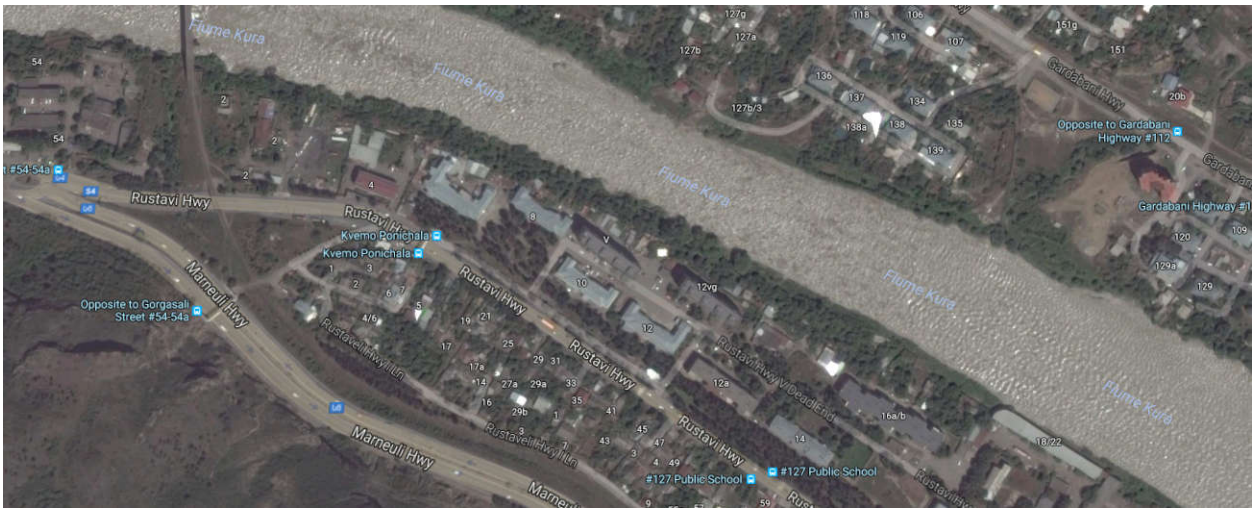
Ambient vibration survey and dynamic identification of residential buildings

Phonichala, Tbilisi



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Summary

Introduction

Upon request of MDF - AMENDMENT #1 of CONTRACT No: SUTIP2/C/QCBS/08-2015 - DRC has carried out the monitoring of 9 buildings in Phonichala by Operational Modal Analysis to determine their natural frequencies of vibration.
The monitoring was carried out from 1 April to 8 April.

Dynamic identification techniques provide a valuable knowledge of the dynamic behavior of monitored structures for the assessment of safety conditions respect to external stimulations.
Operational Modal Analysis (OMA) permits to reconstruct the structural dynamics in the range of small vibration amplitudes generated by unknown excitation inputs in real operating conditions. Typical excitation forces are wind, traffic and any type of ground tremors of natural or artificial origin. Such type of data processing “Output only” algorithms are the best option for online monitoring system, to constantly monitor the vibrations of a structure, without the application of a measurable (known) input to the system.

The objective of the present work is the determination of structural dynamic parameters (such as natural frequencies, damping ratios and mode shapes) during the monitoring phase. The measurements are performed with high sensitive piezoelectric sensors along the X and Y axes of the buildings linked to automatic data acquisition and recording system.

The investigated structures are located in Phonichala distric, Tblisi(Figures 1 and 2. “Location of buildings”).

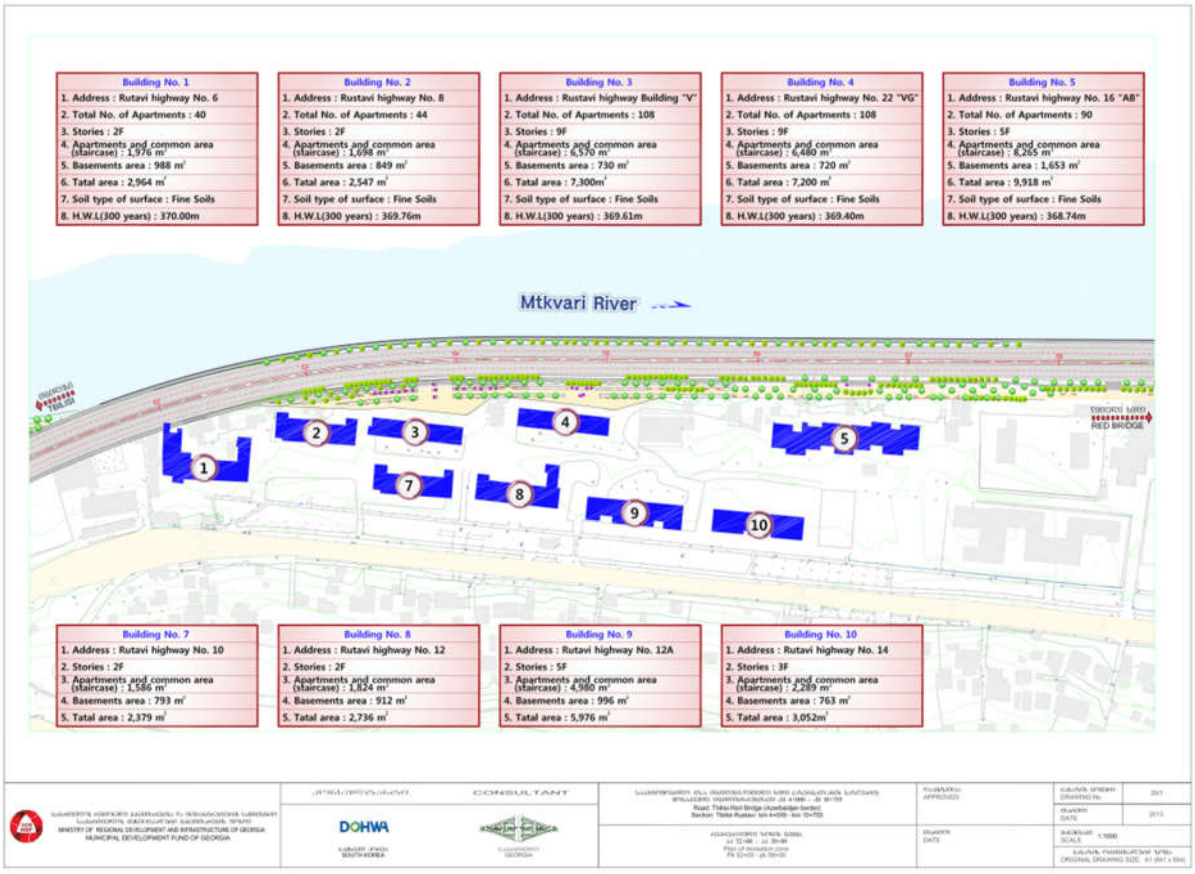


Fig. 1 Location of studied buildings

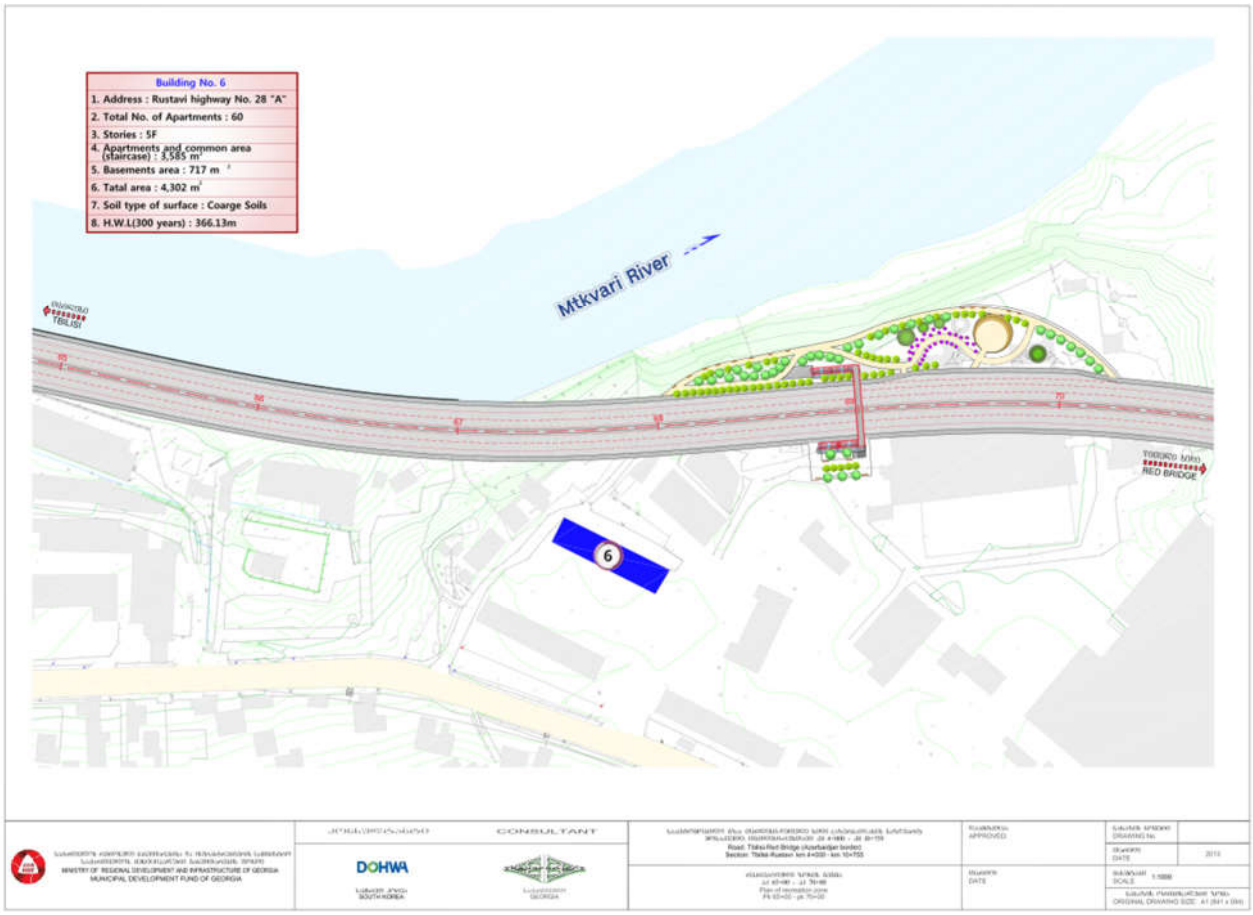


Fig. 2. Location of studied buildings

Ambient Vibration Surveys (AVS)

Dynamic Identification approach

The methodology applied in the monitoring belongs to the family of non-destructive test, having no interaction with the structure of the building. It implies the acquisition of signals by high sensitive accelerometers fixed in several selected points of the monitored building; the output data are sampled at the same time interval. The control unit permits the high precision time synchronization of data collections among the sensors, a condition that is absolutely necessary for the further correct processing needed to extract the frequencies.

Data are acquired with ata sample rate of 1.000Hz for a minimum of 30 min per measurement. Measurements are performed at several floors of the monitored building with sensors at the opposite corners and oriented along the X, main axis , and Y shorter axis of the building. By that it is possible to obtain the translational and torsion modes of the structure.

The method used in this application works is in time domain, and it is based on a state-space description of the dynamic problem using the Covariance Stochastic Subspace Identification (SSI-Cov) algorithm. Using this algorithm the modal parameters (frequencies, mode shapes and damping ratios) can be extracted. The measurements are performed at several floors of each monitored building.

The collected measurements are originally sampled at 1.000Hz. They were reduced by a factor of 20 before processing to have the final data of 50 Sample per Second (SPS).
The duration of data recording varied between thirty minutes and one hour to minimize the influence of possible non-stochastic excitations (random noise or random peaks) that may occur during the test. This procedure was used for each AVS.

Standards

Measurements were performed according to the following standards:

- ISO/FDIS 4866 – “Mechanical vibration and shock, Vibration of fixed structures, Guidelines for the measurement of vibrations and evaluation of their effectson structures”;

Equipment

A wired sensor network composed of the following elements was used:

- piezoelectric sensors (Integrated Electronic Piezoelectric - IEPE) KS48C-MMF with voltage sensitivity of 1V/g and measurement range of ±6g. (calibration certificates dated about 40 days before the test)
- digital recorder (DaTa500) composed by a24-bitDigital Signal Processor (DSP),ananalog anti-aliasing filter andahigh-frequency acquisition range (0.2Hz to 200kHz).

		KB12	KB12VD	KS48C	
Output		Charge	IEPE	IEPE	
Piezo Design		Bender	Bender	Shear	
Charge Sensitivity	B_{qa}	6500±20%	-	-	pC/g
Voltage Sensitivity	B_{ua}	-	10 000±10%(1)	10 000±5%(1)	mV/g
Range	A_+ / a.	±3	±0,6	±6	g
Destruction limit	a_{max}	200	200	1000	g
Linear Frequency Range	$f_{3\,dB}$ $f_{10\%}$ $f_{5\%}$	260 160 130	0,08.. 260 0,16.. 160 0,25.. 130	0,1 .. 4000 0,2 .. 2600 0,3 .. 2000	Hz Hz Hz
Resonant Frequency	f_r	>0,35(+15dB)	>0,35(+15dB)	>7 (+25dB)	kHz
Noise Densities	0,1Hz a_{n1} 1 Hz a_{n2} 10 Hz a_{n3} 100Hz a_{n4}	- - - -	0,3 0,06 0,03	1 0,6 0,1 0,06	µg/√Hz µg/√Hz µg/√Hz µg/√Hz
Costant Current Supply	I_{const}	-	2 .. 20	2 .. 20	mA
Output impedance (I_{const} = 4mA)	r_{out}	-	< 130	<130	Ω
Operating Temperature Range	T_{min}/T_{max}	-20/80	-20/80	-20/120	°C
Temperature Transient Sensitivity	b_{at}	0,01	0,002	0,0005	ms^{-2}/K
Acoustic Noise Sensitivity	b_{ap}	0,1	0,1		ms^{-2}/kPa
Weight (no cable)	m	150/5,3	150/5,3	165/5,8	g/oz
Mounting Thread		M5/M10	M5/M10	M8	
Case Material		Alluminio	Alluminio	Acciaio INOX	

Image 1 – Sensor Accelerometer

Dati Tecnici Generali	
Numero Canali	8 Canali simultanei
Segnali Misurabili	Tensione, Ponte Intero (IEPE, Charge, Termocoppie e RTD /adattatore MSI
Risoluzione	24 bit
ADC tipo	Sigma - Delta
Frequenza Acquisizione	10 to 200 000 Hz 204.8 kS/s
Input Range	Voltage ±0,01 V, ±0,1 V, ±1 V, ±10 V,
	Voltage via adattatore MSI
	Ponte Intero ±10 mV/V, ±100 mV/V, ±1000 mV/V
	Half bridge
	IEPE—MSI adapter ±0,1 V, ±1 V, ±10
	Termocoppie (-200°C a 1000°C e da 0 a 6.5kOhm)
DC Accuracy	10V range: 0,1% del valore, +1 mV 1 V range: 0,1% del valore, +0,5 mV 100mV range: 0,1 del valore, +0.1 mV 10mV range: 0.1% del valore, +0.1 mV
Tensione Sensori	±5 V 0.1% @ 100mA, 12V@400mA per singolo canale
Protezione Sovraccarico	±0 70V

Caratteristiche Dinamiche	
Rumore Segnale @fs<1000Hz	< -100 dB
Crosstalk	< -100 dB
Ambiente di lavoro	
Temperatura Operativa	0 to 50 °C
Temperatura Storage	-20 to 70 °C
Umidità Relativa	10 to 90%
Vibrazione	MIL-STD 810F 516.5
Shock - Urto	MIL-STD 810F 516.5
Dimensioni	
Dimensioni	223 x 78 x 45mm
Peso	0,72 Kg
Consumi	
Consumo tipico	5 W
Massimo consumo sensori	6 W
Requisiti Sistema	
Interfaccia	USB 2.0
Sistema Operativo	Windows XP, Vista, 7
Sistema - Hardware	PC completo di software DeVsoft

Image 2 Data Acquisition system

- RG58 coaxial cableslinkfrom ccelerometers to recorder;
- M28 and M32 signal conditioners with frequency range of 0.1 to 100kHz and adjustable e gain.

	M28	M32
Input	IEPE—BNC connettore	
IEPE Sensors Alimentazione	Shear	
Indicazione Stato sensore	Tre Indicazioni LED: circuito aperto=off ; OK=giallo; Corto Circuito=rosso	
Guadagno	1 ± 0,5%	1 /10/100 ± 1% typ; ± 2% max
Livello Output	> ± 10_{pp} (in funzione del sensore)	> ± 10_{pp}
Rumore Output	< 1 μV_{eff} (2 .. 25kHz) < 1 μV_{ms} (2 .. 25kHz)	< 1 mV_{pp} (1 .. 50kHz) < 1 mV_{pp} (1 .. 50kHz)
Frequency Range (-3dB)	0,1 Hz .. 100 kHz	0,1 Hz .. 30kHz
Filtro Low Pass	-	Modello Plug-in serie FB2*
Tipologia Filtro	-	4 poli, butterWorth >70dB
Alimentazione	5 .. 26 VDC / 100mA	5 ..26 VDC / 200mA
Connettore Alimentazione	DIN 453232 circolare—bananaplug	
Range Temperatura	-10 .. 55 °C, 95% Umidità relativa	
Dimensioni	33x59x44 mm^3	56x59x44 mm^3
Peso	120g	170g
Accessori	2 banana plug filettati	
Accessori - Opzionali	FB2 Modulo Filtro Low Pass (30Hz) M28/32 DIN adattatore Barra DIN PS500 Alimentatore 500mA PS1600 Alimentatore 1,6A	

Assemblato M32—M28

Image 3 – Signal conditioner

Estimation of the structural dynamic parameters

Estimation of structural modes is donethrough“stabilization diagrams”showing the alignments of stable poles, for increasing model orders.

The method used in the presented application works is in time domain, and it is based on a state-space description of the dynamic problem using the Covariance Stochastic Subspace Identification (SSI-Cov) algorithm. In fact, the second order problem, stated by the differential equation of motion, is converted into two first order problems, defined by the so-called “state equation” and

"observation equation." Such equations, in the output-only case, can be written as follows for the generic discrete time instant $t = k\Delta t$, where Δt is the sampling period and $k \in \mathbb{N}$:

$$\{x_{k+1}\} = [A]\{x_k\} + \{w_k\} \quad (1)$$
$$\{y_k\} = [C]\{x_k\} + \{v_k\} \quad (2)$$

where $\{x_k\} = \{x(k\Delta t)\}$ is the discrete time state vector yielding the sampled displacement and velocities, $\{y_k\}$ is the sampled output, $[A]$ is the discrete state matrix, $[C]$ is the discrete output matrix, $\{w_k\}$ is the "processed noise" due to disturbances and model inaccuracies, $\{v_k\}$ is the "measurement noise" due to sensor inaccuracy. These vector signals are both immeasurable.
Once the state space model has been constructed, the modal parameters (frequencies and damping ratios) can be extracted by the Eigen-decomposition of the system matrix $[A]$.
Natural frequencies are, then, obtained from the complex modules of the continuous-time poles as:

$$f_j = \frac{|\lambda_{cj}|}{2\pi}$$

while damping ratios are given by:

$$\xi_q = \frac{Re(\lambda_{cj})}{(\lambda_{cj})}$$

The mode shapes φ_j at the sensor locations are observed parts of the system eigenvectors Ψ and are obtained using the observation equation

$$\Phi = C\Psi$$

In conclusion the modal parameters $\omega_j, \xi_j,$ and φ_j can be extracted analytically from the identified system matrices $[A]$, $[C]$.

A modal parameter extractor developed in Labview programming language carried out data processing. It can perform analyses in time domain according to the SSI-Cov procedure mentioned before.

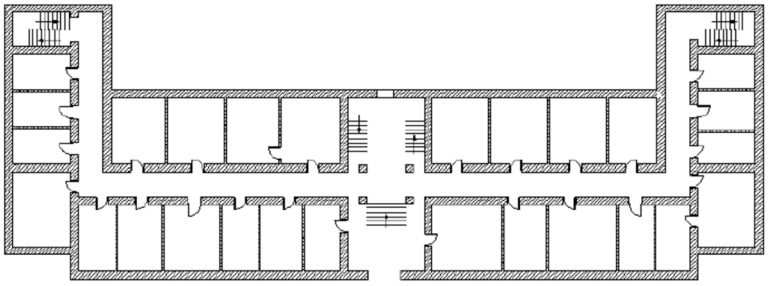
Estimation of structural modes is done through "stabilization diagrams" that show the alignments of stable poles, for increasing model orders. It also allows the determination of the "n" eigenvectors of dynamic matrix $[A]$ which completely describes the structural parameters.
The points in red indicate the negative result of the stability test and the points in green indicate the positive results: because the natural modes show the intrinsic characteristics of the structure, they are invariant to the process and the order of the NM. By that it is possible to isolate the natural modes from the numerical ones by increasing the order of the model and checking the stability of the results.
The stability of a pole is defined as follows:

- the estimated frequency is considered stable if it does not change more than 2%;
- the damping for different orders should not be deviated more than 10%;
- the modal shape obtained by a certain order is compared with the same achieved by a minor order by Modal Assurance Criterion (MAC) that must be at least equal to 90%.

After this step, consistency checks permit the discrimination between structural modes and spurious frequencies. Candidate modes are selected according to an identification process based scientific bibliography and according to relevant method of best practice. Frequencies associated with a damping ratio higher than 10% are not considered.

Results of the dynamic identification for each building are presented in the following chapters.

BUILDING 2



TYPICAL PLAN

Image 4 : building n.2

SENSORS LAYOUT

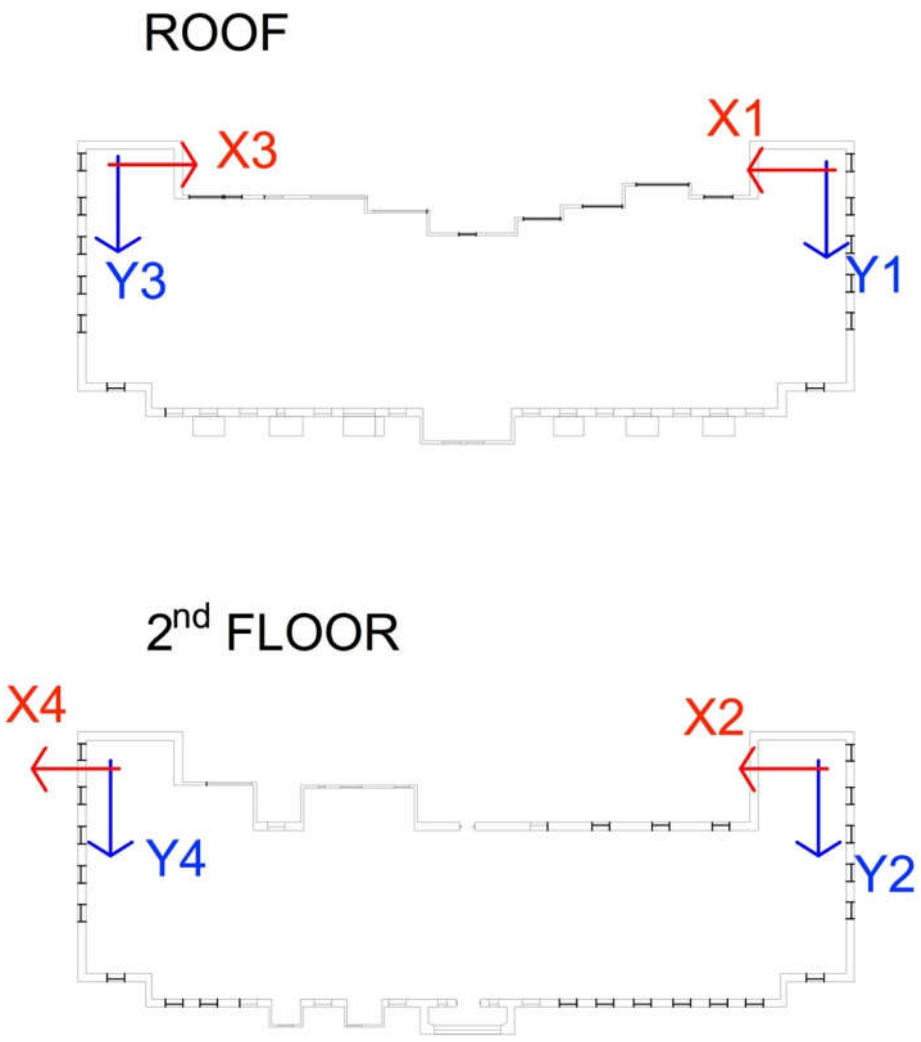
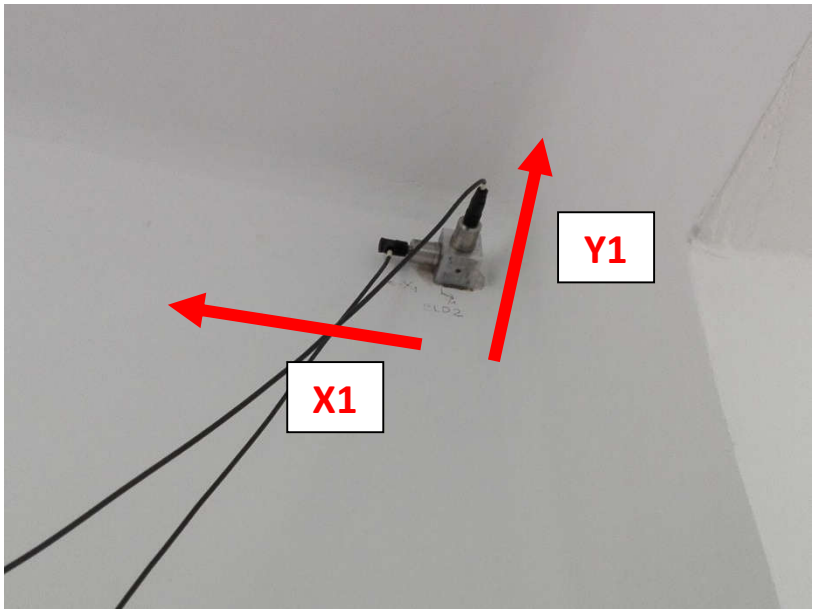
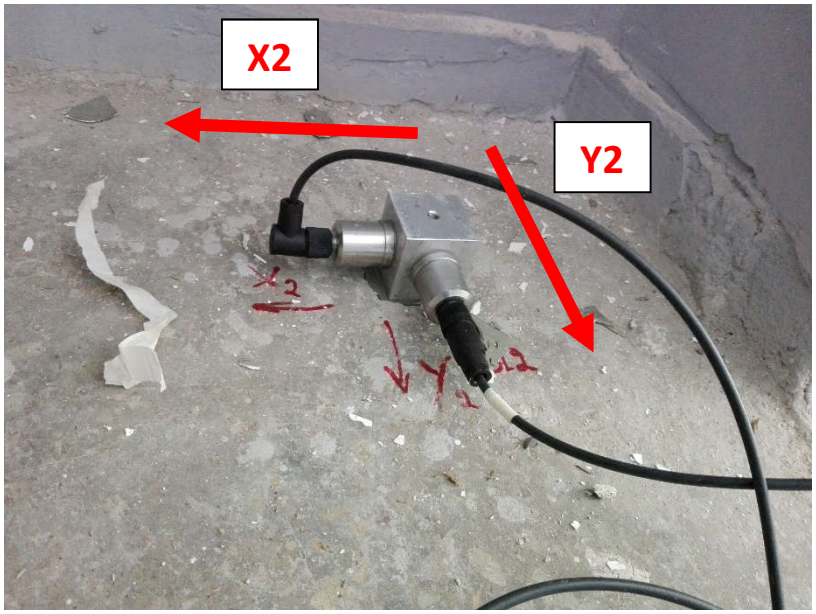
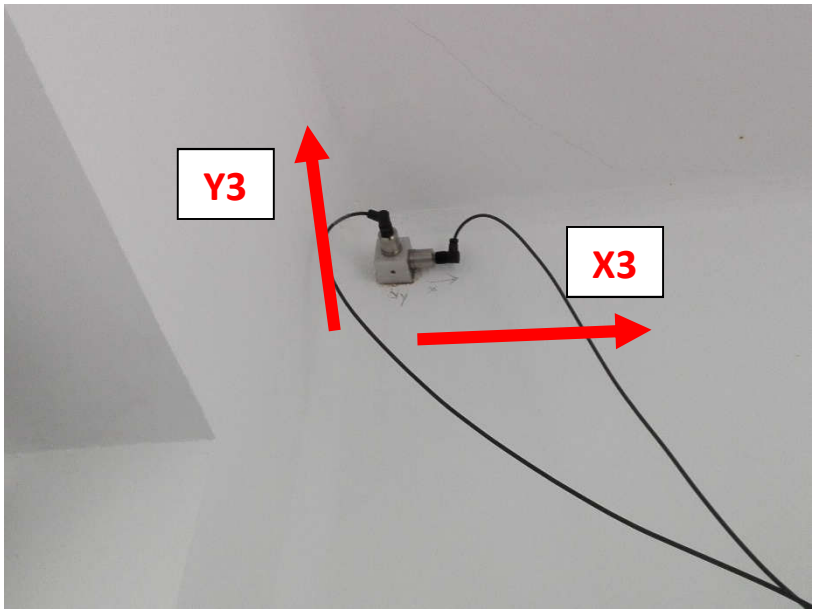


Image 5 : sensors layout


Y1
X1





Images 6 and 7 : sensors

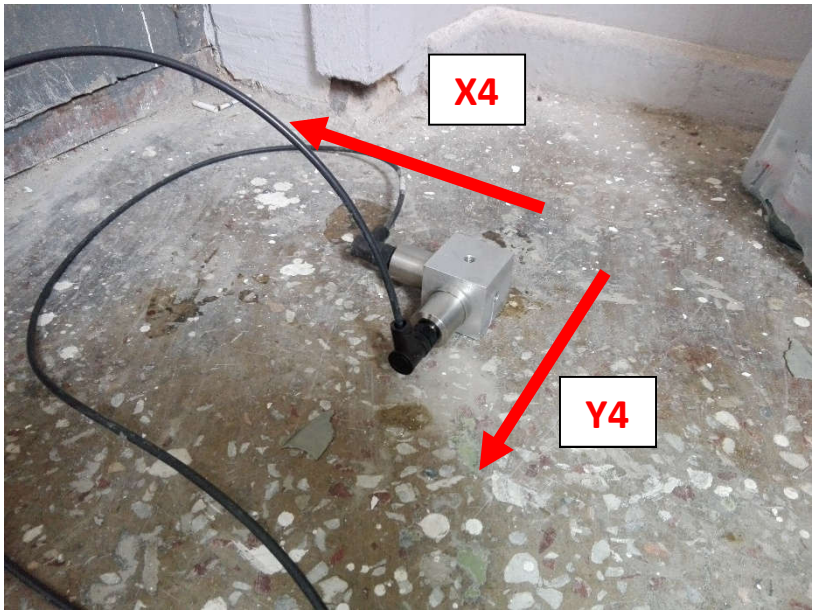


Image 8. Sensors

ACQUISITION OF TIME HISTORIES

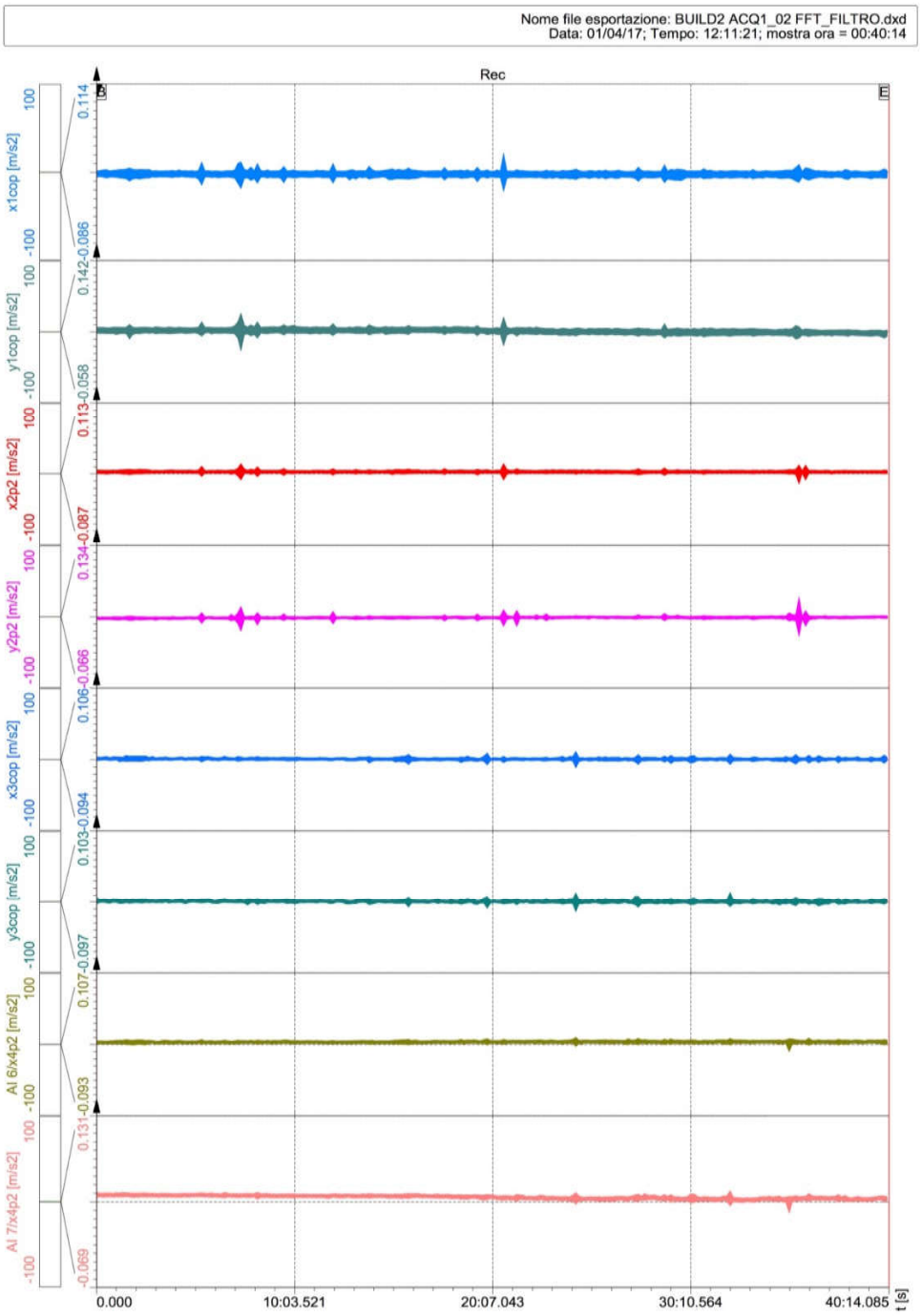


Image 9 time histories diagram

FREQUENCY CONTENT OF THE SIGNALS

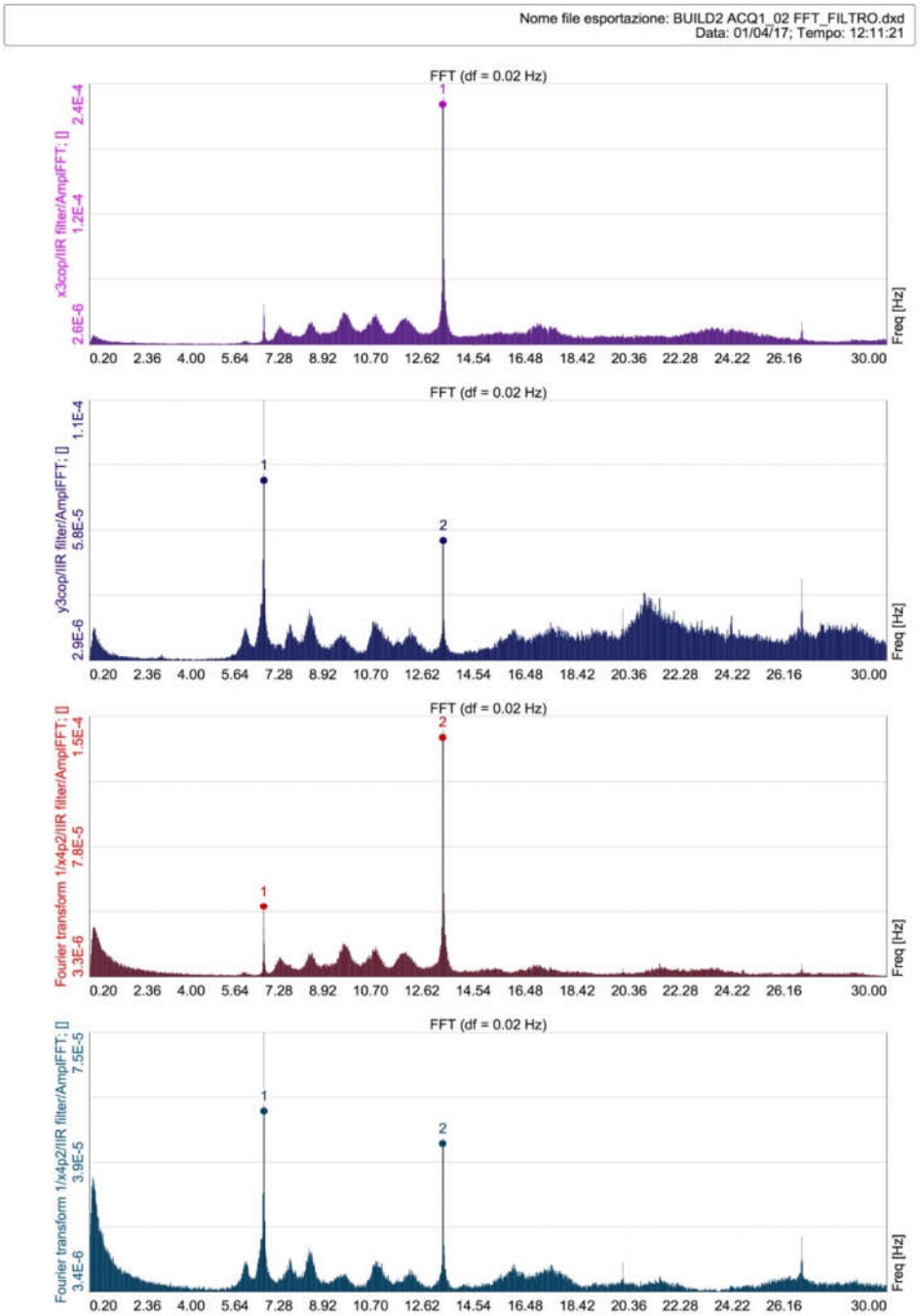


Image 10 frequency content

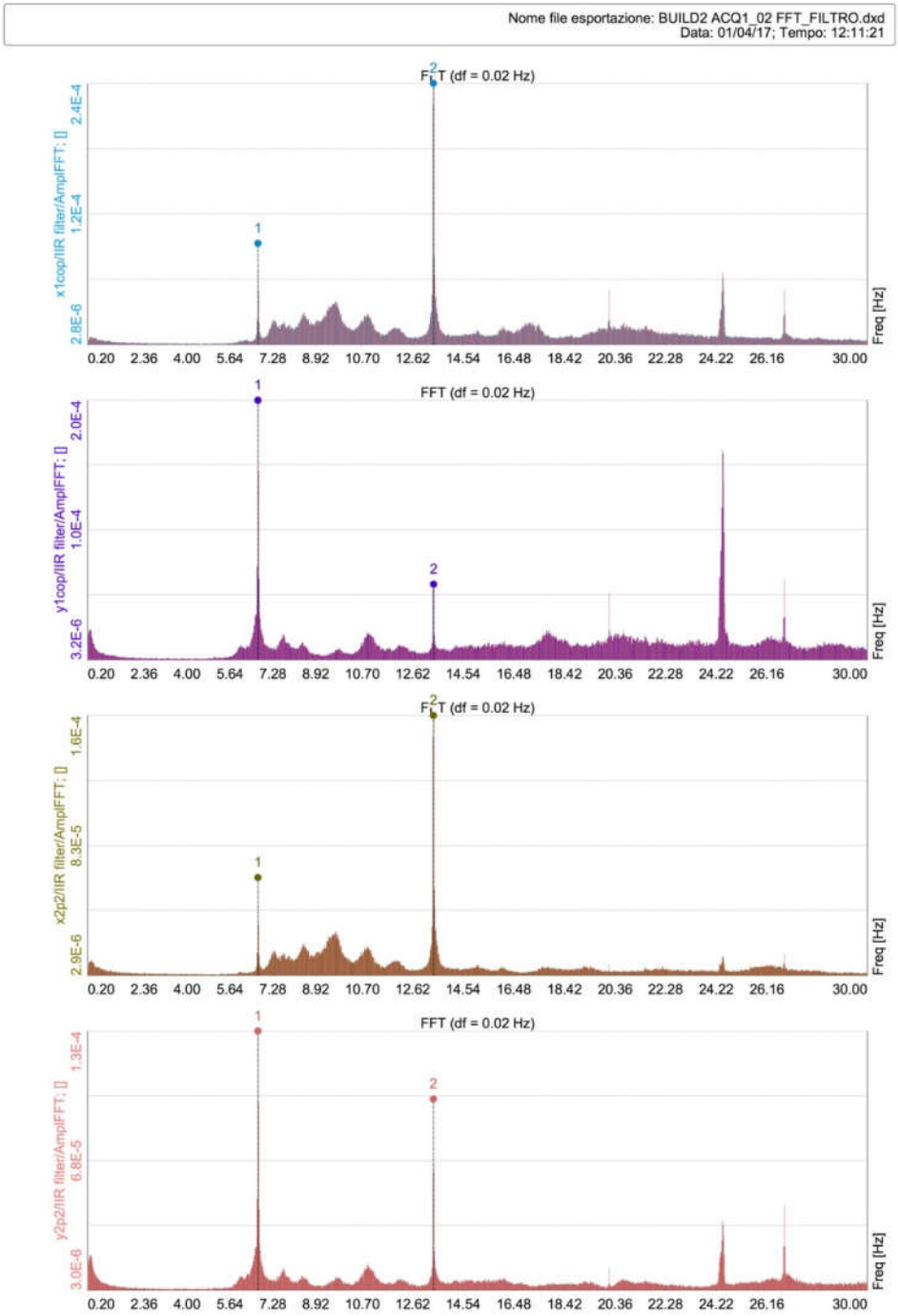
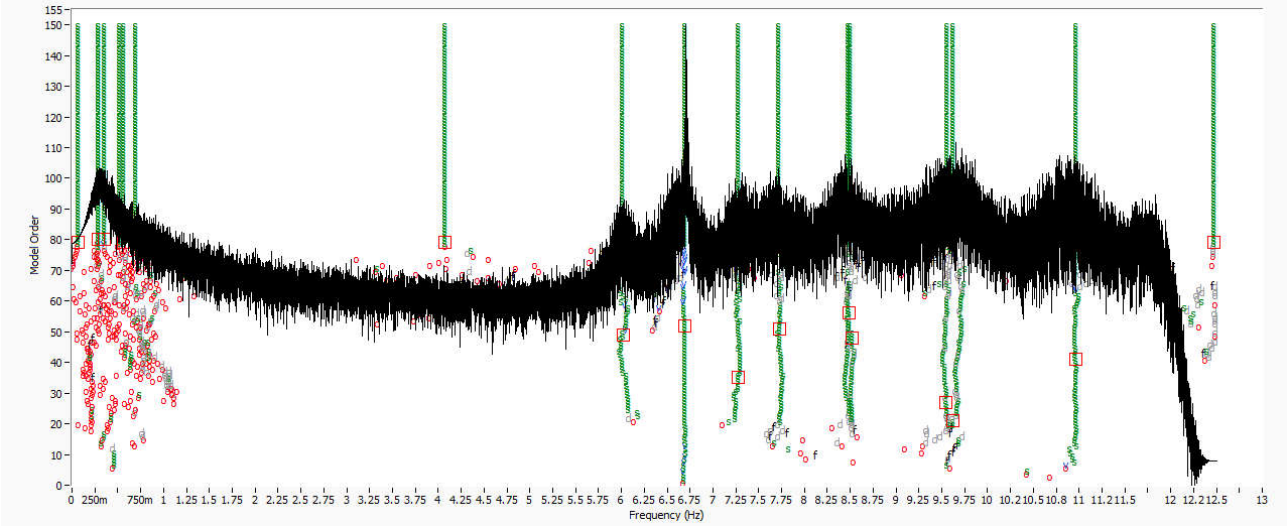


