Bauhaus-Universität Weimar

Experimental structural dynamics and Structural monitoring

Final project:
3D Frame – Modal analysis

Group 10:

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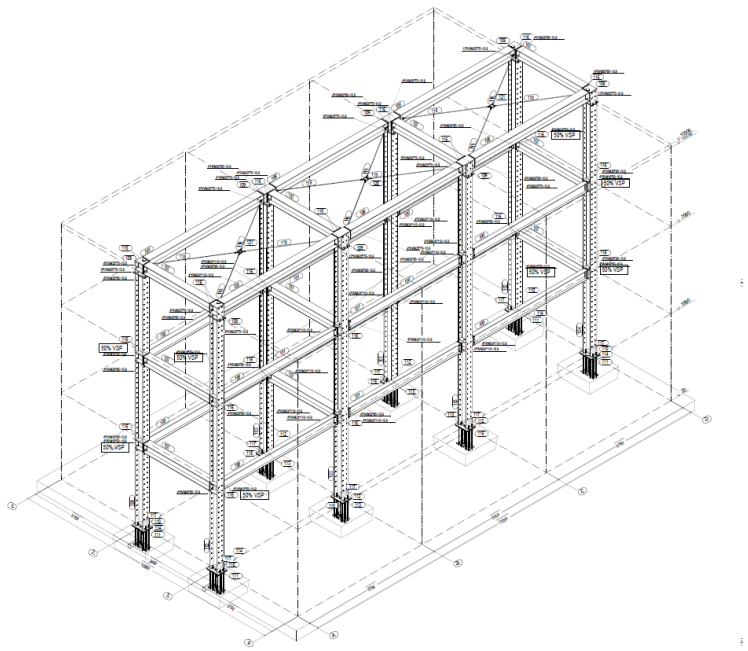
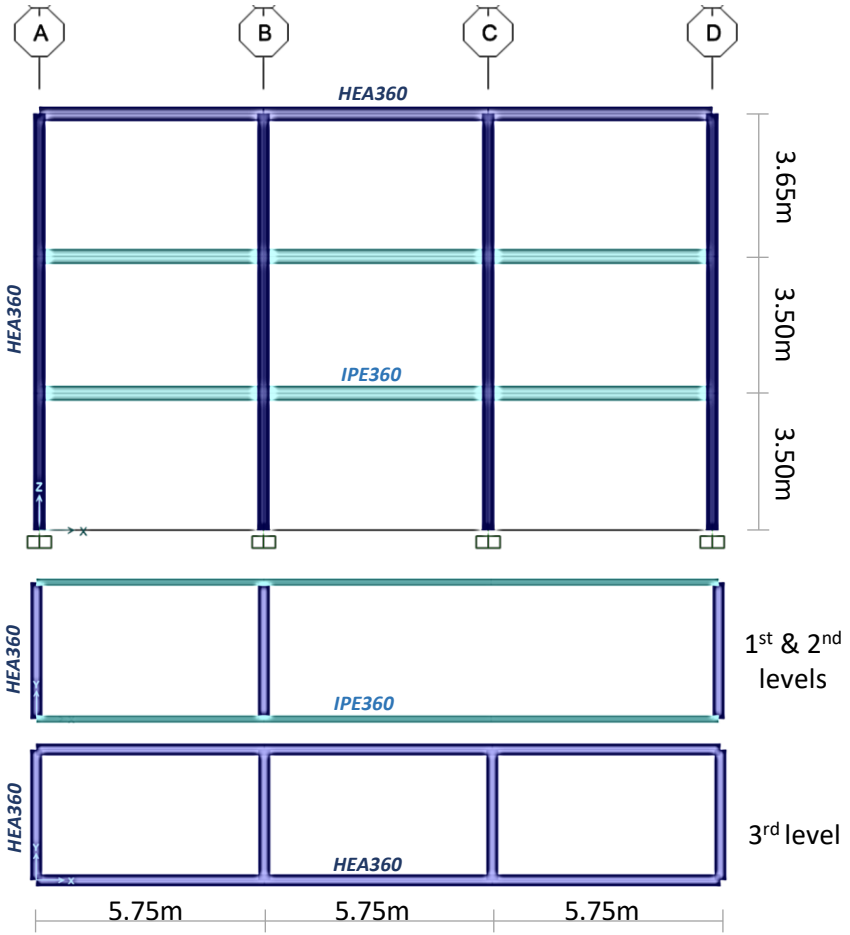
General description of the system

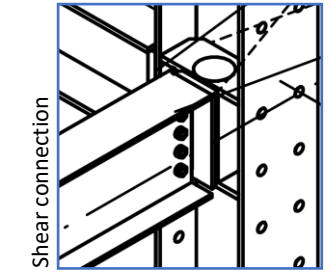
Height: 10.65mts | Longitudinal length: 17.25mts | Transversal length: 3.65mts | Steel sections: HEA360 & IPE360 S265

