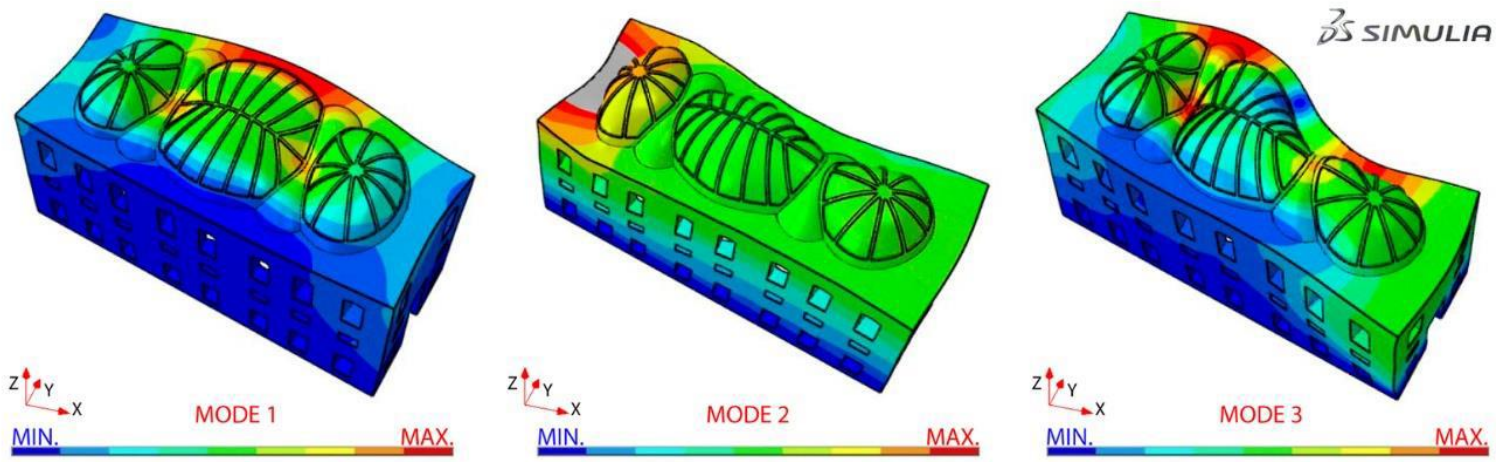
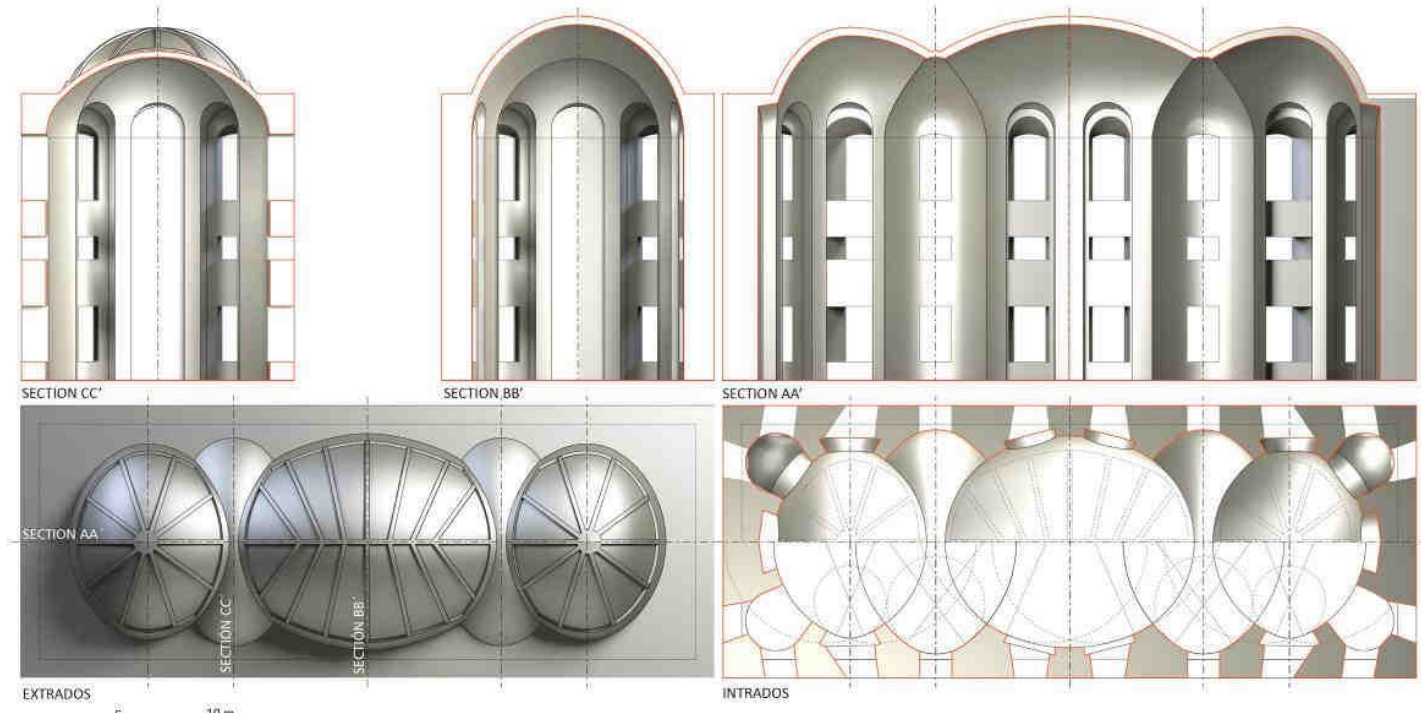
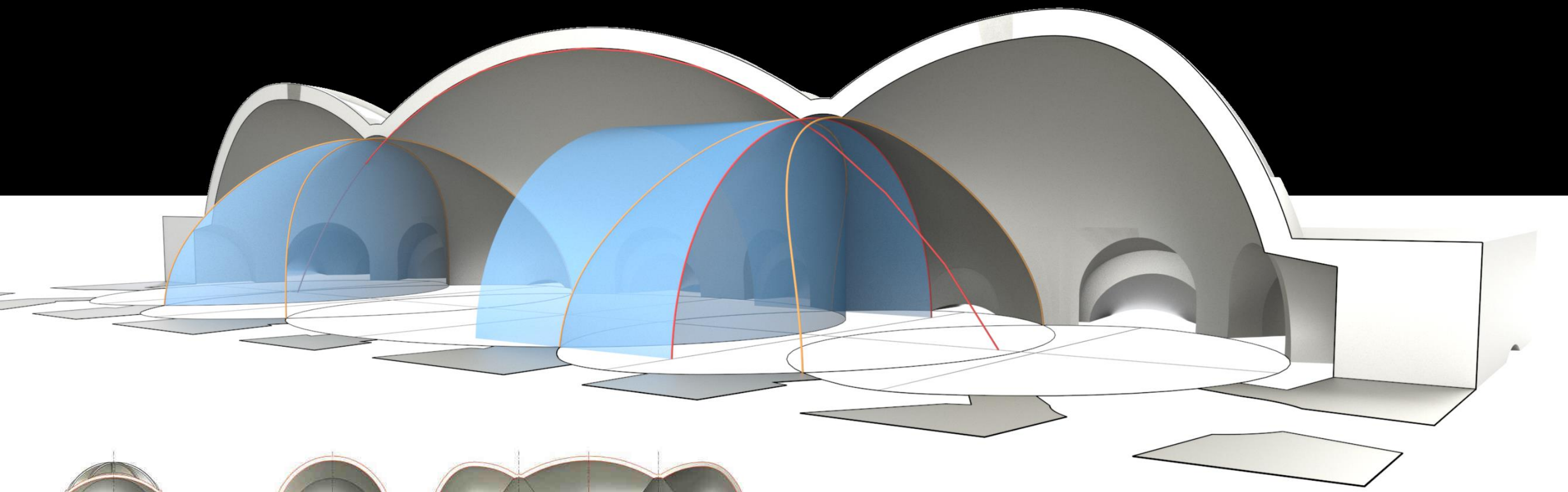