Image 11 frequency content

MODAL IDENTIFICATION RESULTS

Stabilization diagram



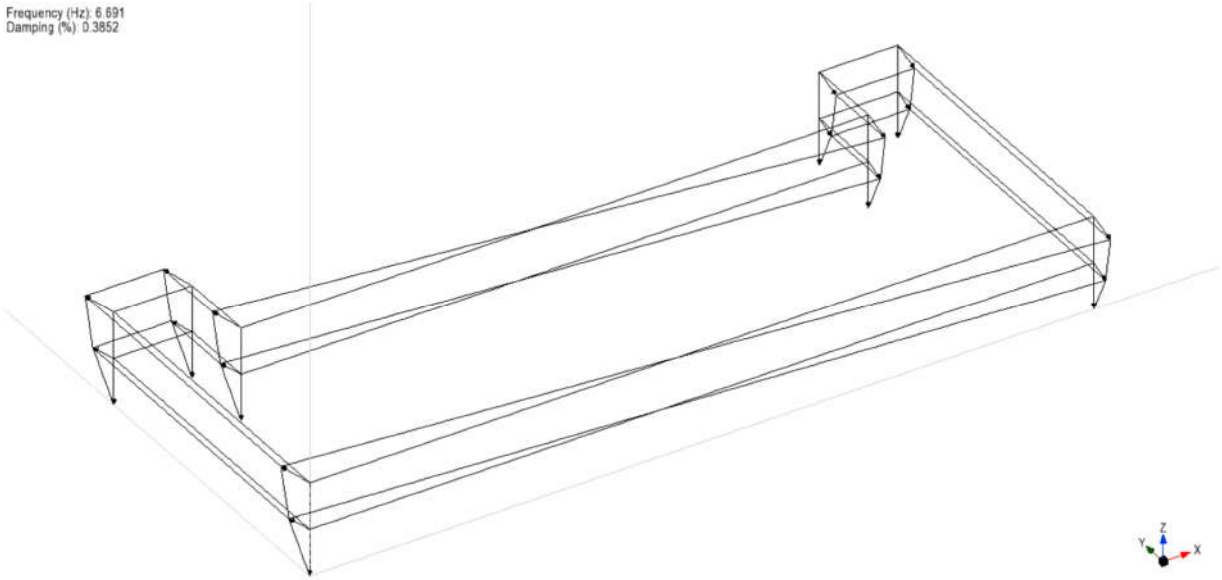
Mode n.	Frequency (Hz)	Damping (%)
1	6.69	0.385
2	7.28	3.639
3	7.73	3.012
4	8.48	2.192

Image 12 Modal identification results

Mode Shapes

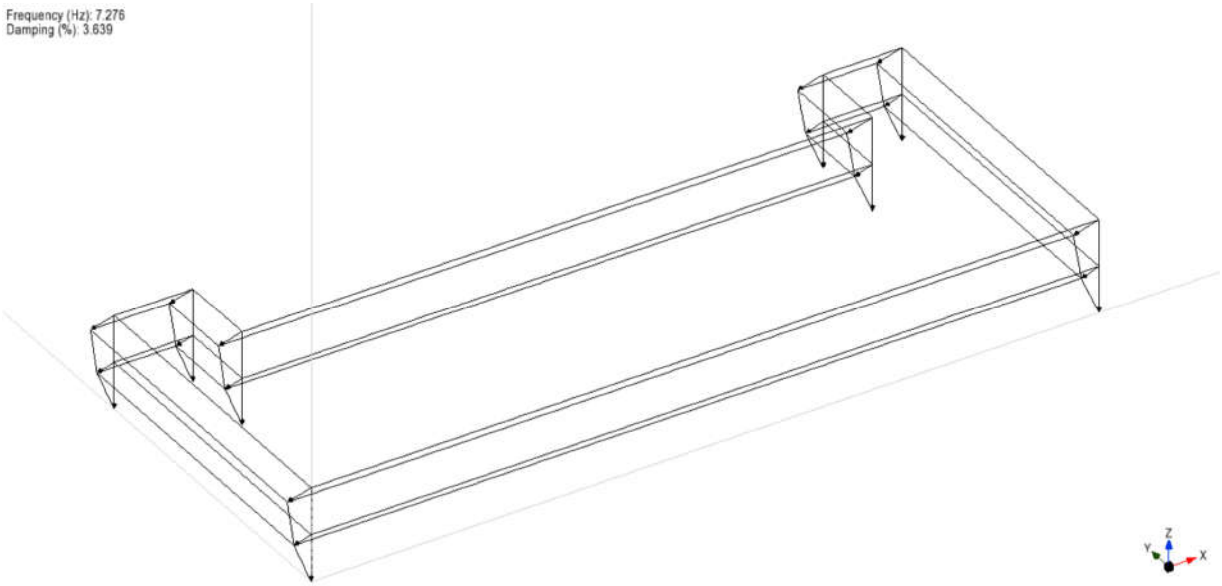
Mode1

6.69Hz - Torsional



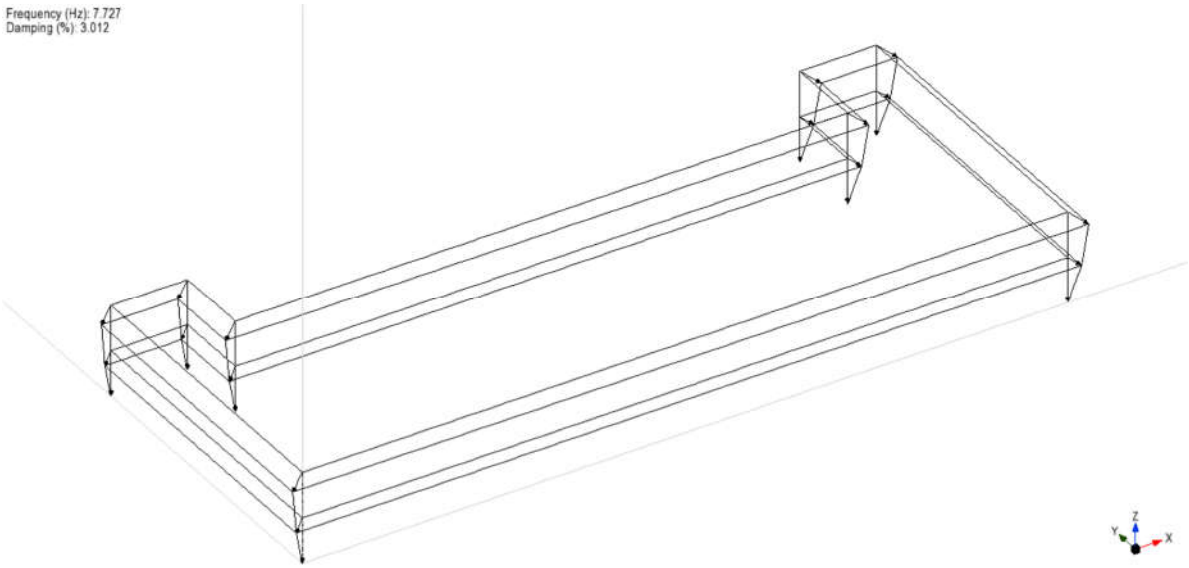
Mode2

7.28Hz – Traslational X

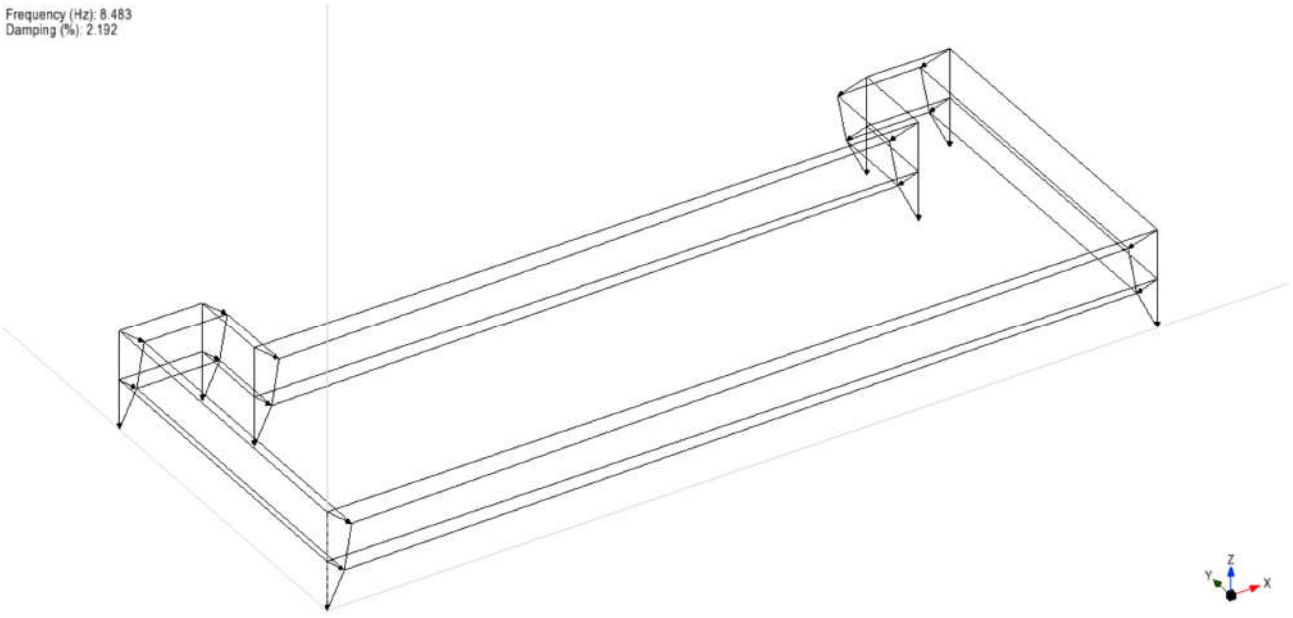


Images 13 and 14. Modal shapes

Mode3
7.73Hz – Traslational Y



Mode4



8.48Hz – Torsional

Images 15 and 16 Modal shapes

BUILDING 3

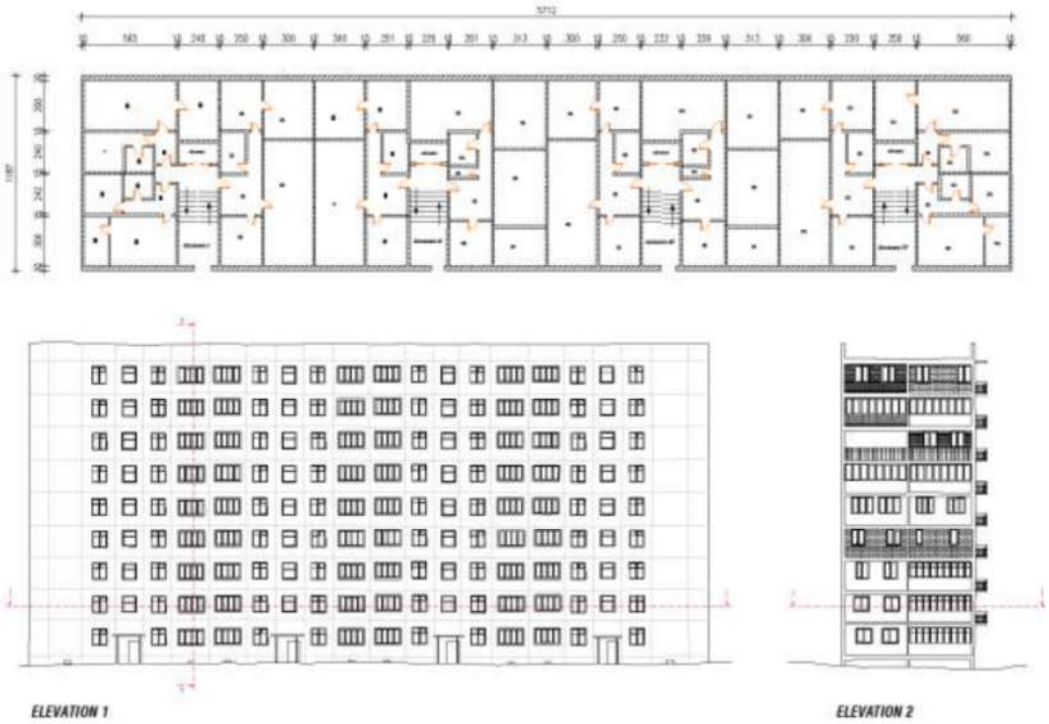


Image 17. Building n.3

SENSORS LAYOUT

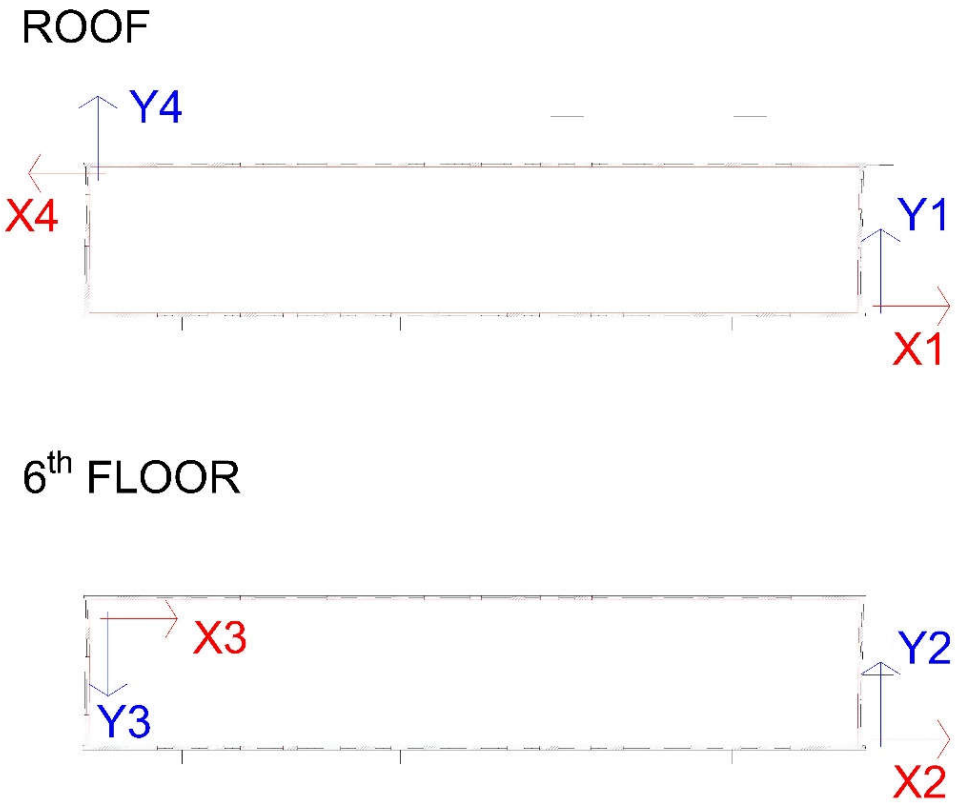
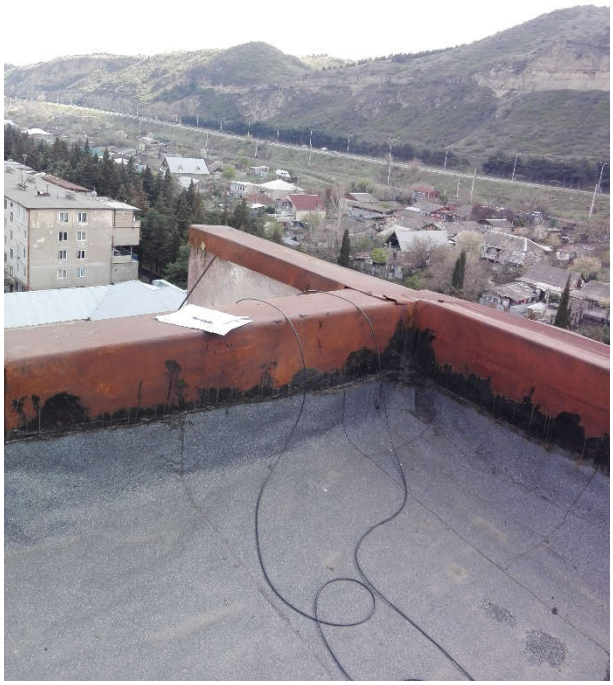
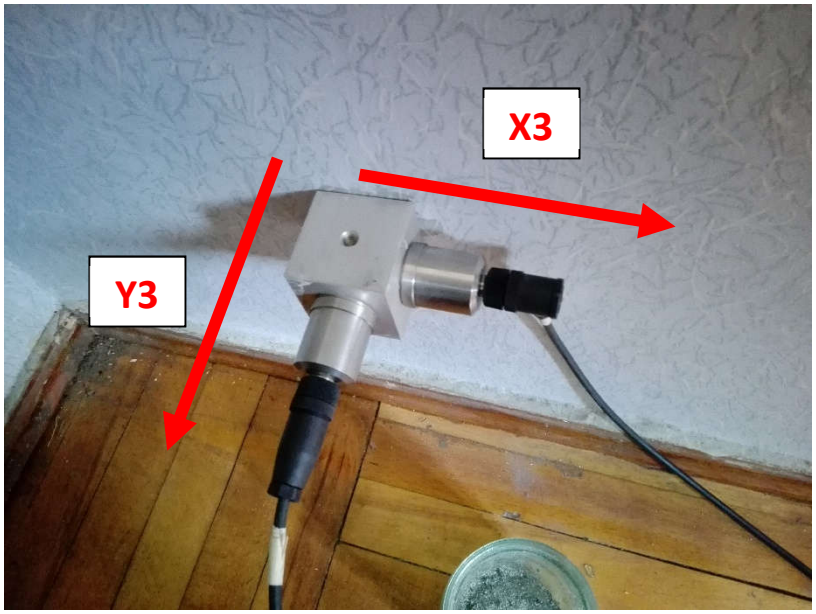
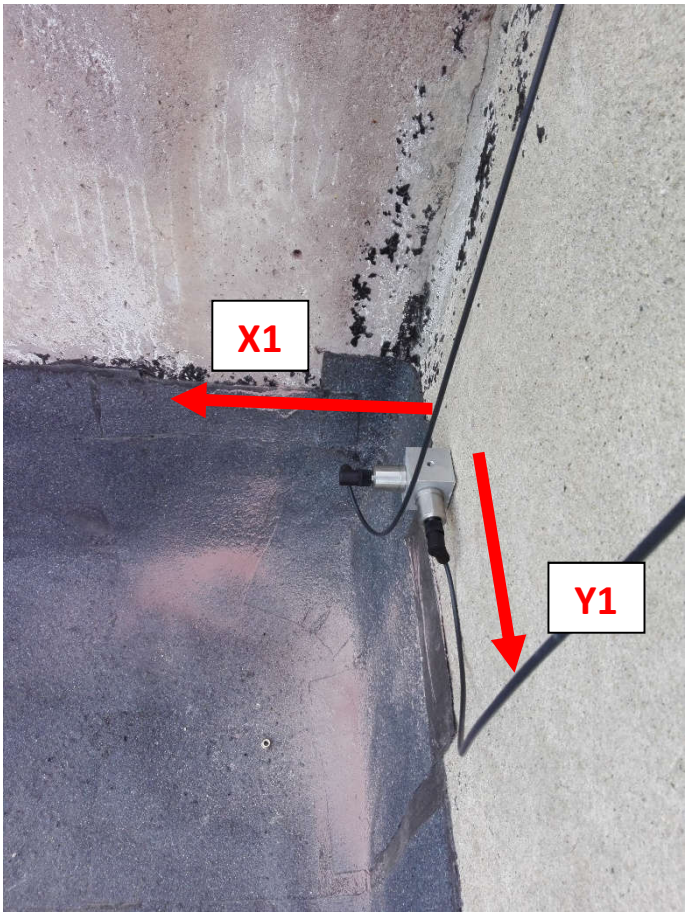


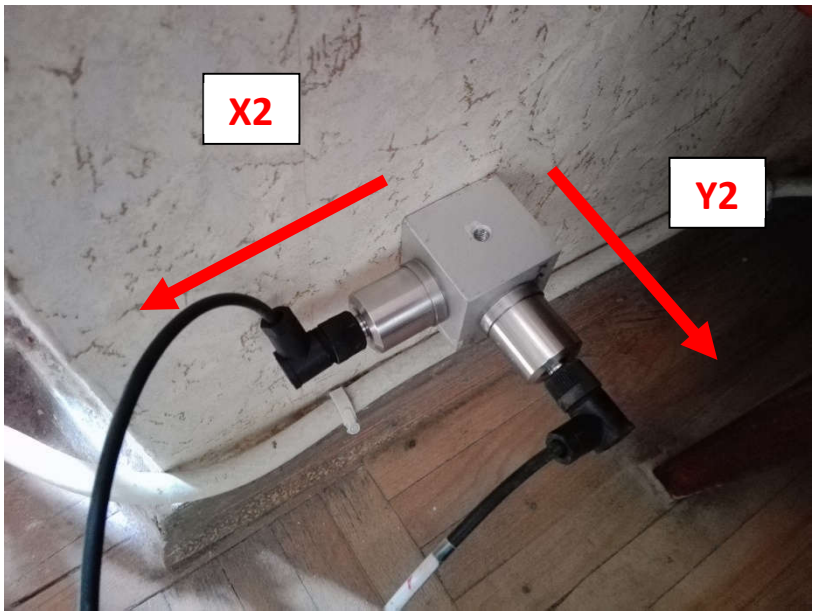
Image 18 sensor layout





Images 19 and 20 sensors





Images 21 and 22 sensors

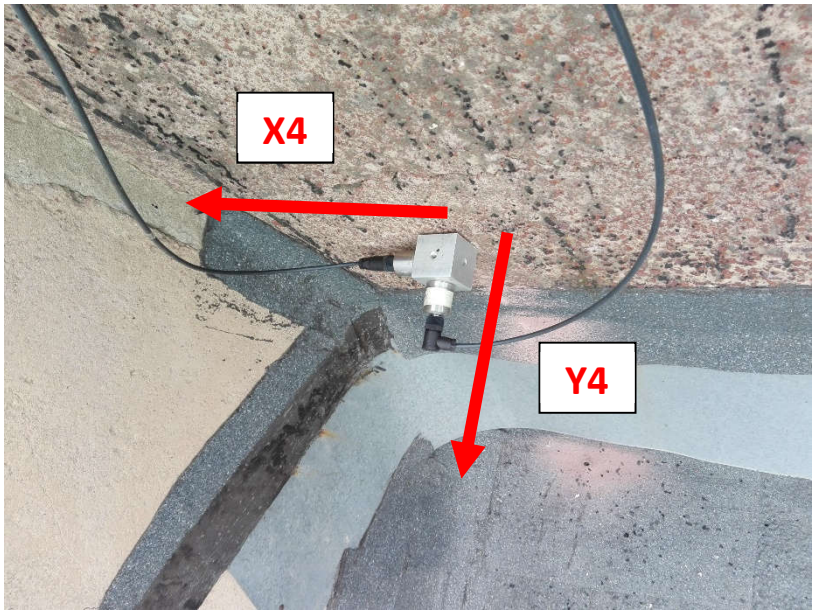
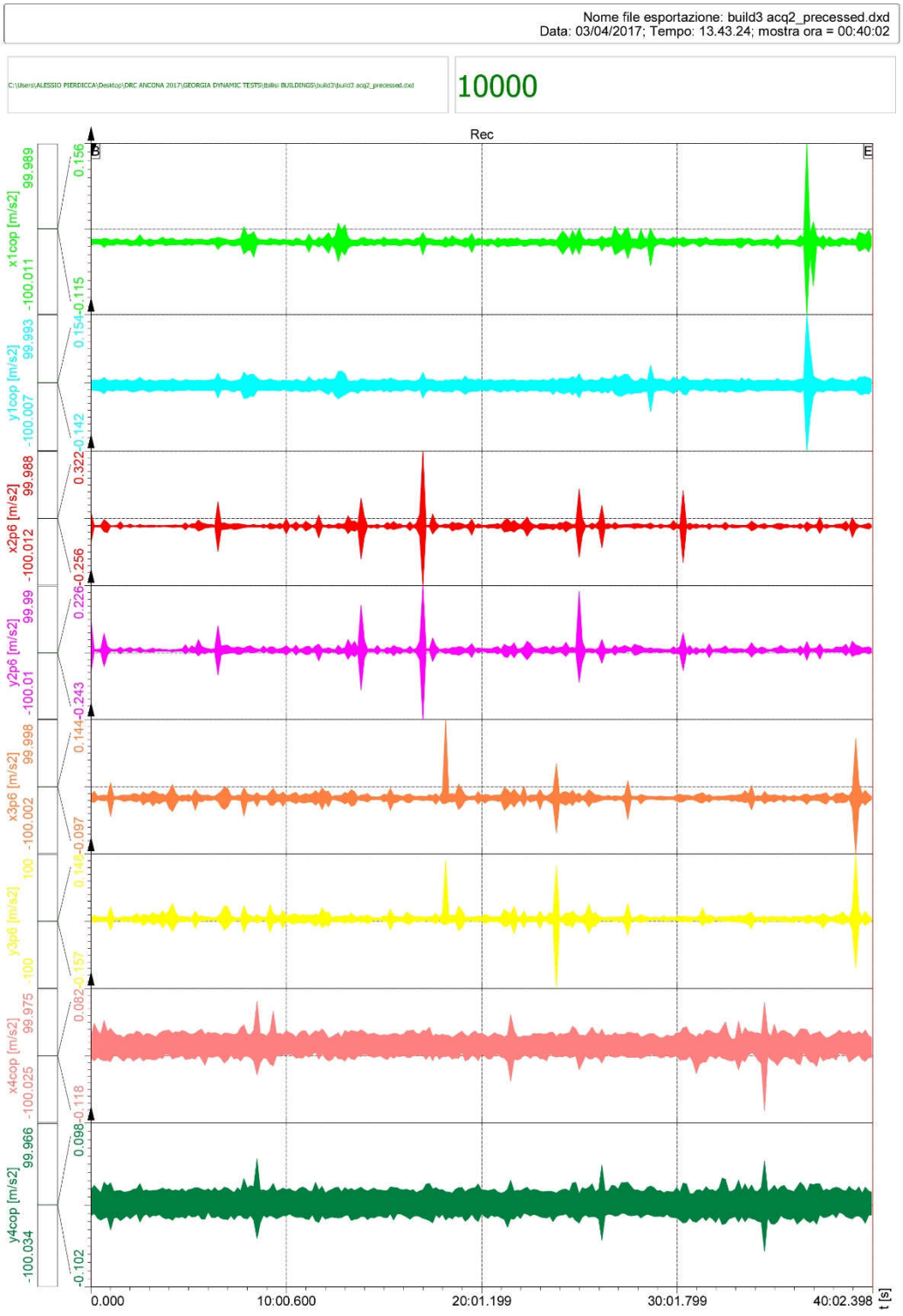


Image 23 sensors

ACQUISITION OF TIME HISTORIES



Images 13 and 14. Time histories

FREQUENCY CONTENT OF THE SIGNALS

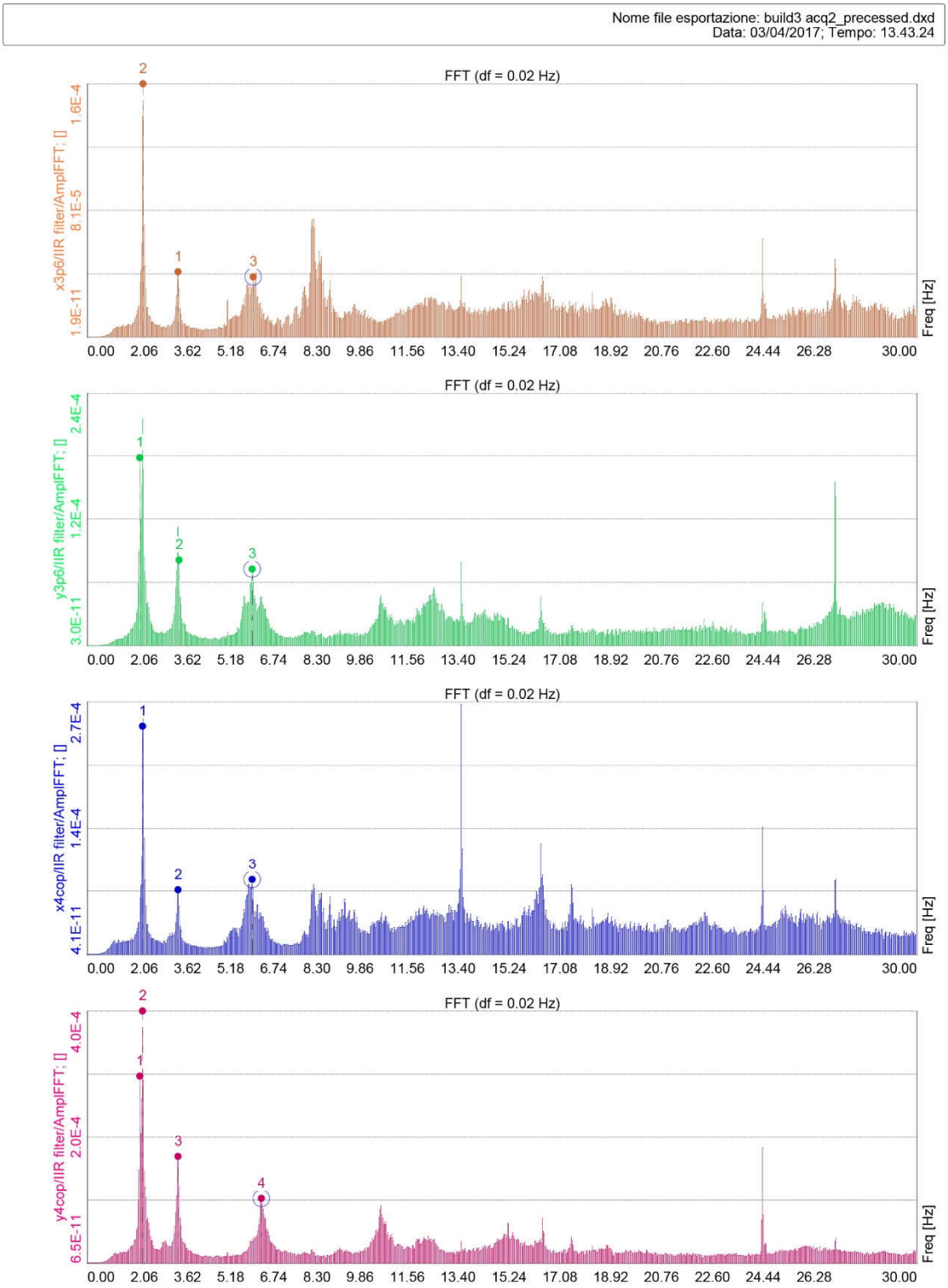


Image 15. Frequency content

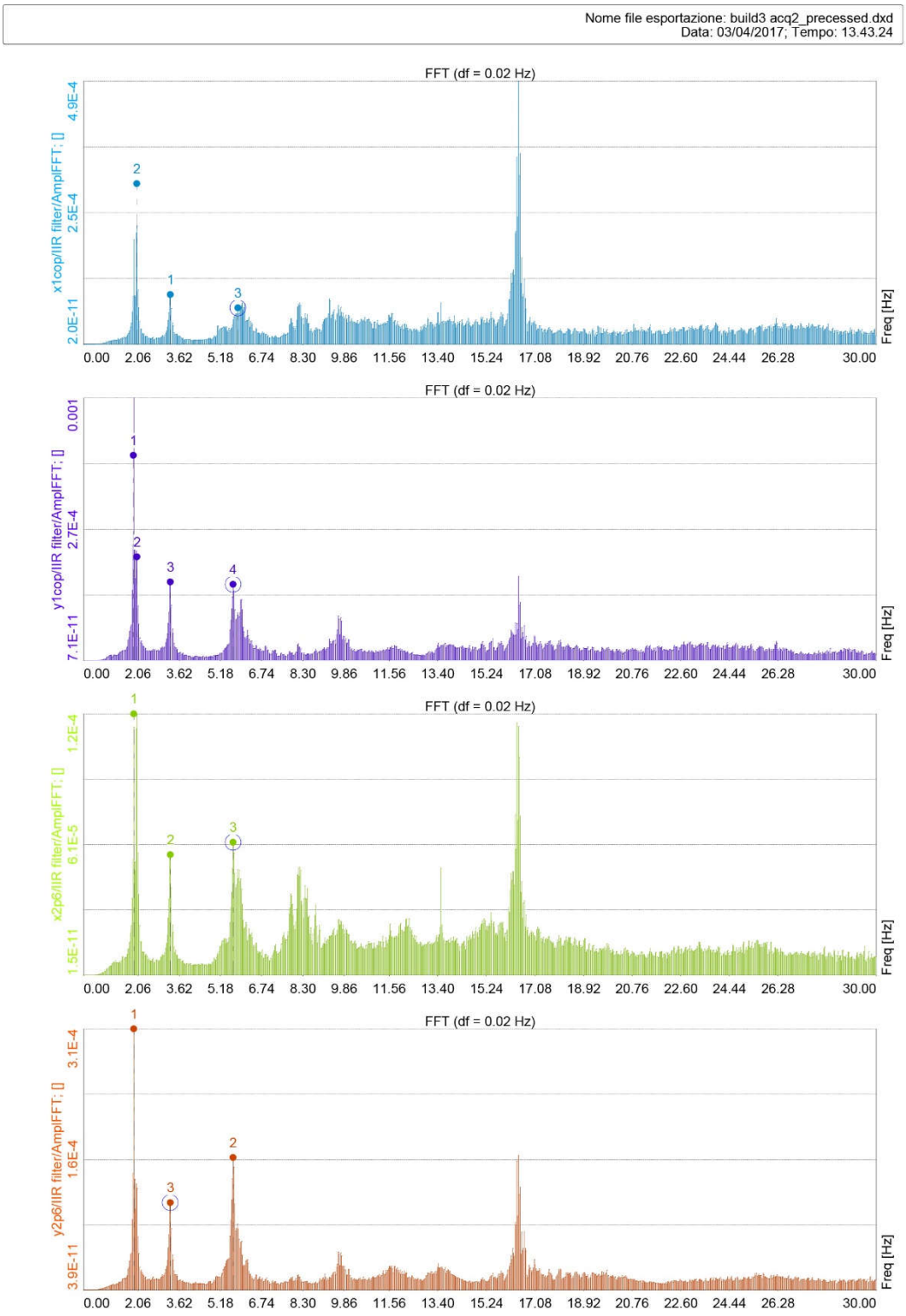
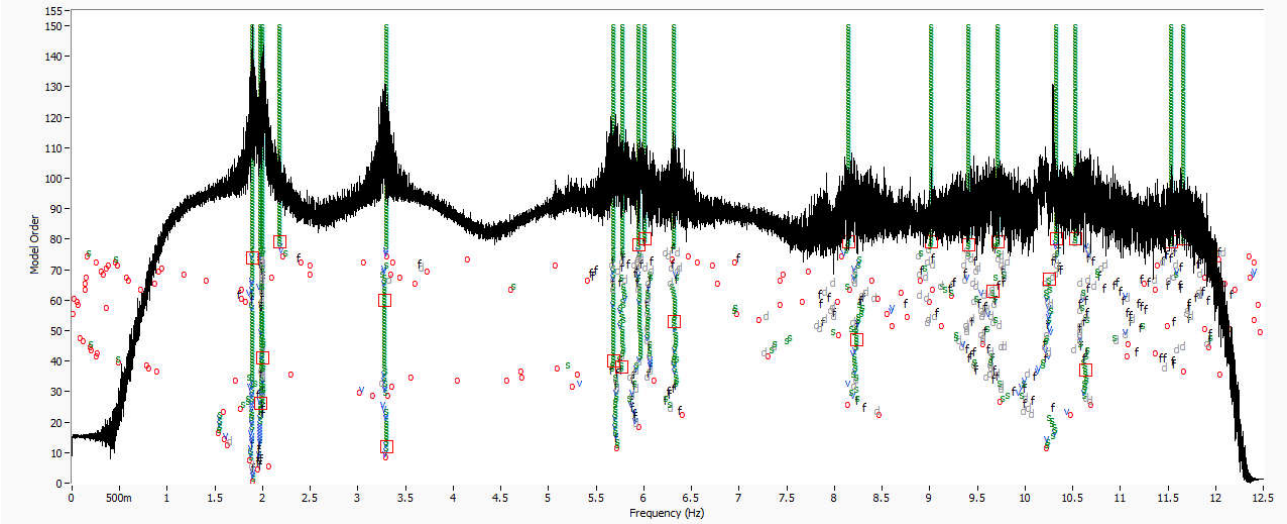


Image 16. Time histories

MODAL IDENTIFICATION RESULTS

Stabilization diagram

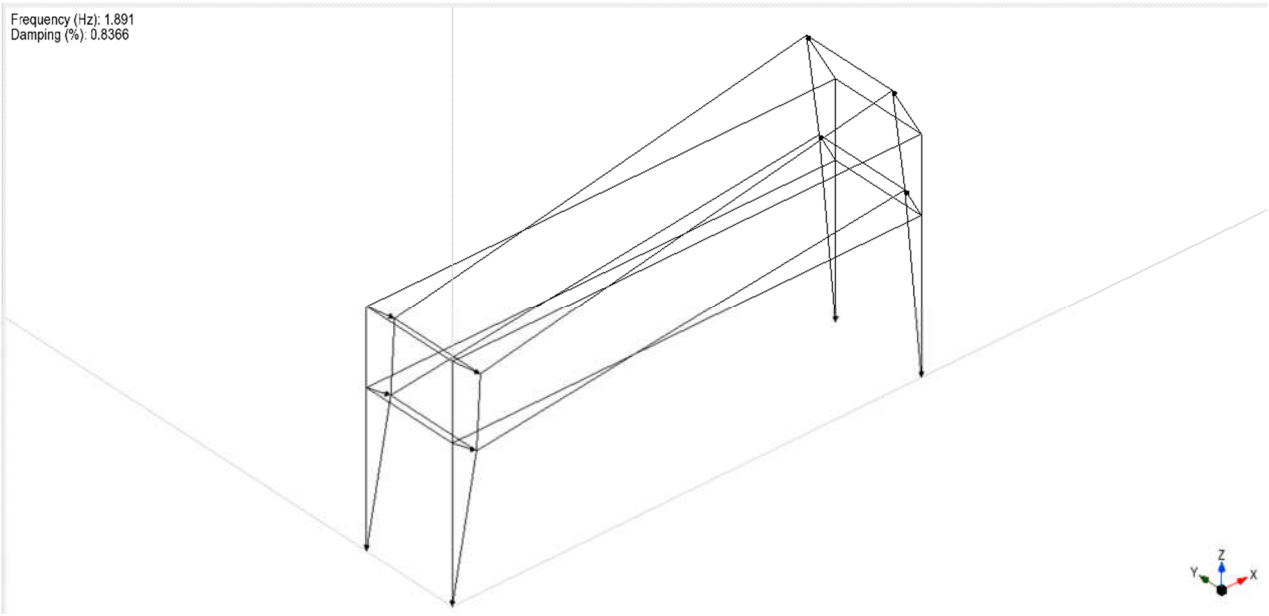


Mode n.	Frequency (Hz)	Damping (%)
1	1.891	0.8366
2	2.005	0.9376
3	3.282	0.8992
4	5.77	2.966