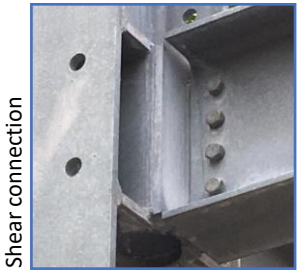


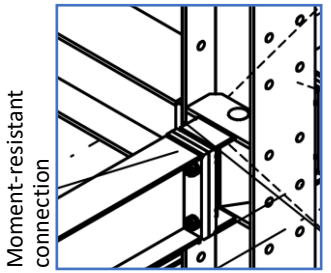


- IPE sections used as beams in the longitudinal direction in 1st and 2nd storeys, the rest of the frame elements have HEA sections.

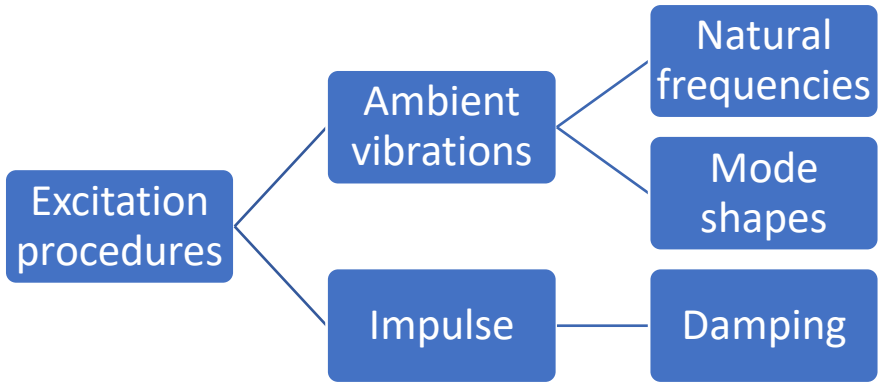
- Shear connections can only be found between outer corner elements in 1st and 2nd levels.
- Columns strong axis towards the transversal direction.







Measurements

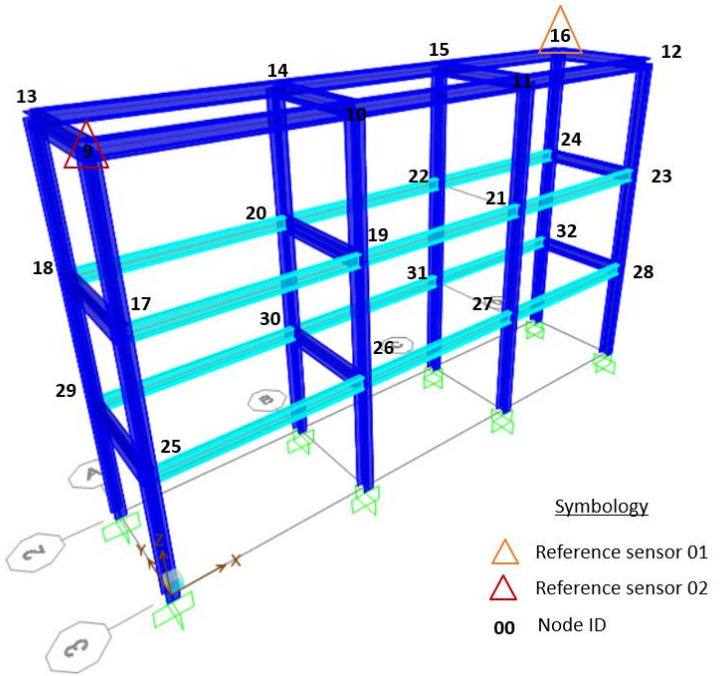


- 5 sensors were used for each one of the setups.
- 2 sensors were fixed and used as reference for each setup.

Ambient vibration was measured using all setups to cover all joints of the structure.

- Impulse vibration was achieved using an elastic rope tied in node 16, pulled several times following the frequency of the 1st mode for weak axis.
- Test was repeated for the strong axis following the frequency of the 2nd mode.

Sensor	Setup No.	1	2	3	4	5	6	7	8
1	Nodes	17	10	11	12	13	14	15	24
2		30	19	21	23	18	20	22	27
3		29	29	32	31	26	25	28	28



Sensors from which data was received

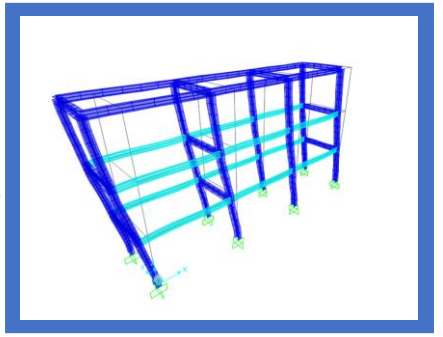
Installation with aid of magnets

Numerical model

- Software:
  - Structural analysis program SAP2000
- Considerations:
  - All connections as moment-resistant.
  - Columns restrains at foundation level as fixed.