# Capilla de la Residencia de Wurzburg. Alemania



Vaults of the Chapel

# Capilla de la Residencia de Wurzburg. Alemania



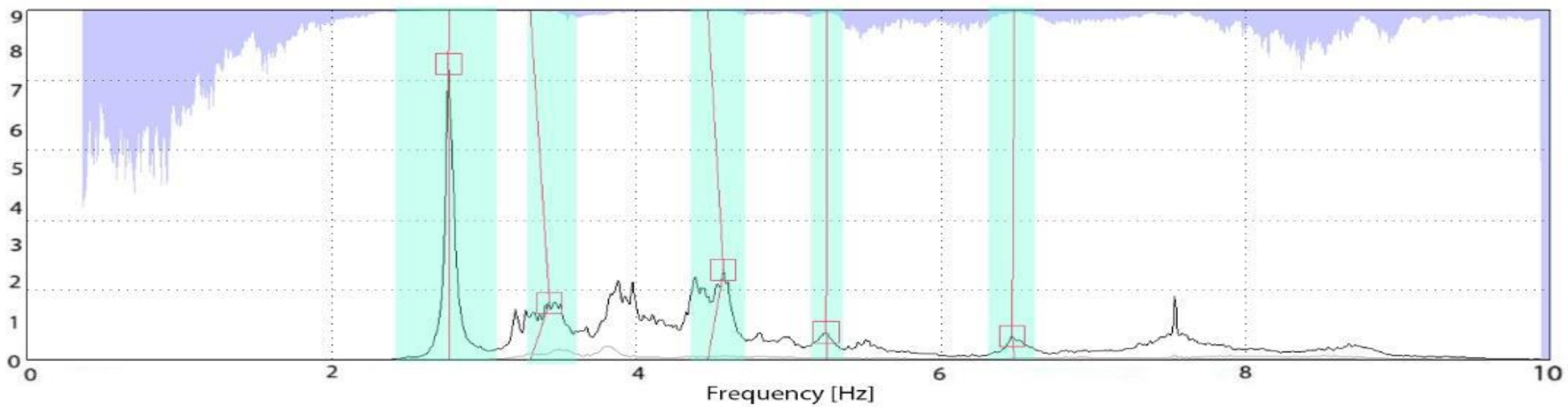
Finite Element Model

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## Enhanced Frequency Domain Decomposition (EFDD)