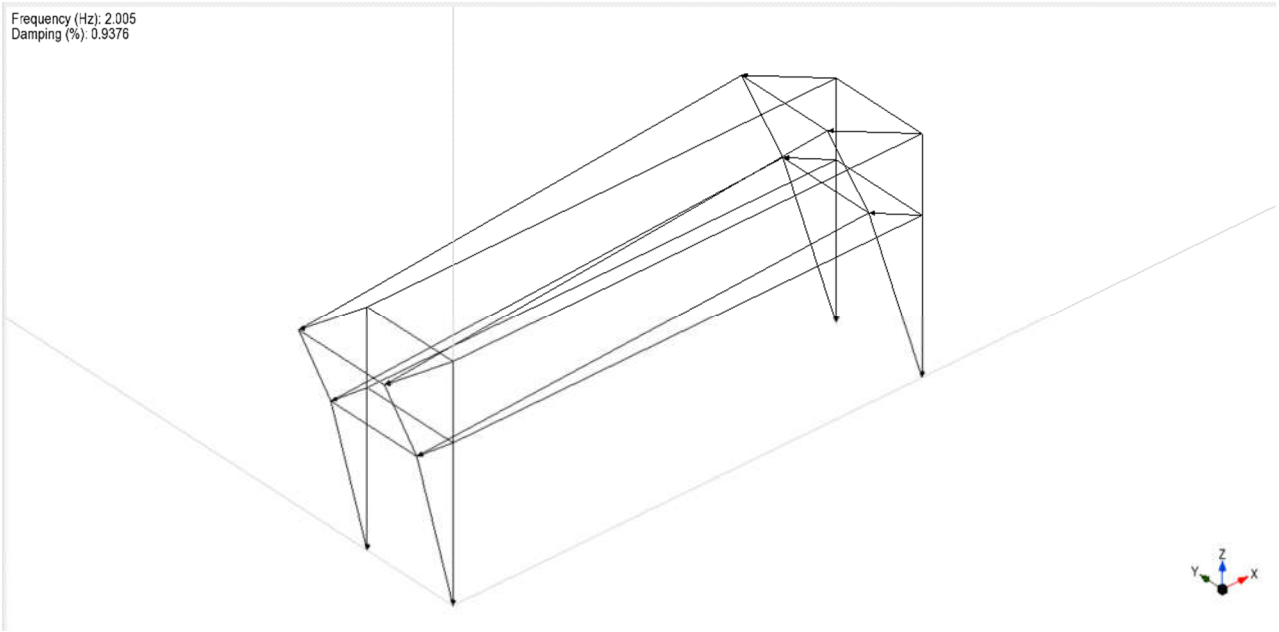
Image 17. Modul idenfication result

Mode Shapes

Mode1
1.891Hz - Torsional



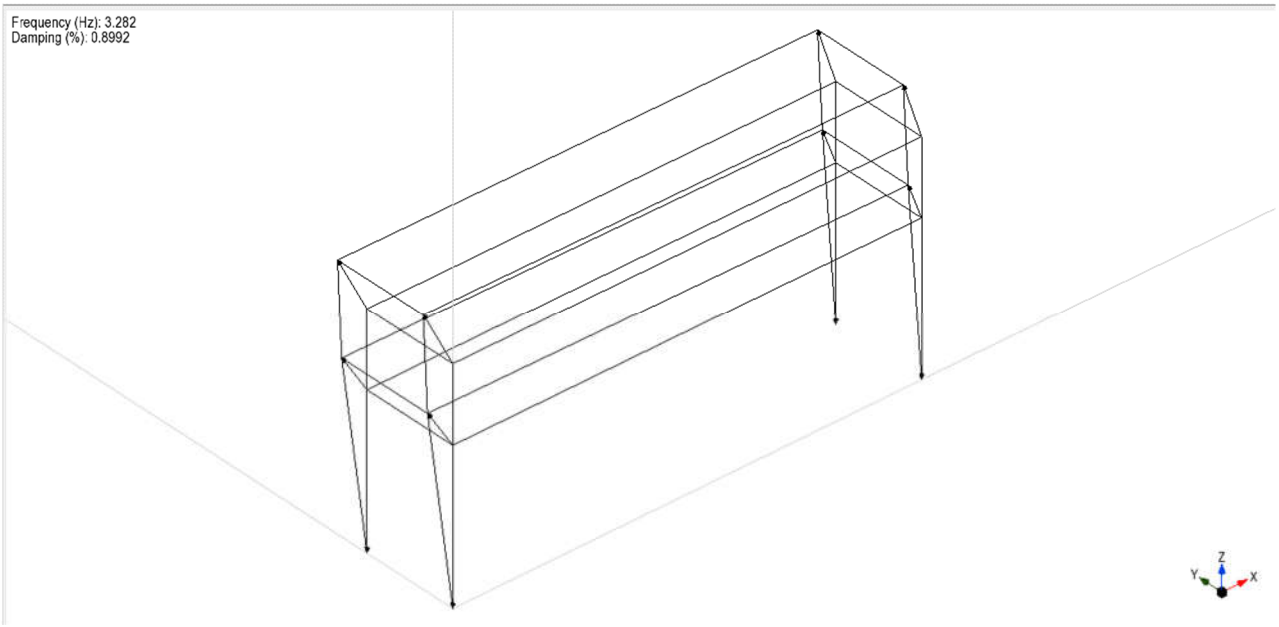
Mode2
2.005Hz – Traslational X



Images 18 and 19. Modal shapes

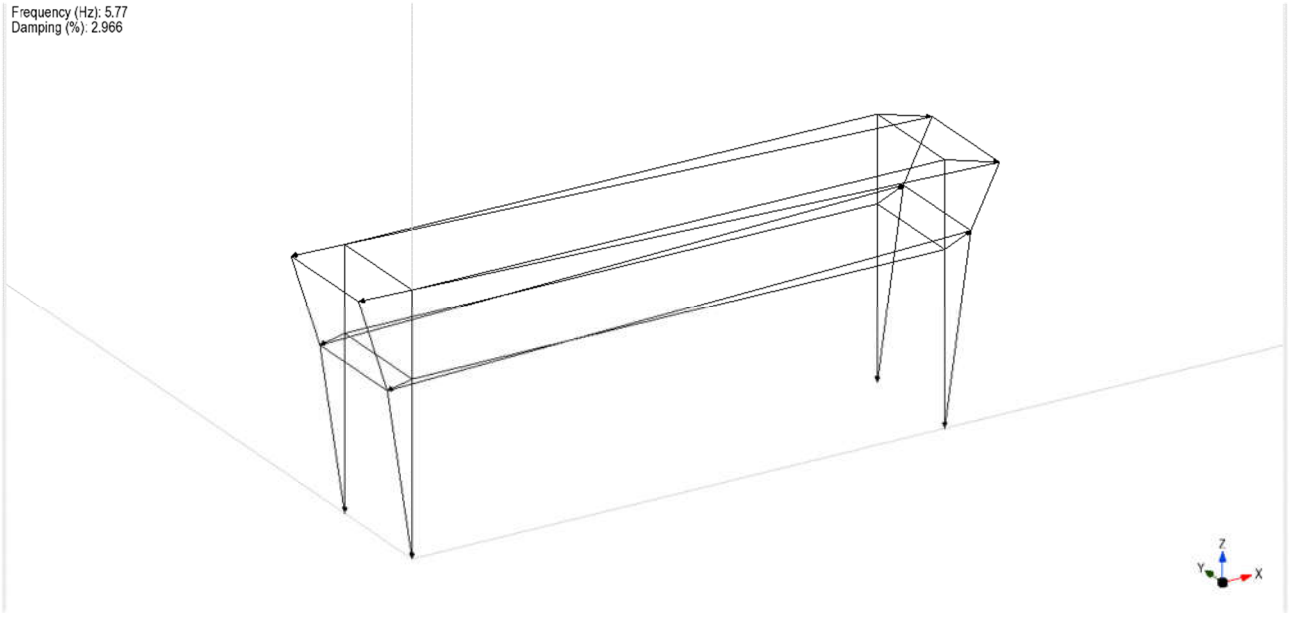
Mode3

3.282Hz – Traslational Y



Mode4

5.77Hz – Traslational X



Images 20 and 21. Modal shapes

BUILDING 4

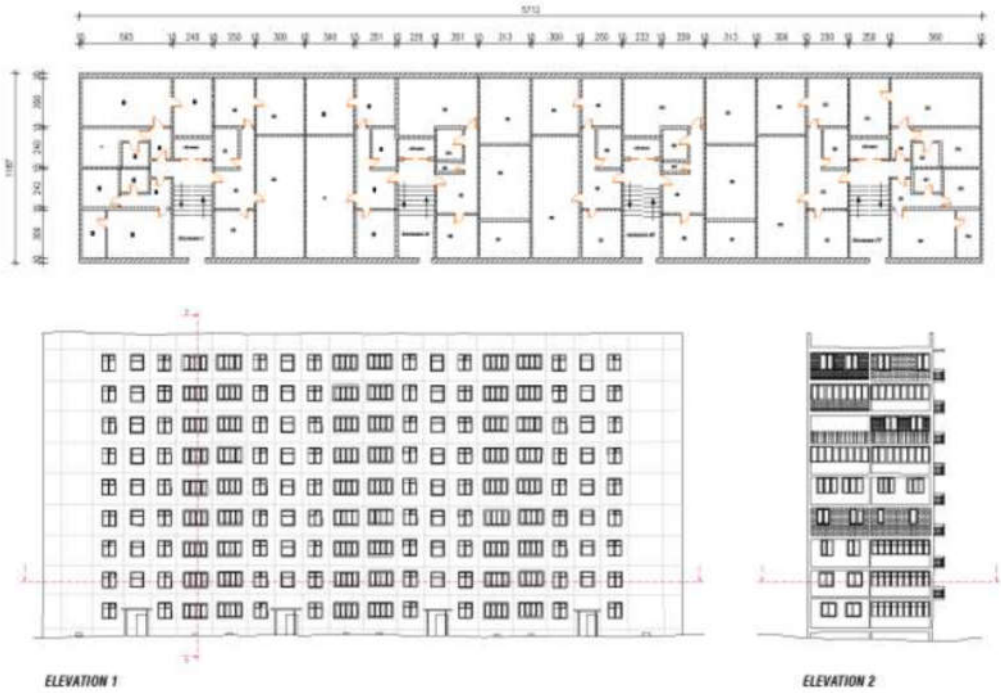
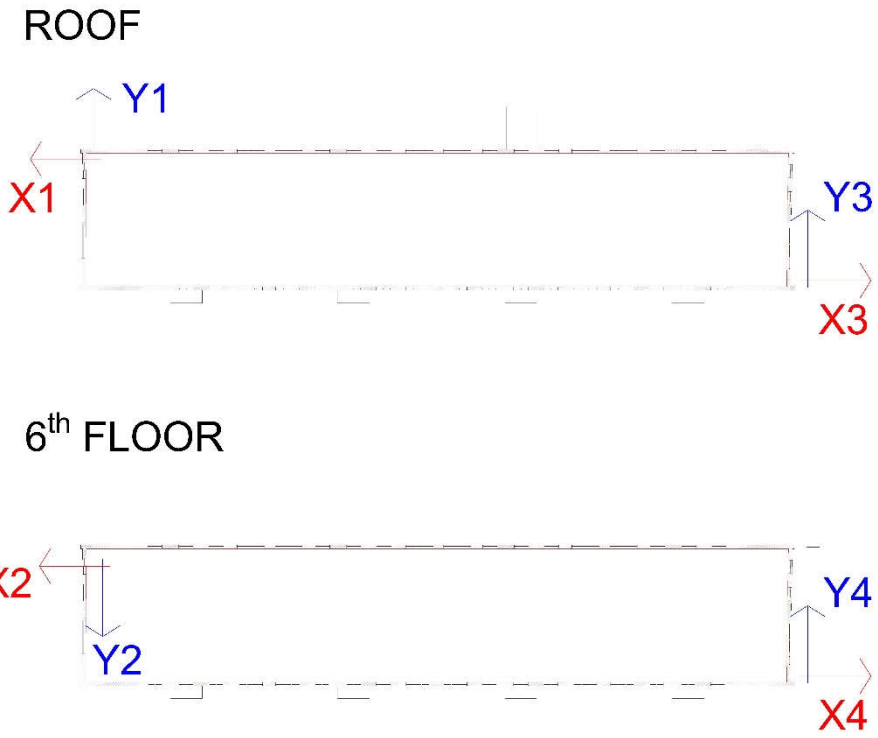
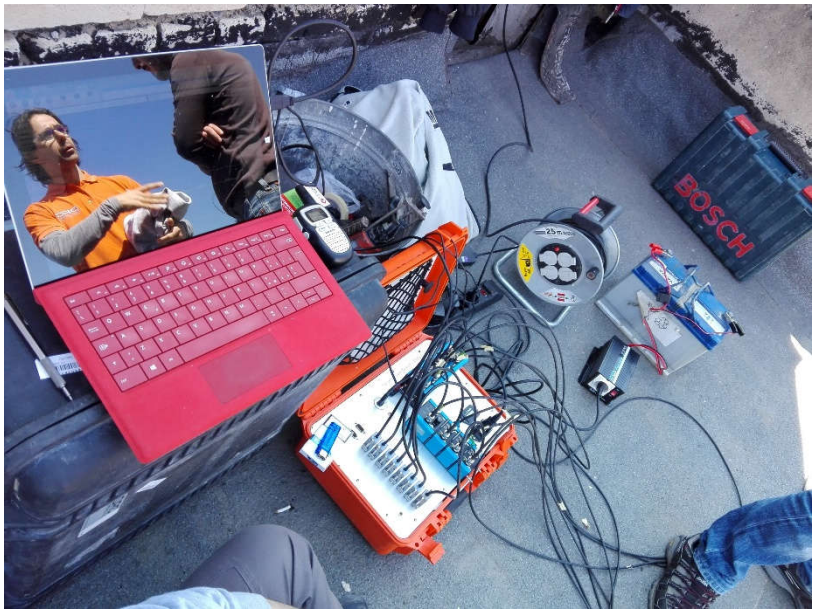


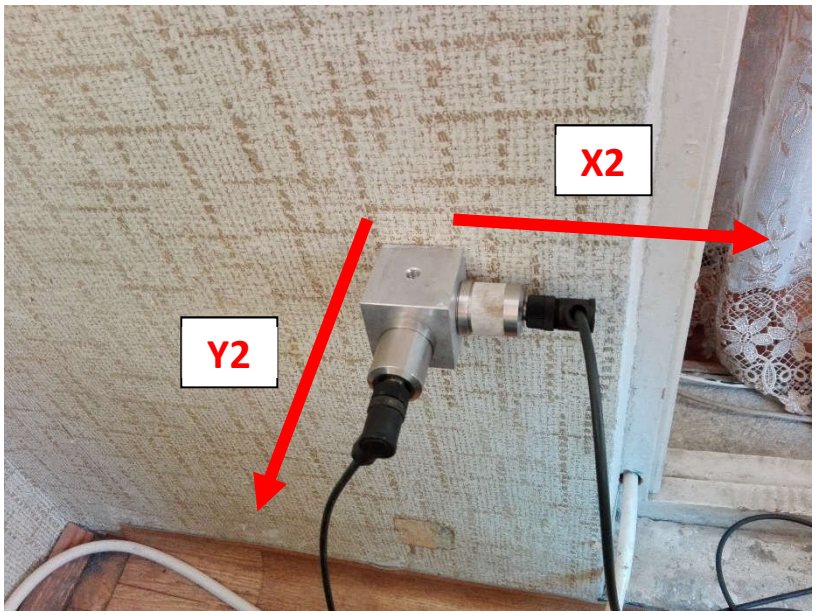
Image 22. Building n.4

SENSORS LAYOUT



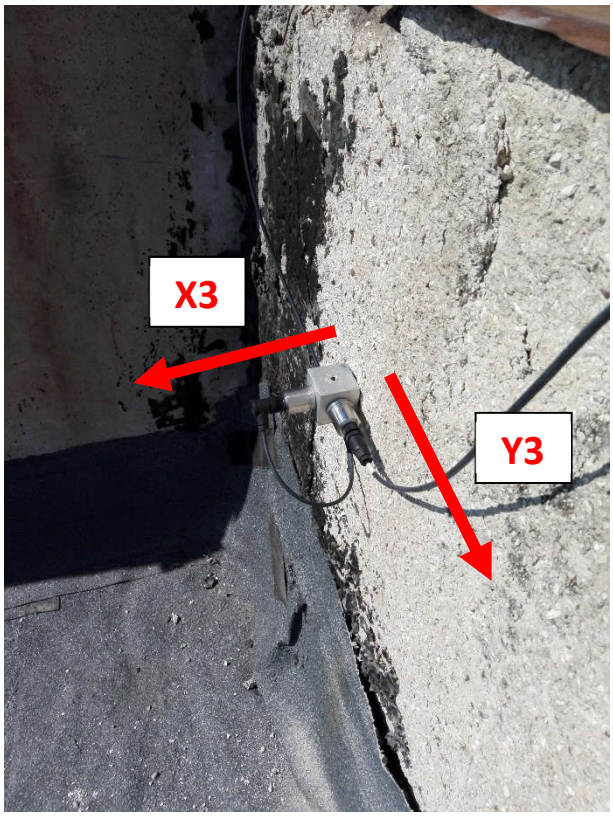


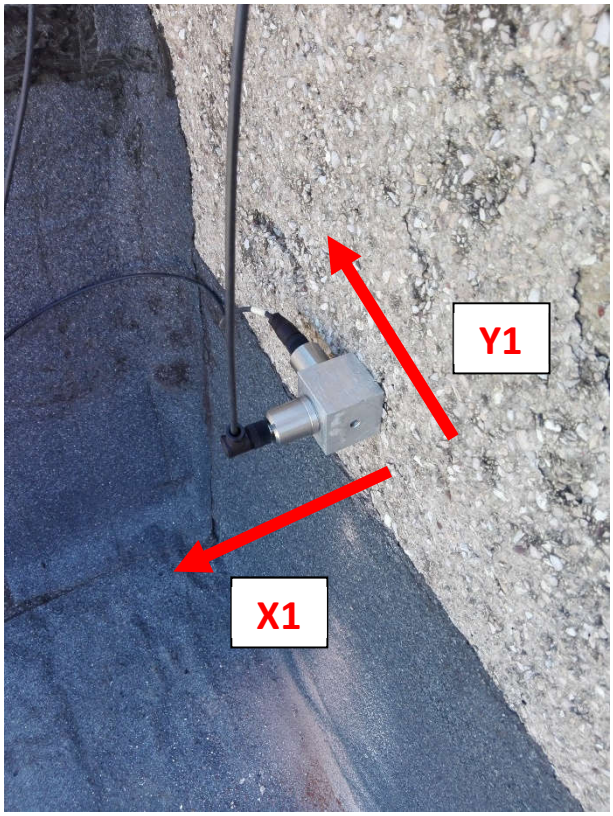
Images 23 and 24. Sensors and data acquisition system



Images 25 and 26. sensors


X4
Y4


X3
Y3



Images 27, 28 and 29. sensors

ACQUISITION OF TIME HISTORIES

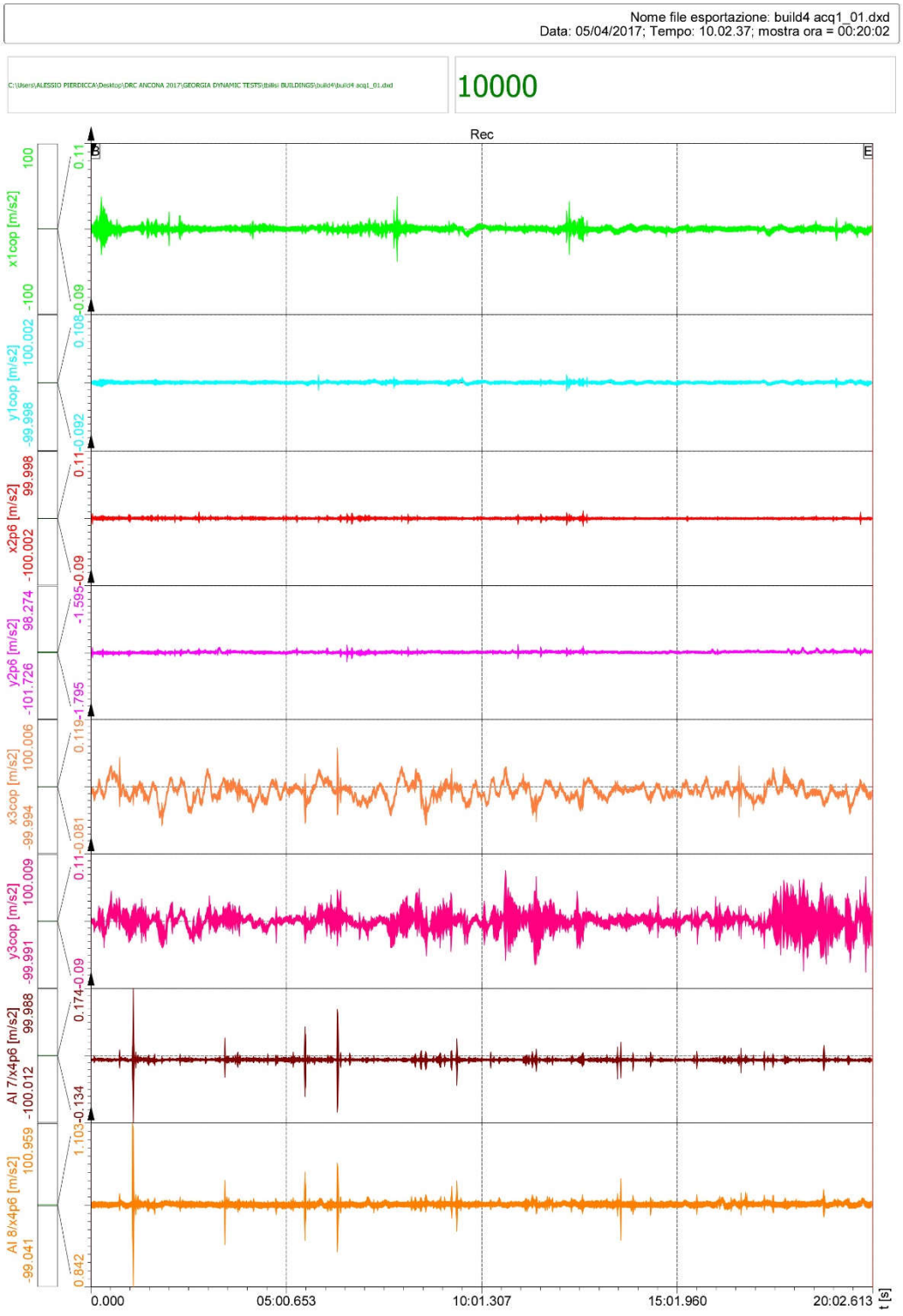


Image 30. Time histories

FREQUENCY CONTENT OF THE SIGNALS

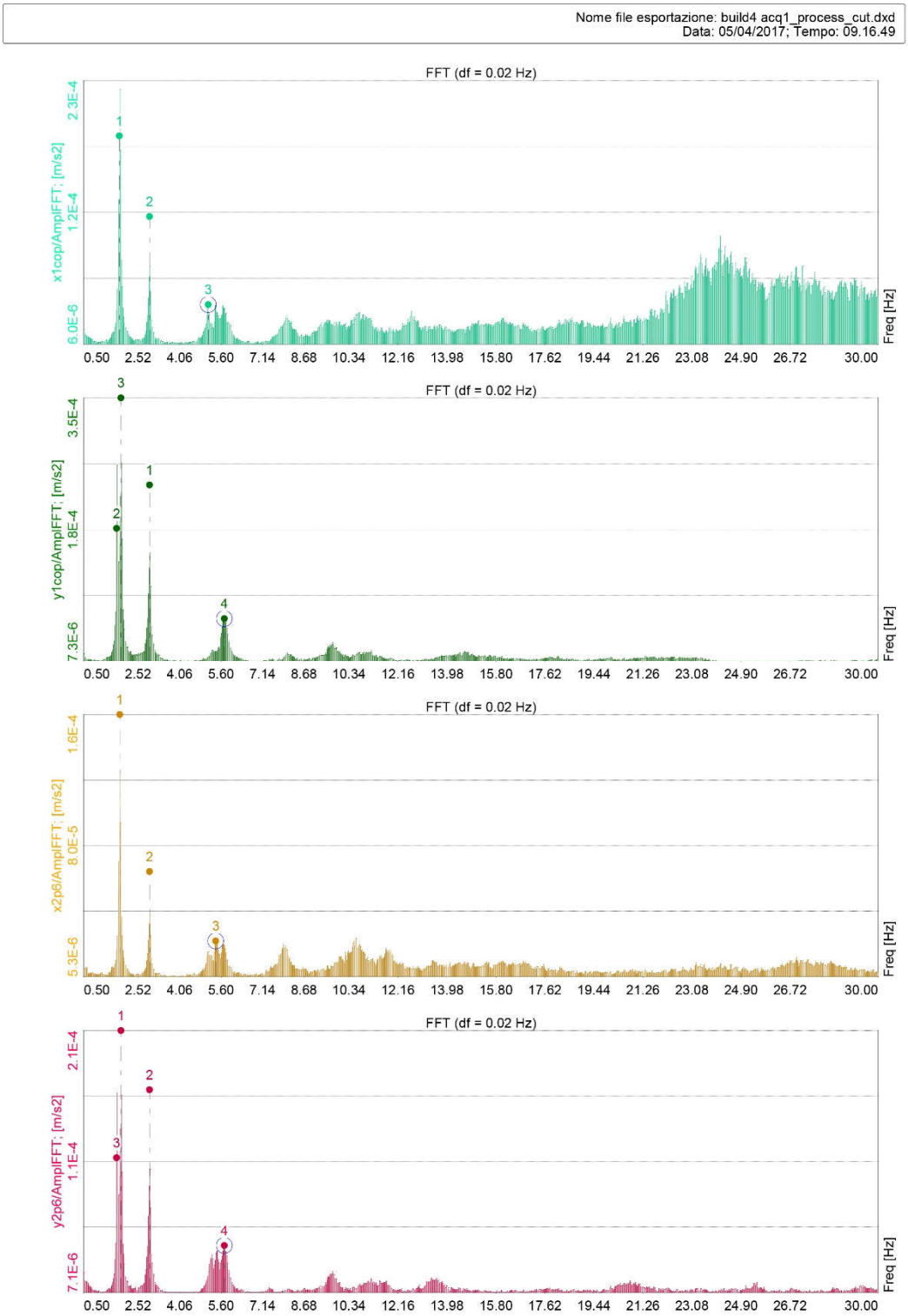
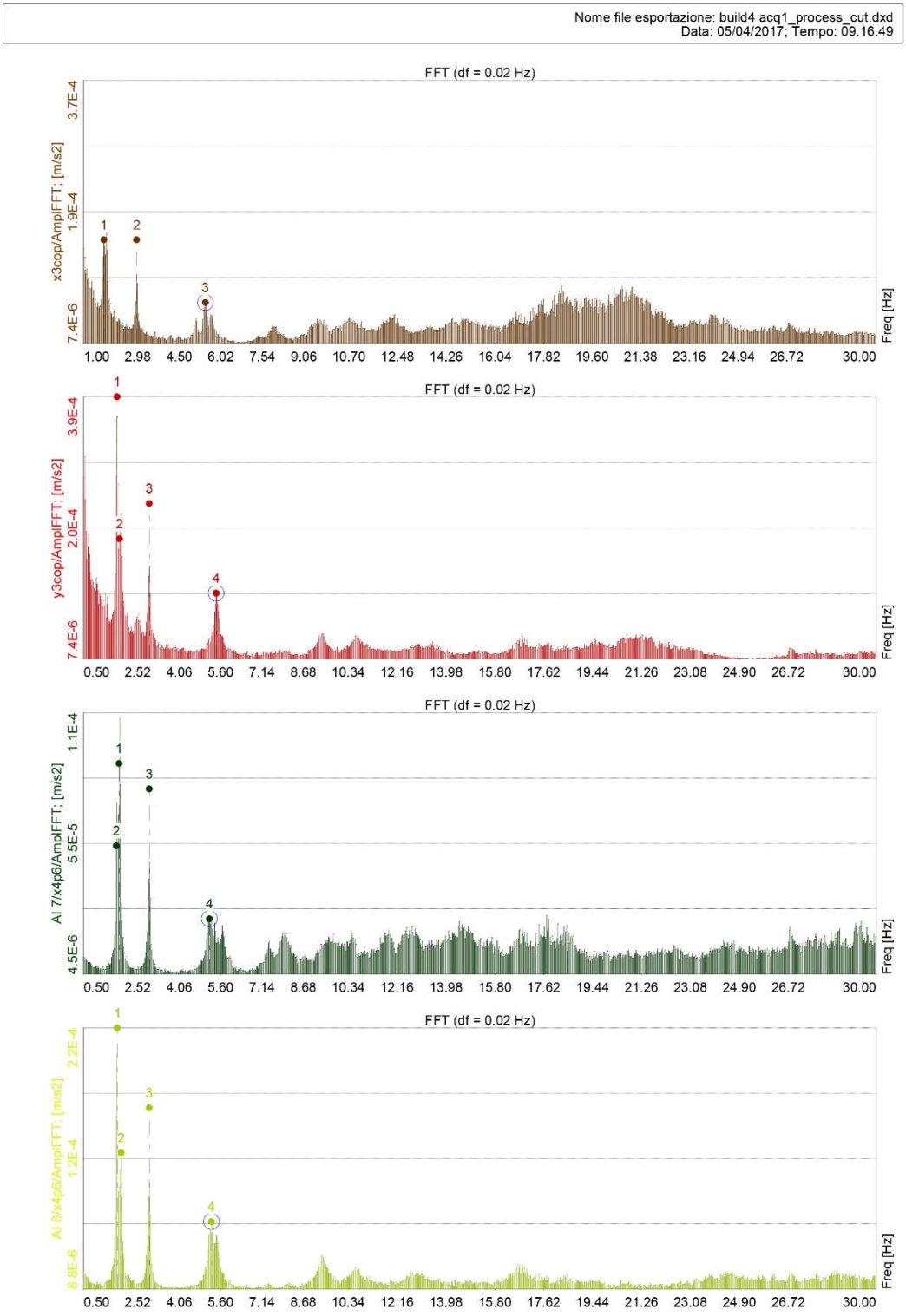


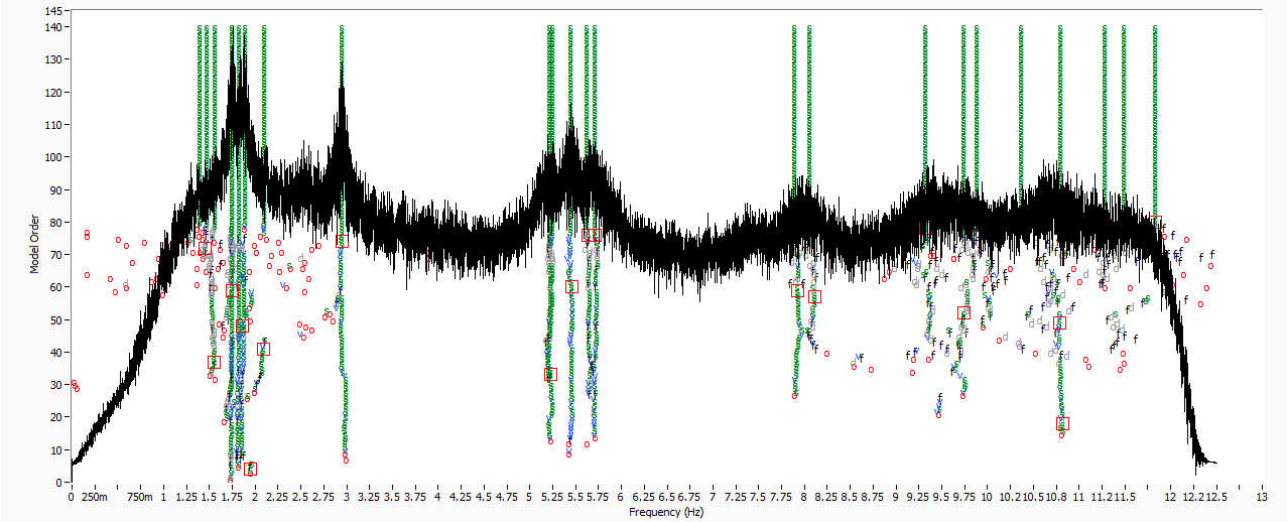
Image 31. Frequency content result



Images 32. Frequency content of signal

MODAL IDENTIFICATION RESULTS

Stabilization diagram

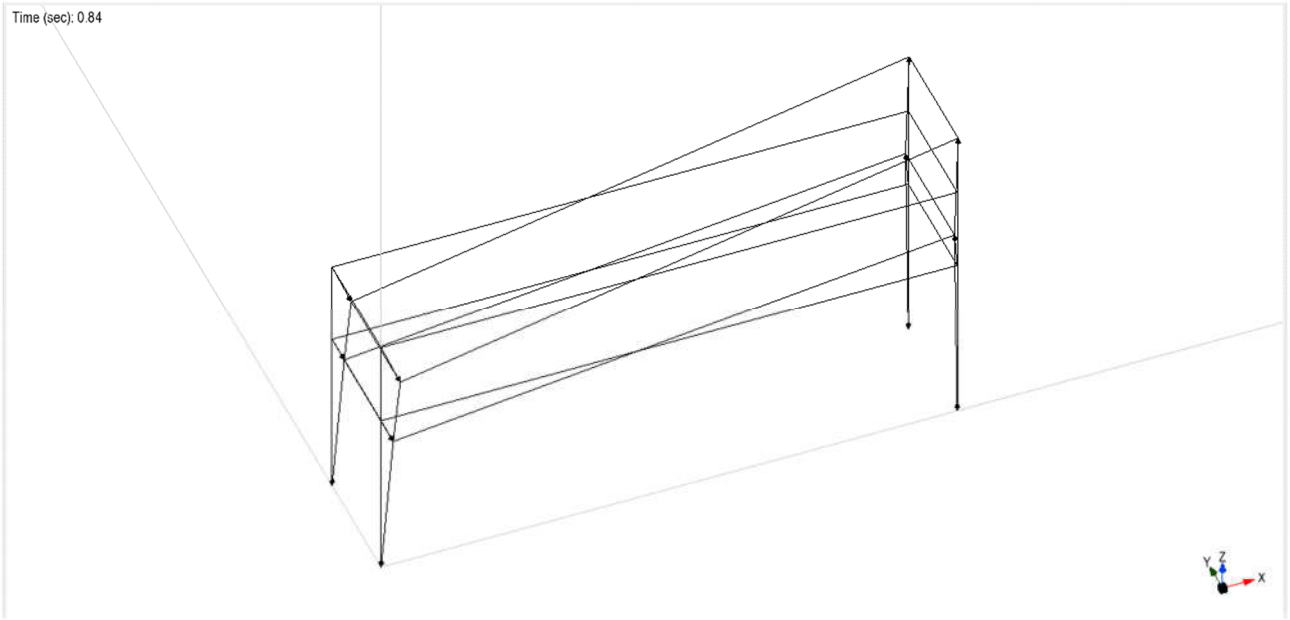


Mode Number	Frequency (Hz)	Damping (%)
1	1.747	0.75
2	2.096	1.2
3	2.953	0.74
4	5.455	1.192

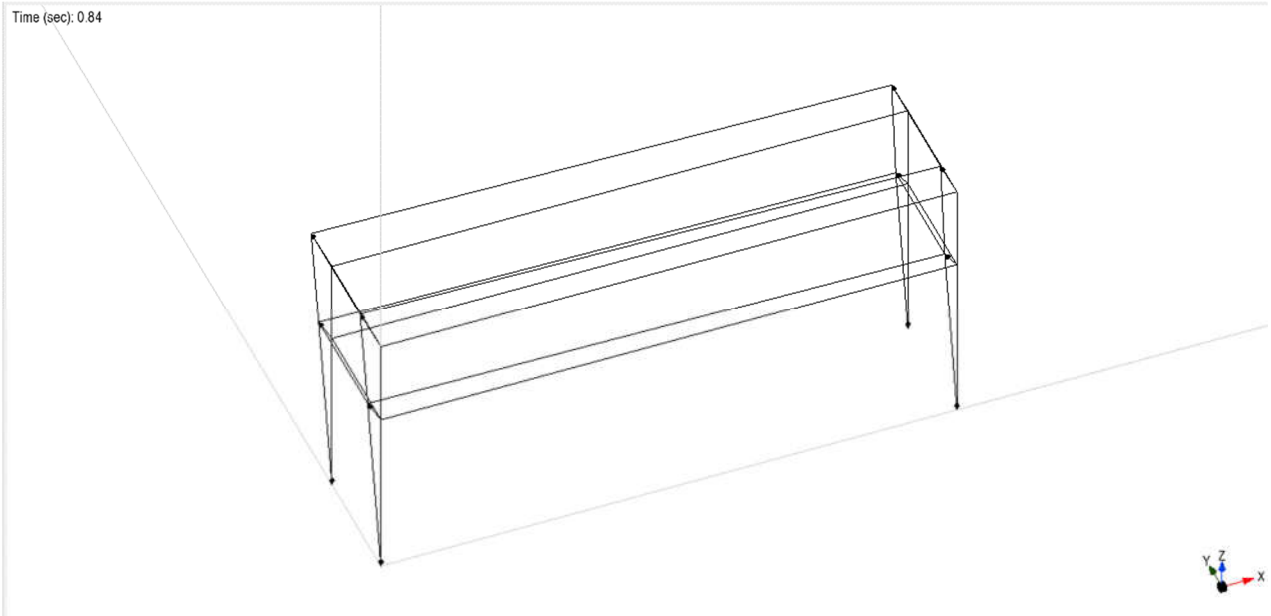
Images 33. Modal identification result

Mode Shapes

Mode1
1.747Hz - Torsional
MODAL SHAPES

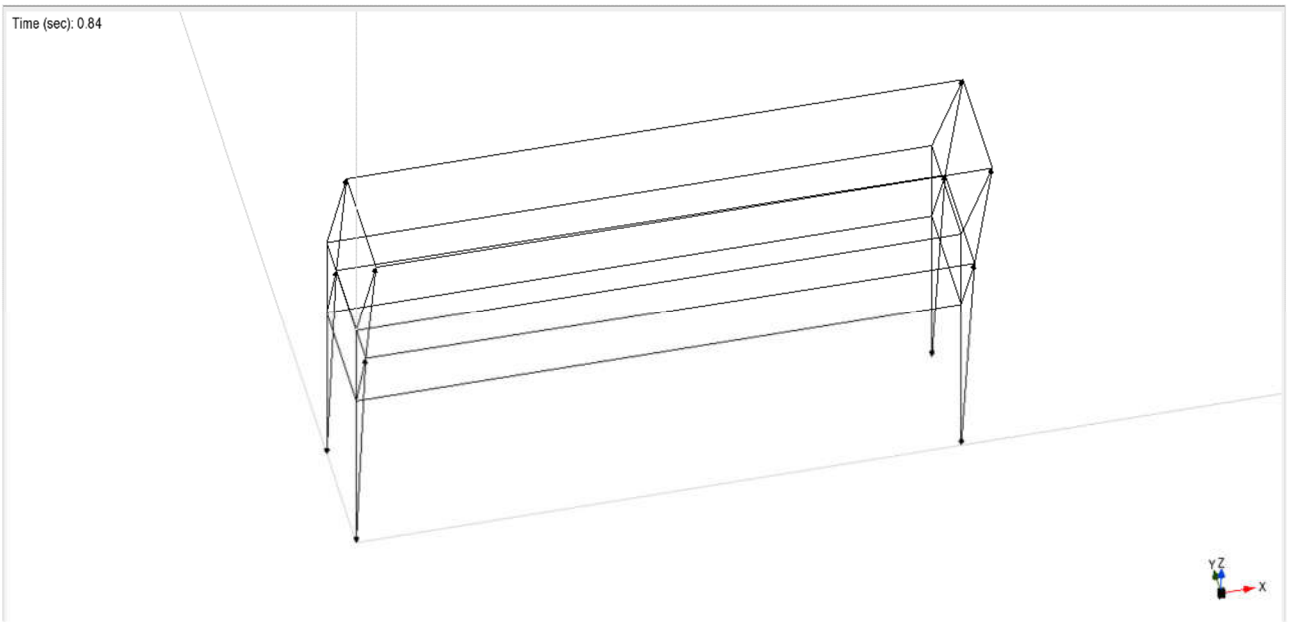


Mode2
2.096Hz – Traslational Y

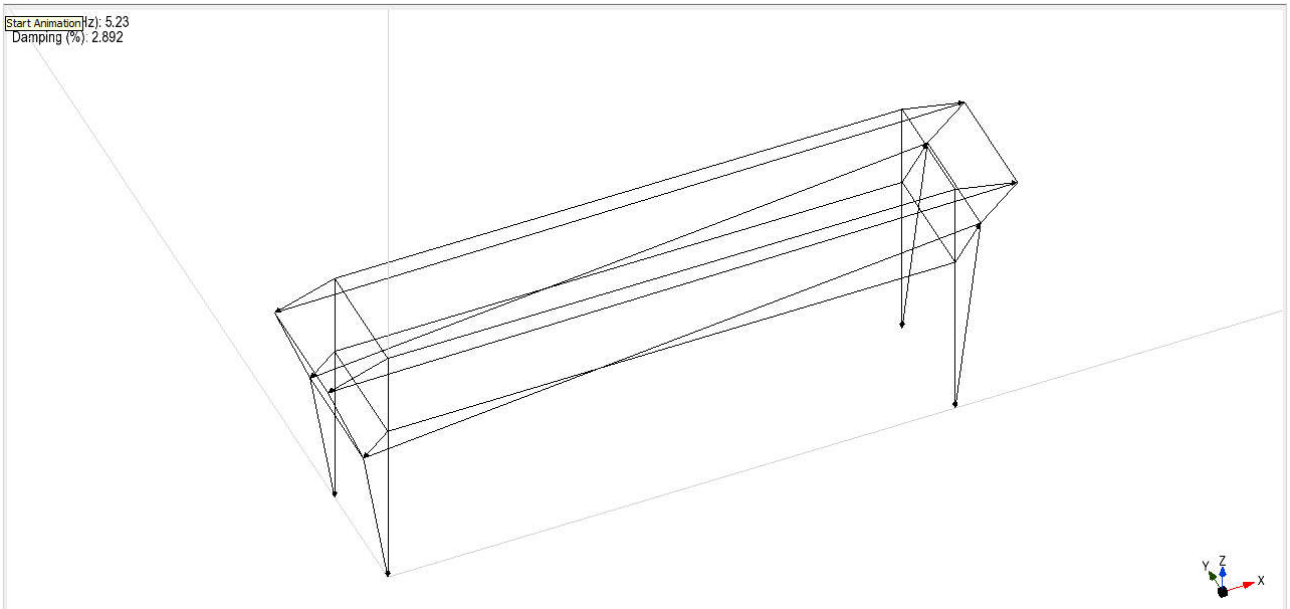


Images 34 and 35. Modal shapes

Mode3
2.953Hz – Traslational Y



Mode4
5.455Hz – Traslational X



Images 36 and 37. Modal shapes

BUILDING 5

Building 5 is composed by three different blocks, separated by a sismic joint. Each block is disconnetted, so three different monitoring were necessary.

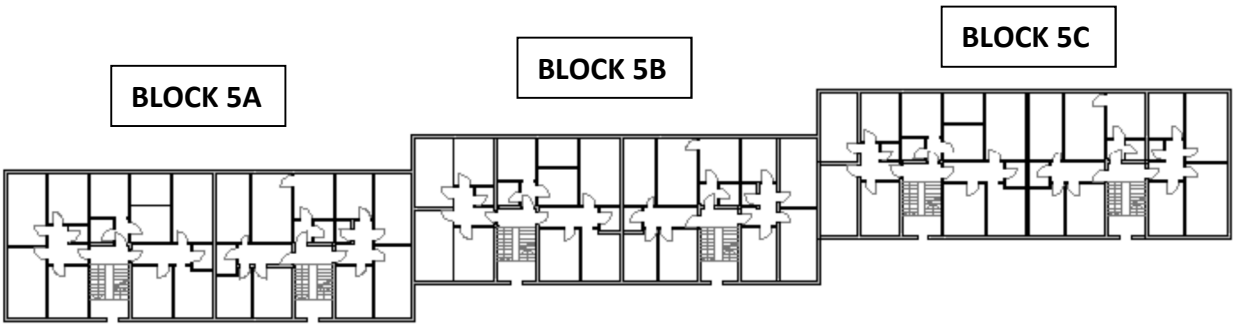
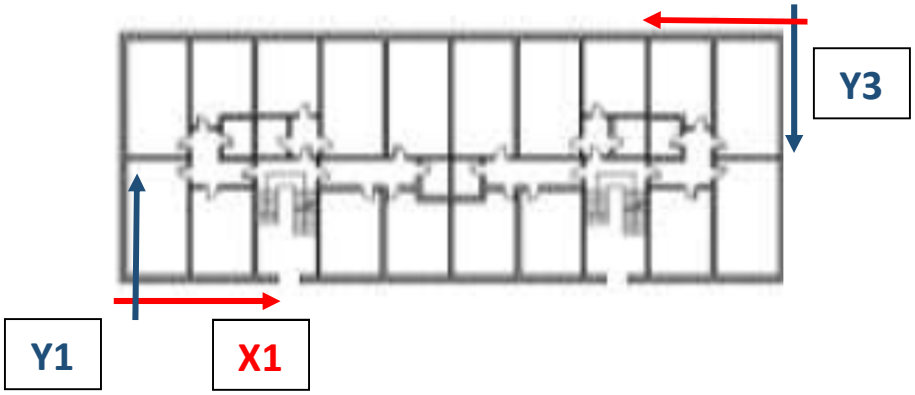


Image 38. Building n. 5

BLOCK 5A

SENSORS LAYOUT

5TH FLOOR



3th FLOOR

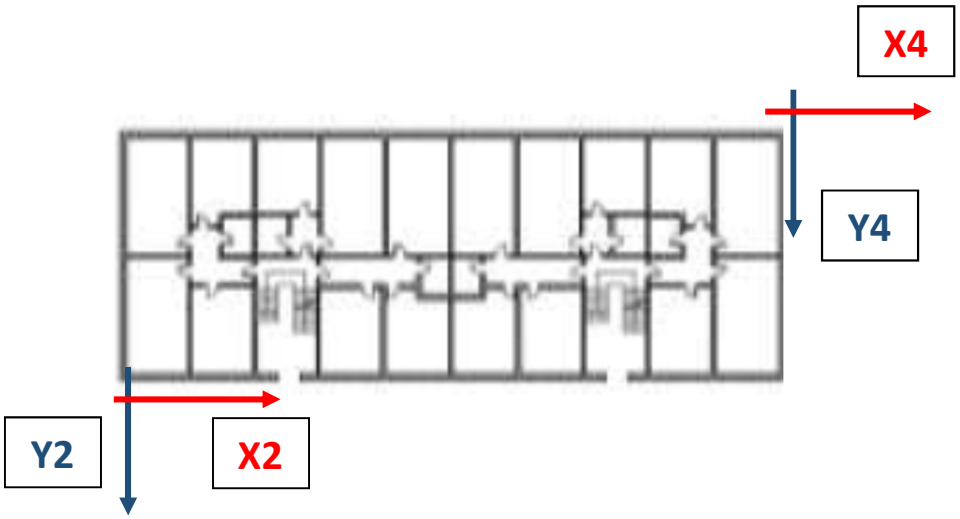
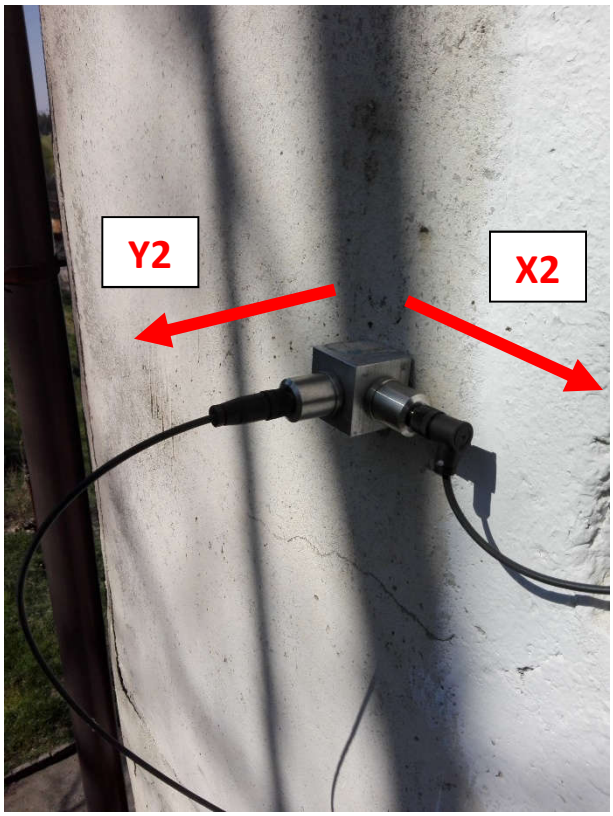
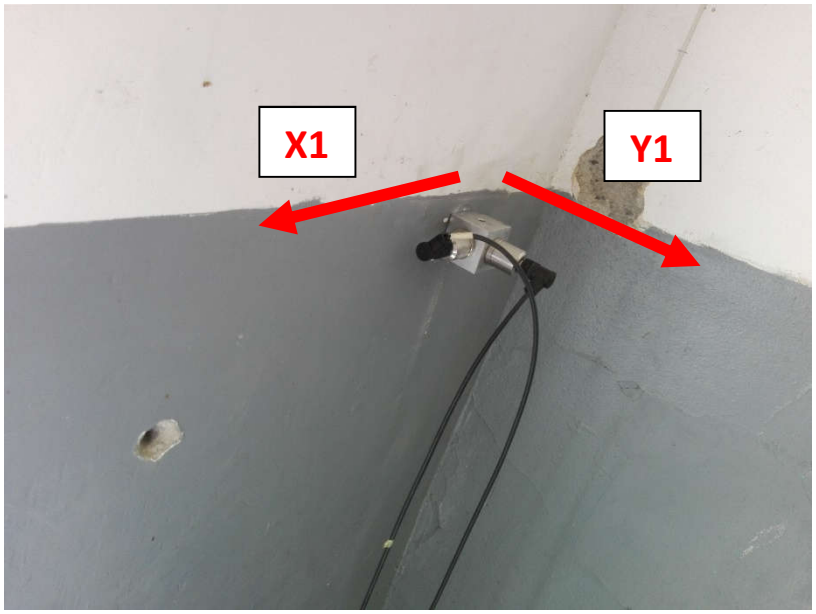