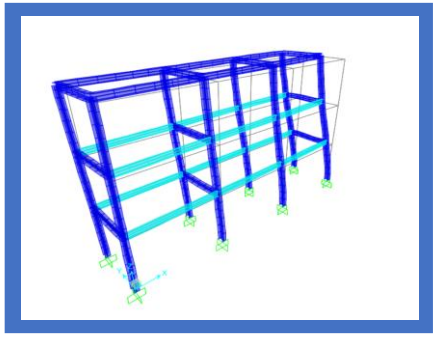
Mode	Period (sec)	Frequency (Hz)	MPMR (x-direction)	MPMR (y-direction)
1	0,26	3,91	**0,870**	0,000
2	0,18	5,61	0,000	**0,770**
3	0,16	6,43	0,000	**0,076**
4	0,08	12,26	**0,100**	0,000
5	0,05	19,75	0,000	**0,120**
6	0,05	20.45	**0,030**	0,000
7	0,05	20,63	0,000	**0,002**
8	0,03	36,41	0,000	**0,016**
9	0,03	37,17	0,000	**0,016**
10	0,02	66,51	0,000	0,000

Mode 1: *f = 3,91Hz*



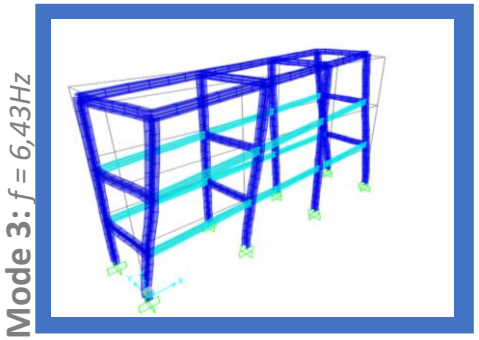
Displacements in longitudinal direction (columns weak axis)

Mode 2: *f = 5,61Hz*



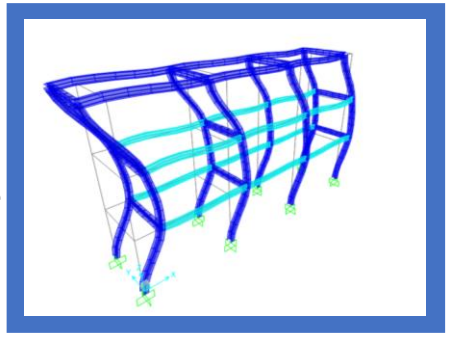
Displacements in transversal direction (columns strong-axis)

Mode 3: *f = 6,43Hz*



Torsional mode, displacements in both horizonal directions

Mode 4: *f = 12,26Hz*



Bending mode, displacements in longitudinal direction(weak axis)

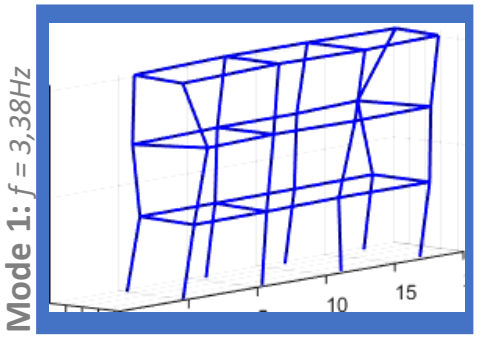
Experimental determination of modal parameters

MACEC steps:

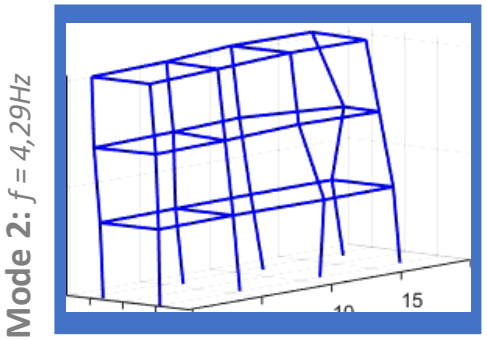
1. Define geometry.
   - Grids, beams and slave joints.
2. Preprocessing.
   - Sampling rate (2000Hz).
   - Offset removal and decimate.
   - Add DOFs.

- Decimate factor selected as 8 for all setups (reduction to 250 Hz).
- The process was repeated for each one of the setups.
- Once all setups were analyzed, documents were joined to obtain the entire structure.