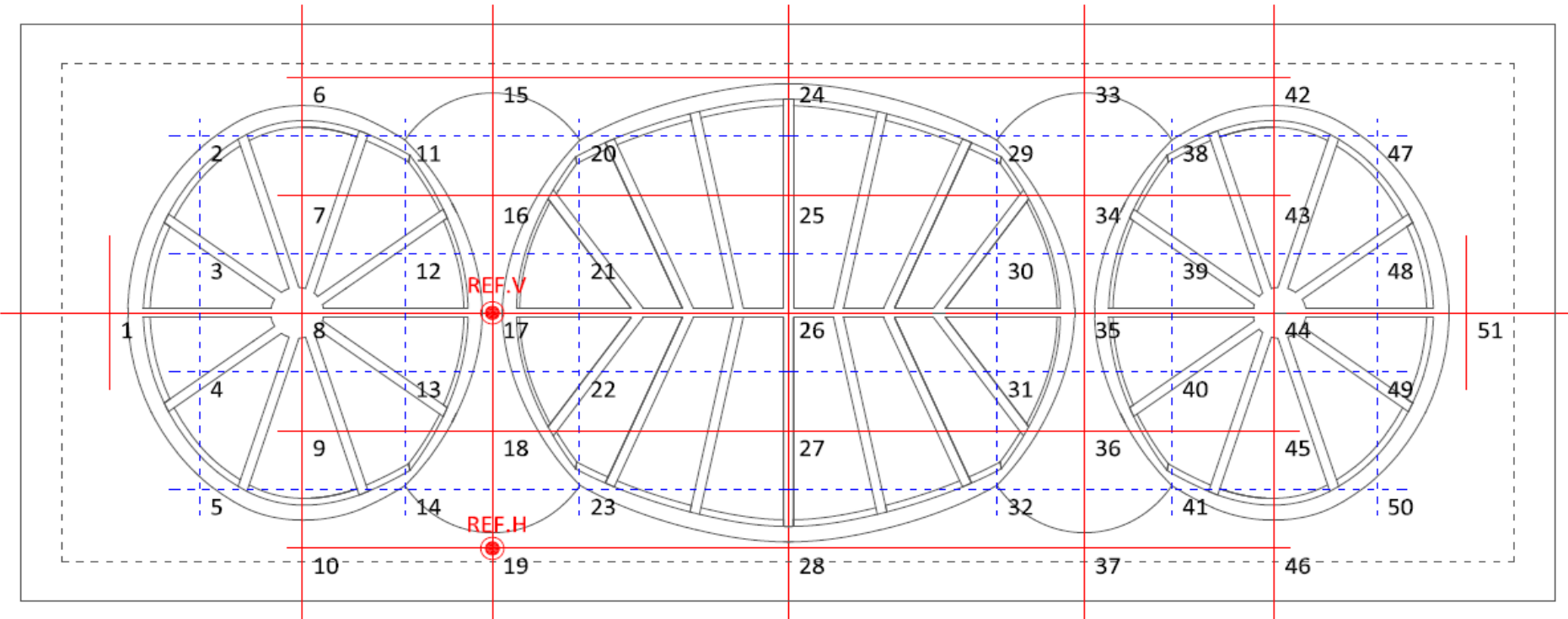
Average of the Normalized Singular Values

dB  
[(cm/s<sup>2</sup>)<sup>2</sup> / Hz]



**Cursor Values**  
Frequency = 10 Hz  
SVD Line = 1

**Indicators**  
 Estimated Mode  
 Modal Domain



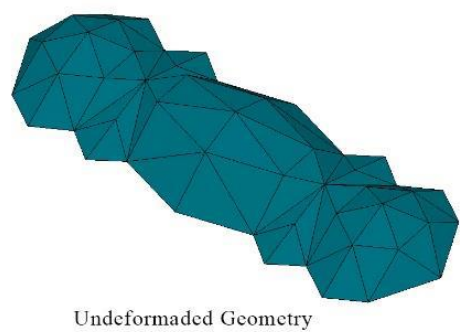
### Ambient Vibration Tests

# Capilla de la Residencia de Wurzburg. Alemania

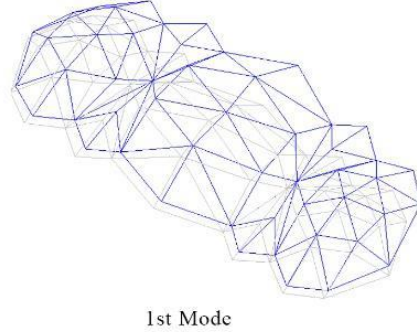
**Table 1.** Results OMA: natural frequencies (f), damping ratios ( $\xi$ ) and standard variances (Std).

	SSI				EFDD				MAC
	f (Hz)	Std. f	$\xi$ (%)	St. $\xi$	f (Hz)	Std. f	$\xi$ (%)	St. $\xi$	
<b>Mode 1</b>	2.77	0.01	1.12	0.40	2.77 (0,0%)	0.01	0.89 (26%)	0.28	0.99
<b>Mode 2</b>	3.28	0.05	1.50	0.68	3.30 (0,6%)	0.37	0.92 (63%)	1.24	0.87
<b>Mode 3</b>	4.52	0.05	2.36	0.66	4.46 (1,4%)	0.20	1.79 (32%)	0.91	0.88
<b>Mode 4</b>	5.26	0.03	1.24	0.48	5.25 (0,2%)	0.02	0.88 (61%)	0.28	0.90
<b>Mode 5</b>	6.48	0.04	2.04	0.95	6.48 (0,0%)	0.03	1.11 (84%)	0.46	0.82

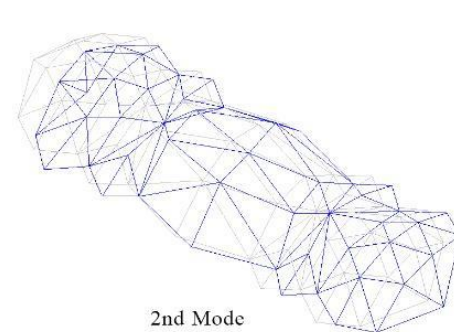
The percentage in parenthesis indicates the relative error taking as reference the results of the SSI method