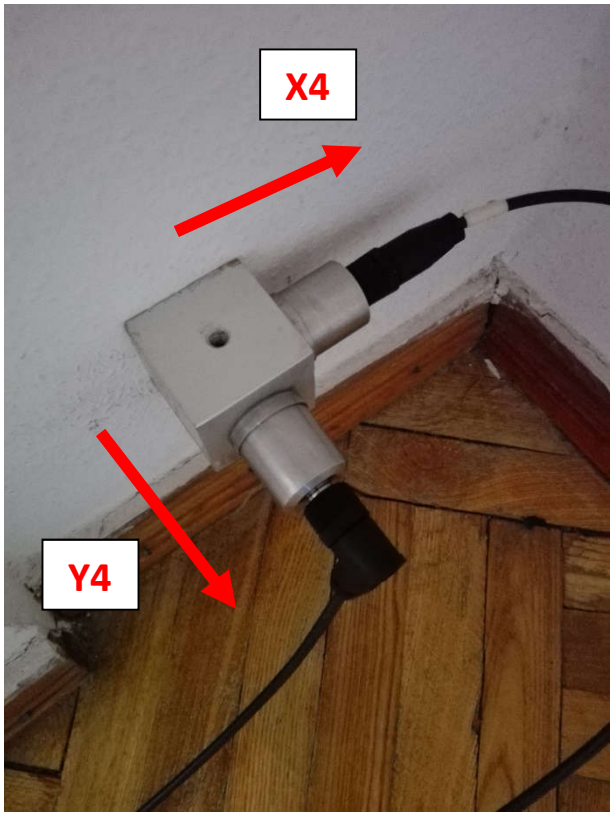
Image 39. Planimetry building n.5A



Images 40 and 41. Sensor and data acquisition system


X1
Y1


X3
Y3



Images 42, 43 and 44. sensors

ACQUISITION OF TIME HISTORIES

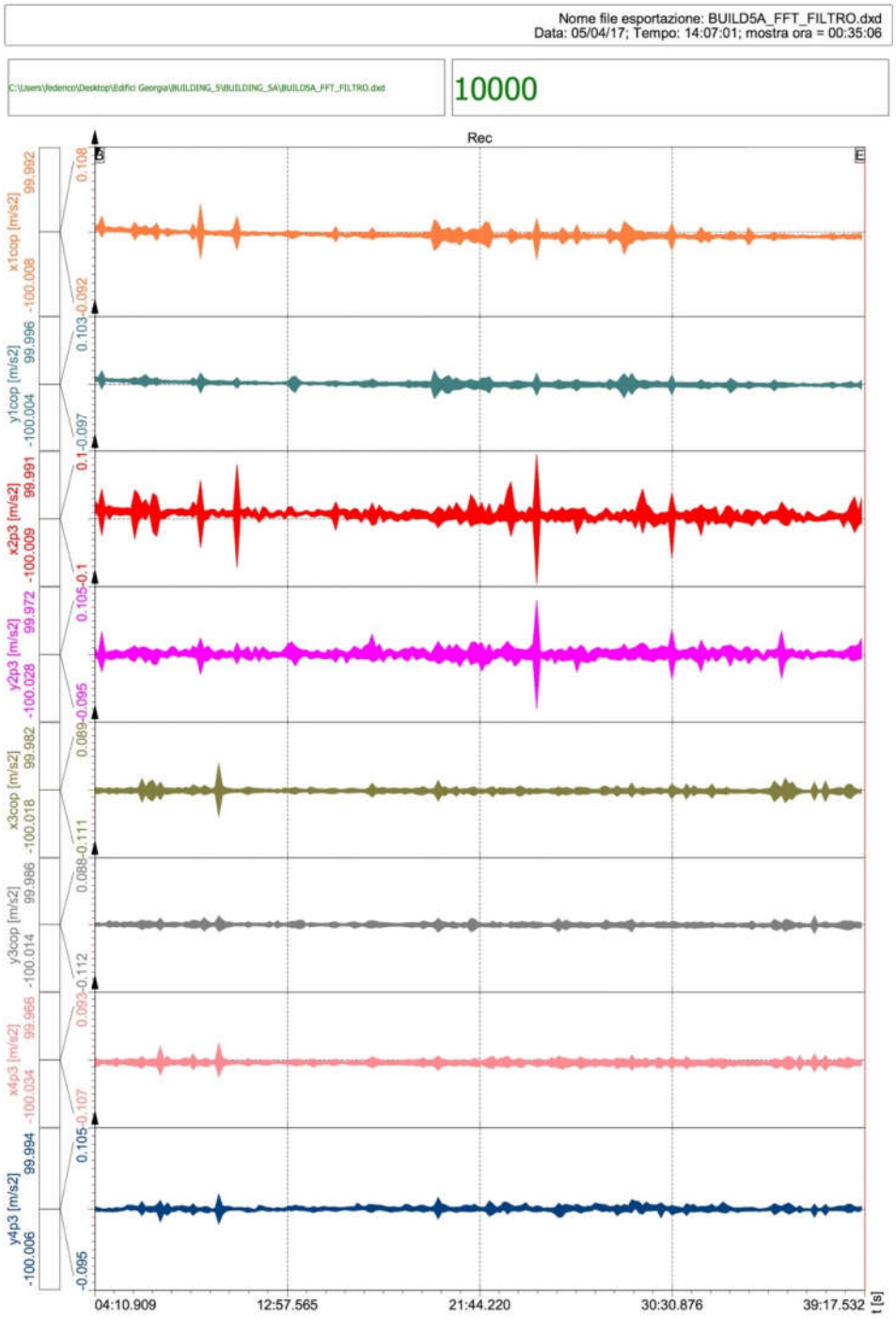


Image 45. Time histories

FREQUENCY CONTENT OF THE SIGNALS

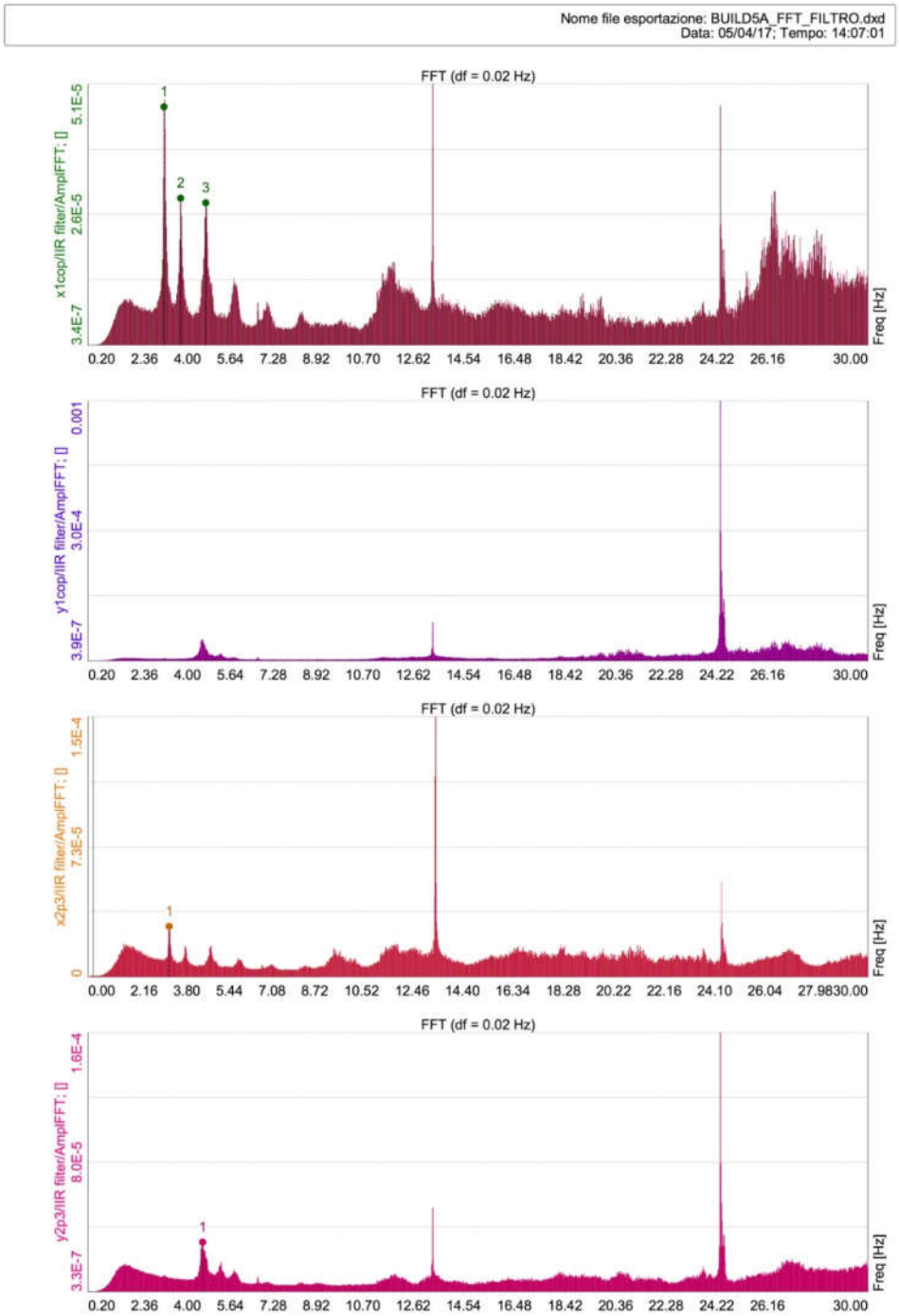
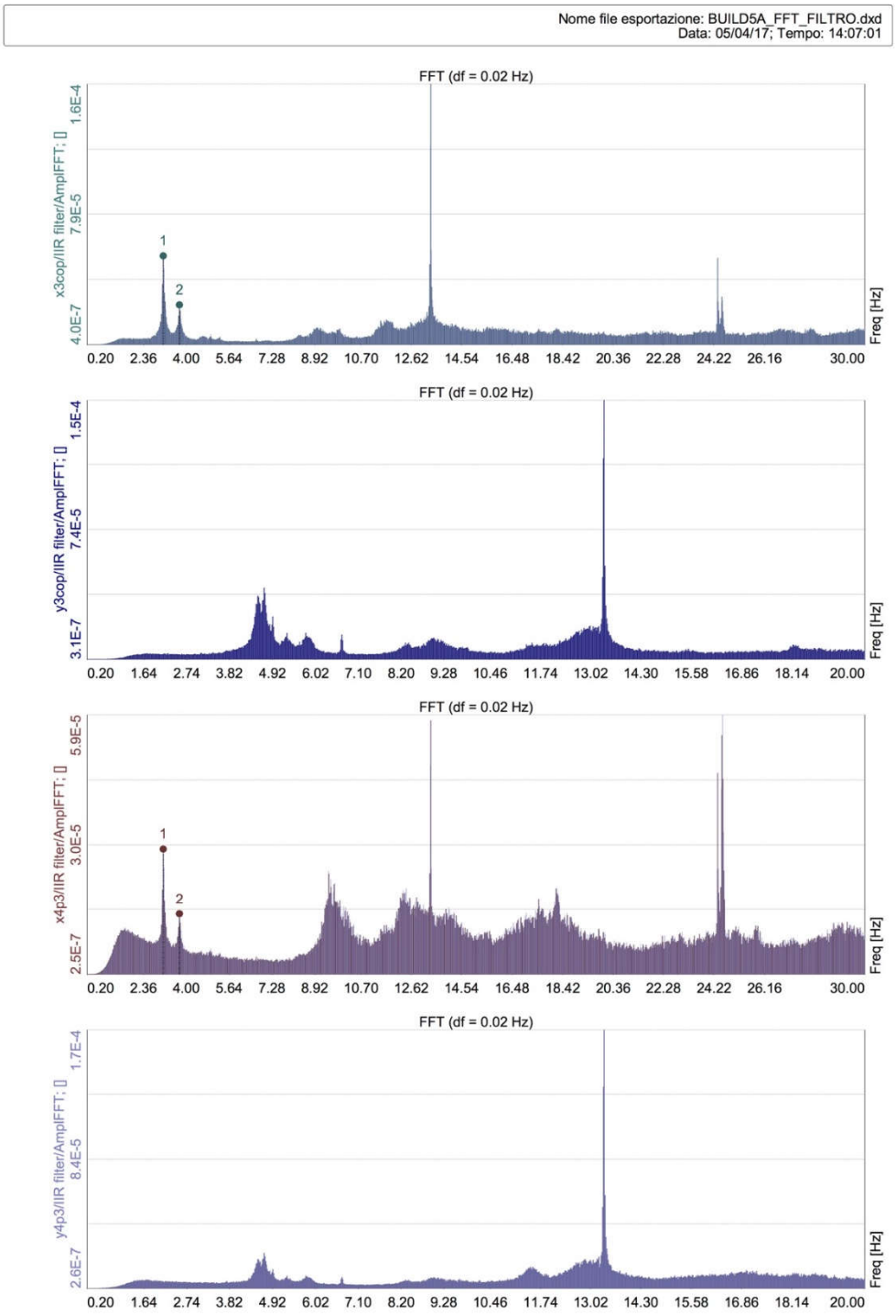


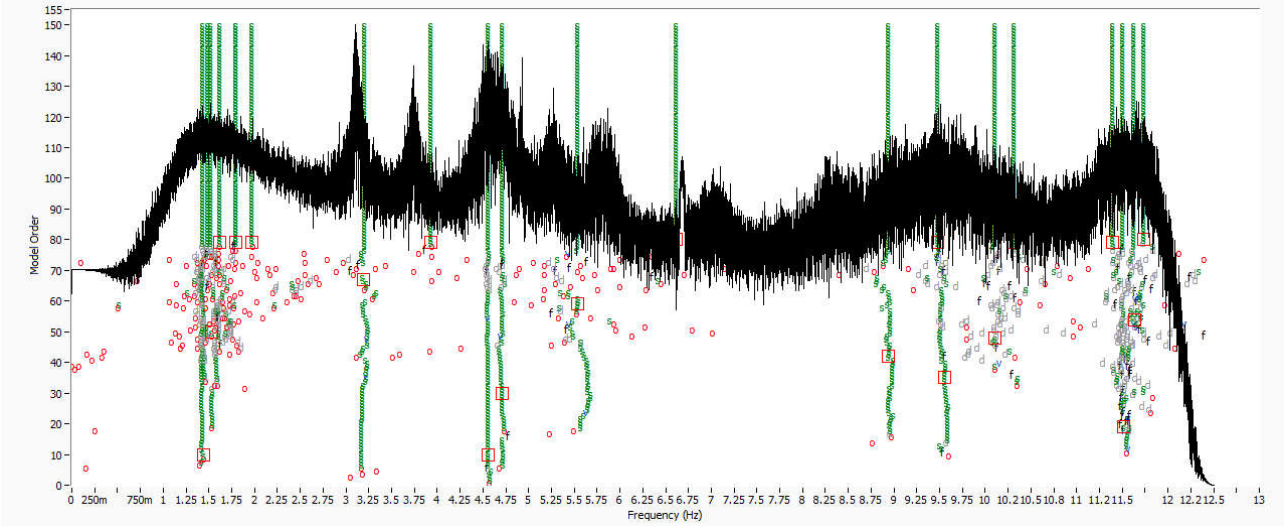
Image 46. Frequency content



Images 47. Frequency content

MODAL IDENTIFICATION RESULTS

Stabilization diagram

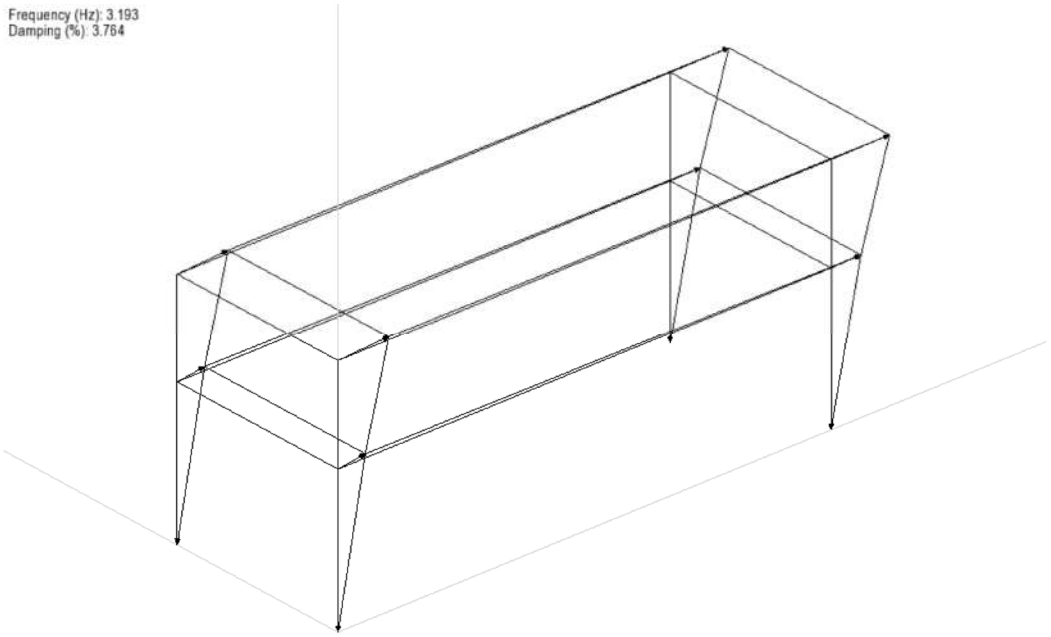


Mode n.	Frequency (Hz)	Damping (%)
1	3.19	3.764
2	4.56	1.317
3	4.71	2.011
4	5.54	4.201

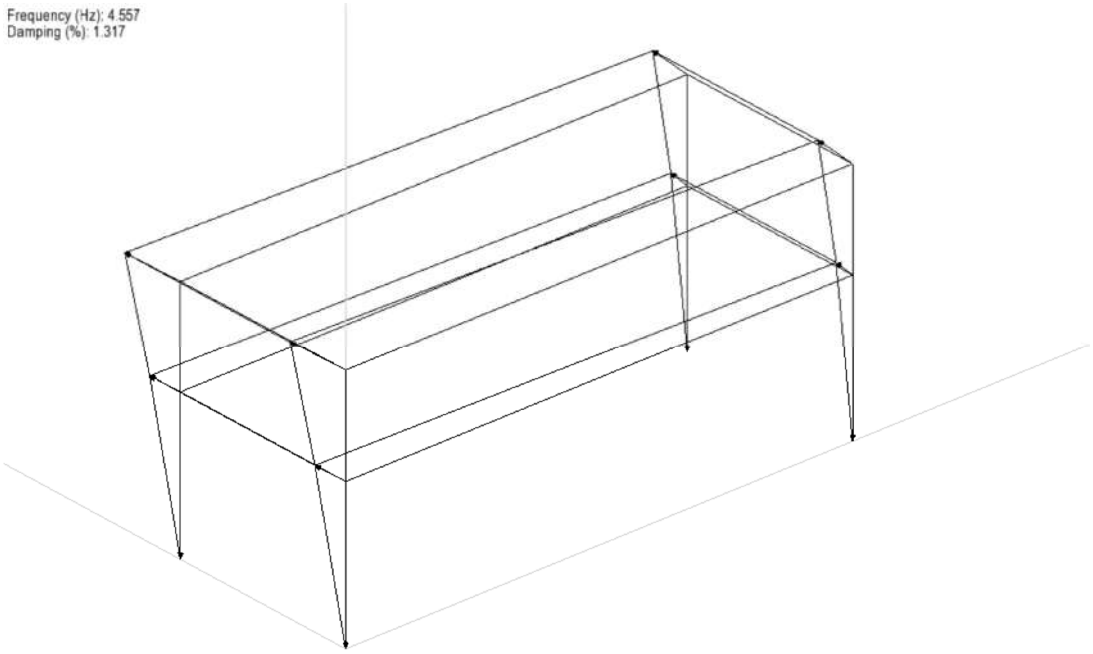
Image 48. Modal identification result

Mode Shapes

Mode1
3.19Hz – Traslational X



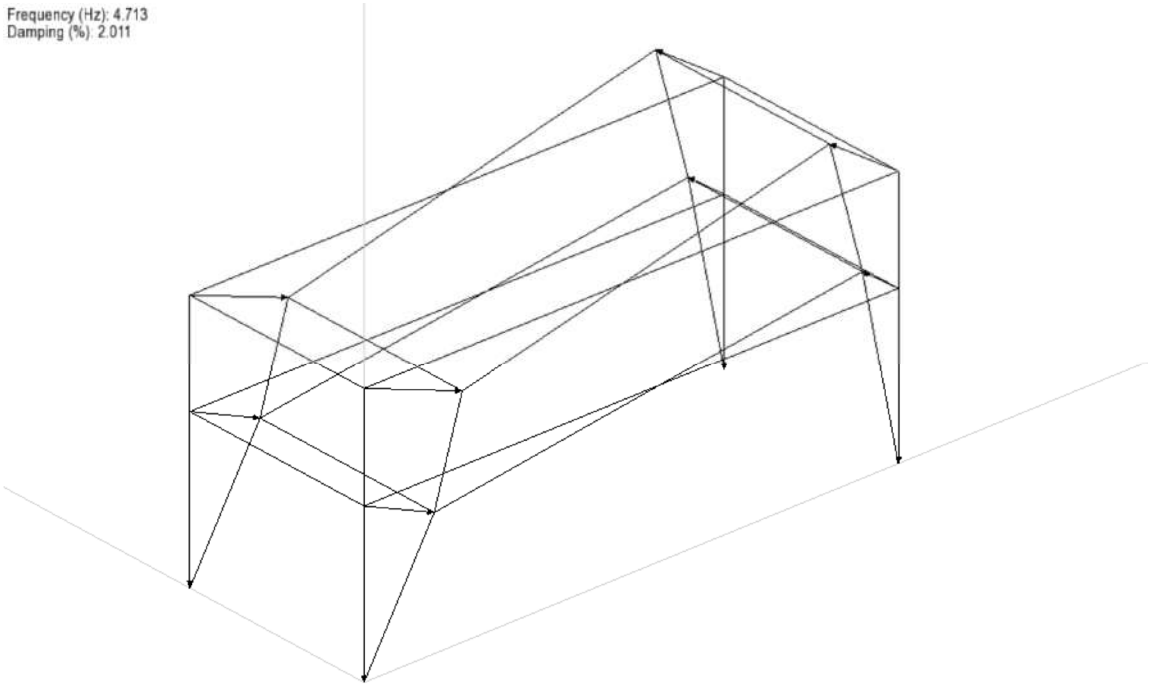
Mode2
4.56Hz – Traslational Y



Images 49. Modal shapes

Mode3

4.71Hz – Torsional



Mode4

5.54Hz – Torsional

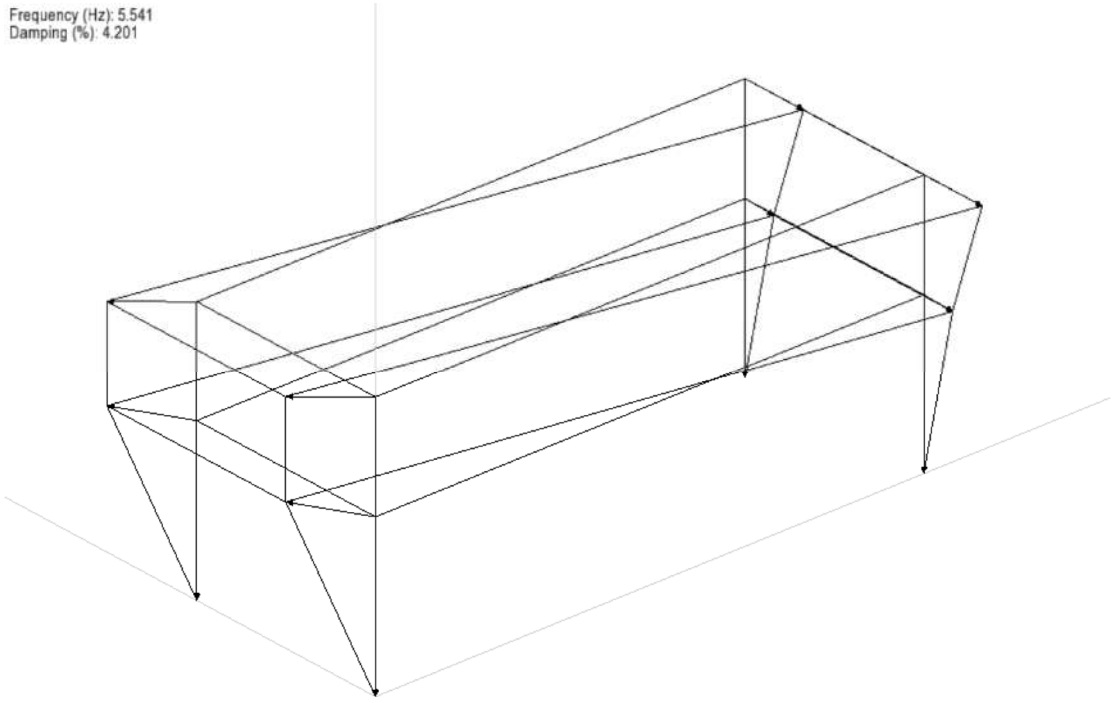
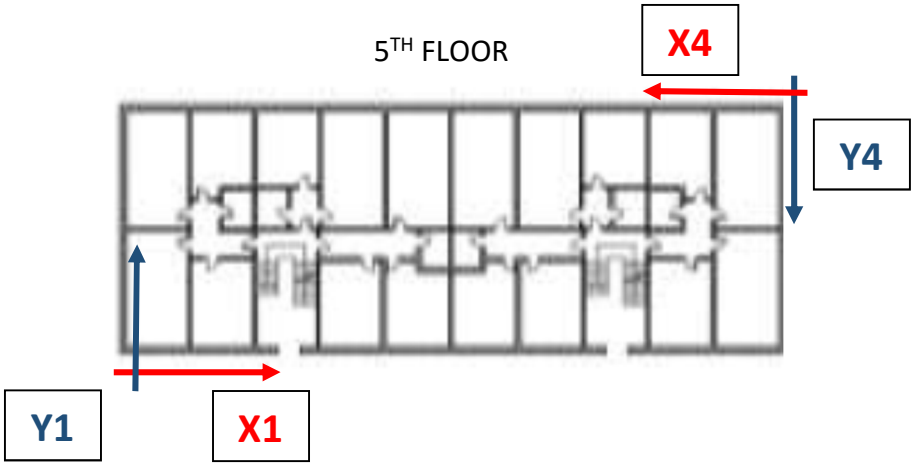


Image 50. Modal shapes

BLOCK 5B

SENSORS LAYOUT



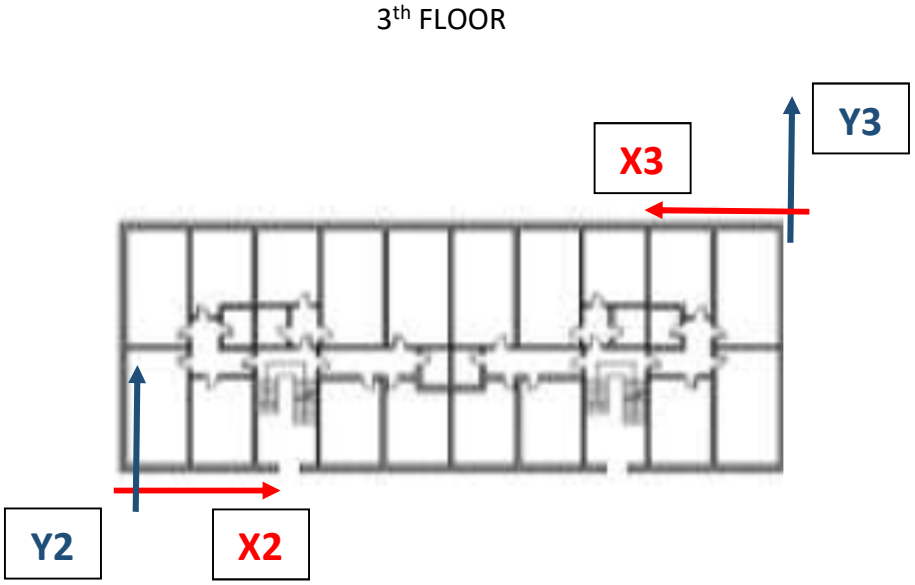
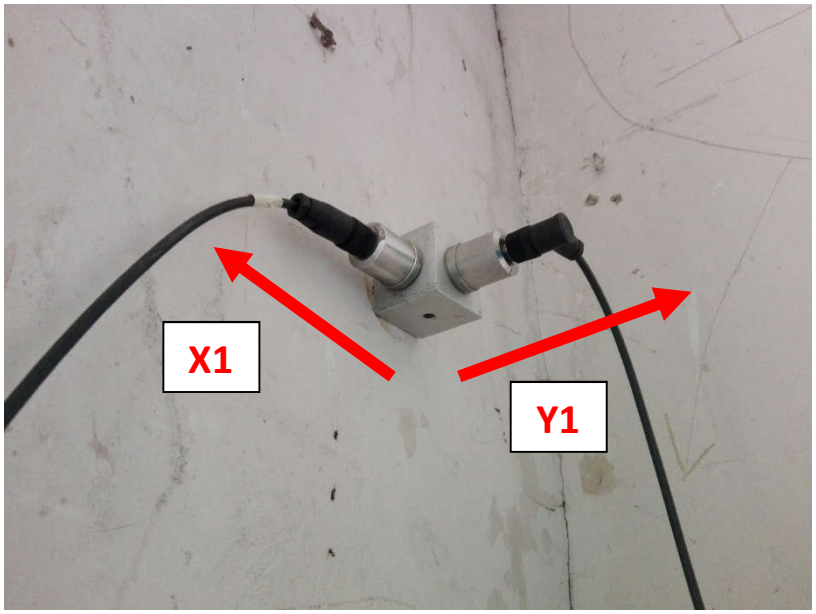
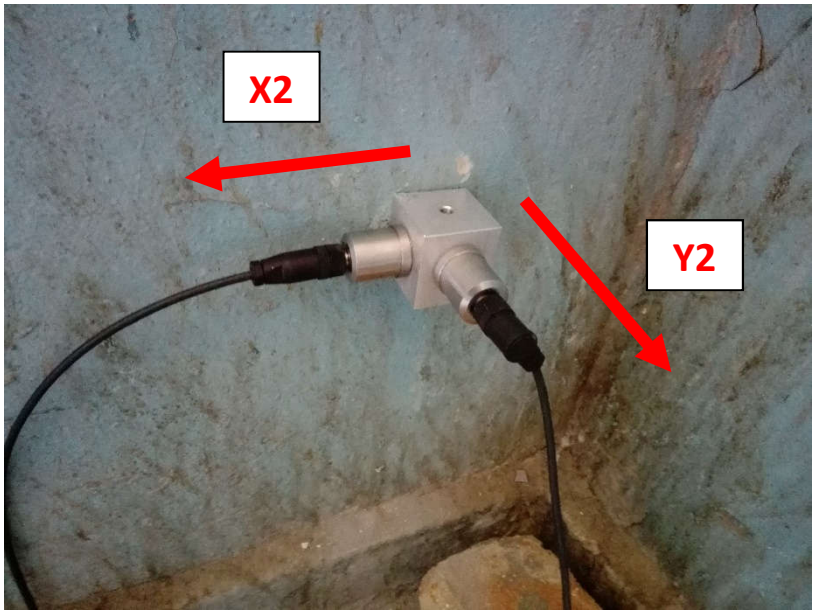
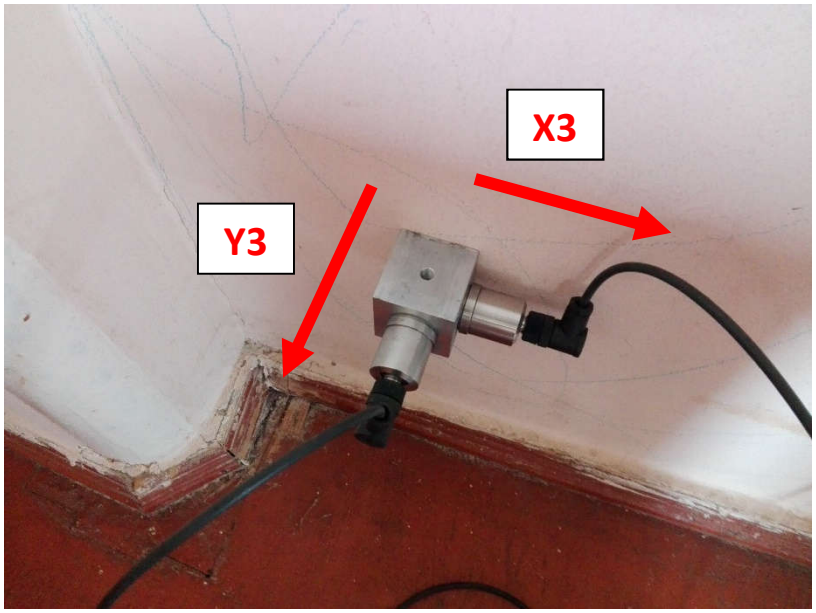


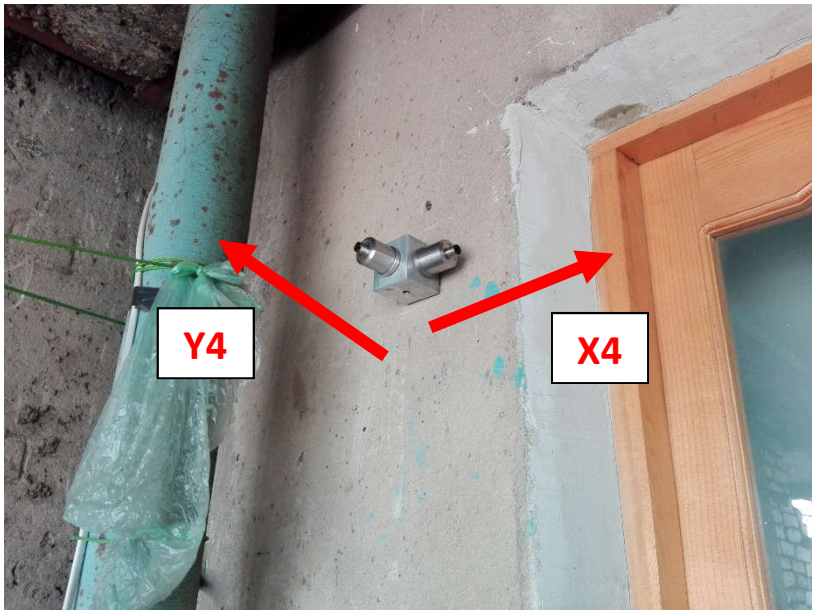
Image 51. Building n.5B - planimetry



Images 52 and 53. Sensors and data acquisition system


X2
Y2


X3
Y3



Images 54, 55 and 56. sensors

ACQUISITION OF TIME HISTORIES

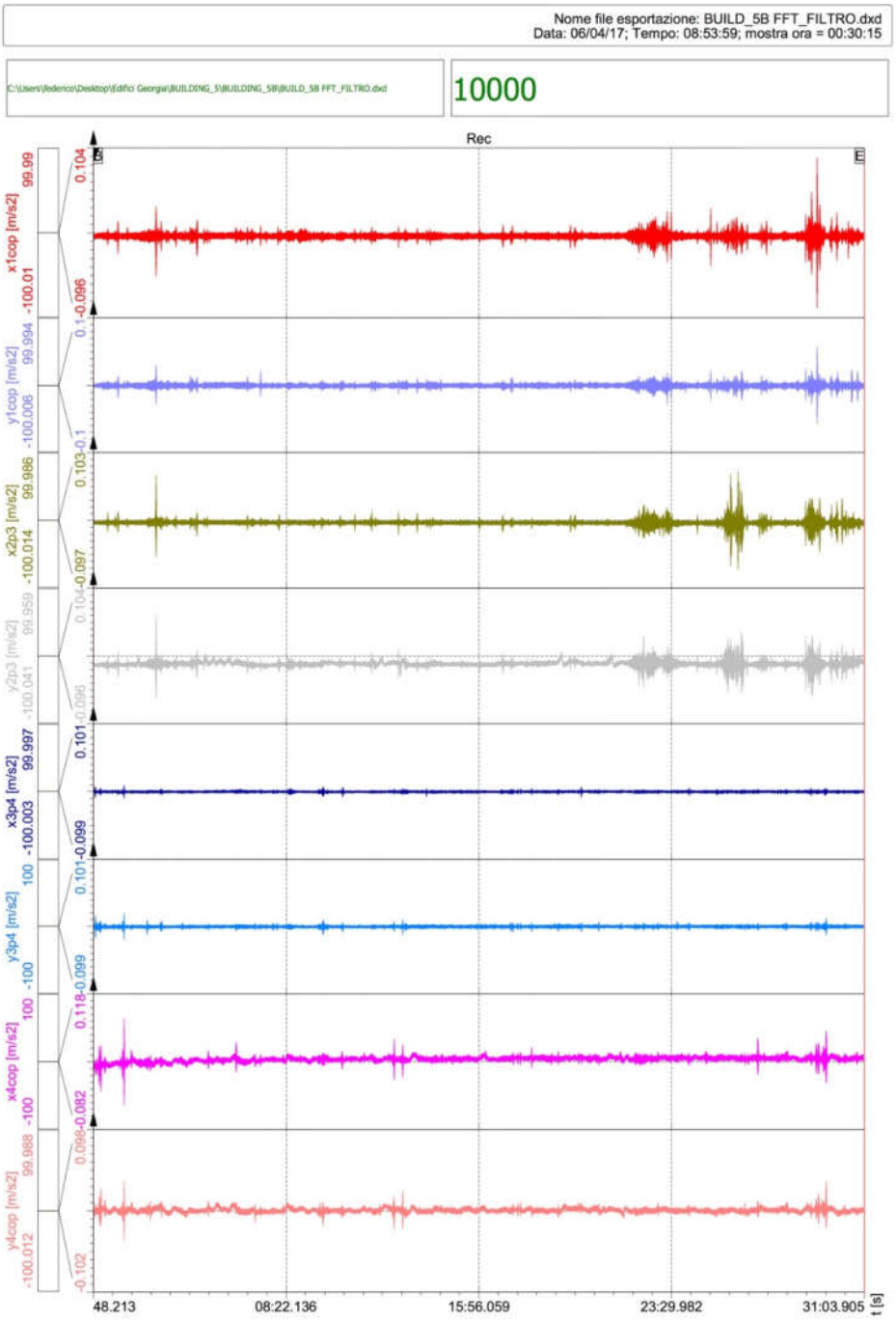


Image 57. Time histories

FREQUENCY CONTENT OF THE SIGNALS

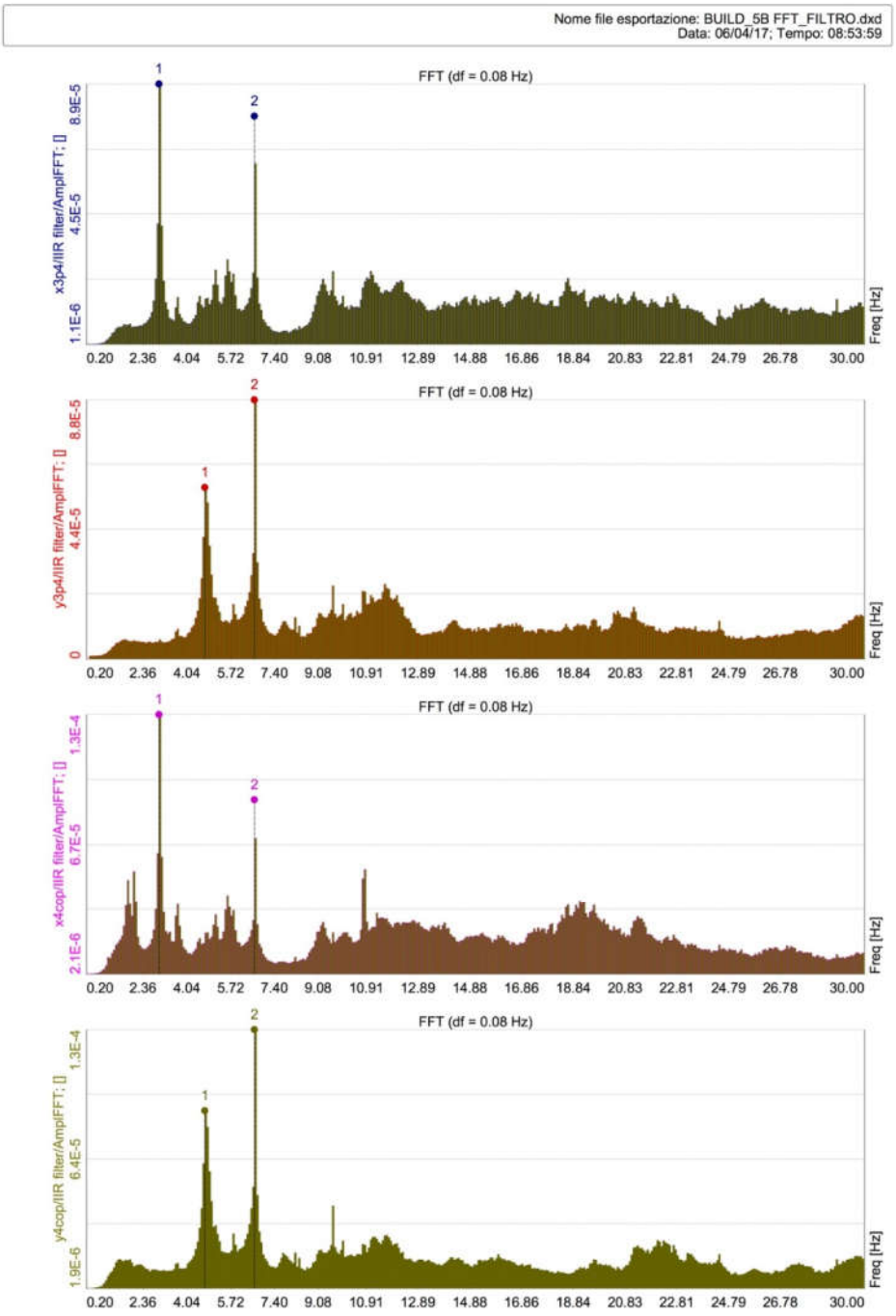


Image 58. Frequency content

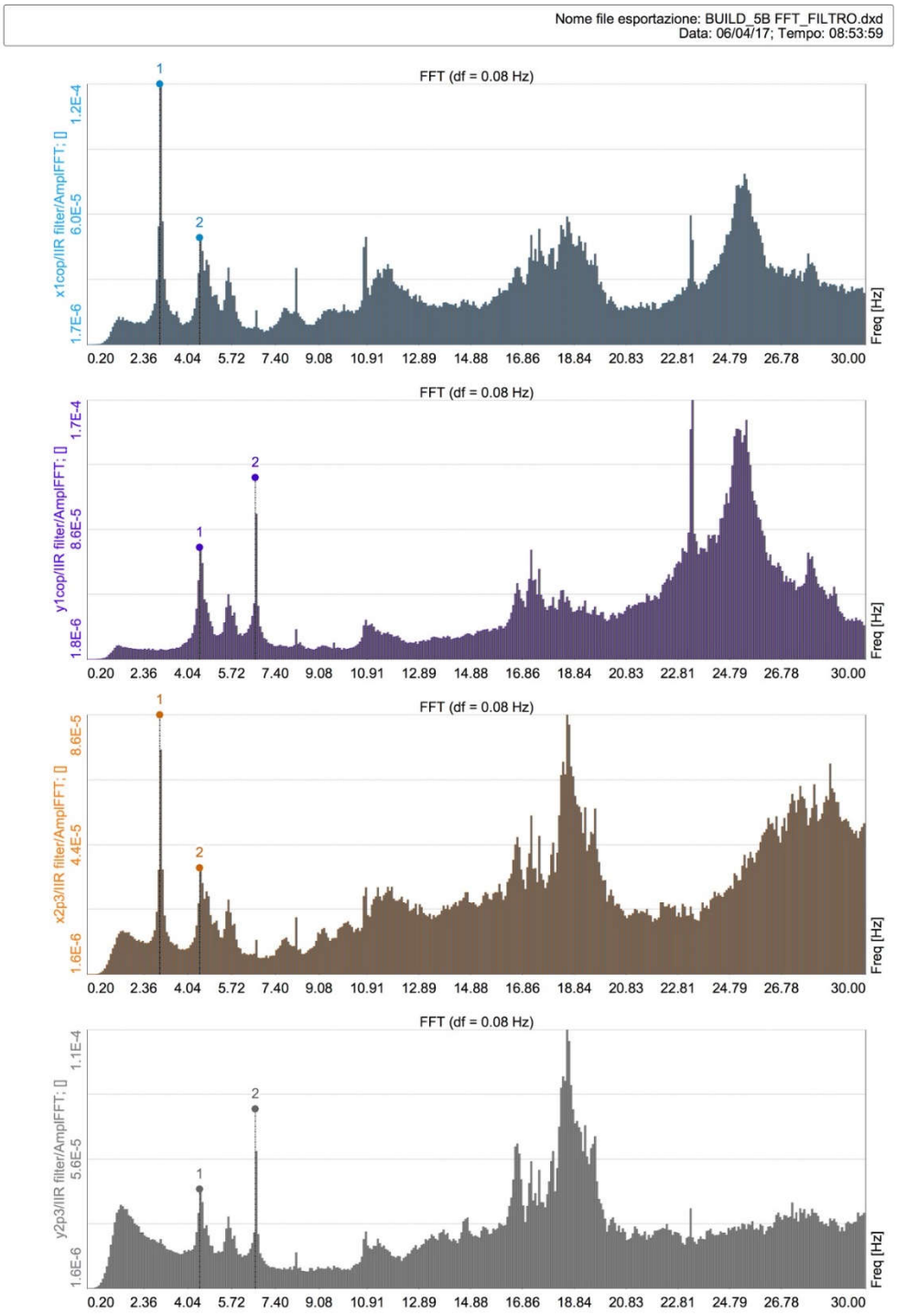
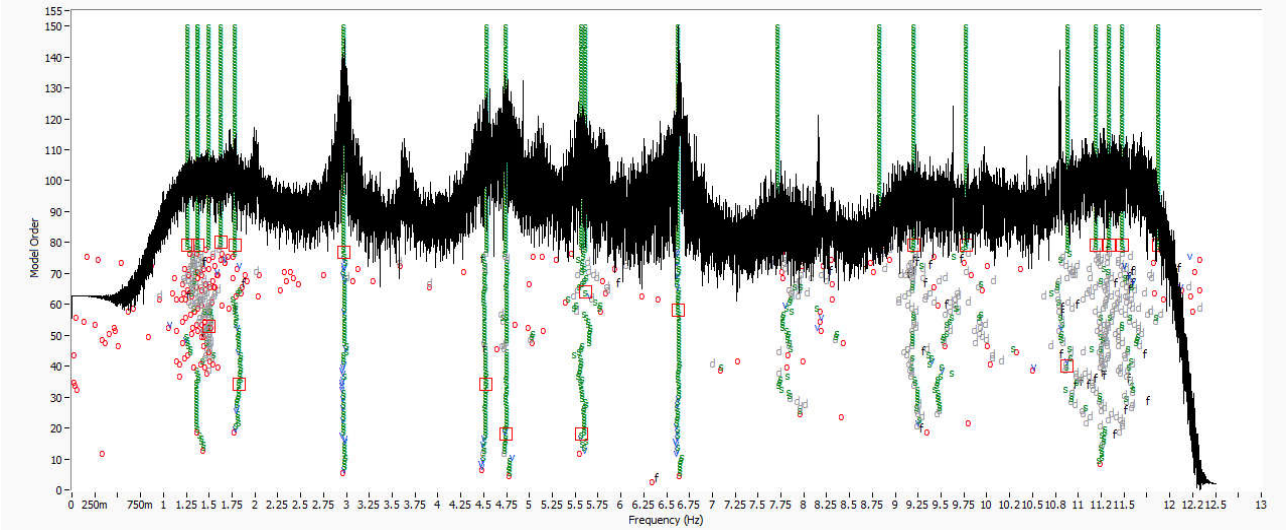