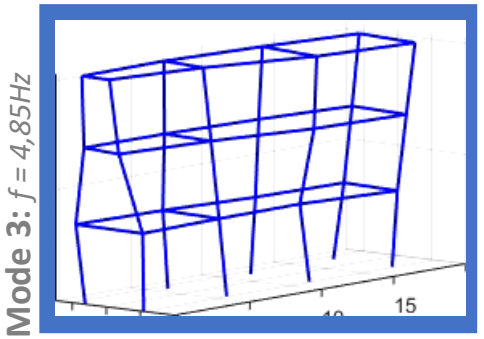
3. Process.
   - System identification with SSI-cov/ref..
   - Expected system order.
   - Construction of stabilization diagram to a model order of 200 (2:2:200).
4. Modal analysis.
   - Stabilization diagram.
   - Positive power spectral density.
   - Selection of first 10 mode shapes from 0 to 30 Hz.
5. Observe modal shape.



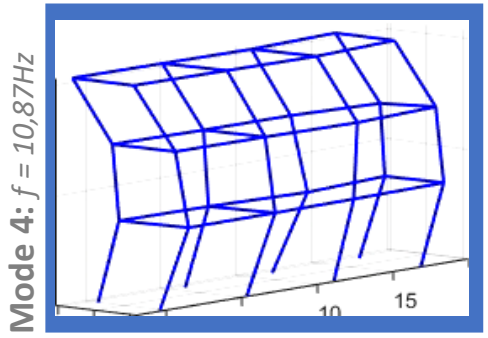
Displacements in longitudinal direction (columns weak axis)



Displacements in transversal direction (columns strong-axis)



Torsional mode, displacements in both horizonal directions



Bending mode, displacements in longitudinal direction(weak axis)

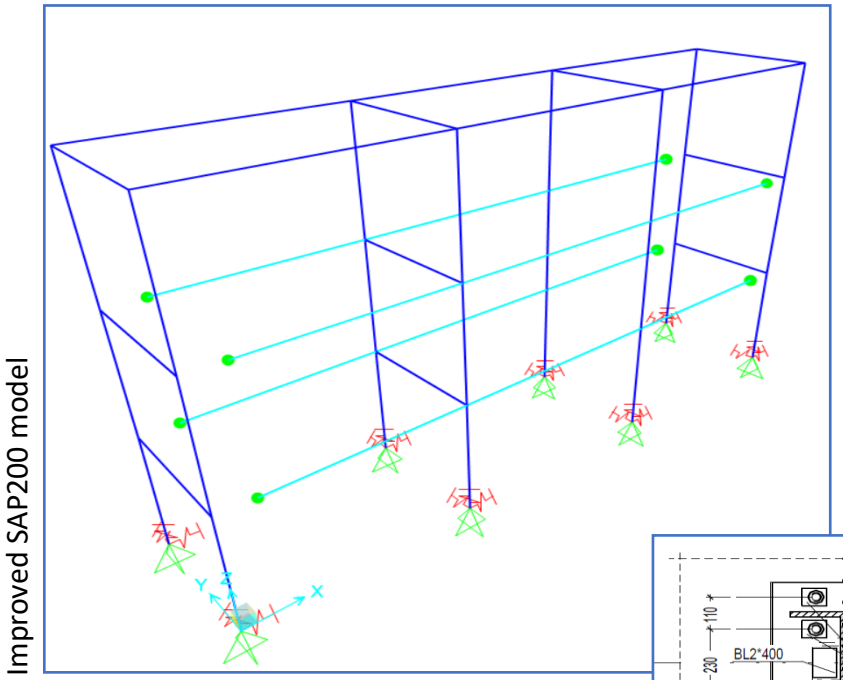
Improved numerical model

Change of frame connections

- All connections initially considered as moment- resistant.
- To improve it shear connections were included.
- Changes only in outer corner elements in 1st and 2nd levels, between IPE and HEA elements.

Change of foundation restrains

- Initially foundation joints were considered totally fixed.
- Changing foundation joints restrains to fix x, y and z displacements.
- Adding springs in the strong and weak axis of the columns at foundation joints.
- Adding torsional spring at foundation joints.



AISC Steel construction Manual (15th edition)

- *Spring stiffness (K_s) for partially restrained connections:*

$$20\frac{EI}{L} < K_s < 2\frac{EI}{L}$$

Weak axis

(semi-rigid connection)

$$K_s = 20\frac{EI_{weak}}{L} = 94644\frac{kN*m}{rad}$$

Strong axis

(flexible connection)

$$K_s = 5\frac{EI_{strong}}{L} = 99270\frac{kN*m}{rad}$$

Torsion

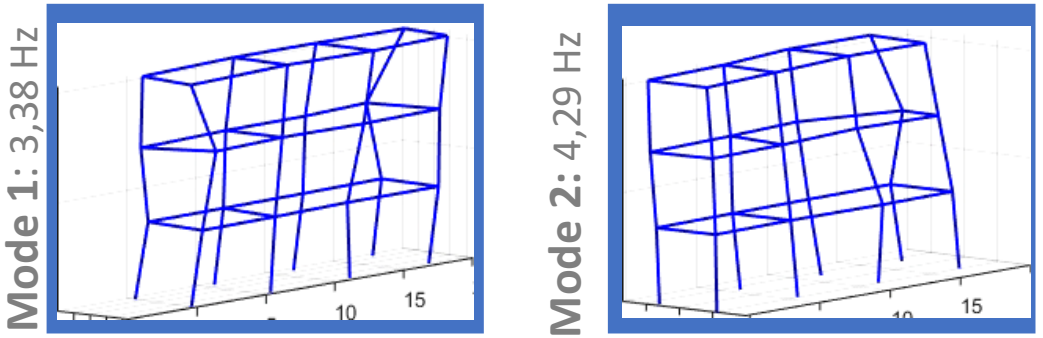
$$K_T = 30\frac{GI_T}{L} = 1048\frac{kN*m}{rad}$$