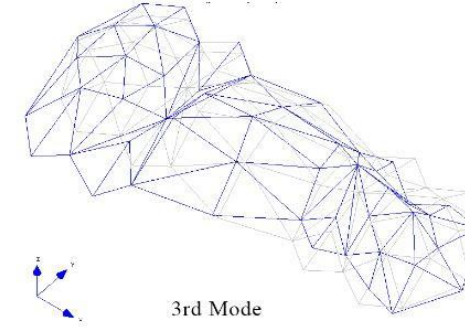
Undeformed Geometry



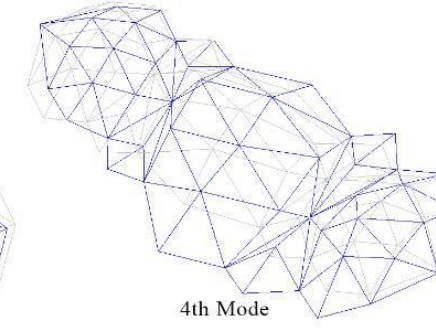
1st Mode



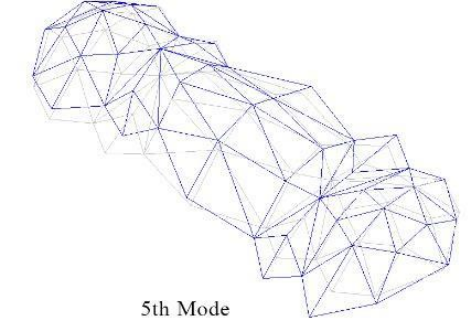
2nd Mode



3rd Mode



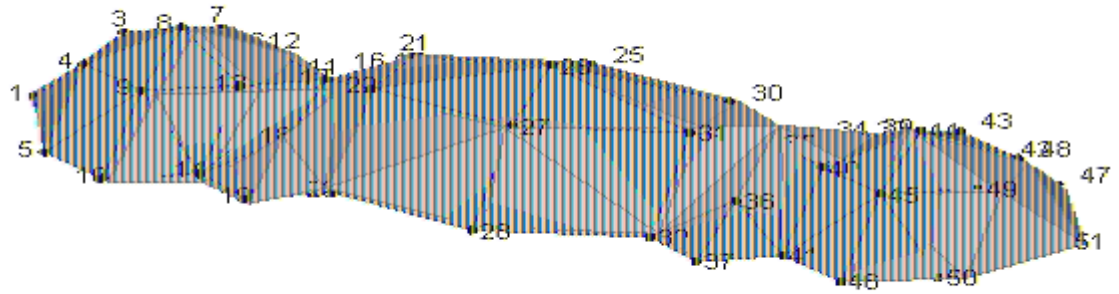
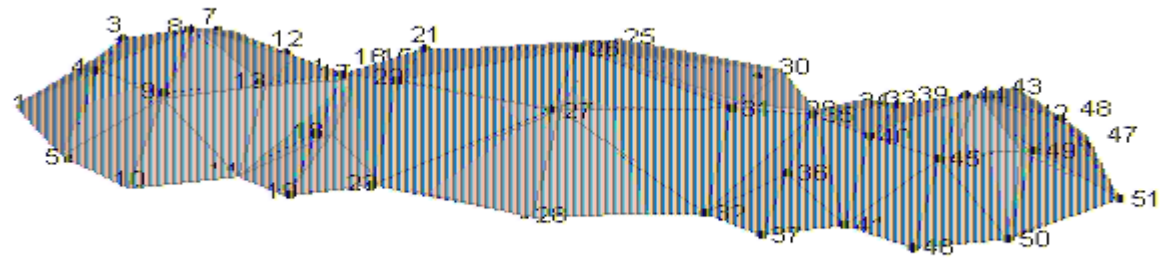
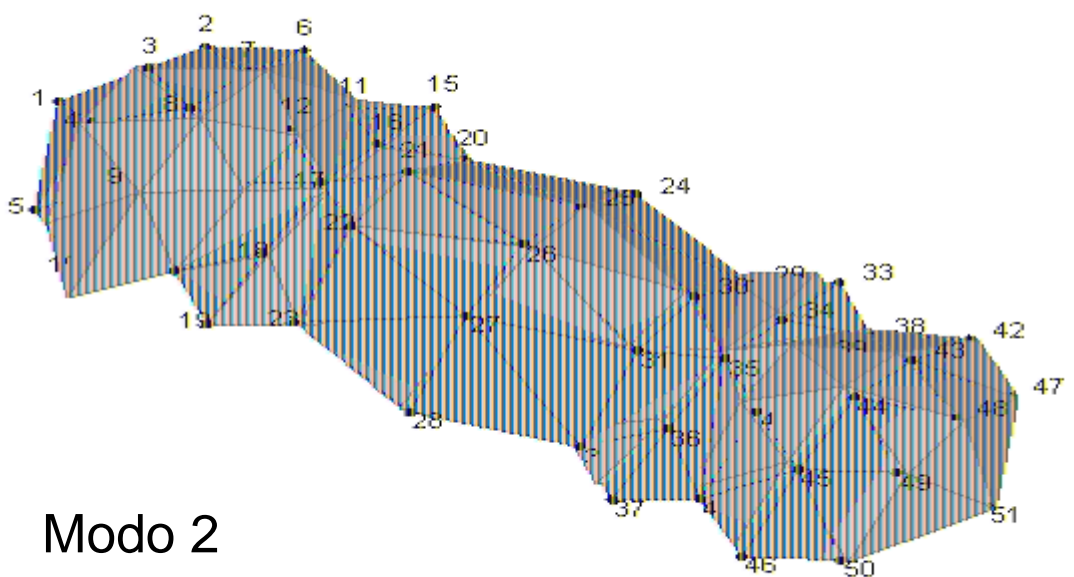
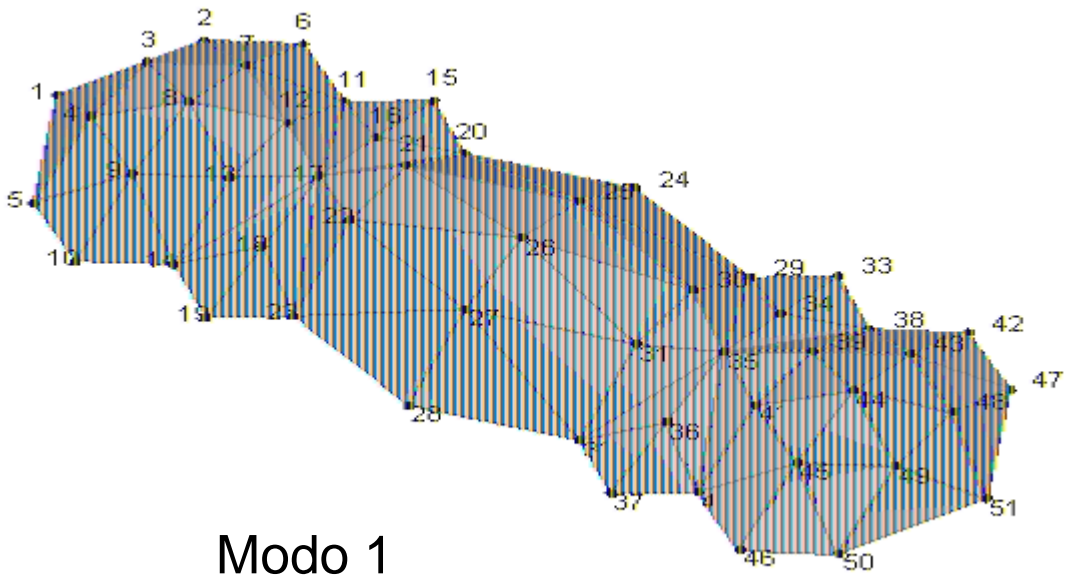
4th Mode