Image 59. Frequency content

MODAL IDENTIFICATION RESULTS

Stabilization diagram



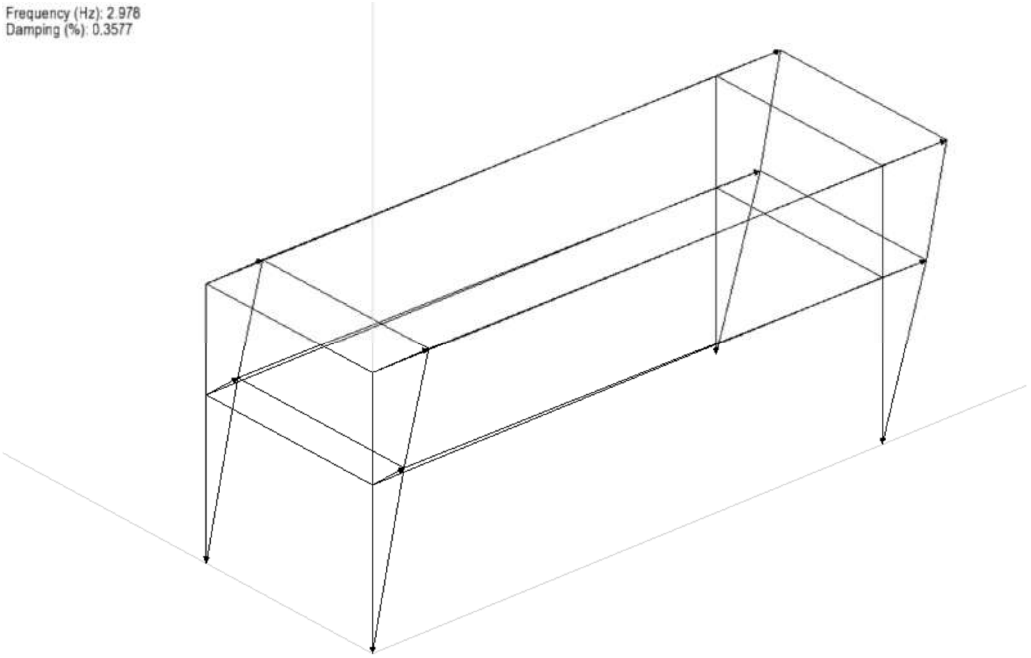
Mode n.	Frequency (Hz)	Damping (%)
1	2.98	0.3577
2	4.53	1.476
3	4.75	1.408
4	6.63	0.815

Images 60. Modal identification result

Mode Shapes

Mode1

2.98Hz – Traslational X



Mode2

4.53Hz –Torsional

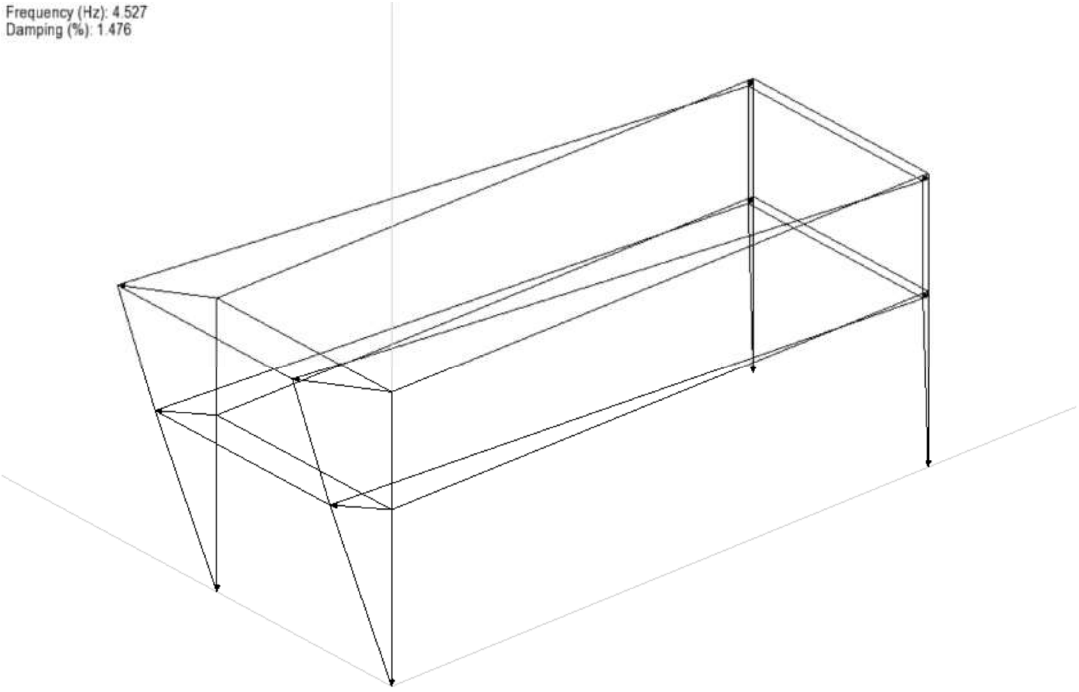
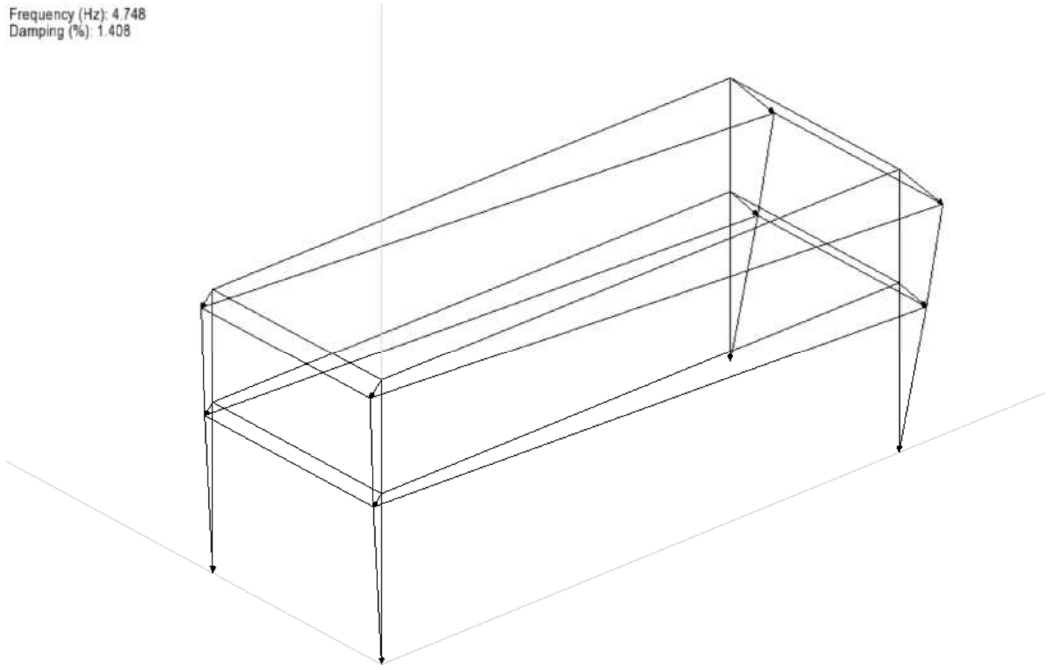


Image 61. Modal shapes

Mode3
4.75Hz –Traslational Y



Mode4
6.63Hz –Torsional

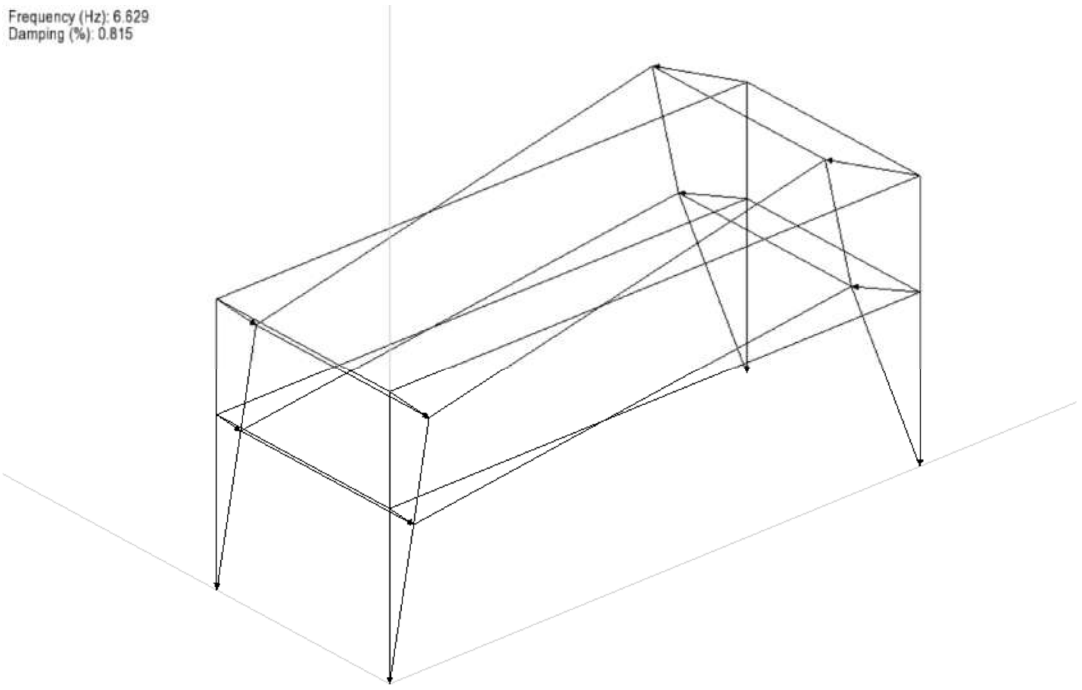


Image 62. Modal shapes

BLOCK 5B_ADDED BLOCKS

In addition to its core structure as built originally, Building 5 includes several additions loosely attached to the main structure. For this reason further investigations were necessary, monitoring in the same time the original structure and the additions in order to catch the relative mode shapes.

Image 63. Building 5 – added blocks

SENSORS LAYOUT

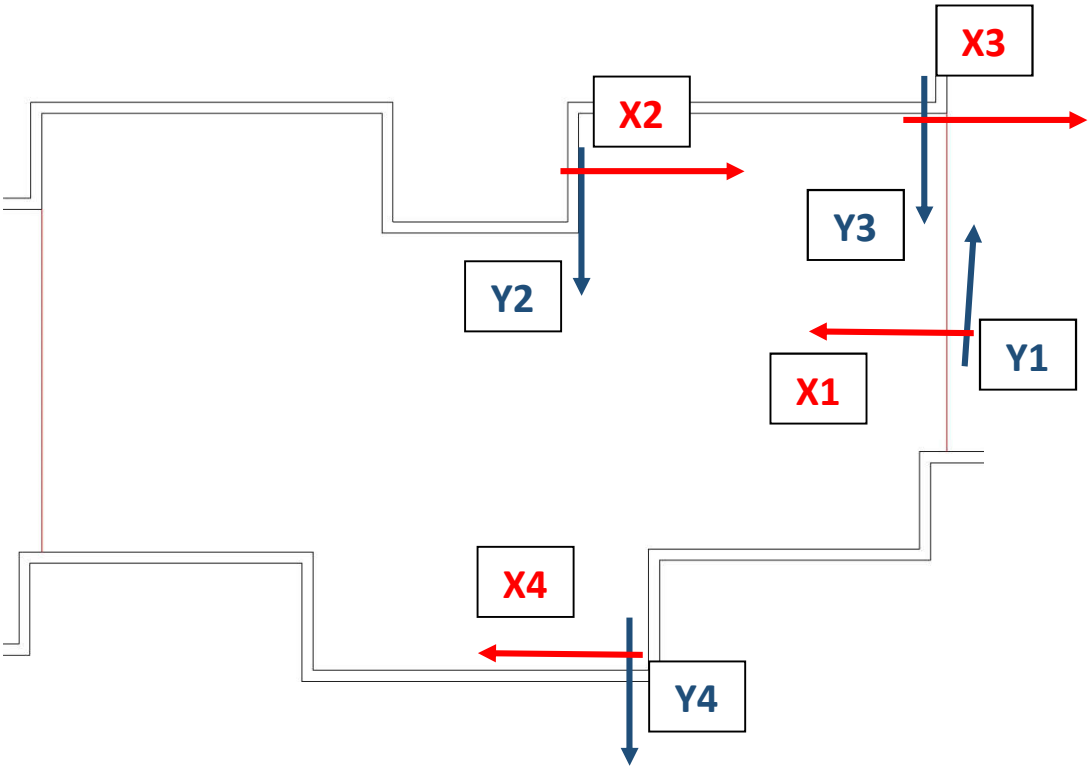


Image 64. Planimetry and sensors on added parts

Images 65 and 66. sensors

ACQUISITION OF TIME HISTORIES

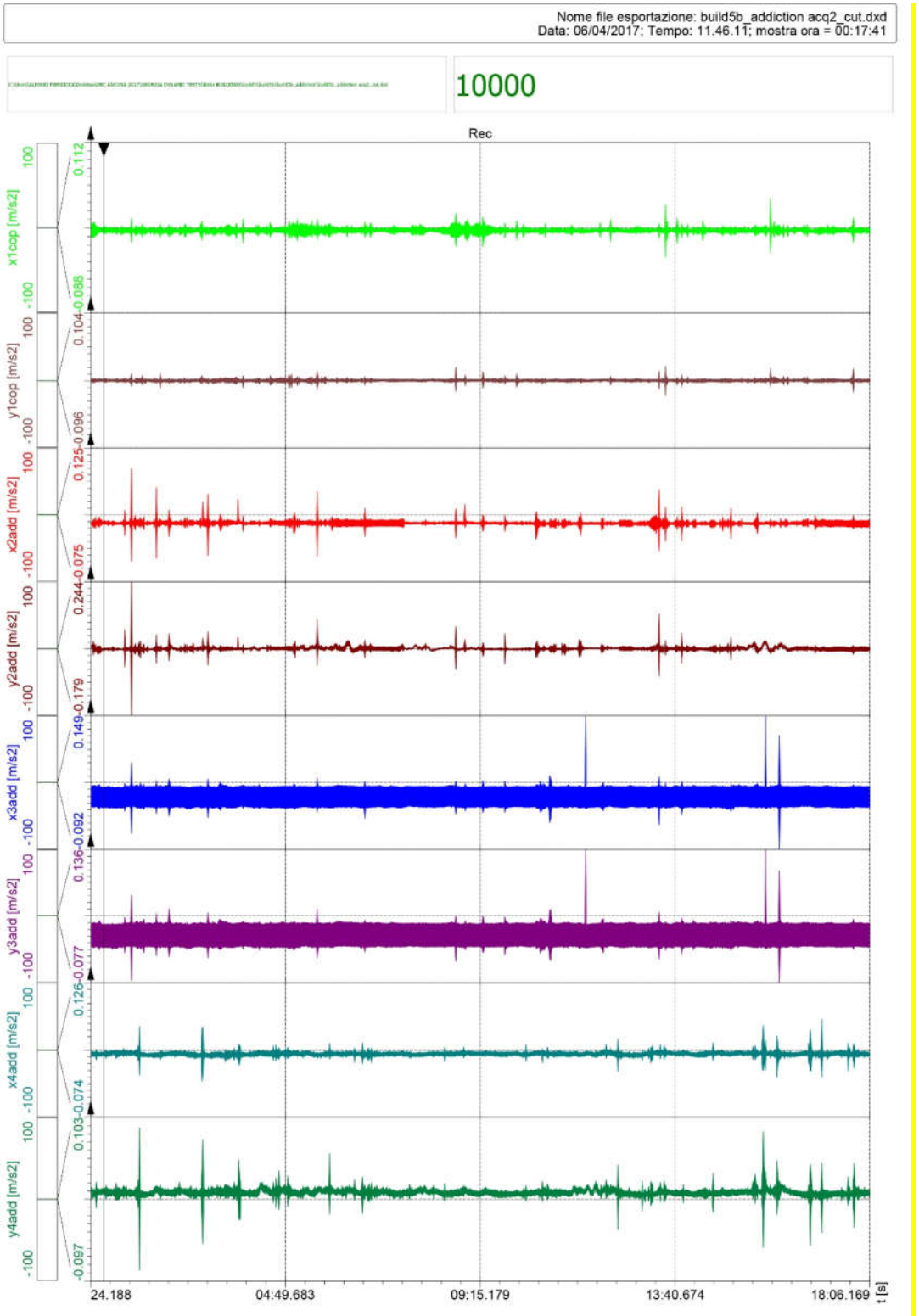


Image 67. Time histories

FREQUENCY CONTENT OF THE SIGNALS

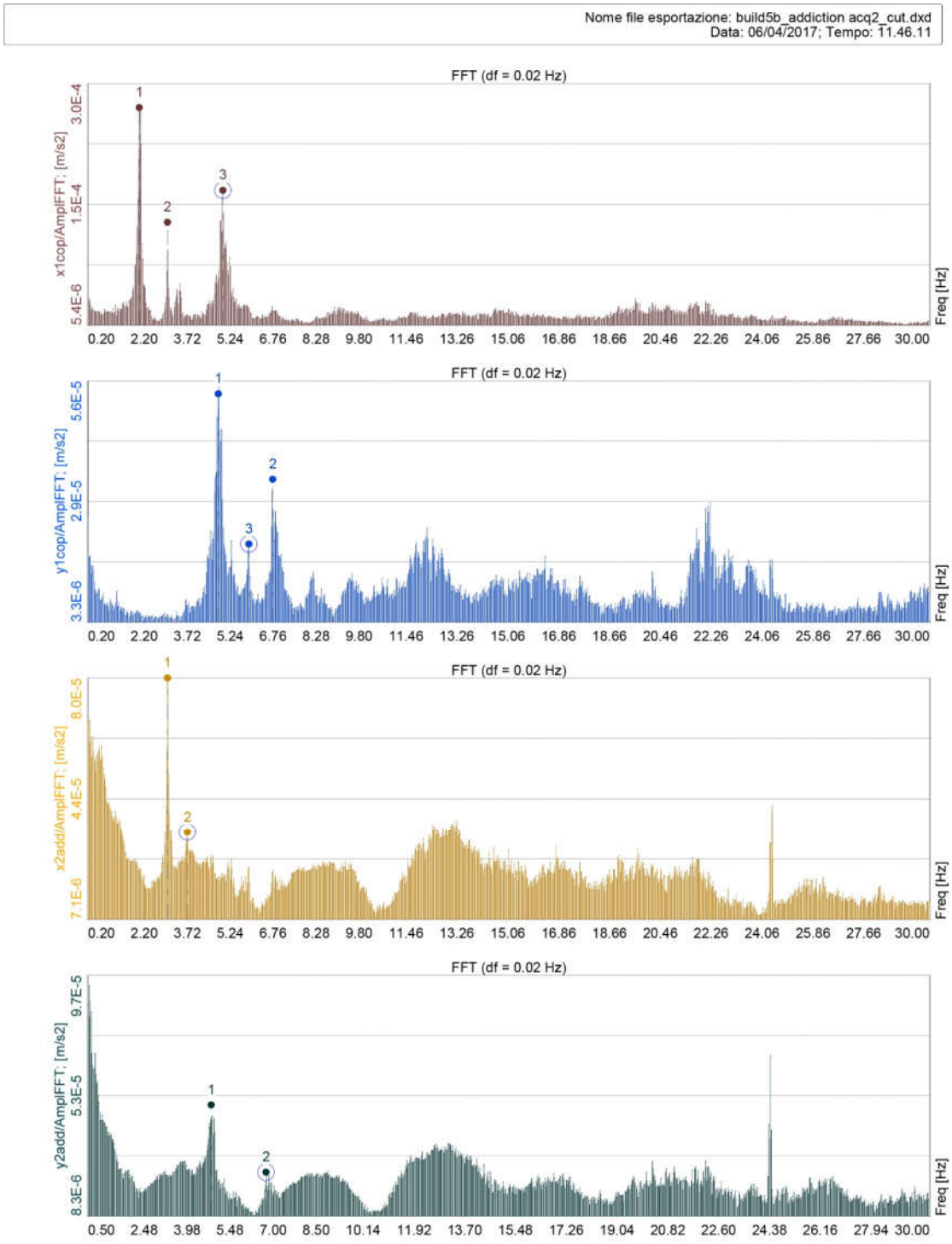


Image 68. Frequency content

Nome file esportazione: build5b_addiction acq2_cut.dxd
Data: 06/04/2017; Tempo: 11.46.11

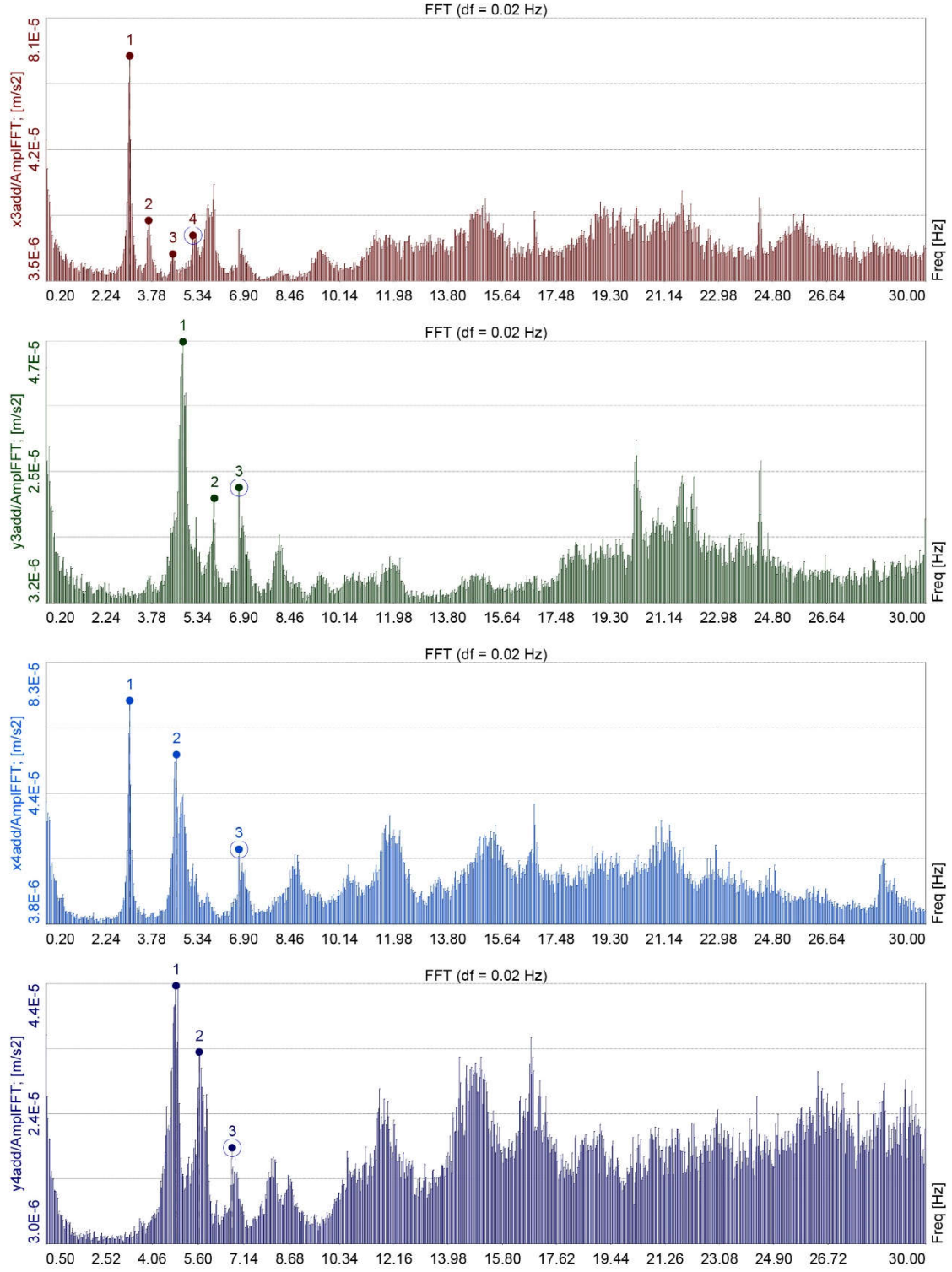
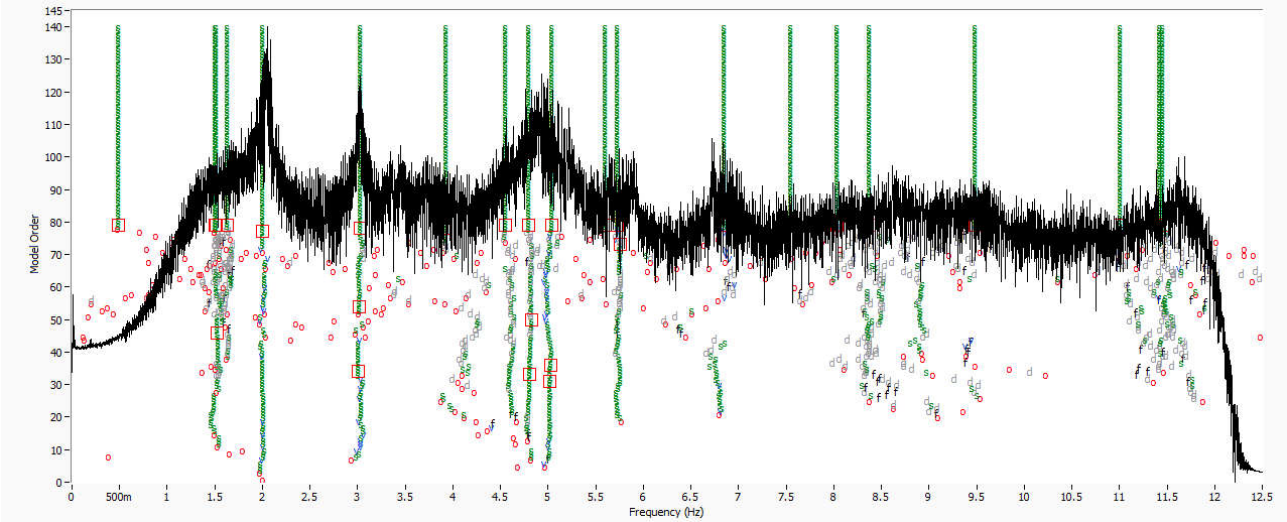


Image 69. Frequency content

MODAL IDENTIFICATION RESULTS

Stabilization diagram

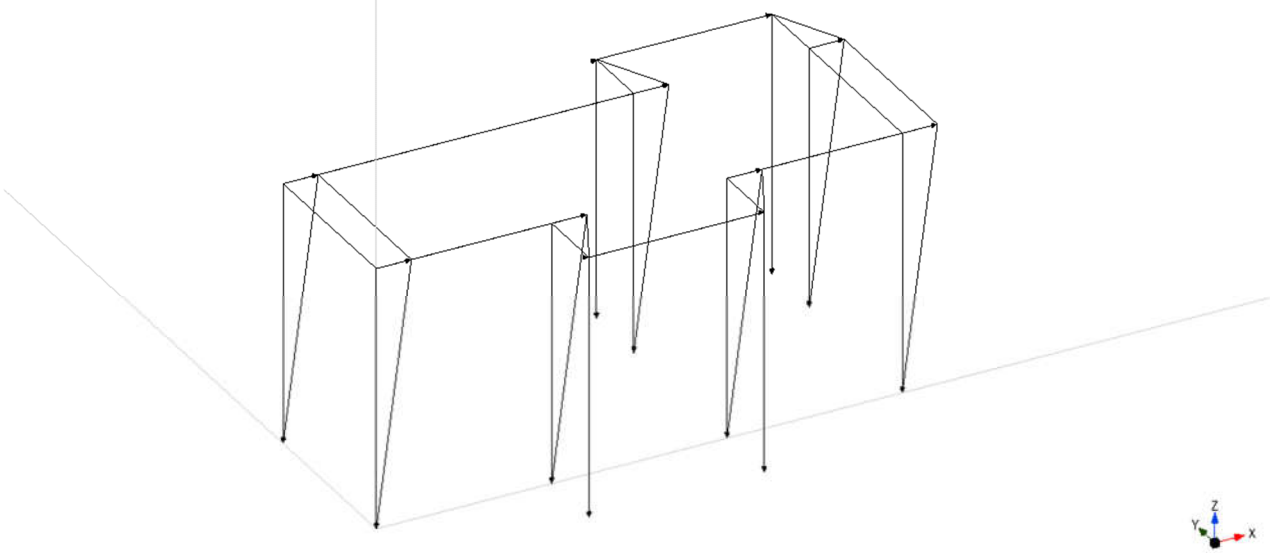


Mode Number	Frequency (Hz)	Damping (%)
1	3.05	1.771
2	4.547	1.613
3	4.806	2.024
4	6.85	1.099

Image 70. Modal identification result

Mode Shapes

Mode1
3.05Hz – Traslational X (original structure)



Mode2
4.54Hz – Traslational X (added block)

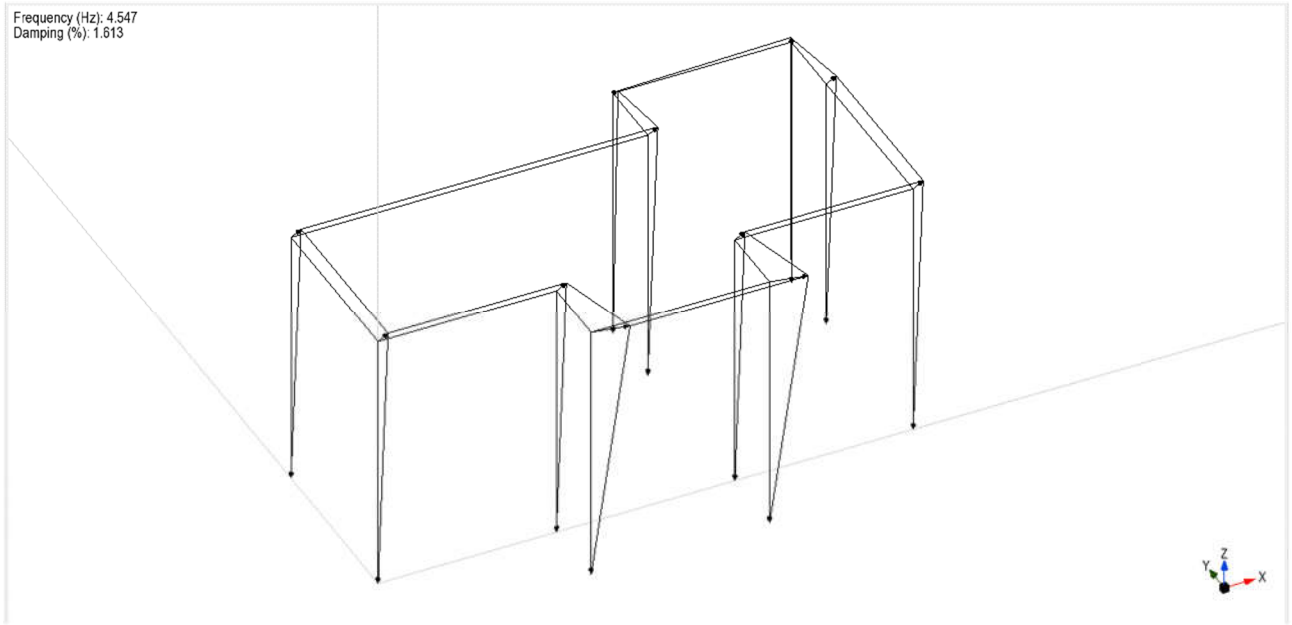
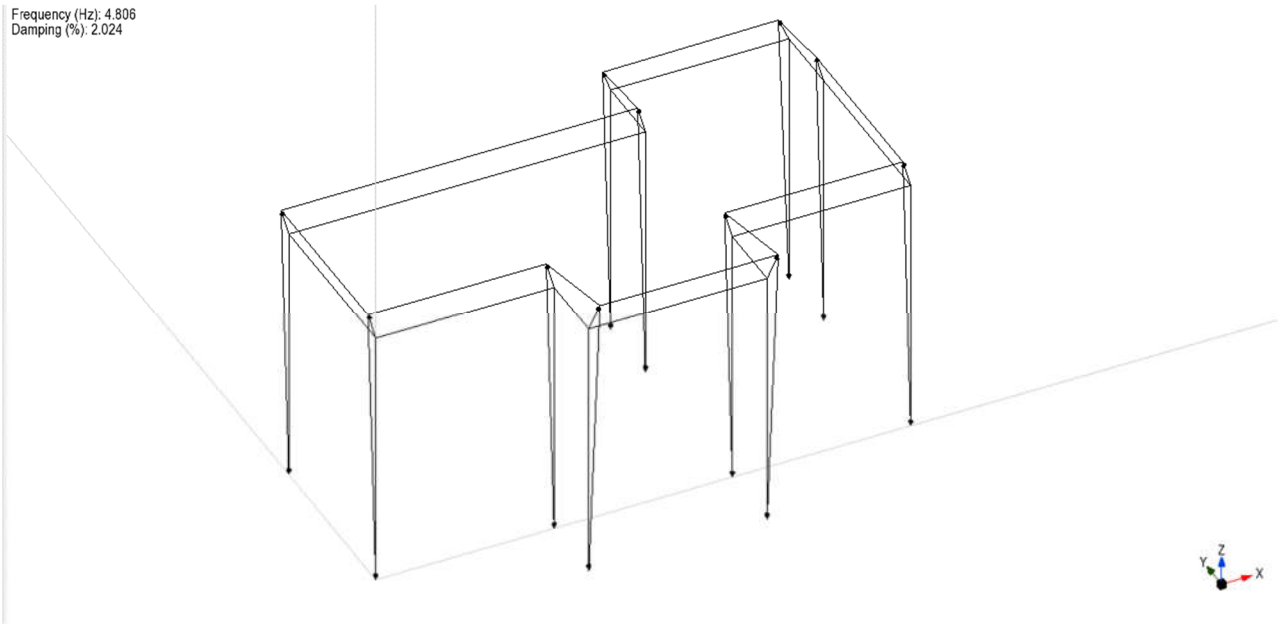


Image 71. Modal shapes

Mode3
4.80Hz – Traslational Y



Mode4
6.85Hz – Torsional

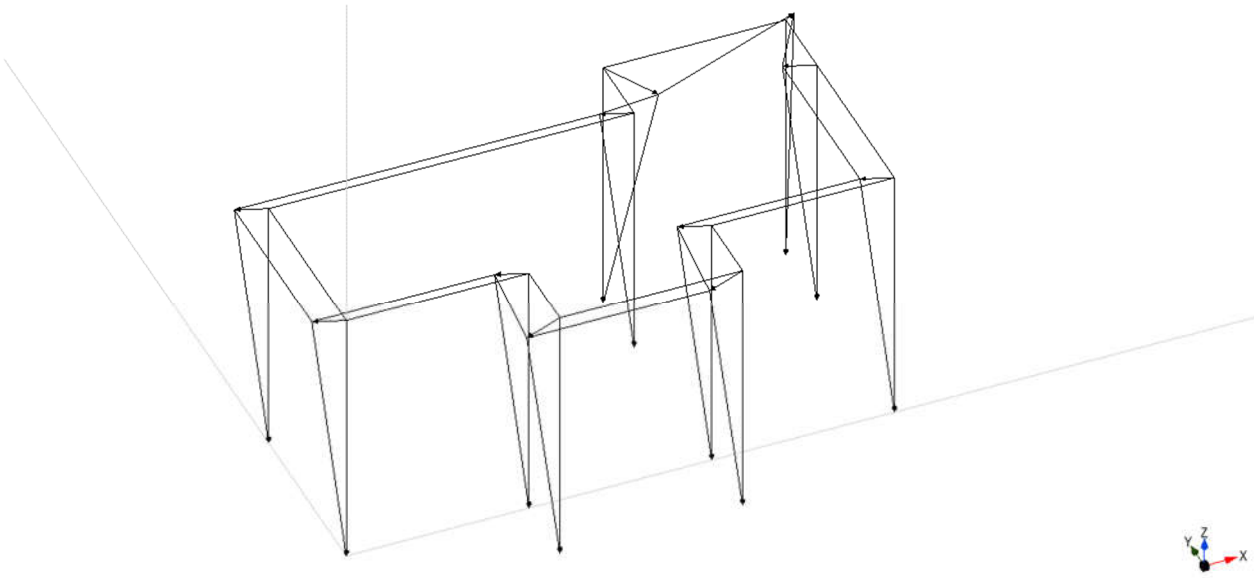
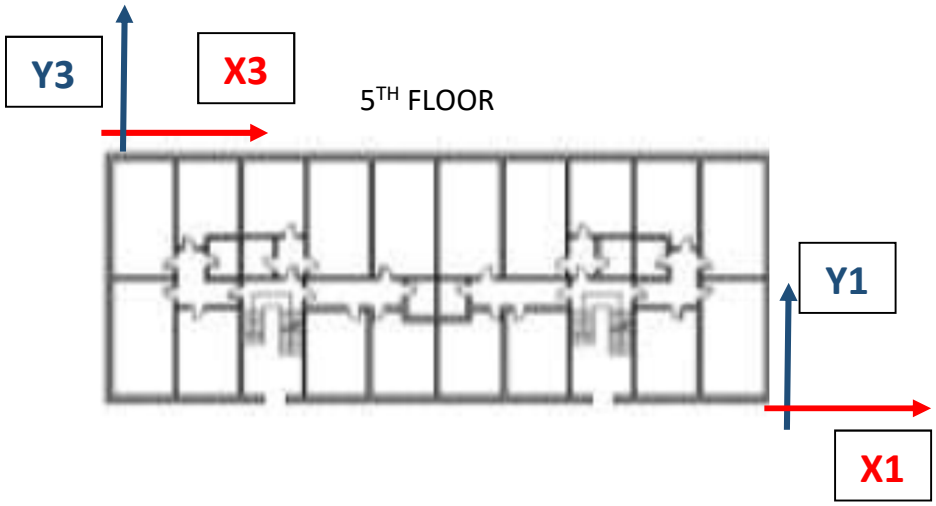