Results

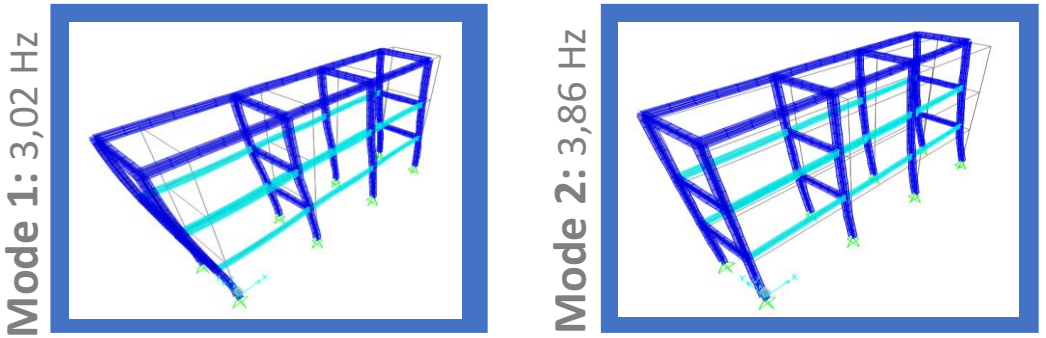
	MACEC model	1st SAP2000 model	2nd SAP2000 Model			Differences [%] SAP vs. MACEC	
Mode	*Frequency (Hz)*	*Frequency (Hz)*	*Frequency (Hz)*	*MPMR (x-direction)*	*MPMR (y-direction)*	*Model 1*	*Model 2*
1	3,38	3,91	3,02	0,87	0,00	13,60	10,55
2	4,29	5,61	3,86	0,00	0,87	23,49	10,14
3	4,85	6,43	4,53	0,00	0,08	24,58	6,51
4	10,87	12,26	10,82	0,11	0,00	11,34	0,45
5	14,52	19,75	15,78	0,00	0,05	26,45	7,96
6	19,46	20,63	19,95	0,00	0,00	5,68	2,49
7	27,16	37,17	34,77	0.02	0,00	26,94	21,91
8	28,62	36,41	33,75	0,00	0,01	21,40	15,20

- MACEC model:
  - Experimental results.
- SAP2000 model:
  - 1st model fixed connections.
  - 2nd model rotational springs connections.

MACEC model



2nd SAP model



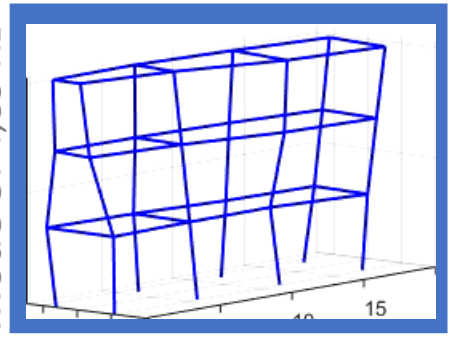
Displacements in longitudinal direction (columns weak-axis)

Displacements in transversal direction (columns strong-axis)