5th Mode

## OMA Technique

# Capilla de la Residencia de Wurzburggo. Alemania



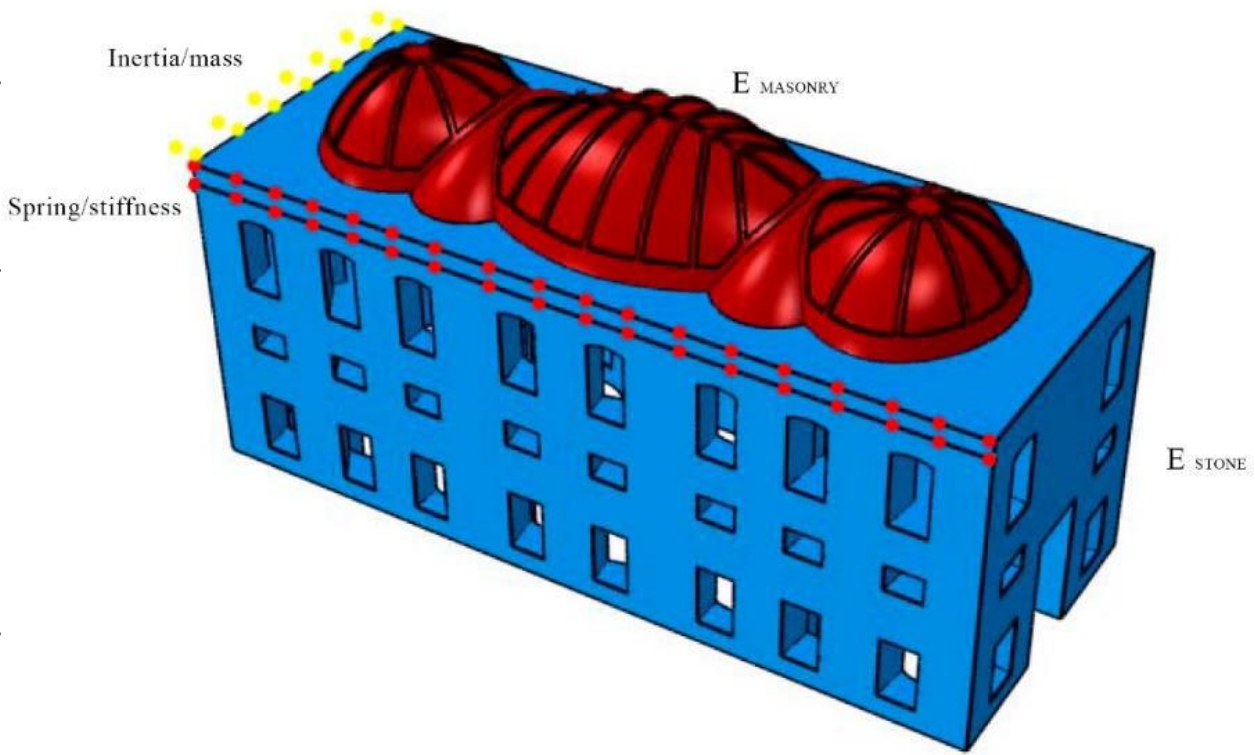
OMA Technique



# Capilla de la Residencia de Wurzburg. Alemania

**Table 2.** Summary of the results of the FE model updating process: parameters.

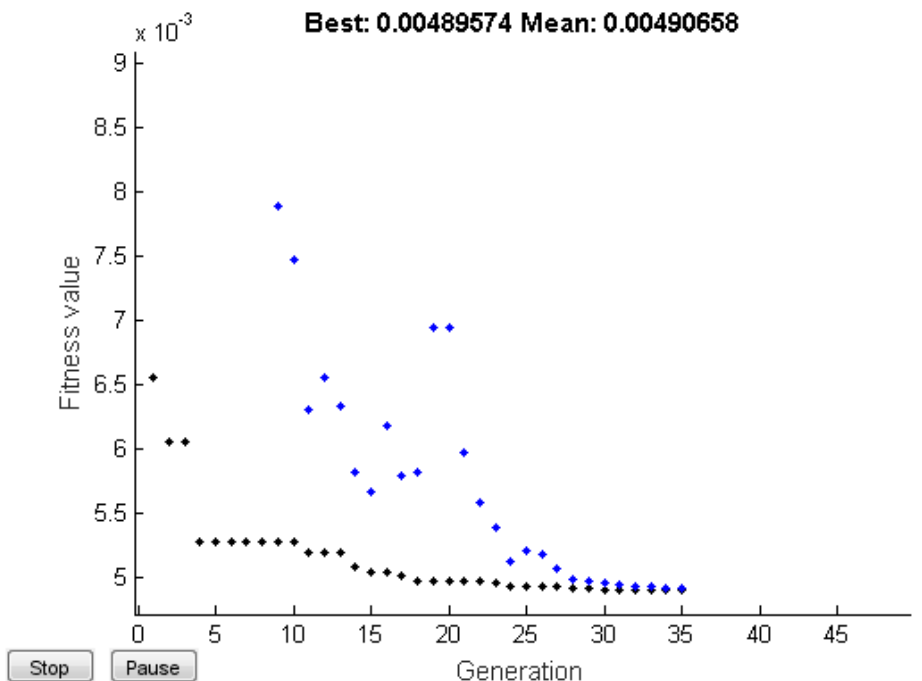
Updating Parameter	Initial Value	Optimizing interval of values		Updated Value
		Lower bound	Upper bound	
$E_b$ (MPa)	1200	700	2000	<b>921</b>
$E_s$ (MPa)	2500	1500	3500	<b>2710</b>
$S_p$ (kN/m)	9000	6000	12000	<b>10800</b>