Image 72. Modal shapes

BLOCK 5C

SENSORS LAYOUT



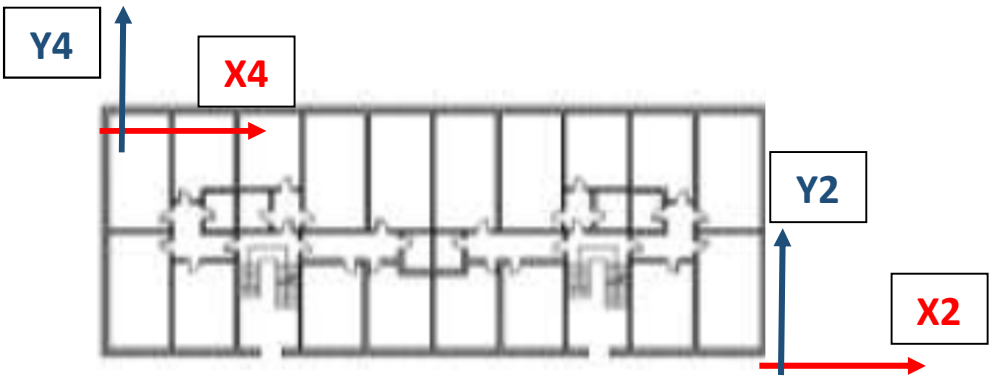
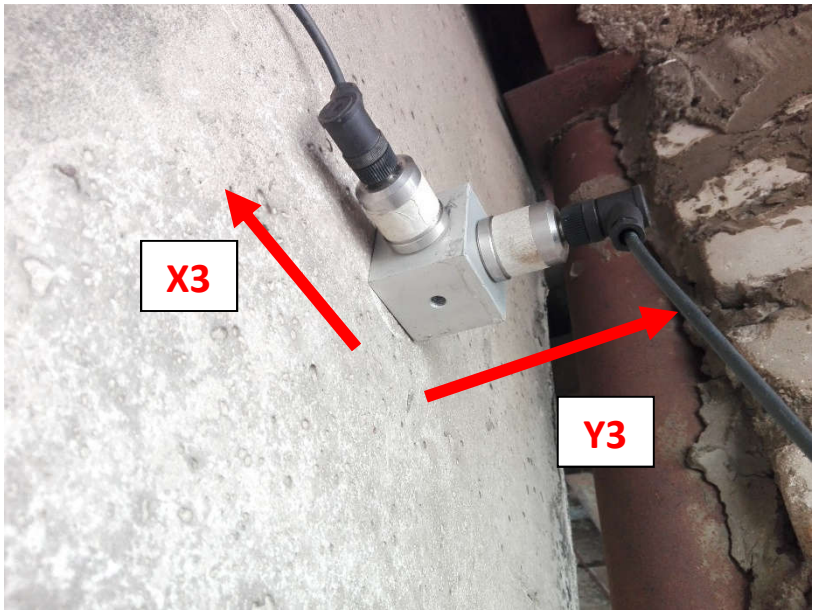
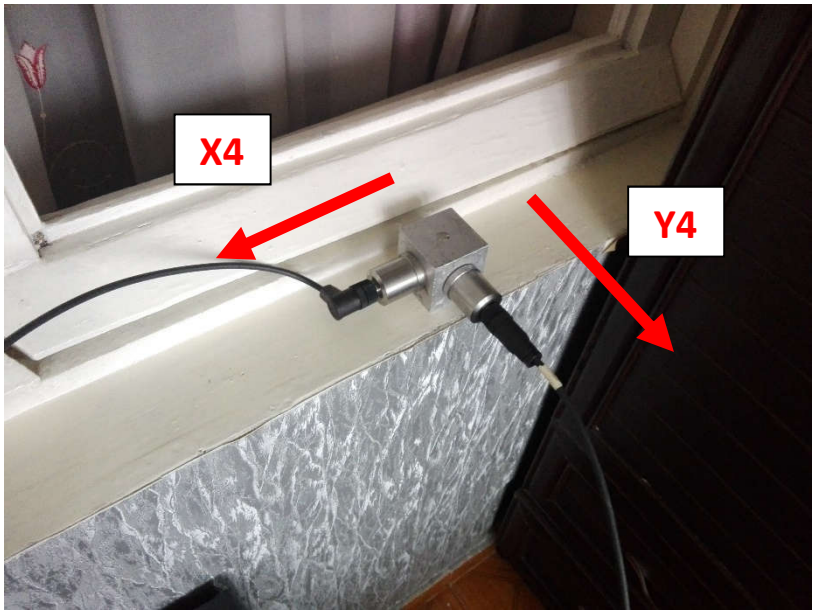
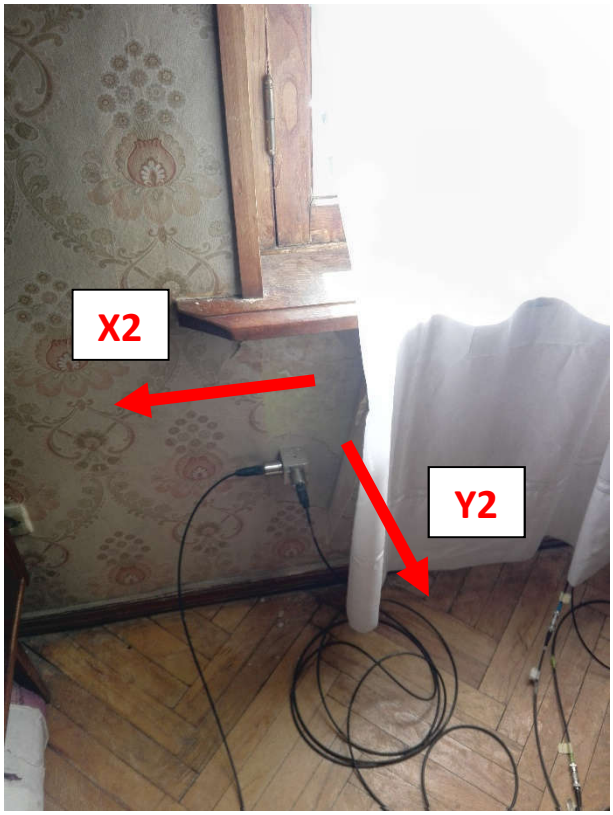


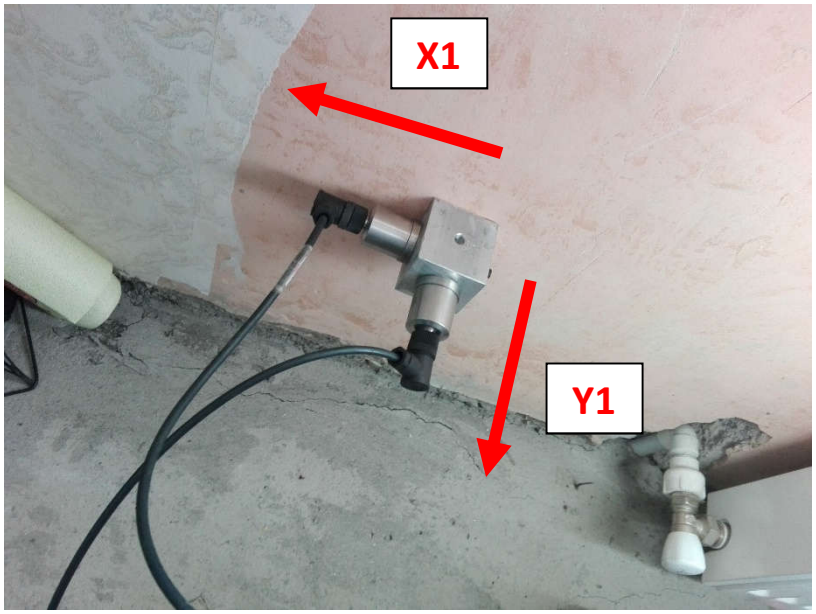
Image 73. Block 5C planimetry



Images 74 and 75. Sensors and data acquisition system


X4
Y4


X2
Y2



Images 76, 77 and 78. sensors

ACQUISITION OF TIME HISTORIES

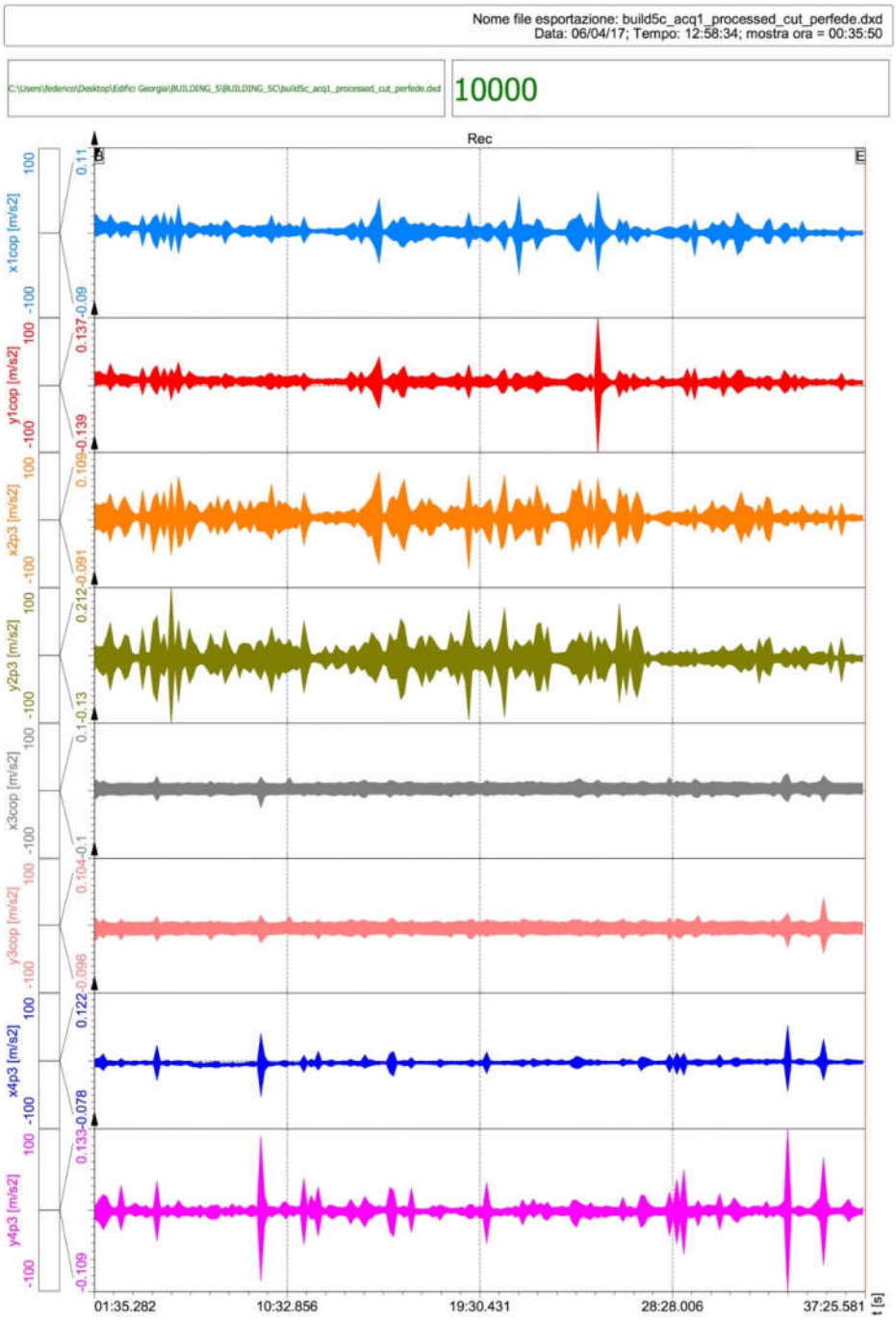


Image 79. Time histories

FREQUENCY CONTENT OF THE SIGNALS

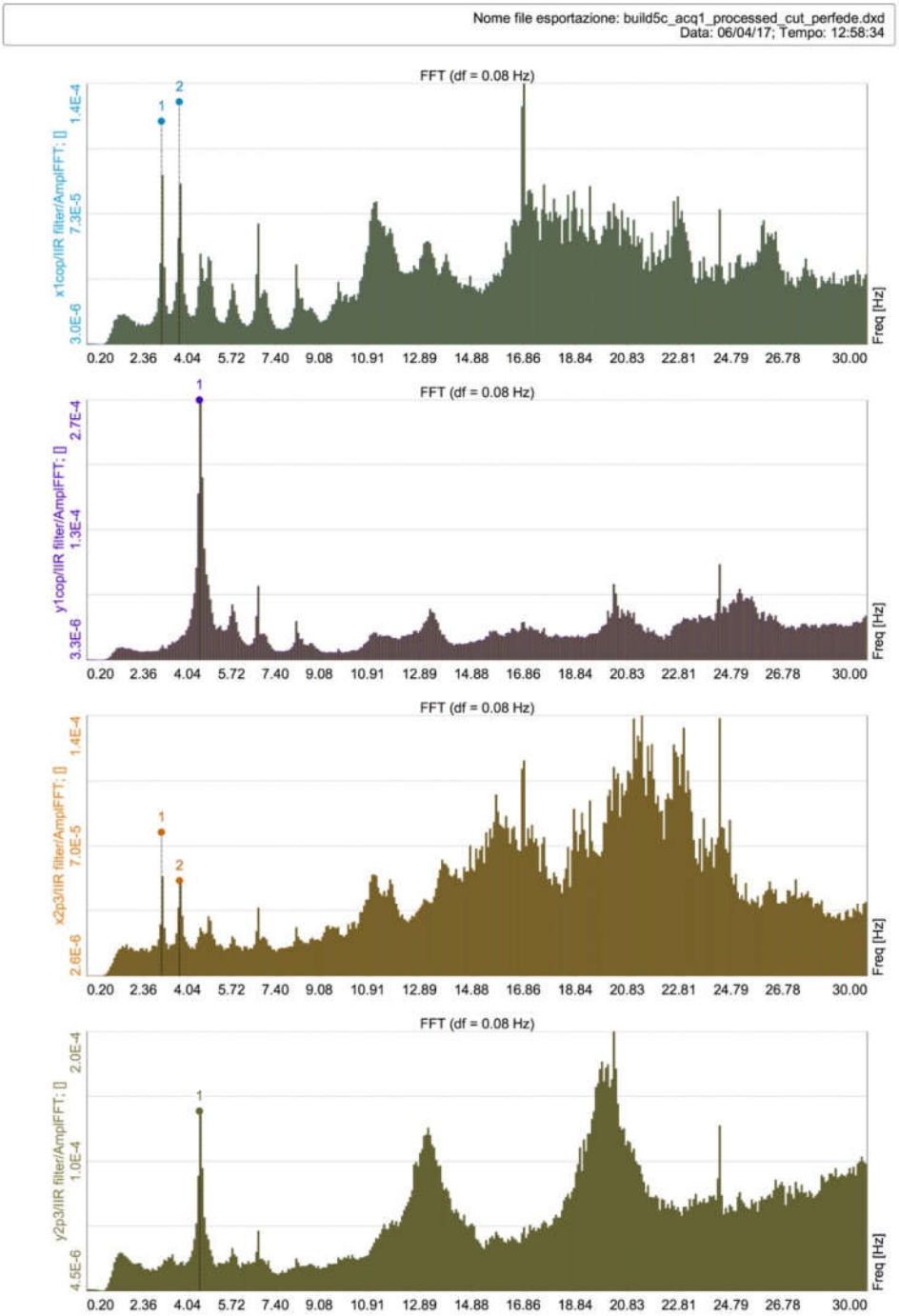


Image 80. Frequency contents

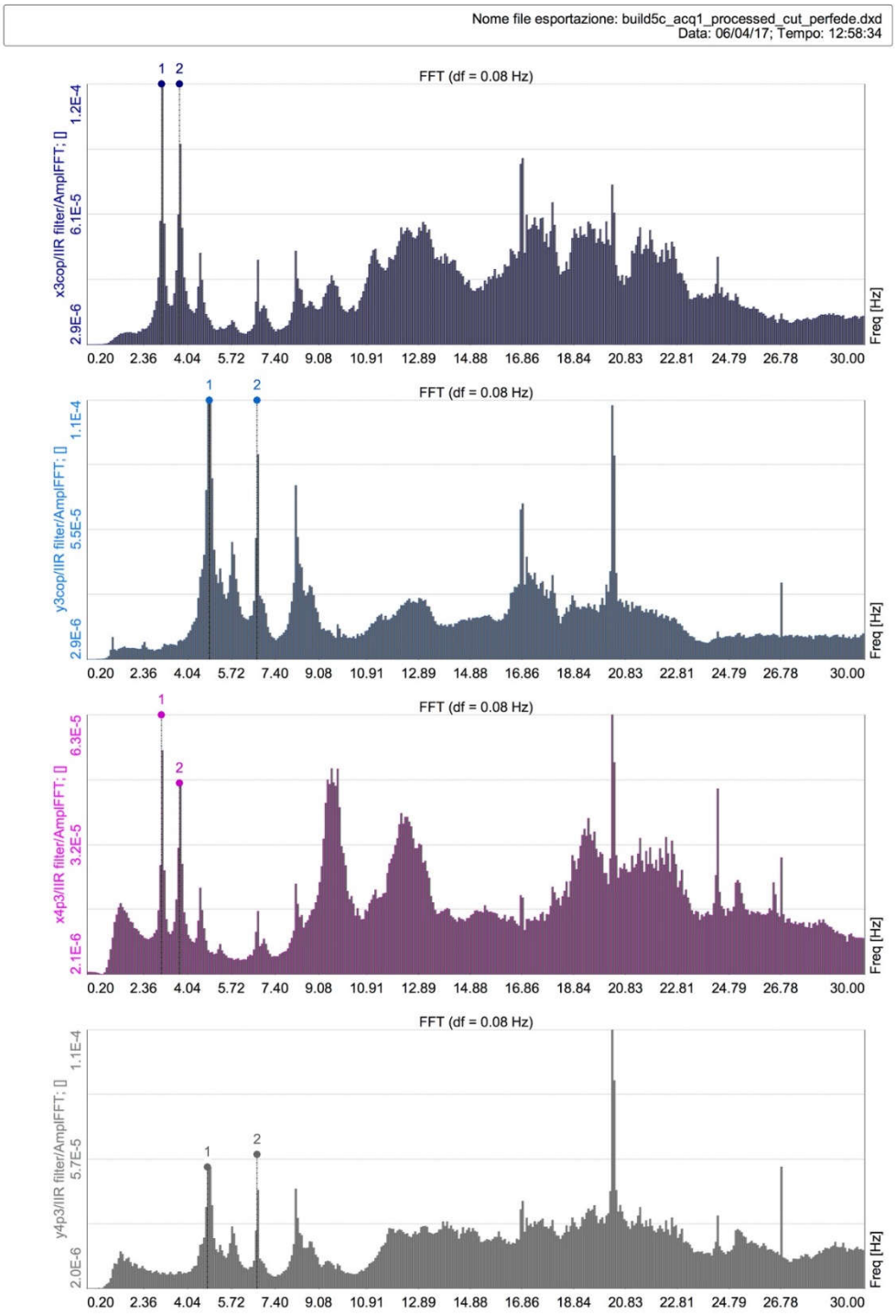
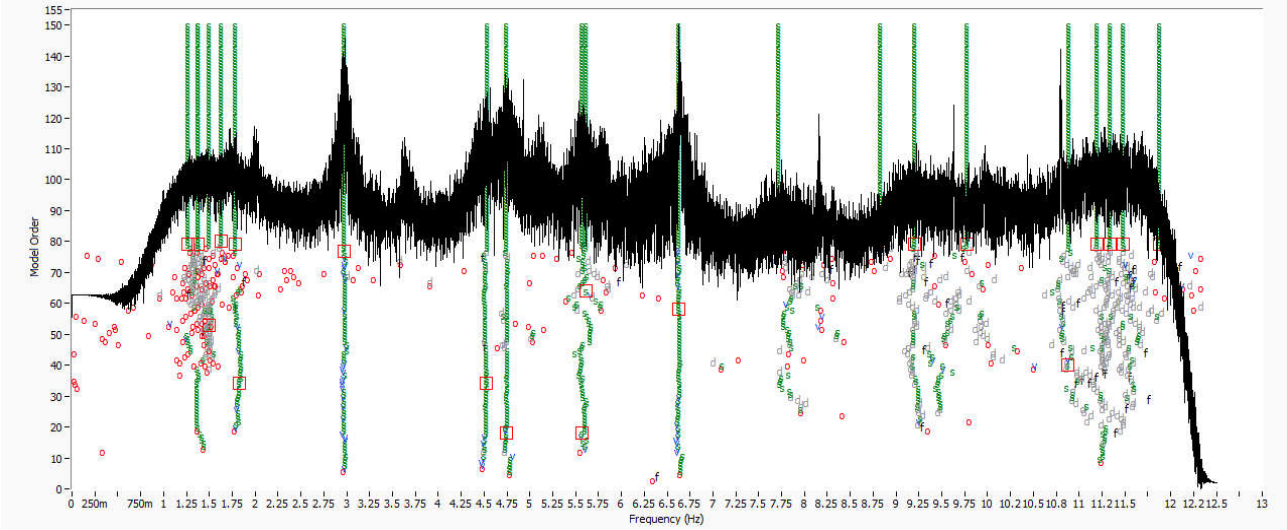


Image 81. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram



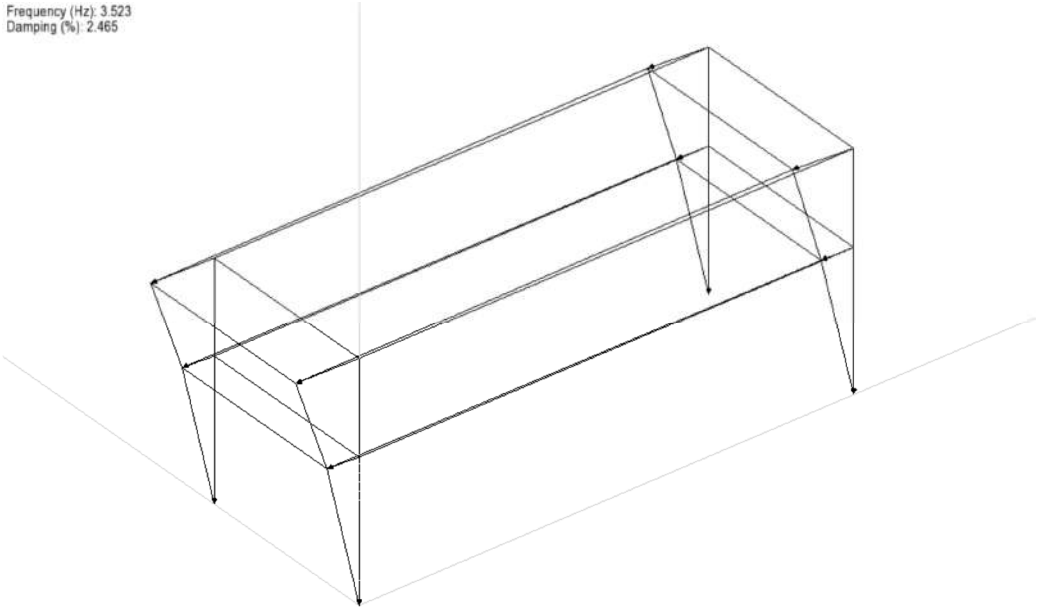
Mode n.	Frequency (Hz)	Damping (%)
1	3.05	2.415
2	4.52	4.512
3	4.86	1.519
4	5.68	3.723

Image 82. Modal identification result

Mode Shapes

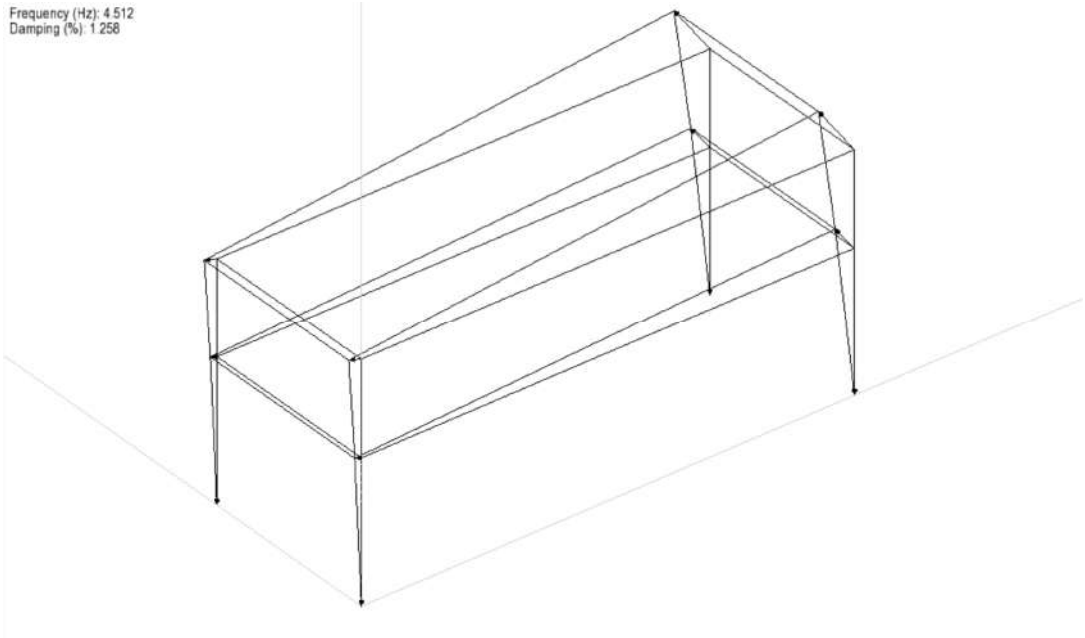
Mode1

3.05Hz – Traslational X



Mode2

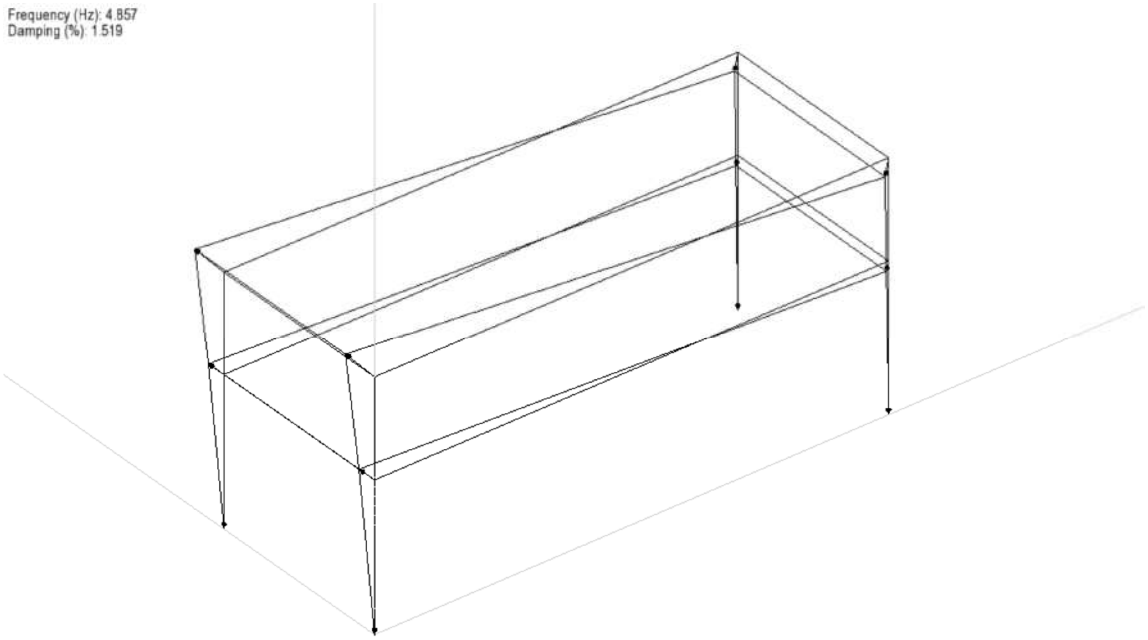
4.52Hz – Traslational Y



Images 83 and 84. Modal shapes

Mode3

4.86Hz – Torsional



Mode4

5.68Hz –Torsional

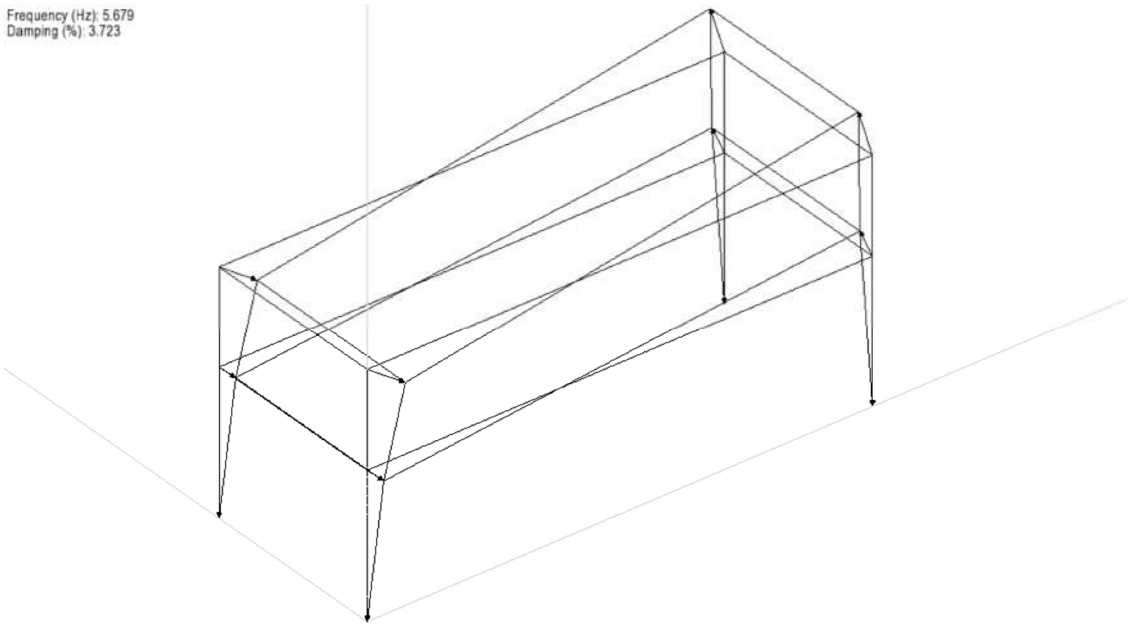


Image 85. Modal shapes

BLOCK 5C_ADDED COMPONENTS (ADDITIONS)

Building 5 includes several additions loosely attached to the main structure. For this reason further investigations were necessary, monitoring in the same time the original structure and the additional buildings in order to catch the relative mode shapes.

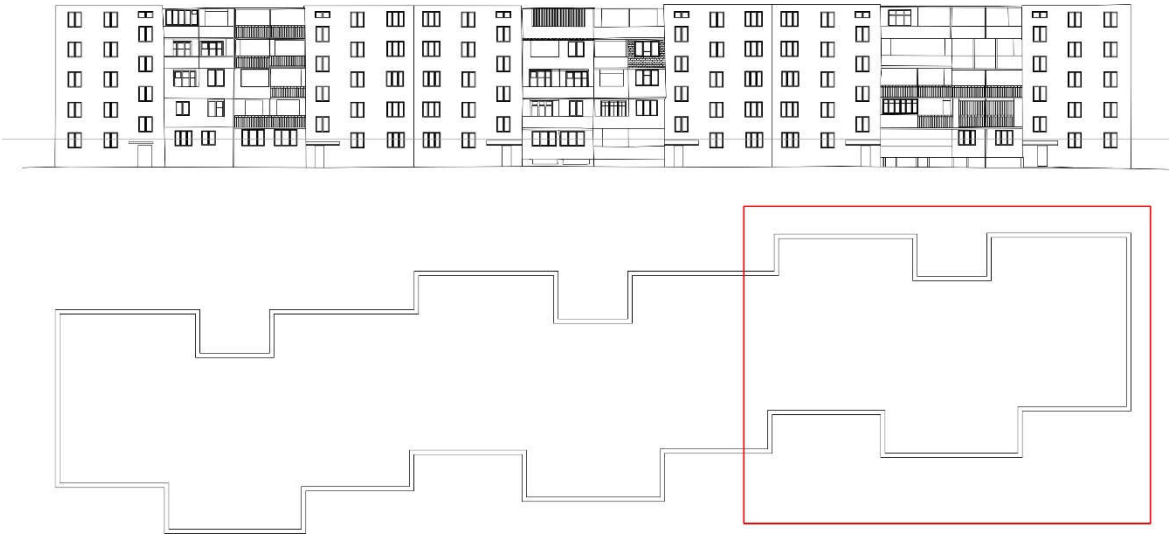
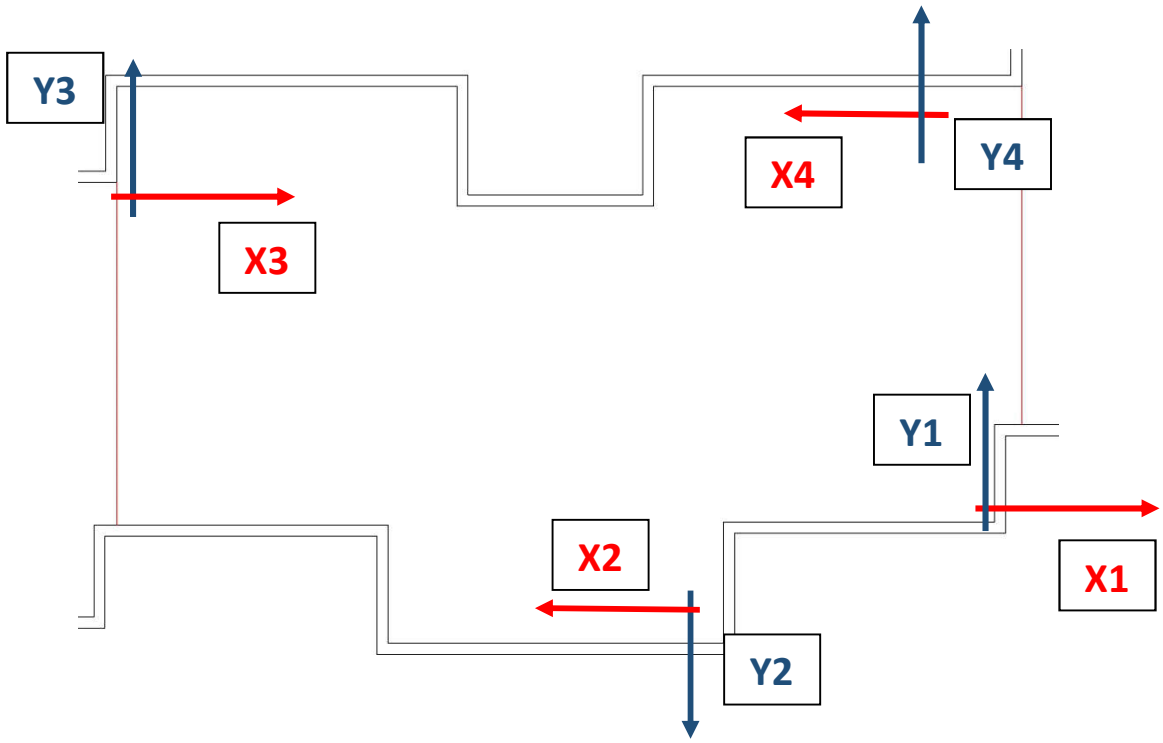
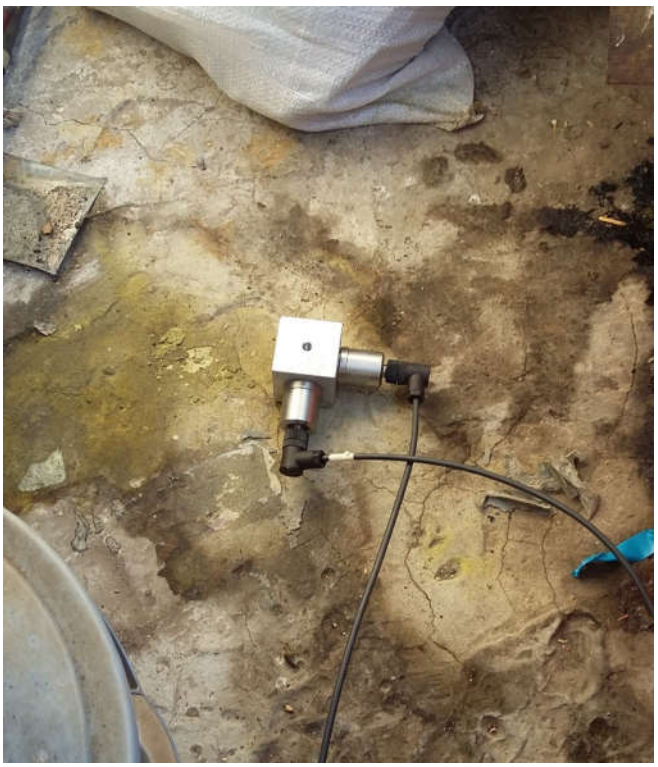


Image 86. Block 5C added parts

SENSORS LAYOUT





Images 86, 87 and 88. Sensors layout and sensors

ACQUISITION OF TIME HISTORIES

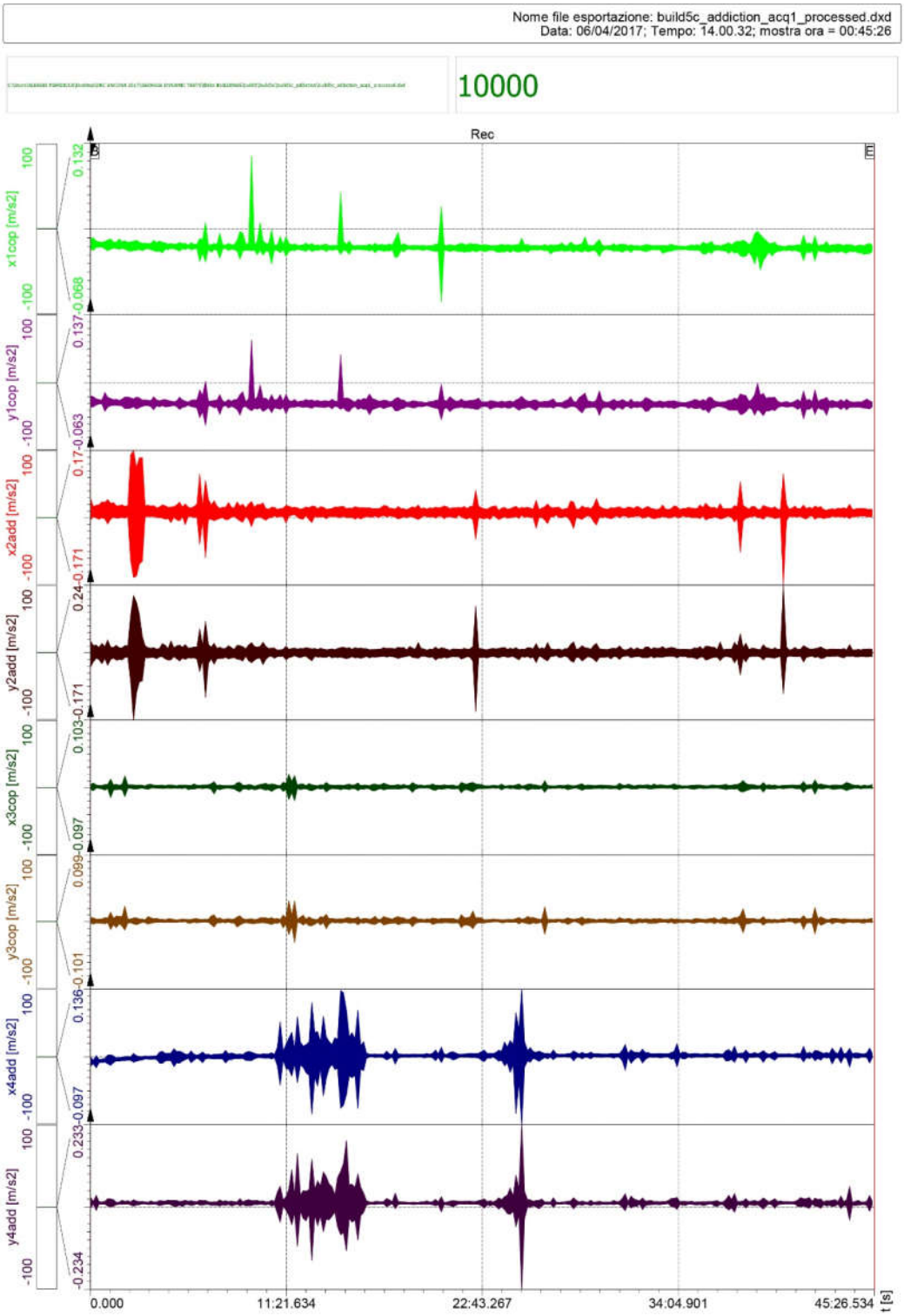


Image 89. Time histories

FREQUENCY CONTENT OF THE SIGNALS

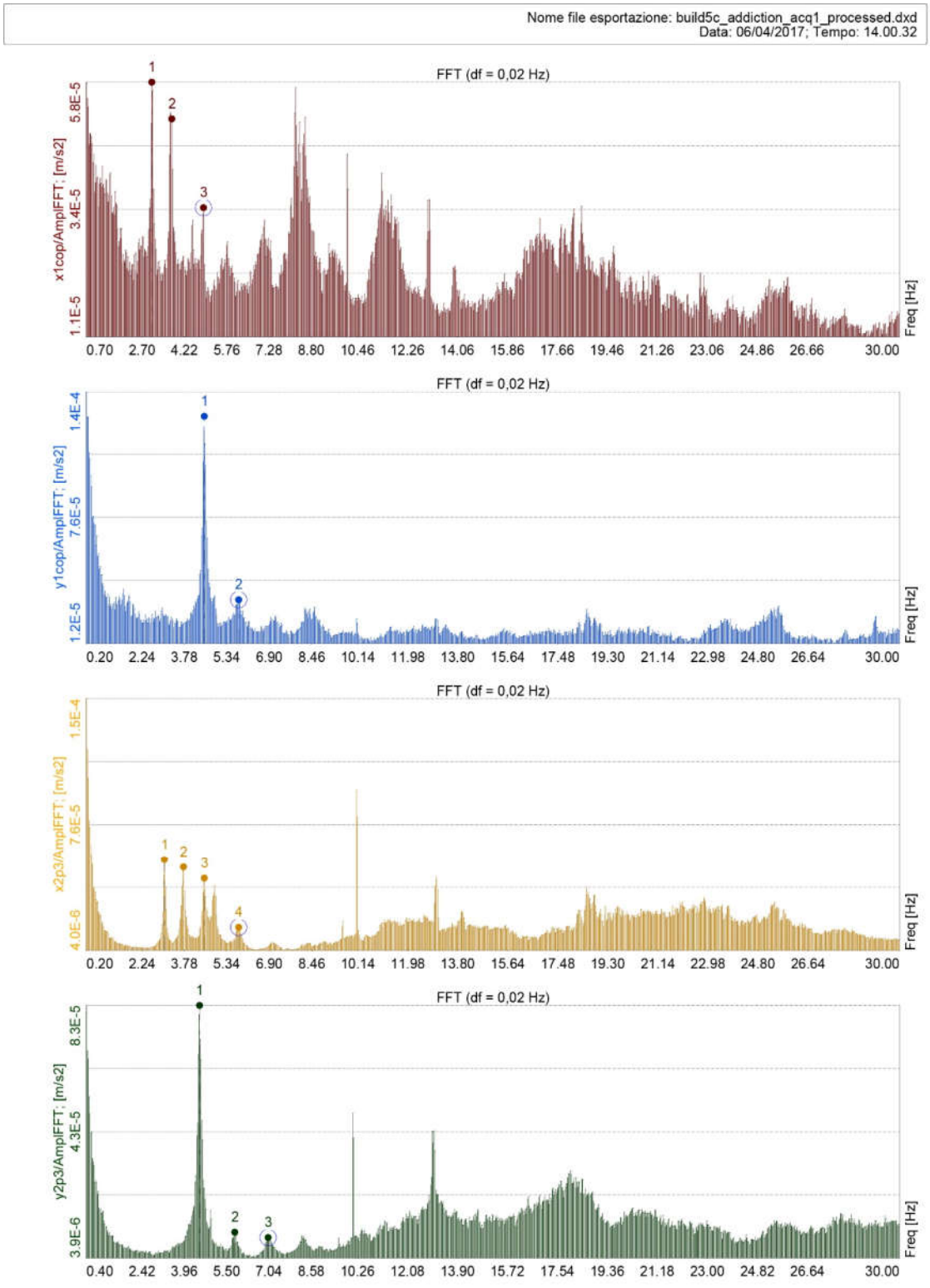


Image 90. Frequency contents

Nome file esportazione: build5c_addiction_acq1_processed.dxd
Data: 06/04/2017; Tempo: 14.00.32