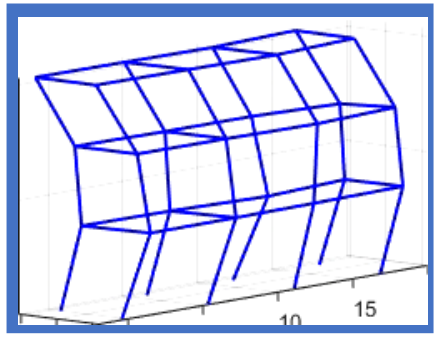
Modal shapes

MACEC model

Mode 3: 4,85 Hz

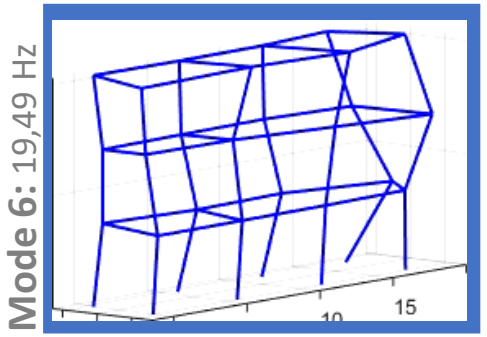


Mode 4: 10,87 Hz

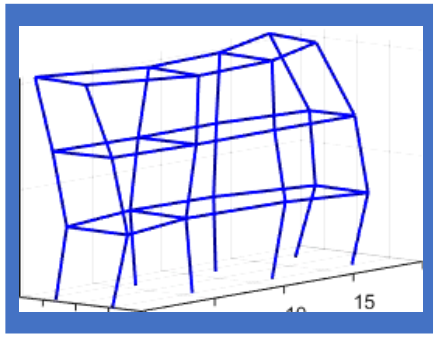


MACEC model

Mode 6: 19,49 Hz

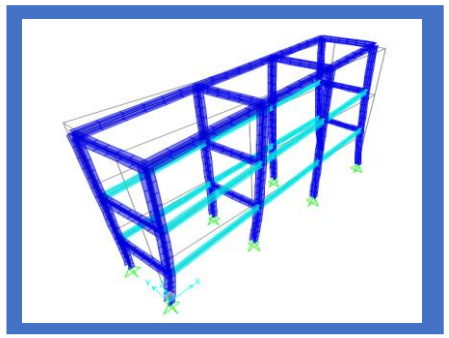


Mode 8: 28,62 Hz



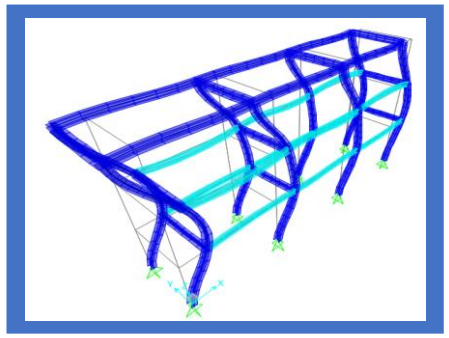
2nd SAP model

Mode 3: 4,53 Hz



Torsional mode, displacements in both horizonal directions

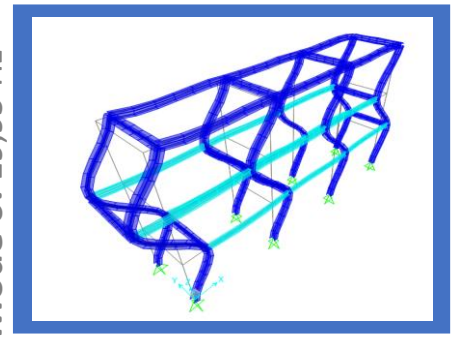
Mode 4: 10,82 Hz



Bending mode, displacements in longitudinal direction (weak axis)

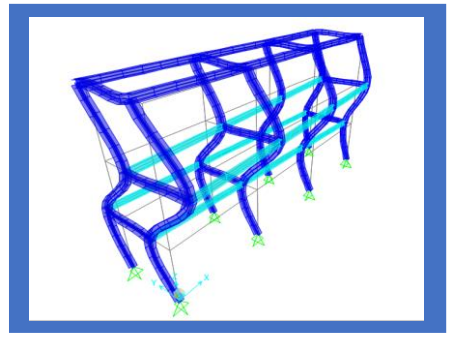
2nd SAP model

Mode 6: 19,95 Hz



Second bending mode, displacements in longitudinal direction (weak axis)

Mode 8: 33,75 Hz

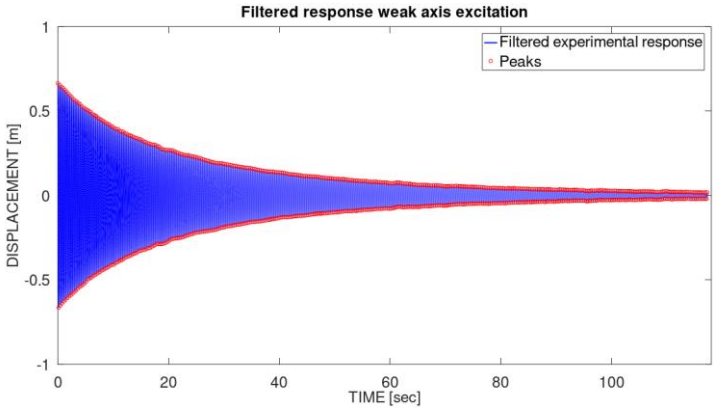


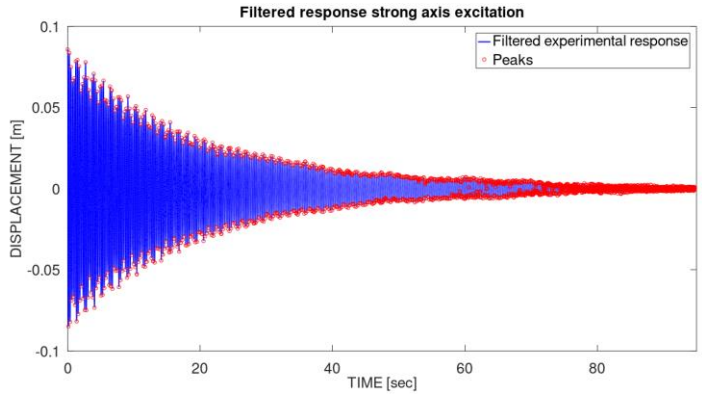
Second bending mode, displacements in transversal direction(strong axis)