$I_p$ (Kg/m <sup>3</sup> )	4000	2000	6000	<b>4680</b>



**Table 3.** Comparison of frequencies (Hz) obtained experimentally ( $f_{EFDD}$ ) and analytically ( $f_{FEM}$ ).

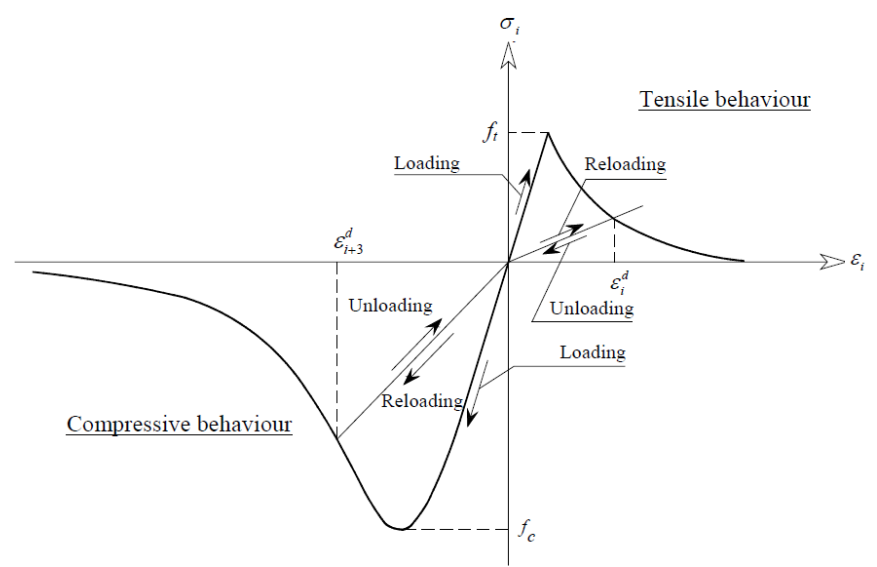
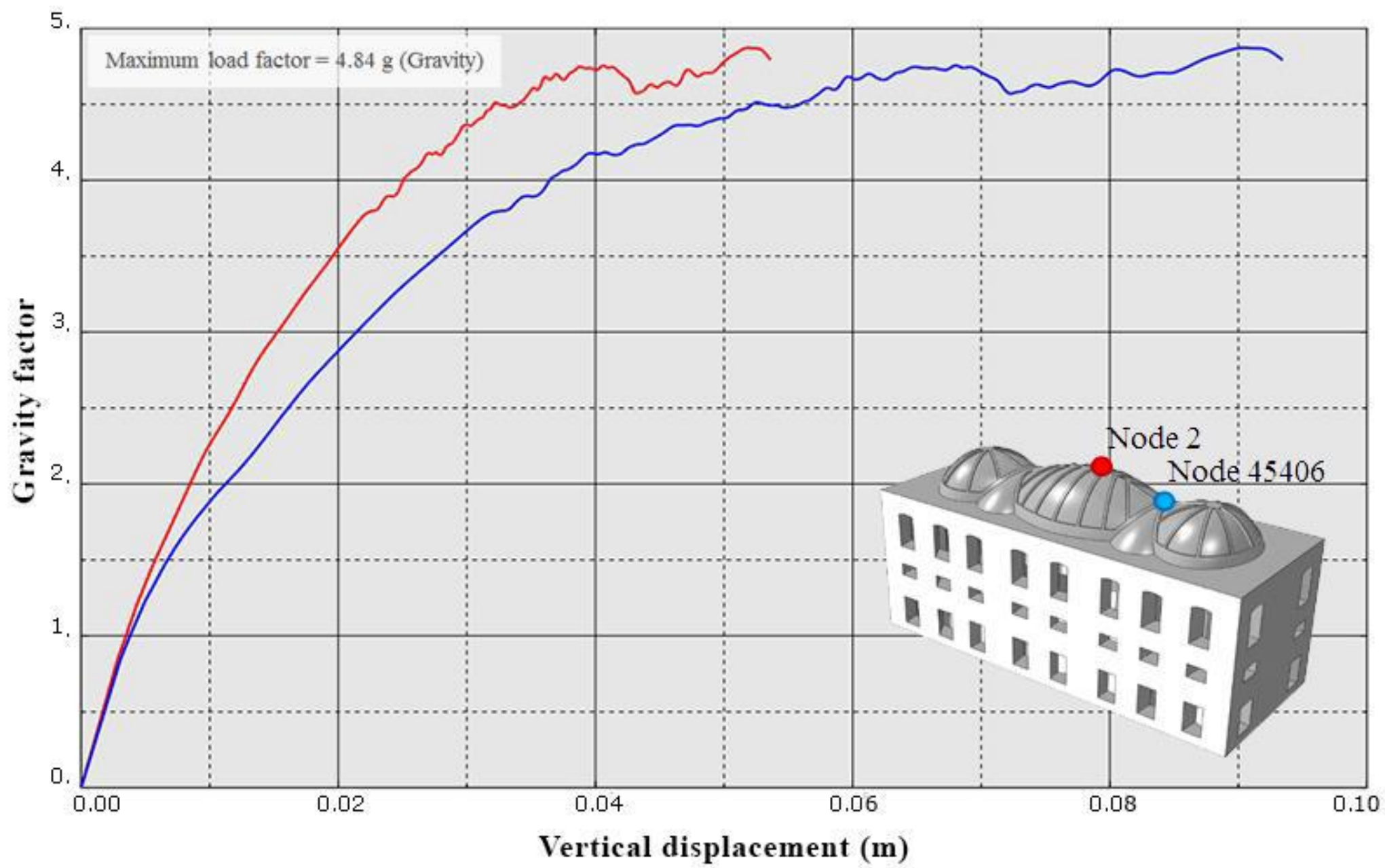
Modes	$f_{EFDD}$	$f$ (Initial FEM)	$f$ (FEM UPDATED)	MAC Value ( $f_{EFDD}$ - $f_{FEM}$ UPDATED)
<b>Mode 1</b>	<b>2.77</b>	2.59 (6.5%)	<b>2.79 (0.71 %)</b>	<b>0.99</b>
<b>Mode 2</b>	<b>3.30</b>	3.04 (7.9%)	<b>3.29 (0.30%)</b>	<b>0.96</b>
<b>Mode 3</b>	<b>4.46</b>	4.15 (6.9%)	<b>4.43 (0.67%)</b>	<b>0.93</b>