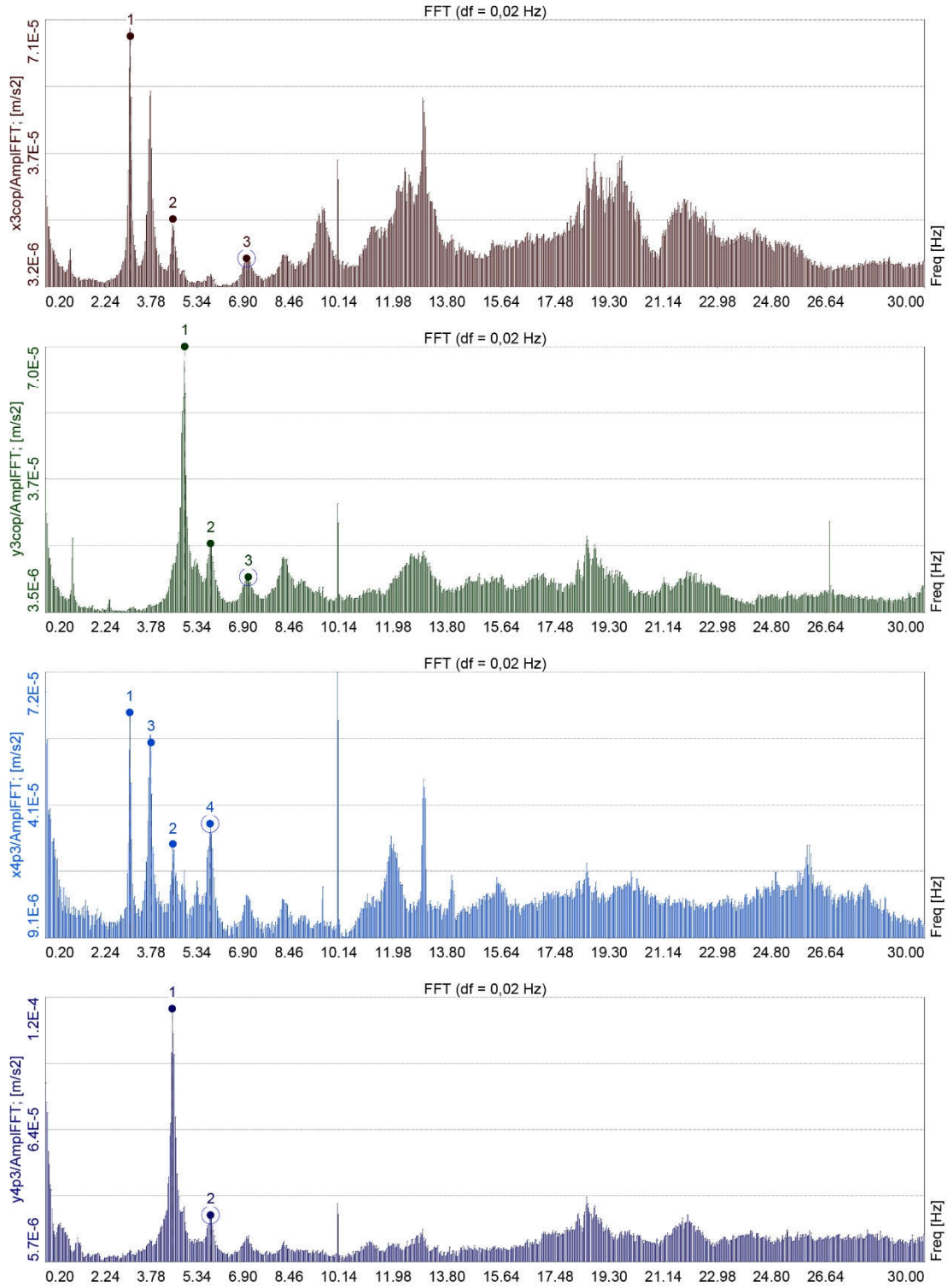
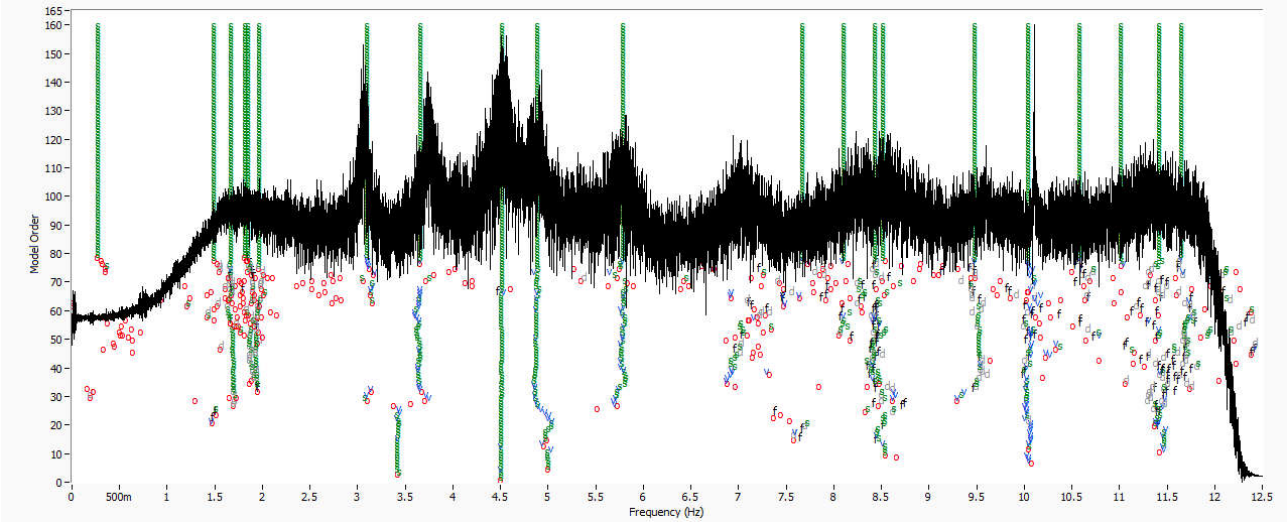


Image 91. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram



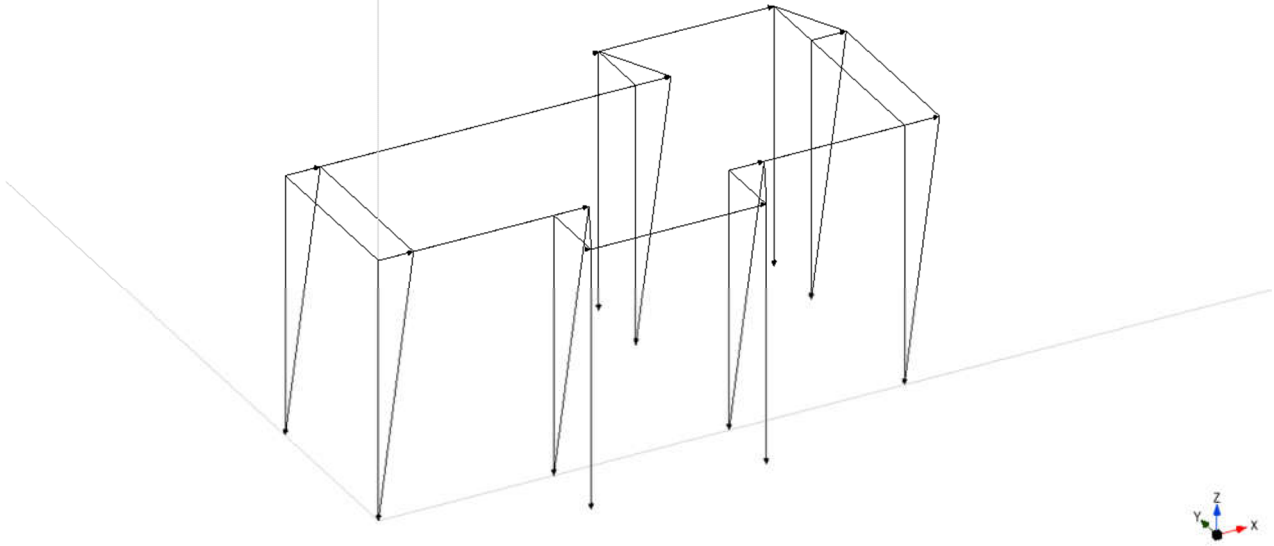
Mode Number	Frequency (Hz)	Damping (%)
1	3.104	0.05
2	4.514	1.288
3	4.884	1.778
4	5.788	3.147

Image 92. Modal identification result

Mode Shapes

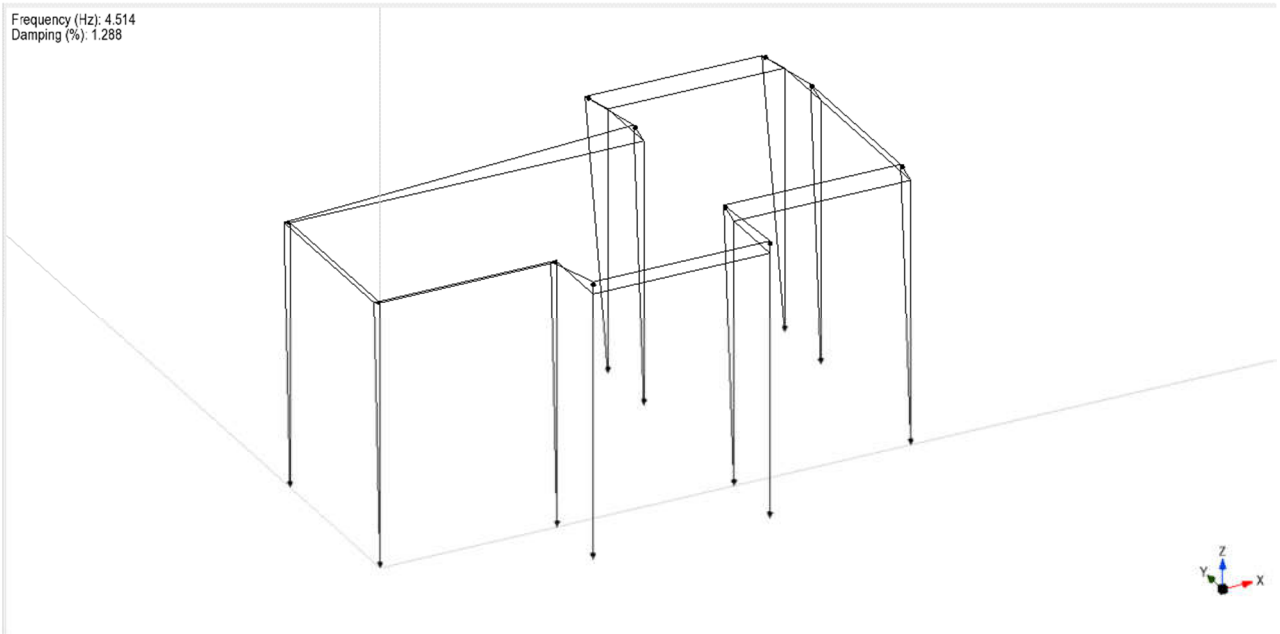
Mode1

3.104Hz – Traslational X (original structure)



Mode2

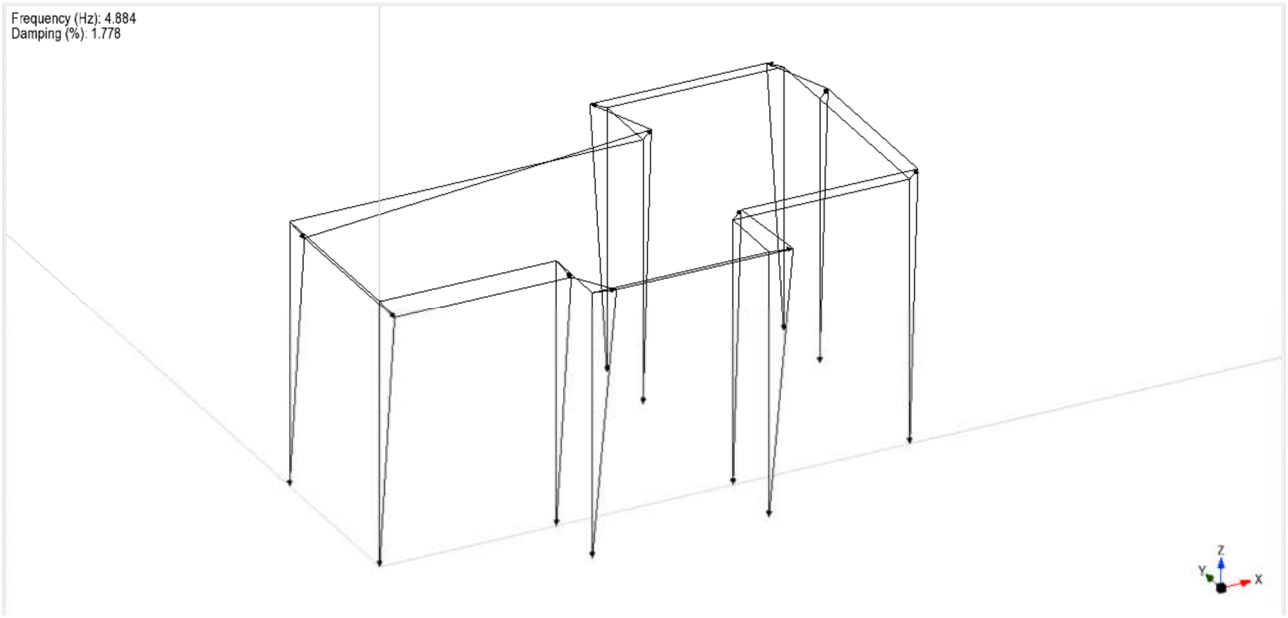
4.514Hz – Traslational Y(added block)



Images 93 and 94. Modal shapes

Mode3

4.884Hz – Torsional



Mode4

5.78Hz – Torsional

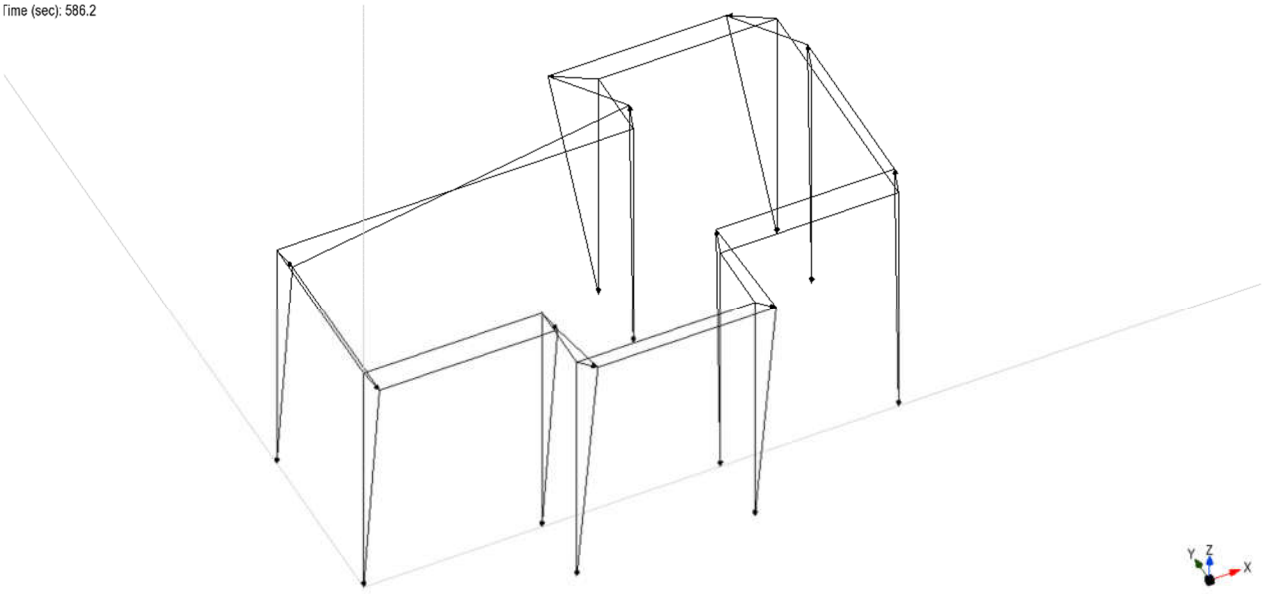
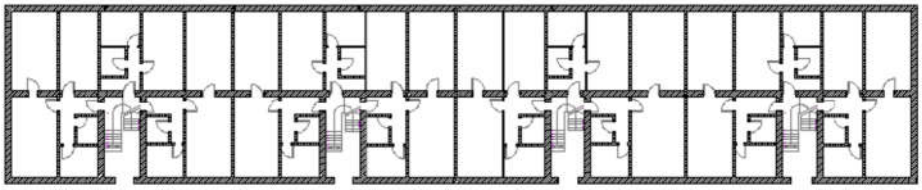
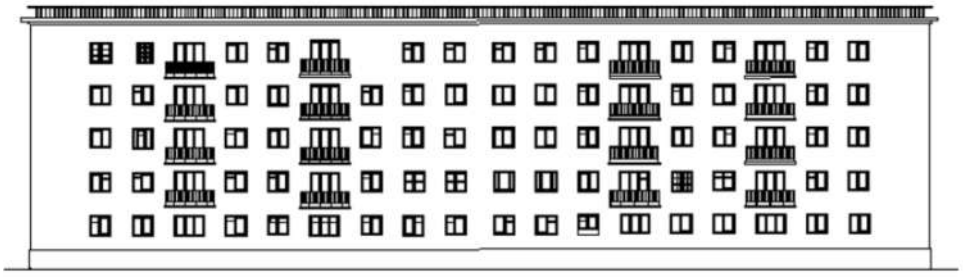


Image 95. Modal shapes

BUILDING 6



TYPICAL PLAN



MAIN ELEVATION

Image 96. Building n.6

SENSORS LAYOUT

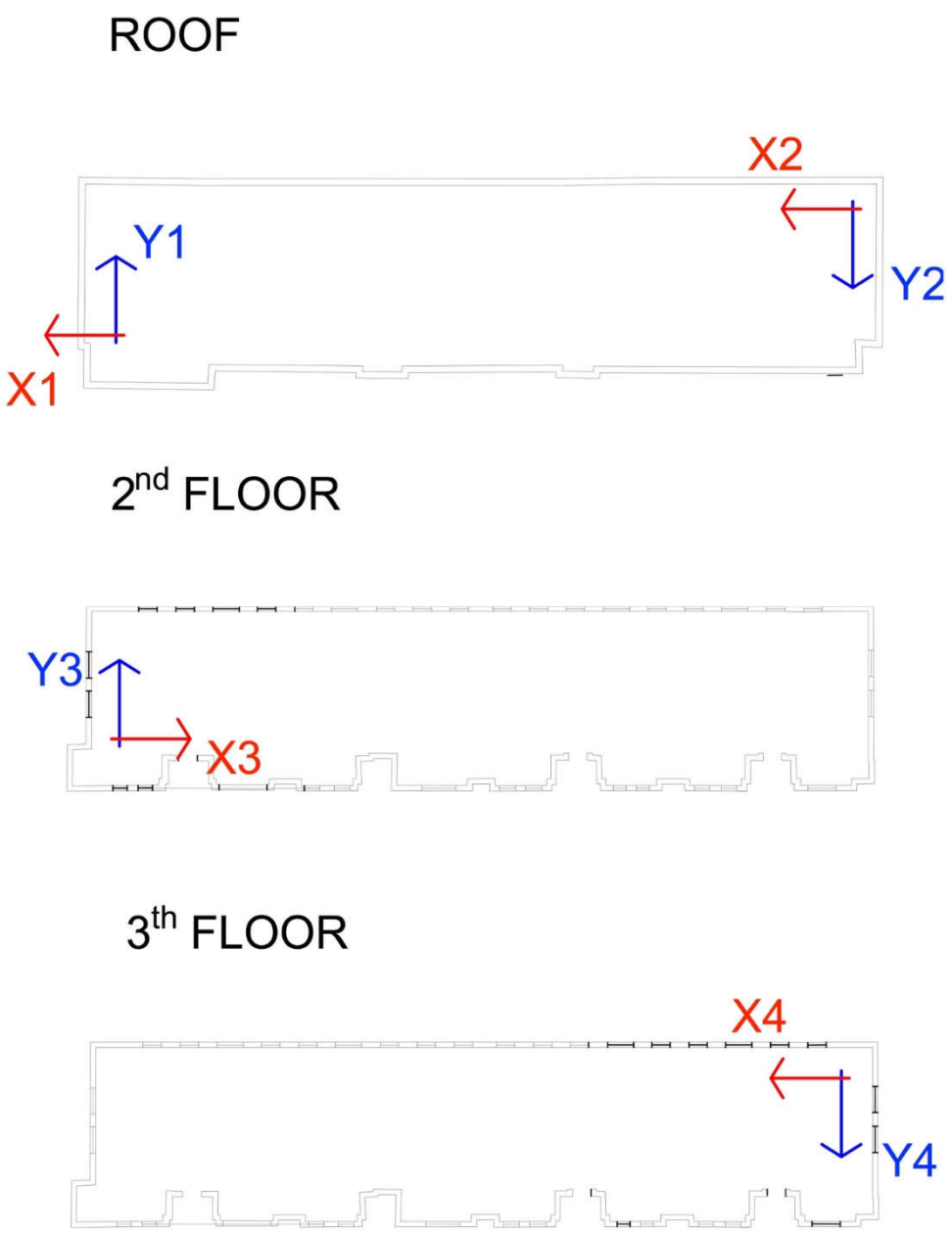
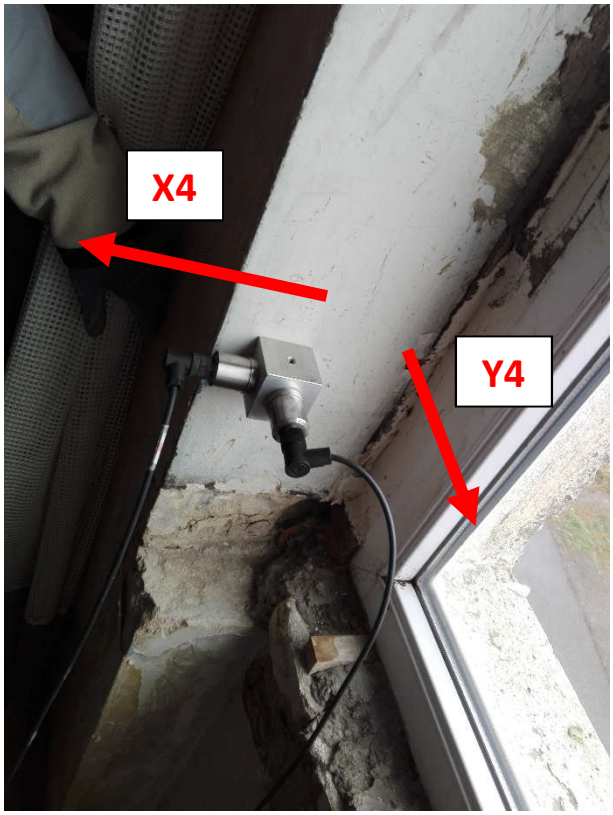
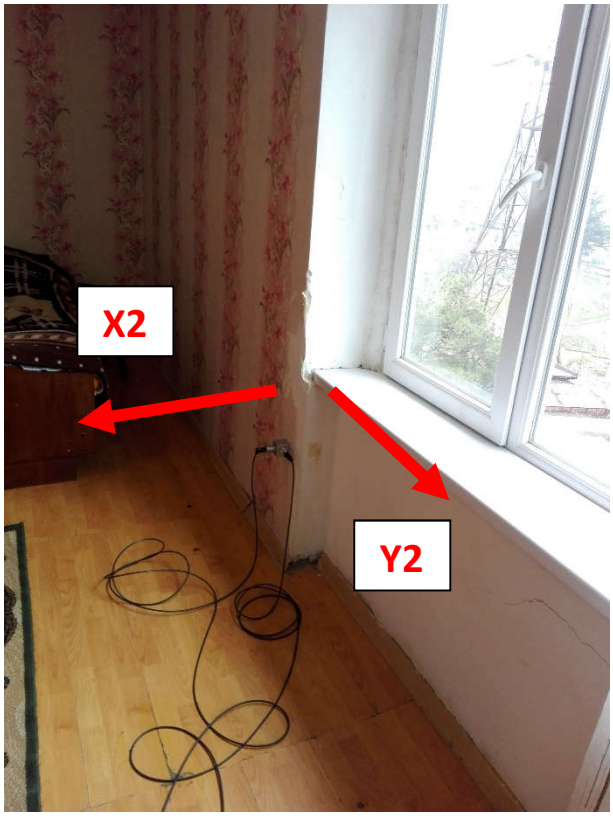
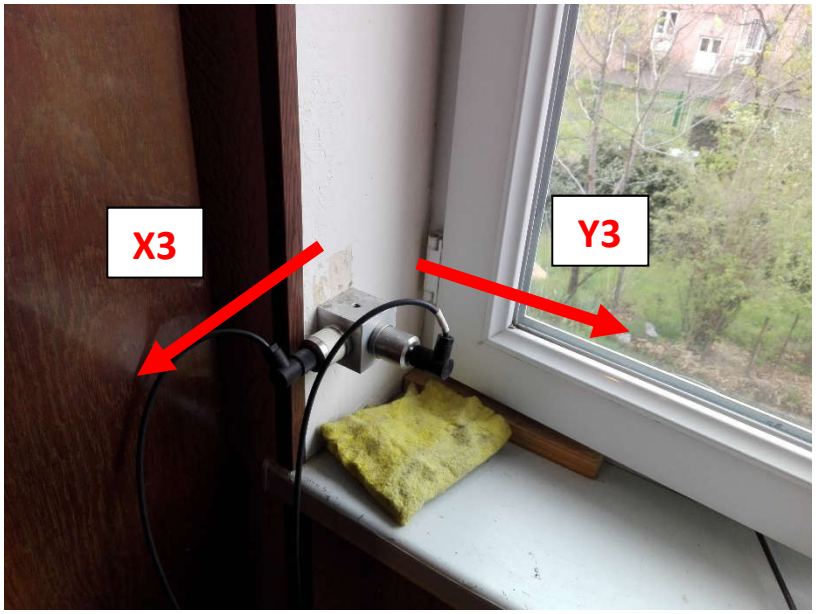


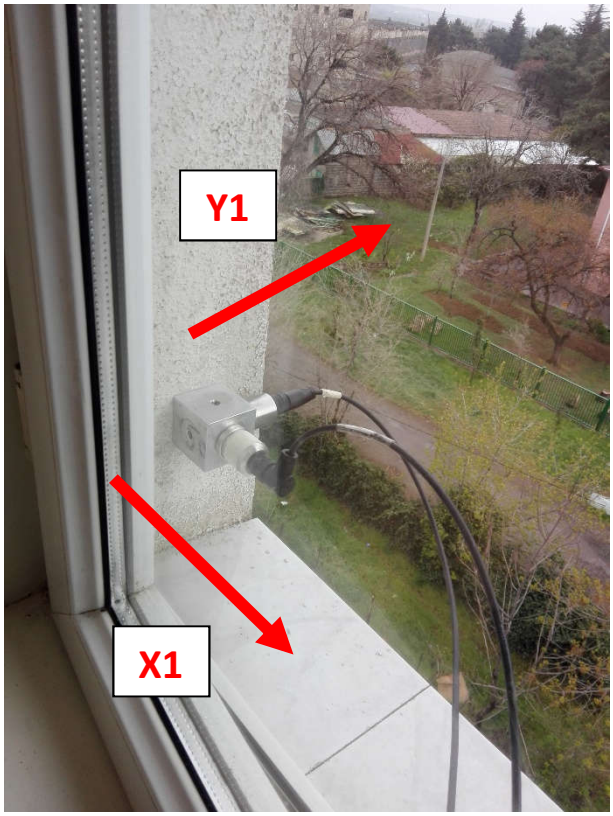
Image 97. Sensors layout



Images 98 and 99. Sensors and data acquisition system


X2
Y2


X3
Y3



Images 100, 101 and 102. sensors

ACQUISITION OF TIME HISTORIES

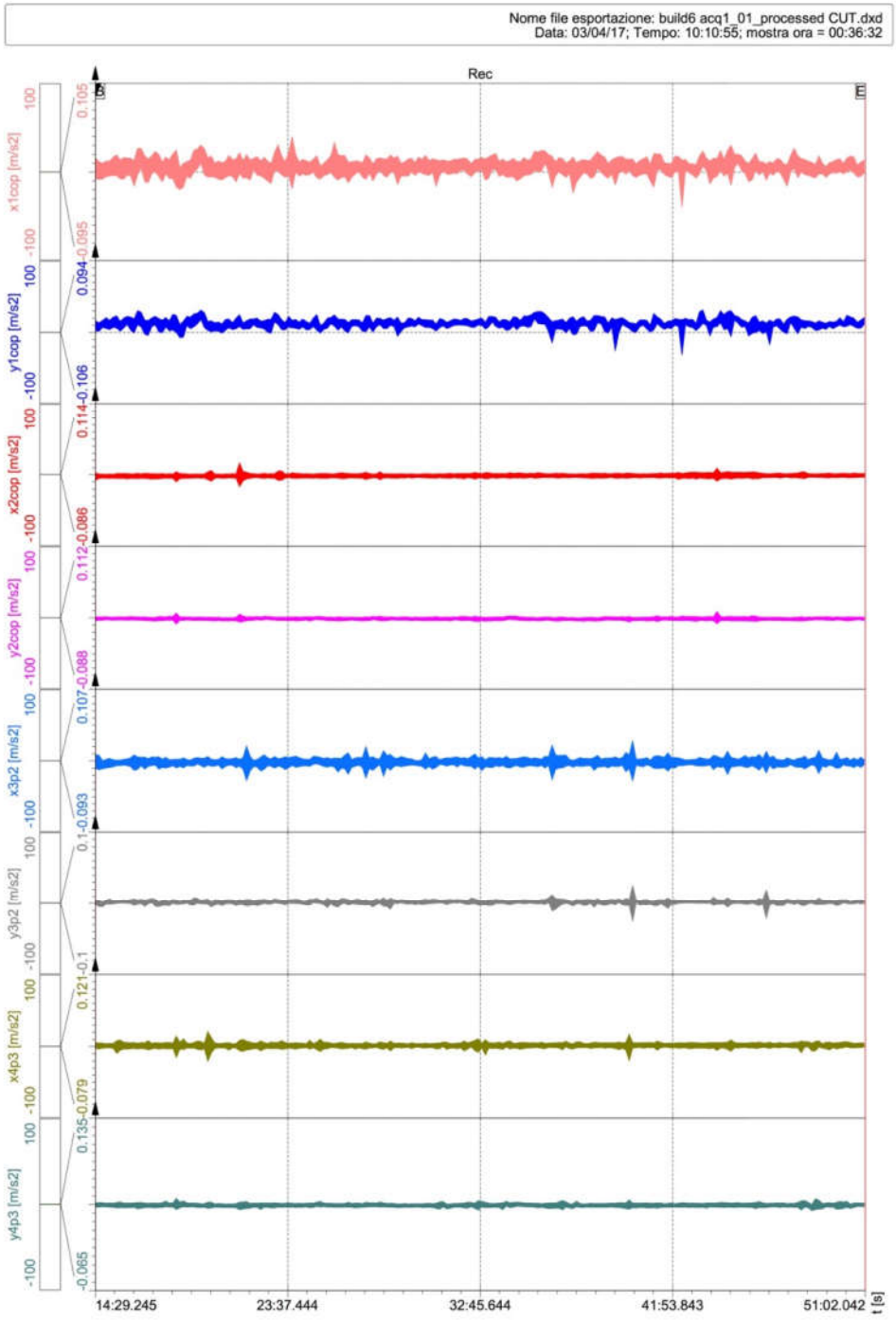


Image 103. Time histories

FREQUENCY CONTENT OF THE SIGNALS

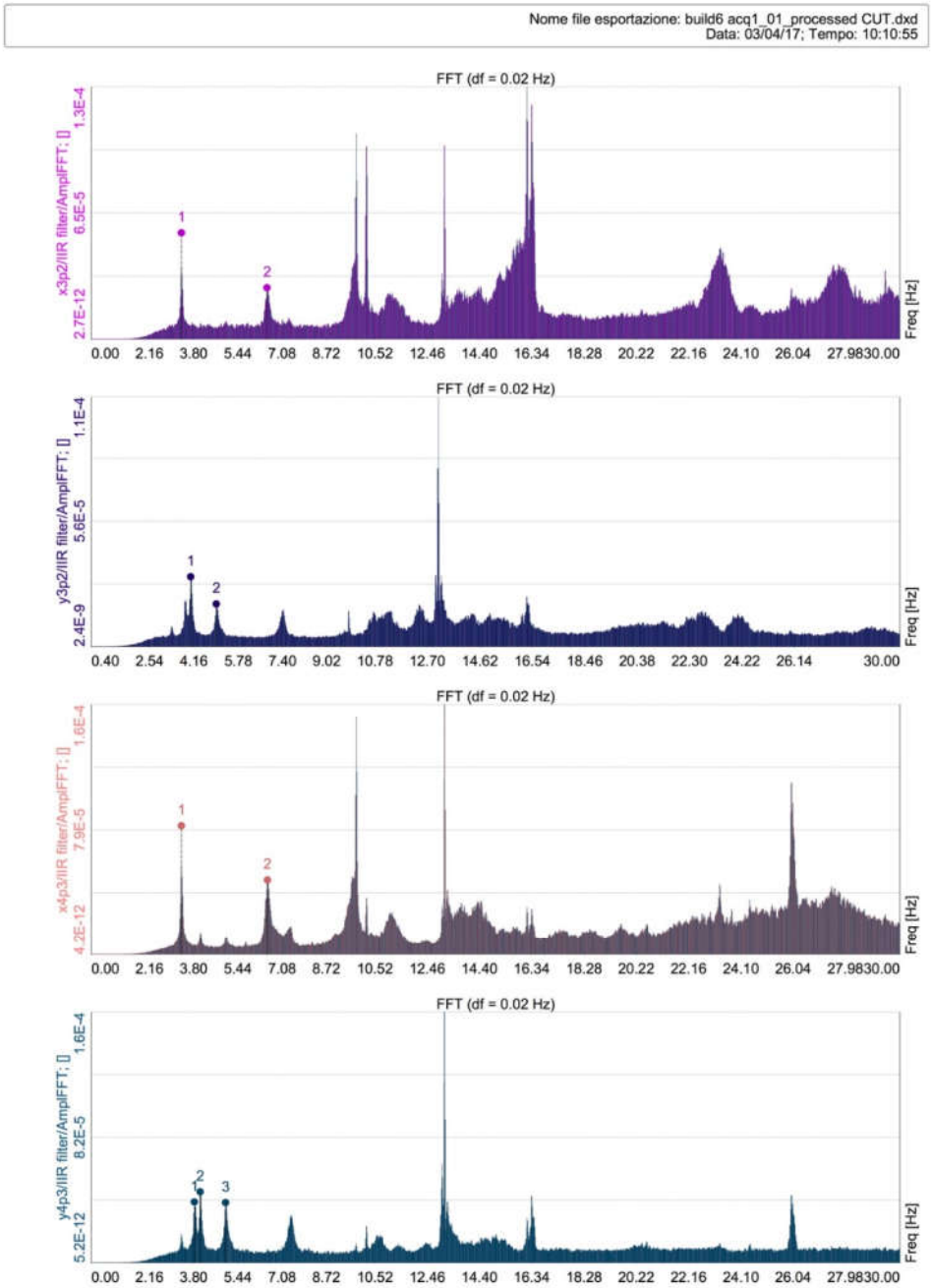


Image 104. Frequency content

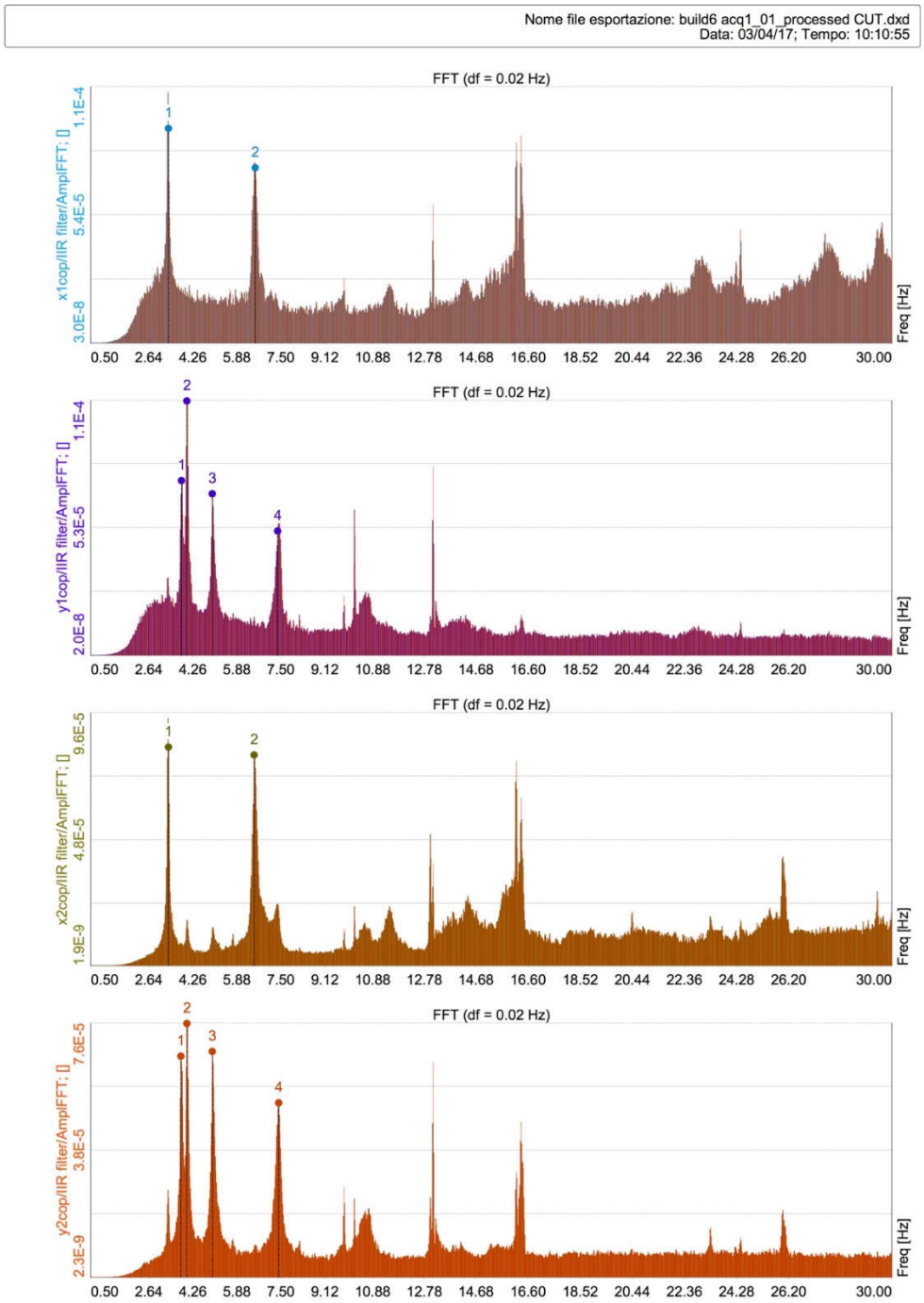
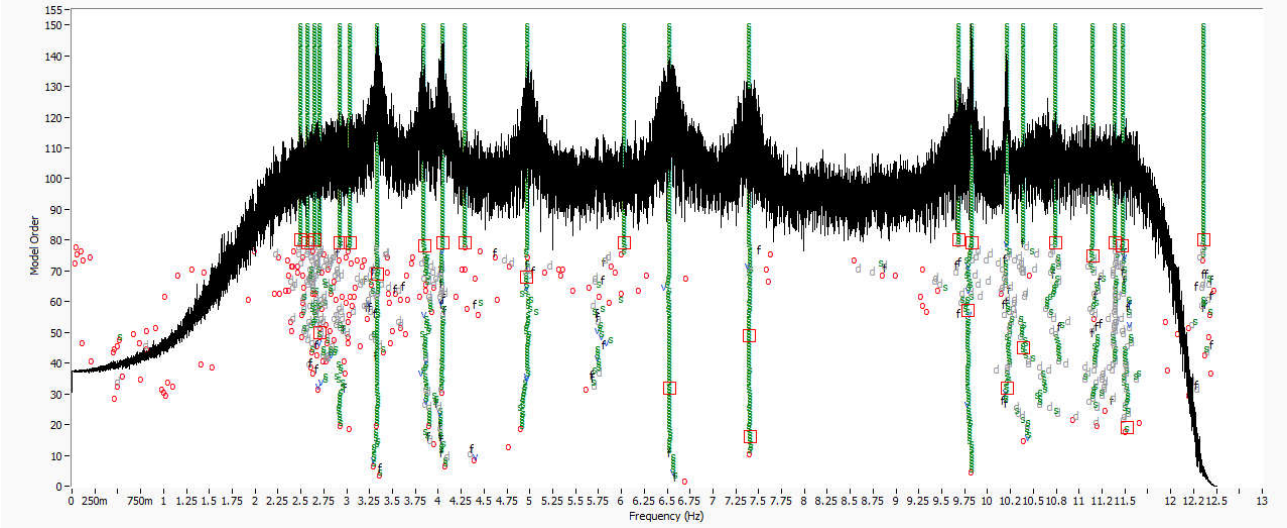


Image 105. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram



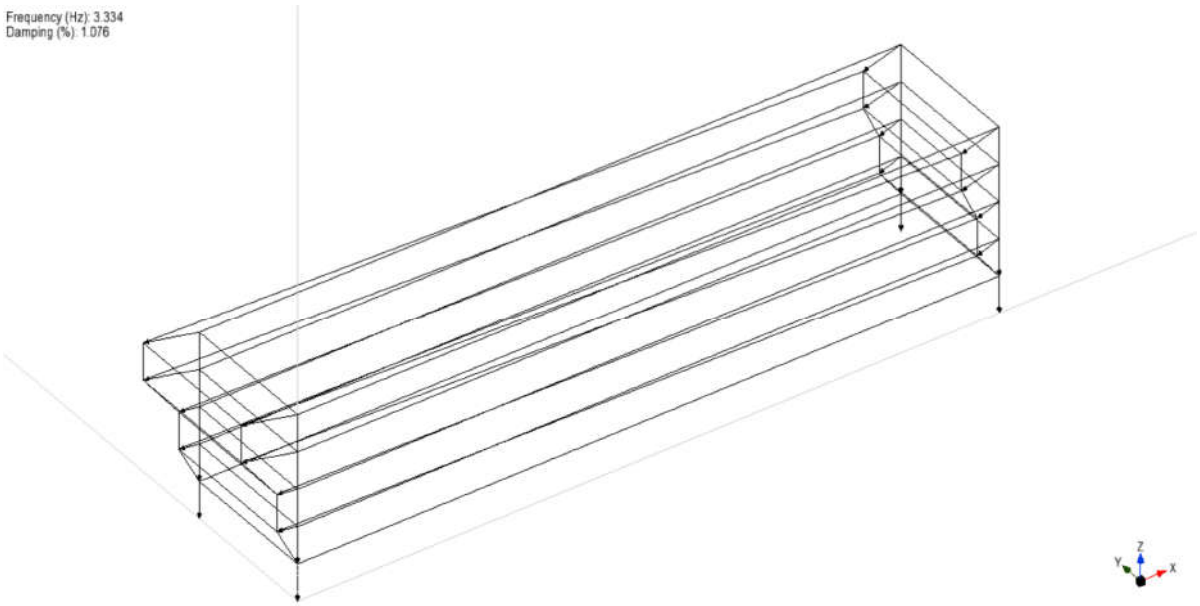
Mode n.	Frequency (Hz)	Damping (%)
1	3.33	1.076
2	3.85	1.894
3	4.05	0.615
4	4.97	1.022