Damping

Experimental signal processing

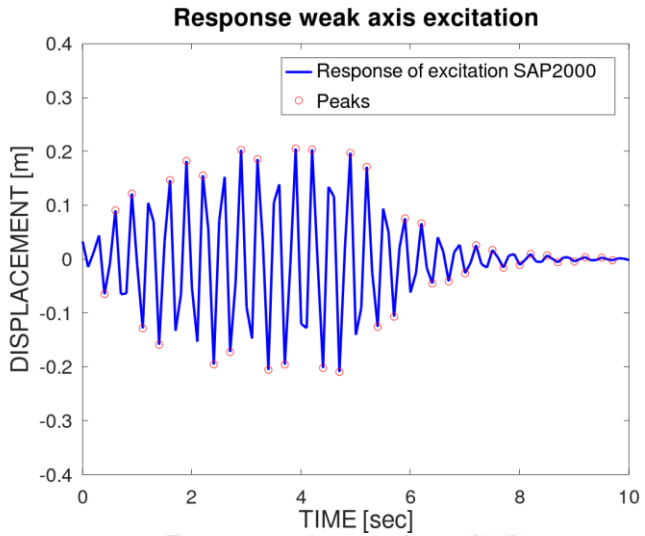
- It is filtered the measured signals using LabView in order to obtain a clearer decaying of the excitation of the structure.
- It is used Octave to obtain the peaks of the signal and to calculate the logarithmic decrement.
- It is obtained a damping of **0,12% for weak axis and 0,08% for strong axis.**

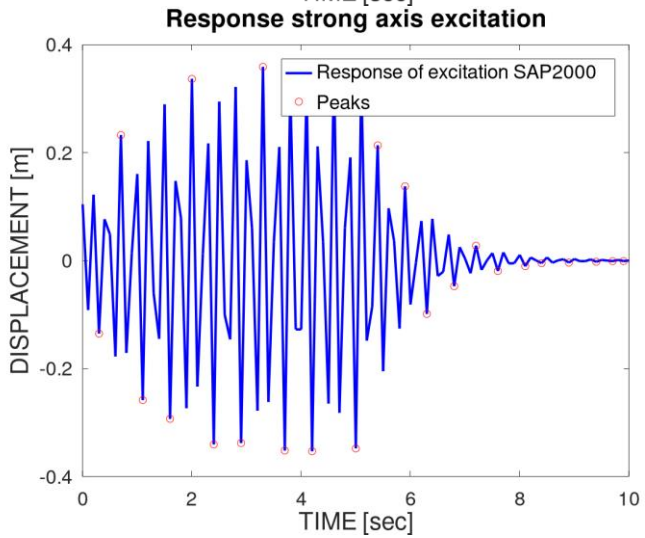




Numerical signal processing

- It is created a time-history in SAP2000 that simulates the experimental excitation, with the frequencies of the first two modes obtained in the numerical model.
- It is used Octave to obtain the peaks of the signal and to calculate the logarithmic decrement.
- It is obtained a damping of **4,2% for weak axis and 6,91% for strong axis.**





Modal Assurance Criterion (MAC)

MAC

- This criterion measures the degree of consistency between the experimental and numerical mode shapes.

Values

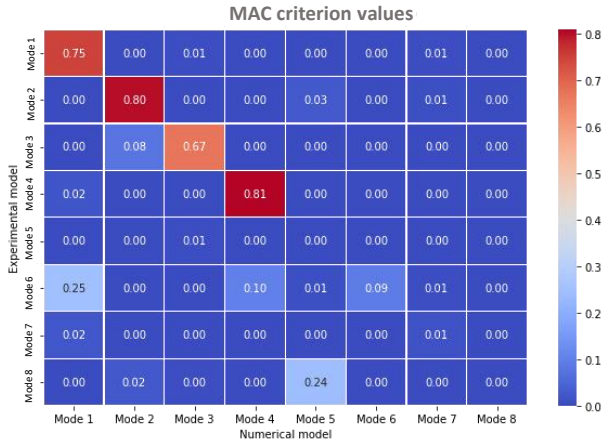
- It is bounded between 0 and 1, with 1 indicating fully consistency and 0 indicates that are not consistency. Diagonal values are the same mode shapes, therefore should be close to 1. The others should be close to 0.