The percentage in parenthesis indicates the relative error taking as reference the results of the EFDD method.



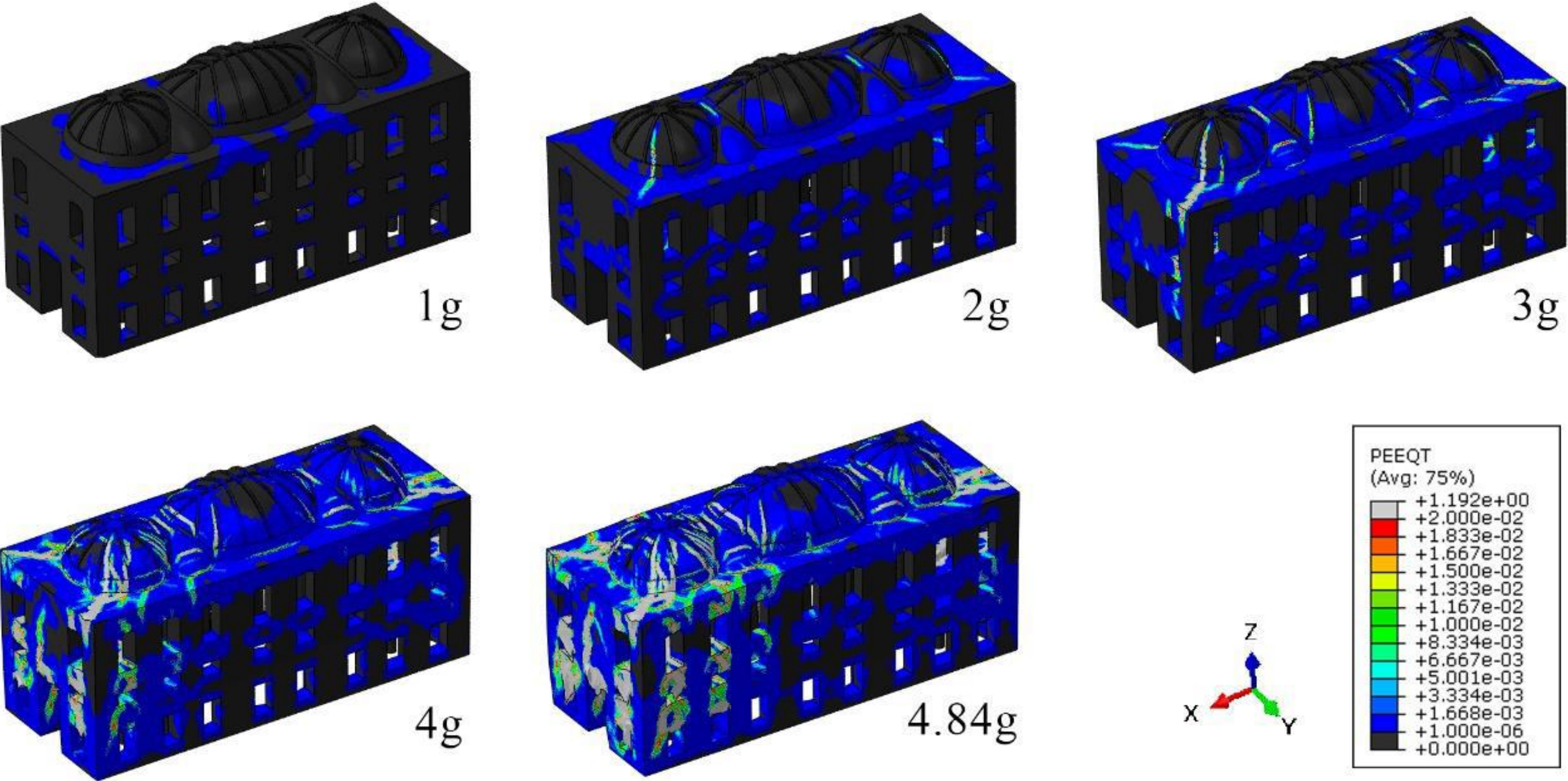
## Modal Updating process

# Capilla de la Residencia de Wurzburg. Alemania



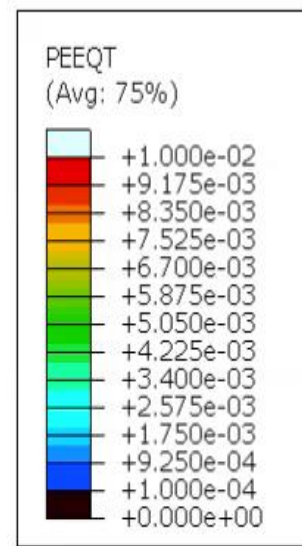
## Non-linear Structural Analysis

# Capilla de la Residencia