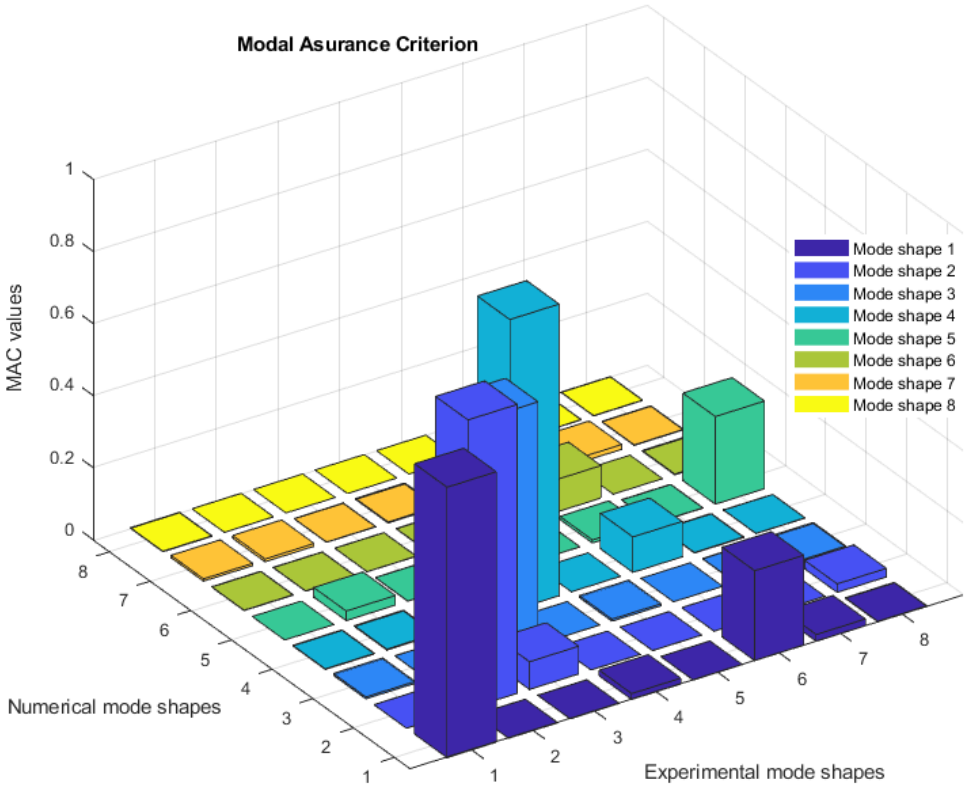
Allemang, R. J. (2003).

- Degree of consistency determined by:

$$MAC = \frac{\{\psi_{exp}\}^H \{\psi_{num}\}\{\psi_{num}\}^H \{\psi_{exp}\}}{\{\psi_{exp}\}^H \{\psi_{exp}\}\{\psi_{num}\}^H \{\psi_{num}\}}$$

ψ_{exp}: experimental modal shapes
ψ_{num}: numerical modal shapes
H: indicates complex conjugate transpose





Conclusions

- It is possible to capture the principal 4 mode shapes of experimental and numerical models that are evaluated with MAC and it is found that they are consistent.
- The sum of the MPMR in X axis is 97,63% and in Y axis 94,57% for the first 4 modes. Therefore, it is possible to conclude that it is captured almost entirely the dynamic behavior of the structure in the improved numerical model.
- Four additional modes are captured with similar frequencies and visually comparable mode shapes; however they are not consistent when evaluated with MAC.
- The average damping is obtained for the first two principal modes, for the experimental (0,12% and 0,08%) and numerical models (4,12% and 6,91%). The results differ considerably due to the difficulty of emulating the experimental excitation in the numerical model.

It is studied the difficulty to connect the assumptions made in numerical models with the real behavior of structures. It is remarkable the changes in the dynamic behavior of the structure due to how are considered of the connections.

References

- Allemang, R. J. (2003). The Modal Assurance Criterion – Twenty Years of Use and Abuse. *SOUND AND VIBRATION*, 8.
- Vacher, P., Jacquier, B., & Bucharles, A. (n.d.). *Extensions of the MAC criterion to complex modes*. 14.
- Wilson, E. L., & Computers and Structures, Inc. (2002). SAP2000. *Integrated Software for Structural Analysis and Design. Analysis reference Manual.* Computers and Structures.
- Reynders, E., Schevenels, M., & De Roeck, G. Faculty of Engineering. KU Leuven. (2014). *MACEC 3.3. A MATLAB toolbox for experimental and operational modal analysis.* Belgium.
- PD Dr.-Ing. habil. Volkmar Zabel. Faculty of Engineering. Bauhaus-University Weimar. (2020). *Experimental Structural Dynamics. Lecture notes.* Germany.
- American Institute of Steel Construction, AISC. (2017). *Manual of Steel Construction, 15th Edition*. Chicago, United States of America.

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Thank you for your attention.

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