de Wurzburg. Alemania

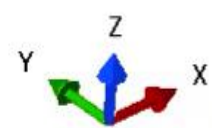
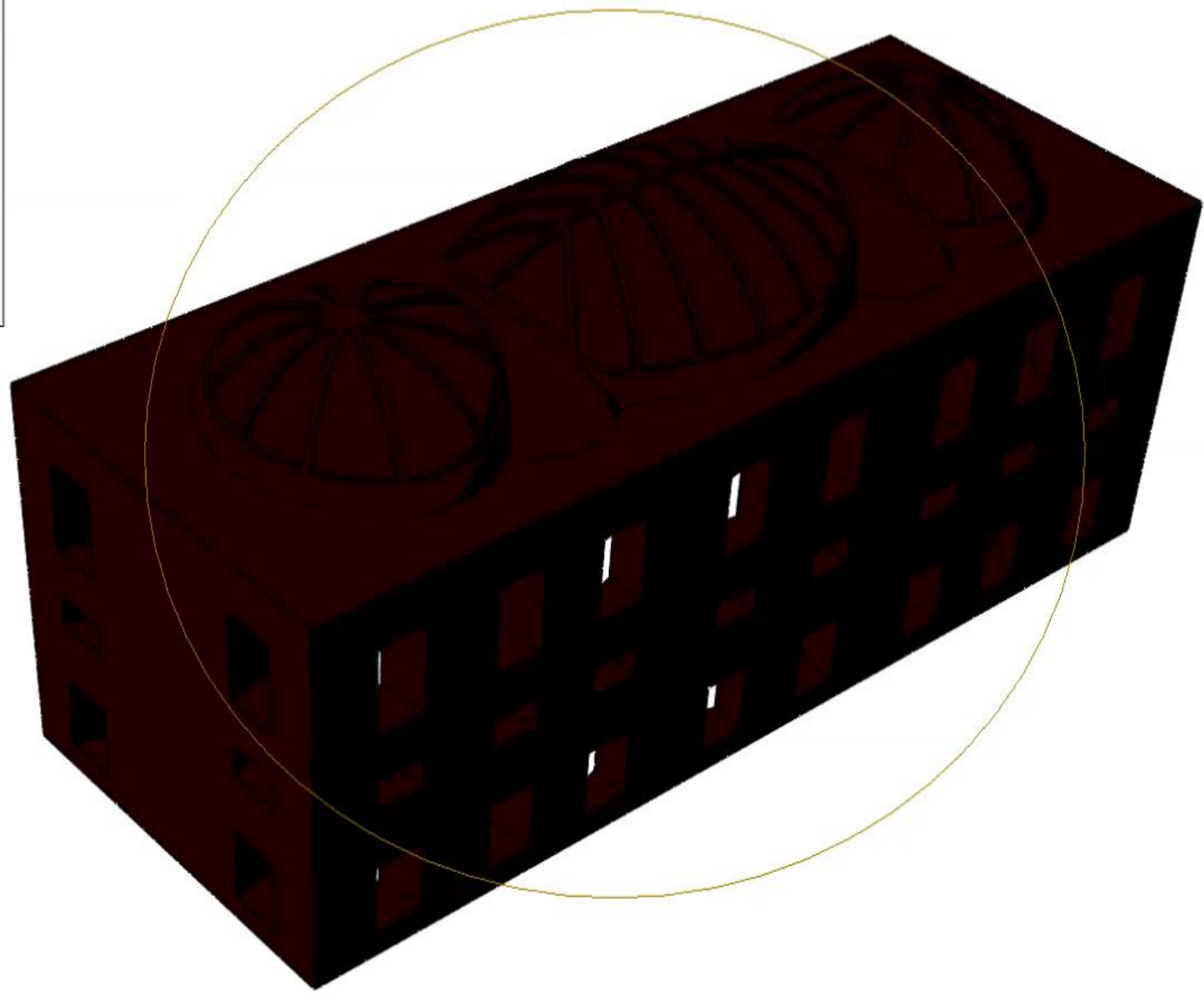


Non-linear Structural Analysis.  
Crack pattern.

# Capilla de la Residencia de Wurzburg. Alemania



Step: Static Frame: 0  
Total Time: 0.000000



Non-linear Structural Analysis.  
Crack pattern.

**Gracias por su atención**