Image 106. Modal identification result

Mode Shapes

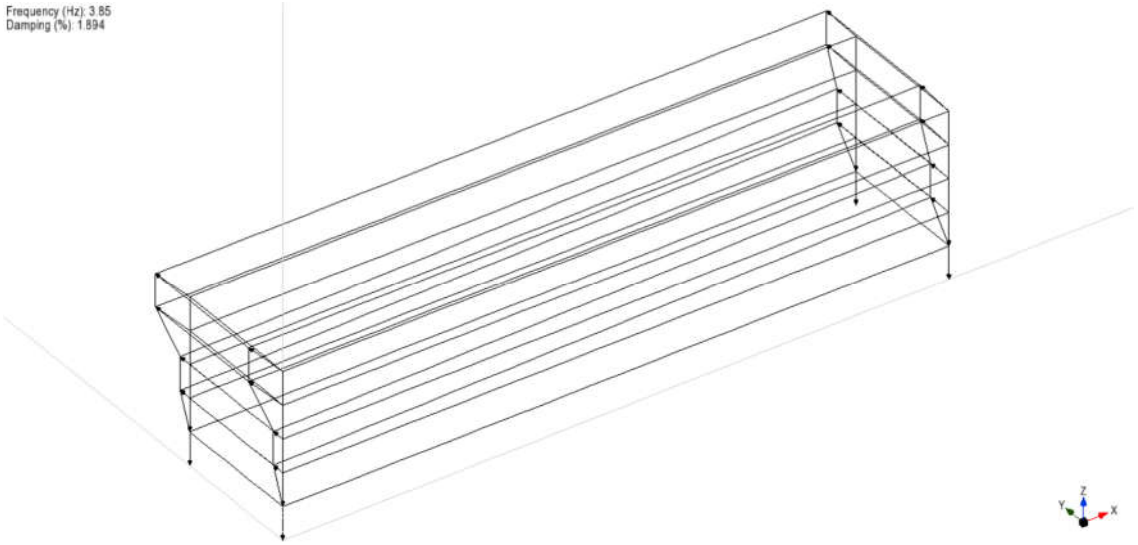
Mode1

3.33Hz – Traslational X



Mode2

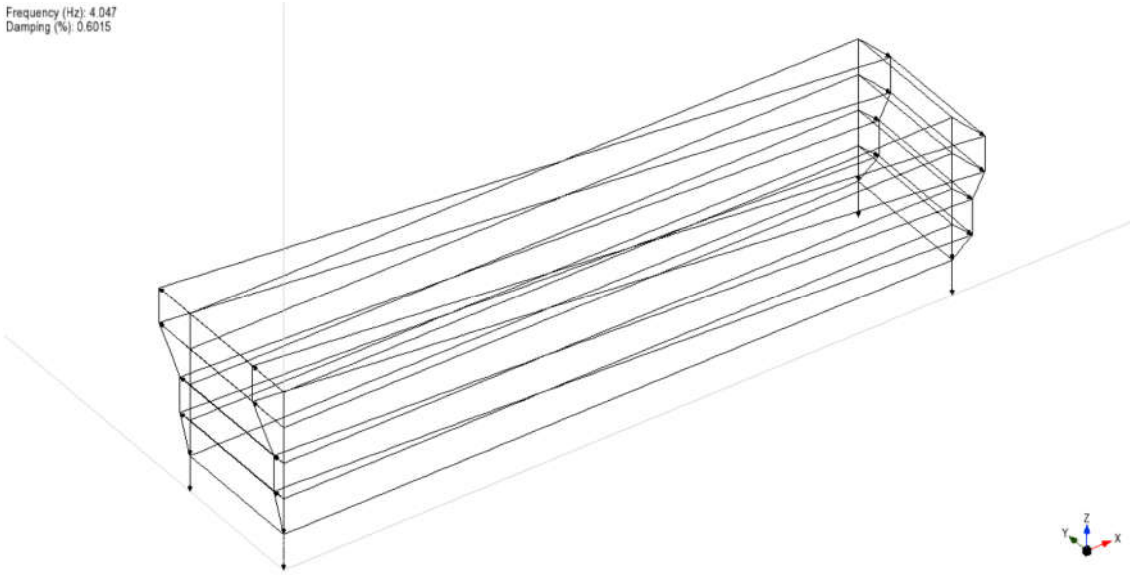
3.85Hz – Traslational Y



Images 107 and 108. Modal shapes

Mode3

4.05Hz - Torsional



Mode4

4.97Hz – Traslational Y

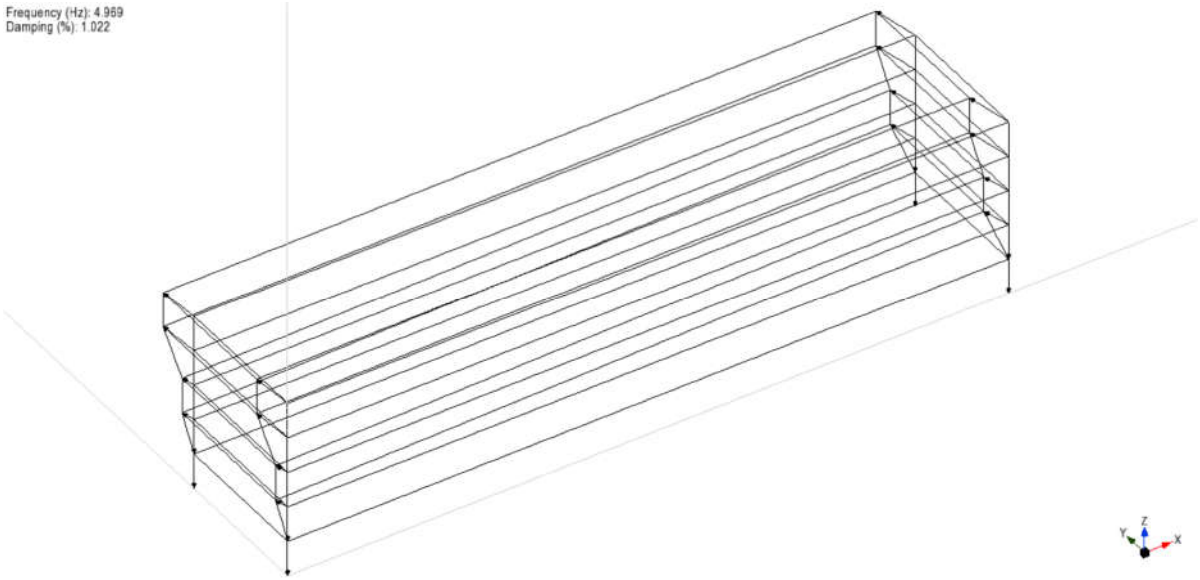
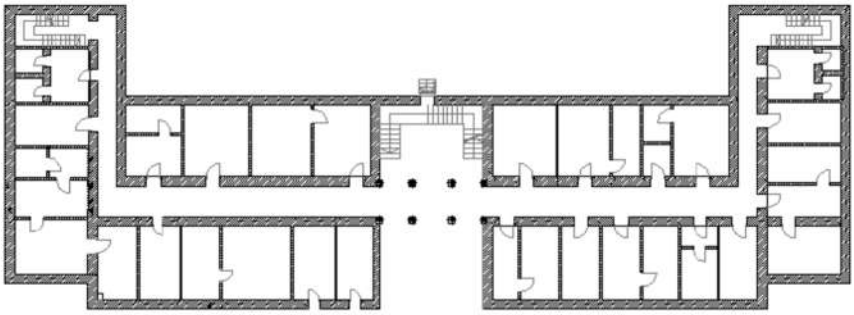


Image 109 and 110. Modal shapes

BUILDING 7



TYPICAL PLAN

Image 111. Building n. 7

SENSORS LAYOUT

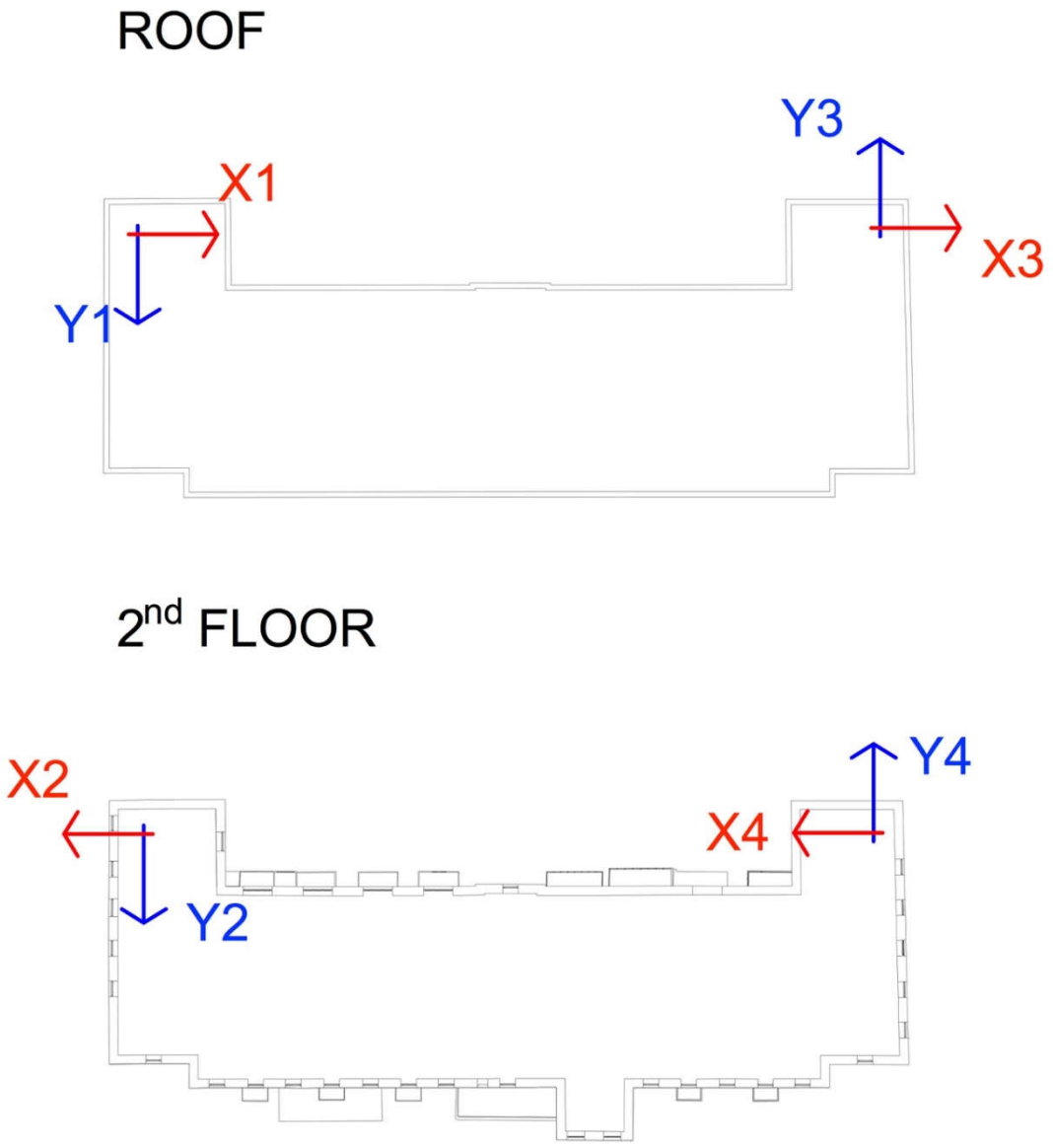
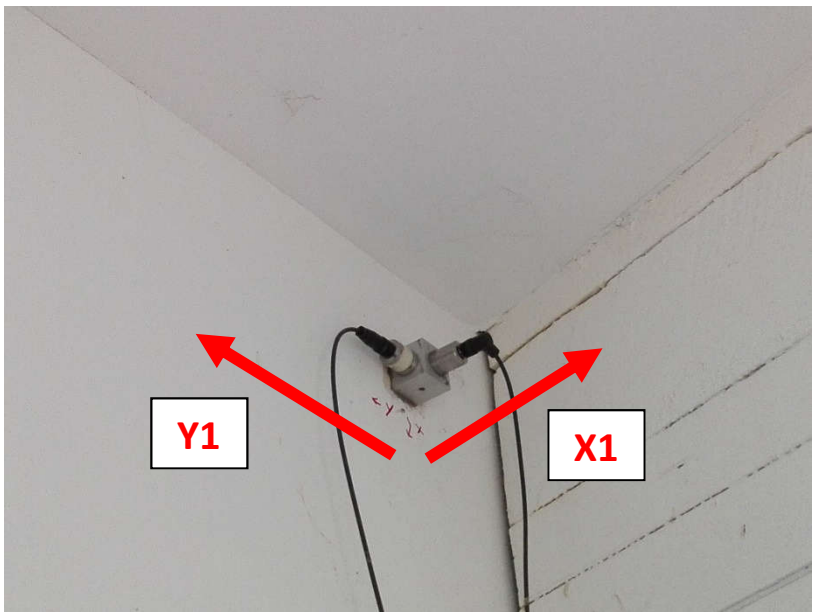
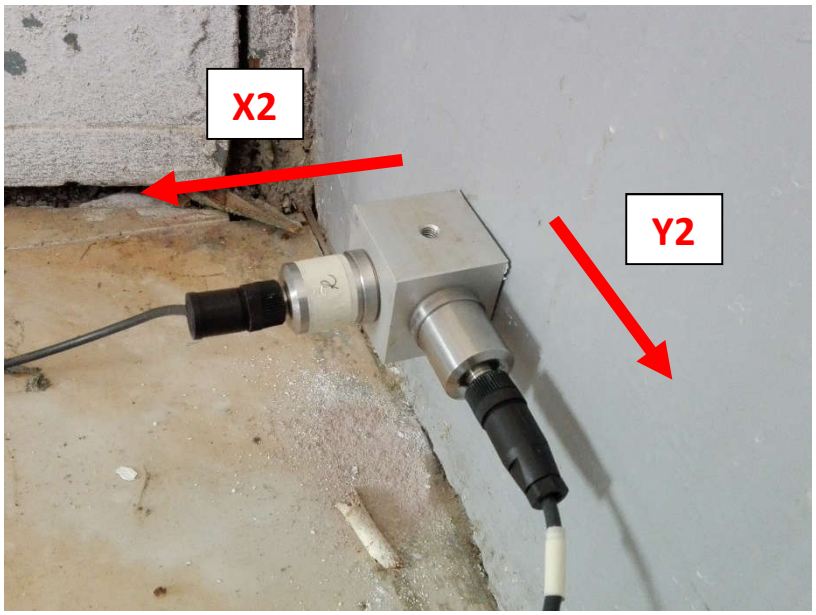
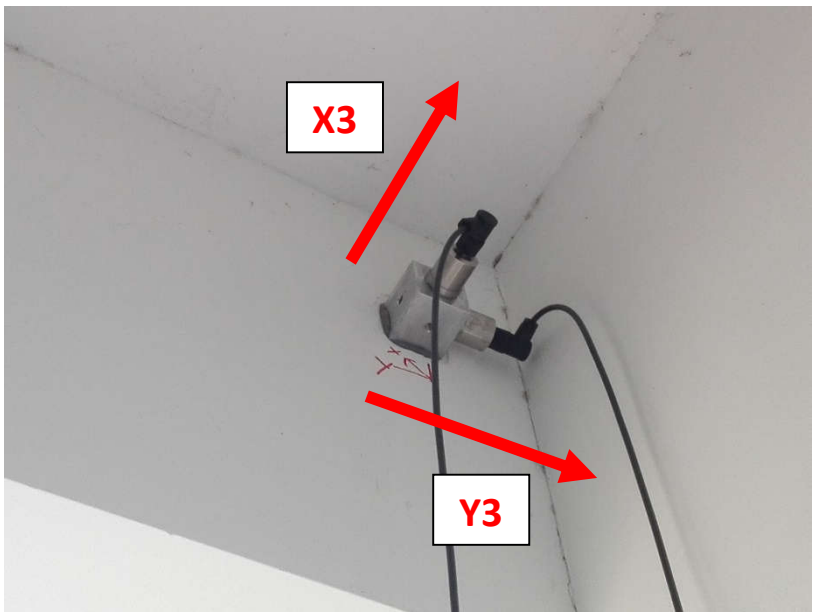


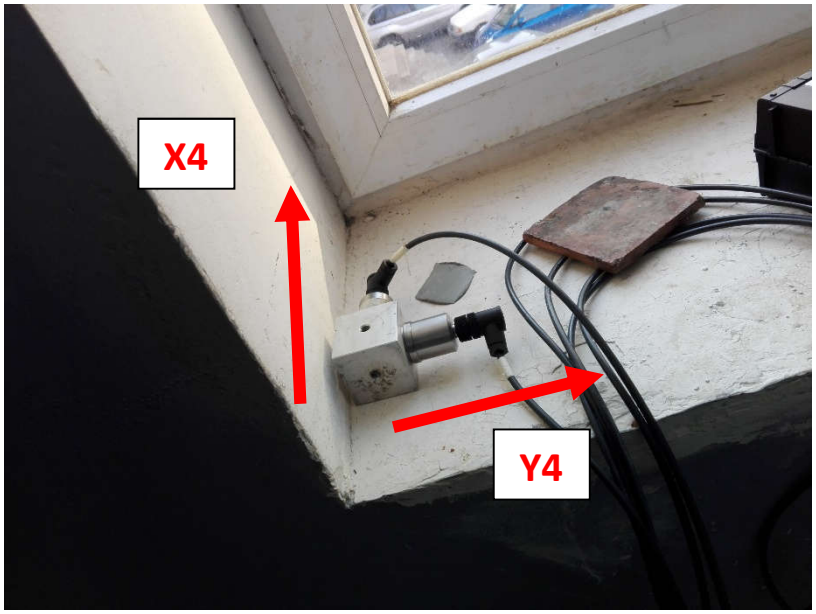
Image 112. Sensor layout



Images 113 and 114. Sensors and data acquisition system


X2
Y2


X3
Y3



Images 115, 116 and 117. sensors

ACQUISITION OF TIME HISTORIES

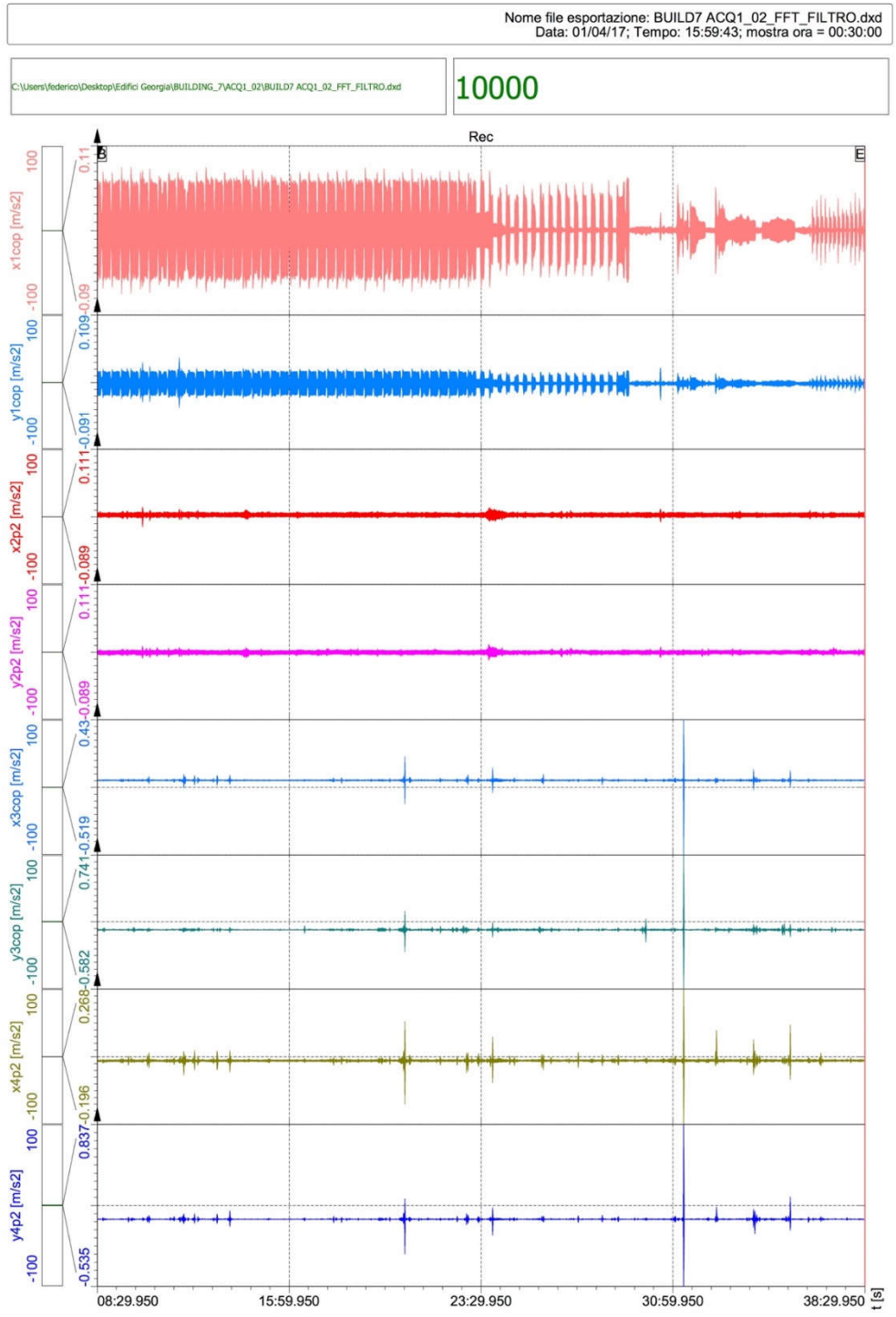


Image 118. Time histories

FREQUENCY CONTENT OF THE SIGNALS

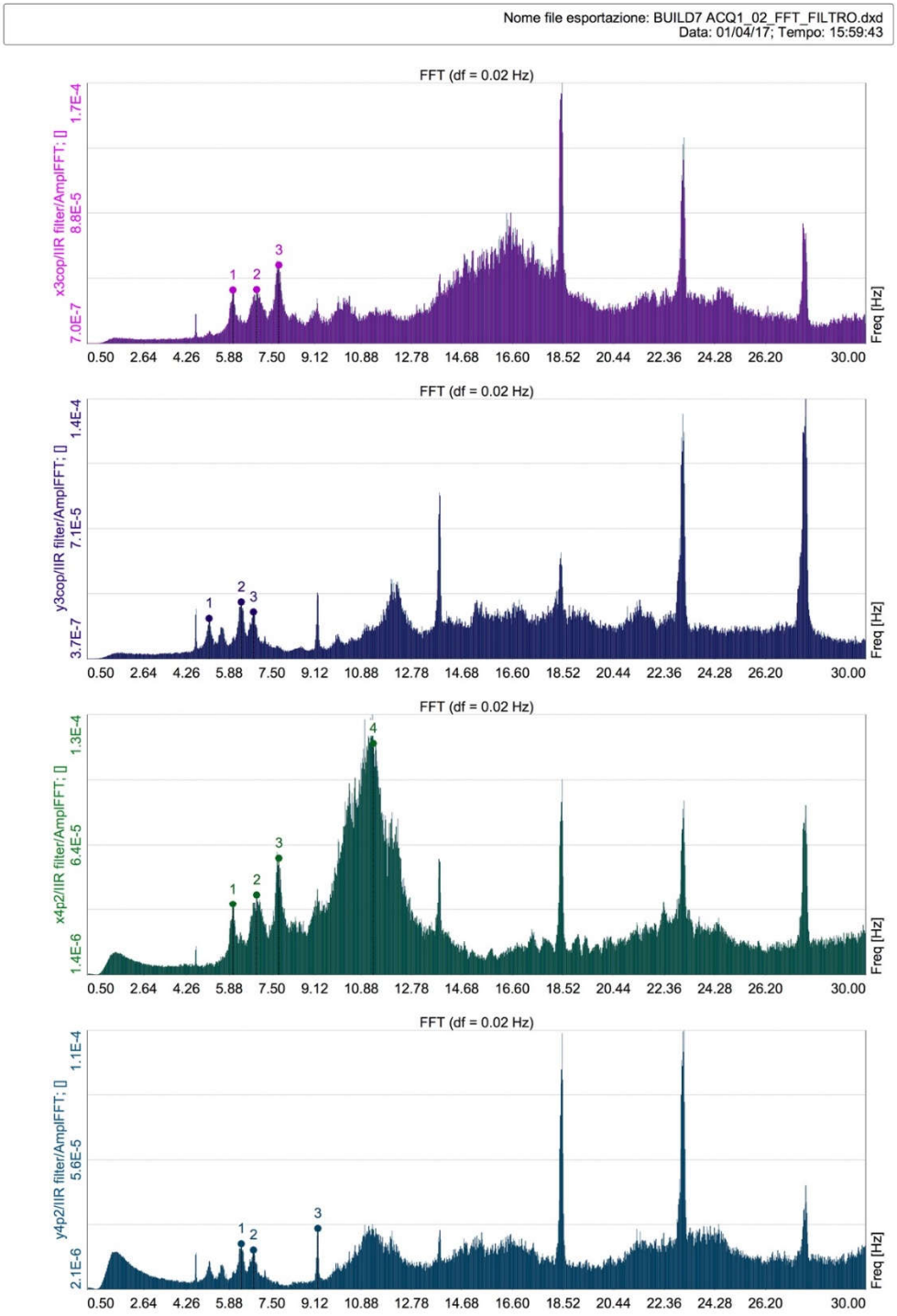


Image 119. Frequency content

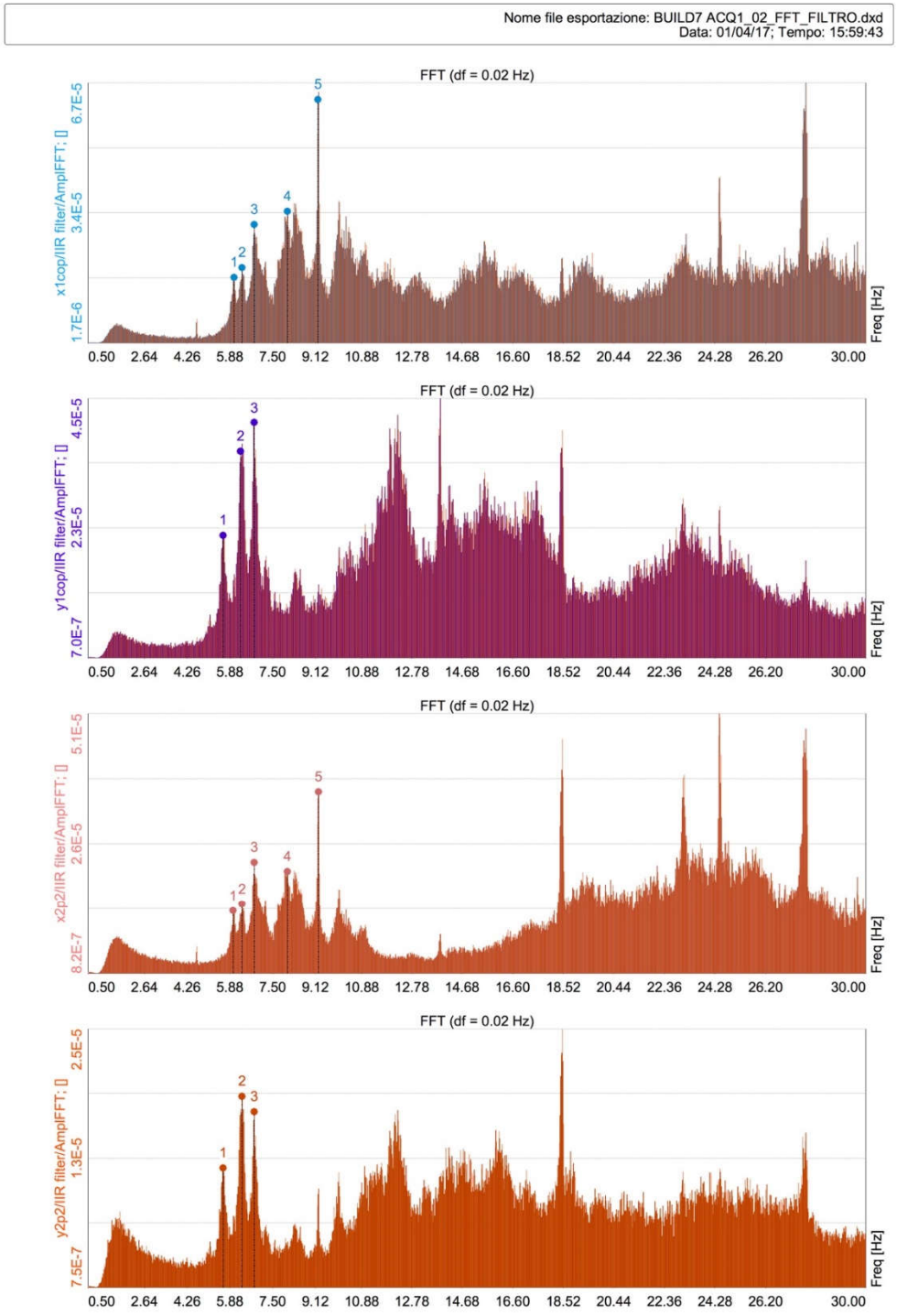
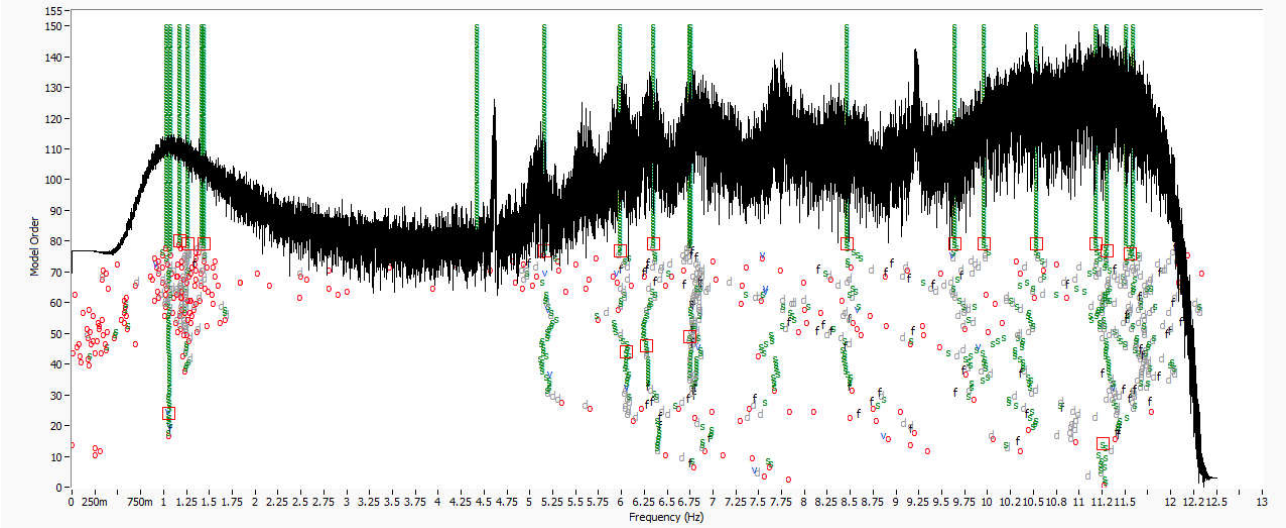


Image 120. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram



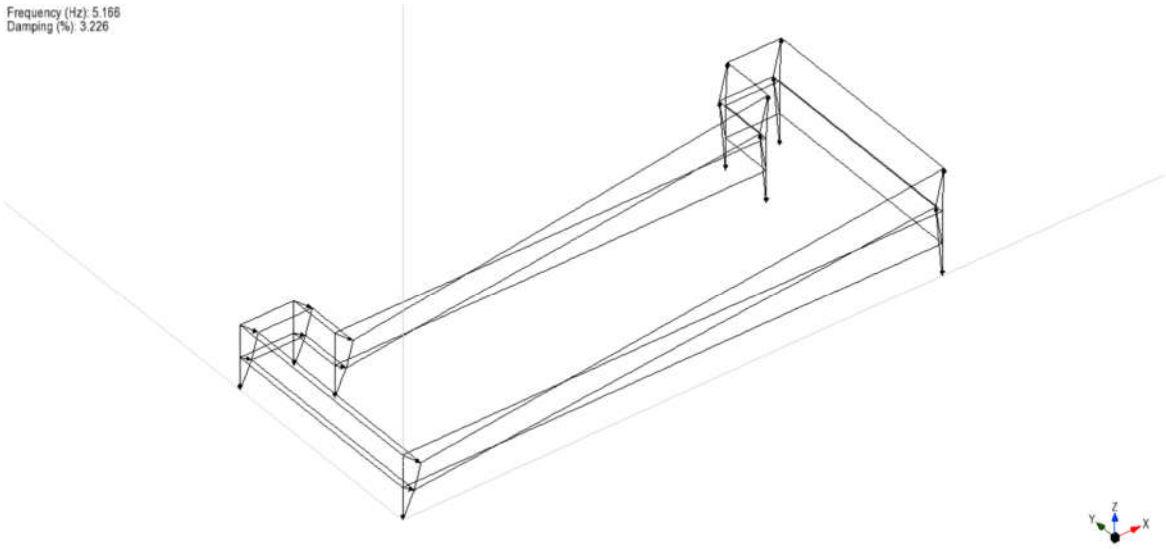
Mode n.	Frequency (Hz)	Damping (%)
1	5.17	3.226
2	6.06	2.223
3	6.35	2.441
4	6.75	1.278

Image 121. Modal identification result

Mode Shapes

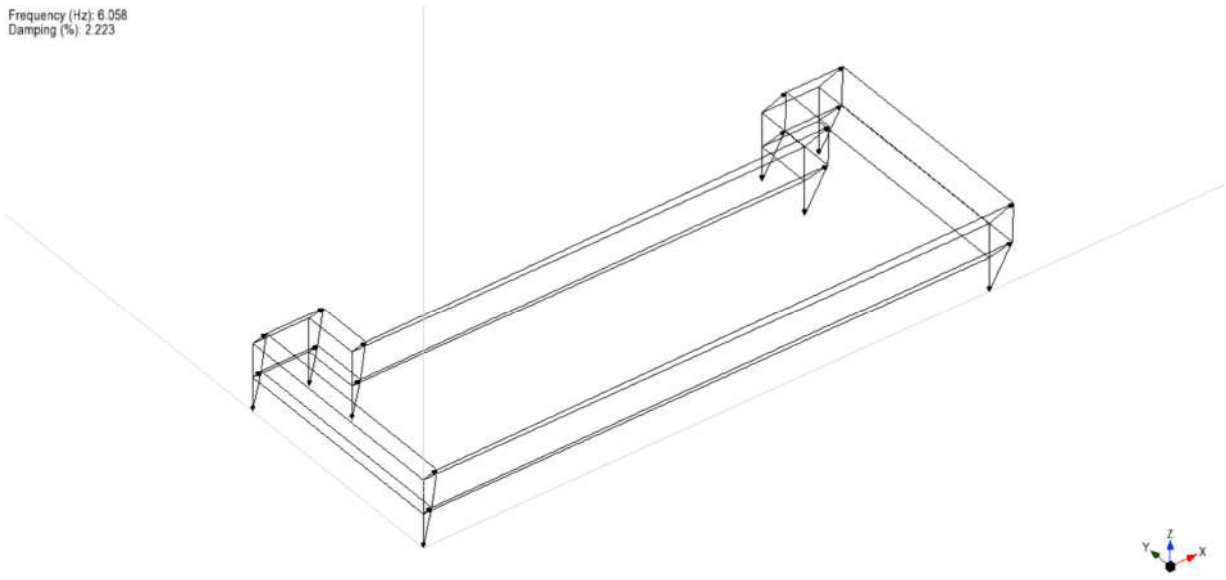
Mode1

5.17Hz - Torsional



Mode2

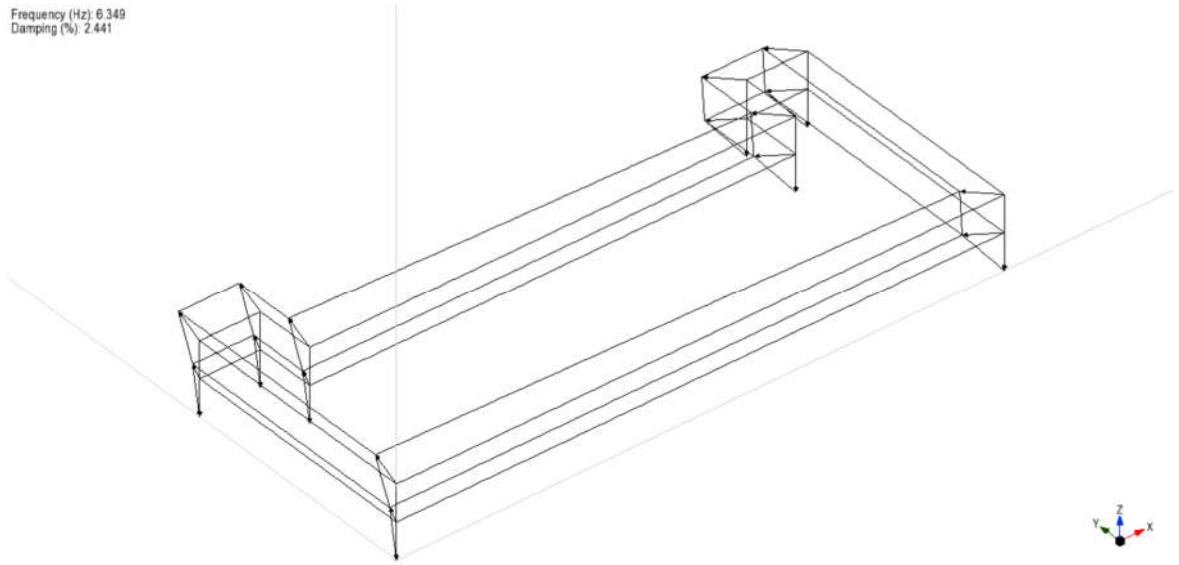
6.06Hz – Traslational X



Images 122 and 123. Modal shapes

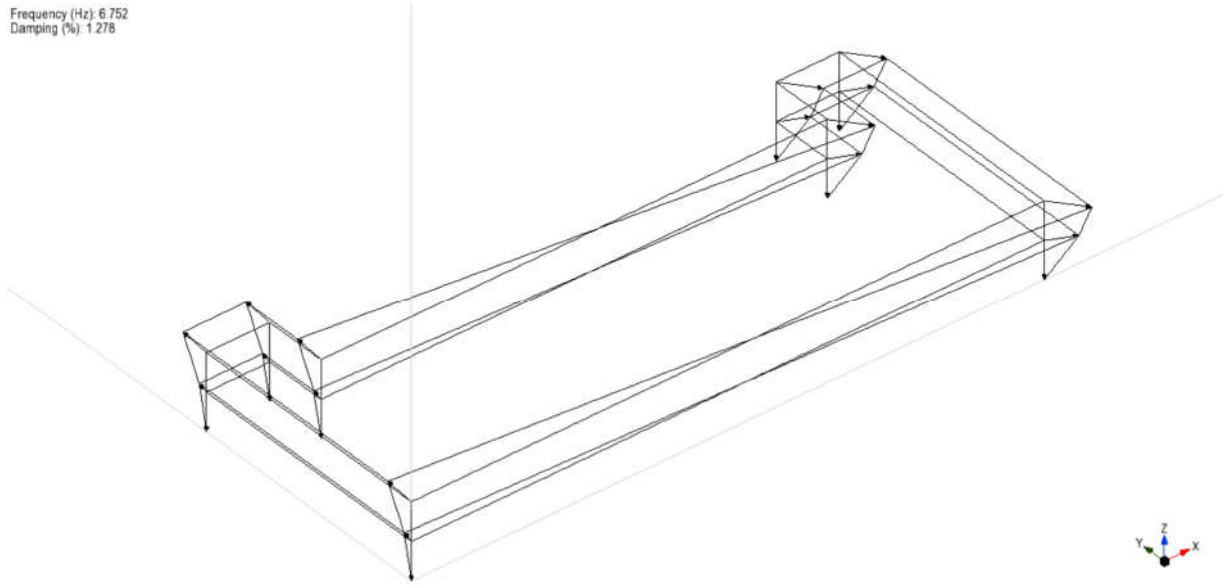
Mode3

6.35Hz – Traslational Y



Mode4

6.75Hz - Torsional



Images 124 and 125. Modal shapes

BUILDING 8

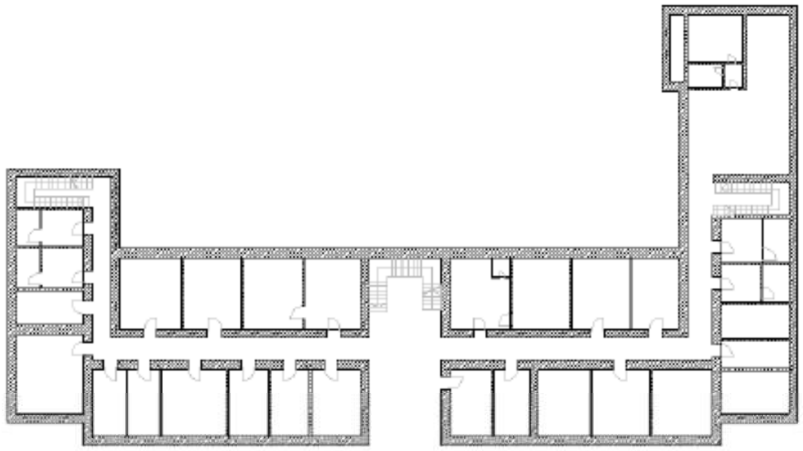
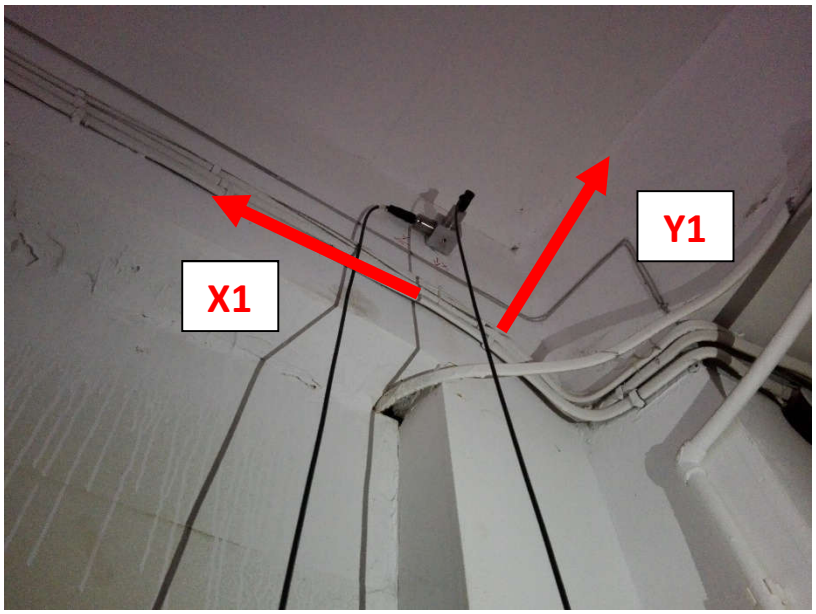


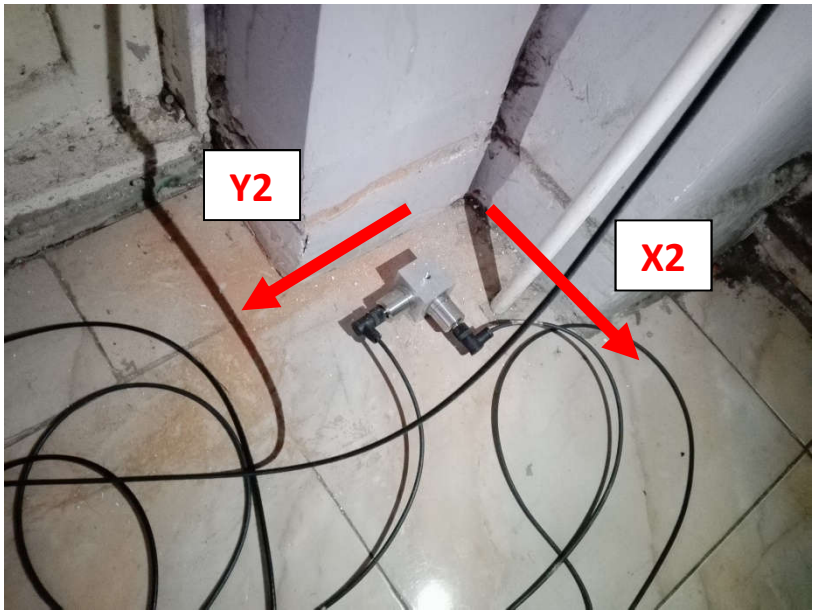
Image 126. Building n.8

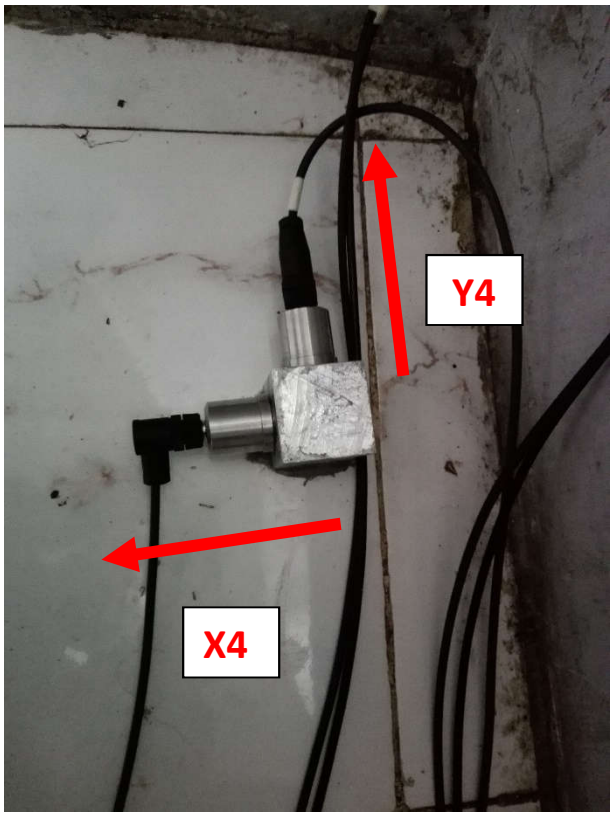
SENSORS LAYOUT

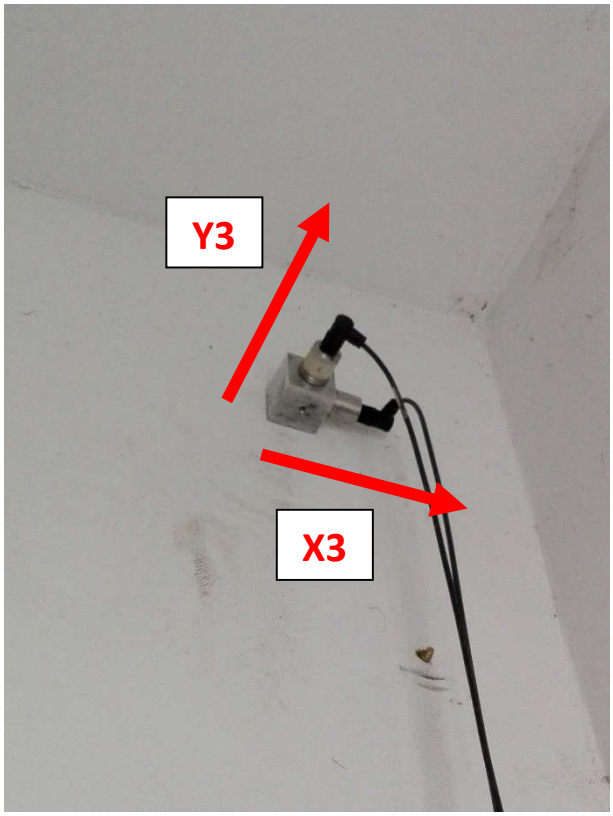
Image 127. Sensor layout



Images 127 and 128. Sensors and data acquisition system


Y2
X2


Y4
X4



Images 129, 130 and 131. sensors

ACQUISITION OF TIME HISTORIES

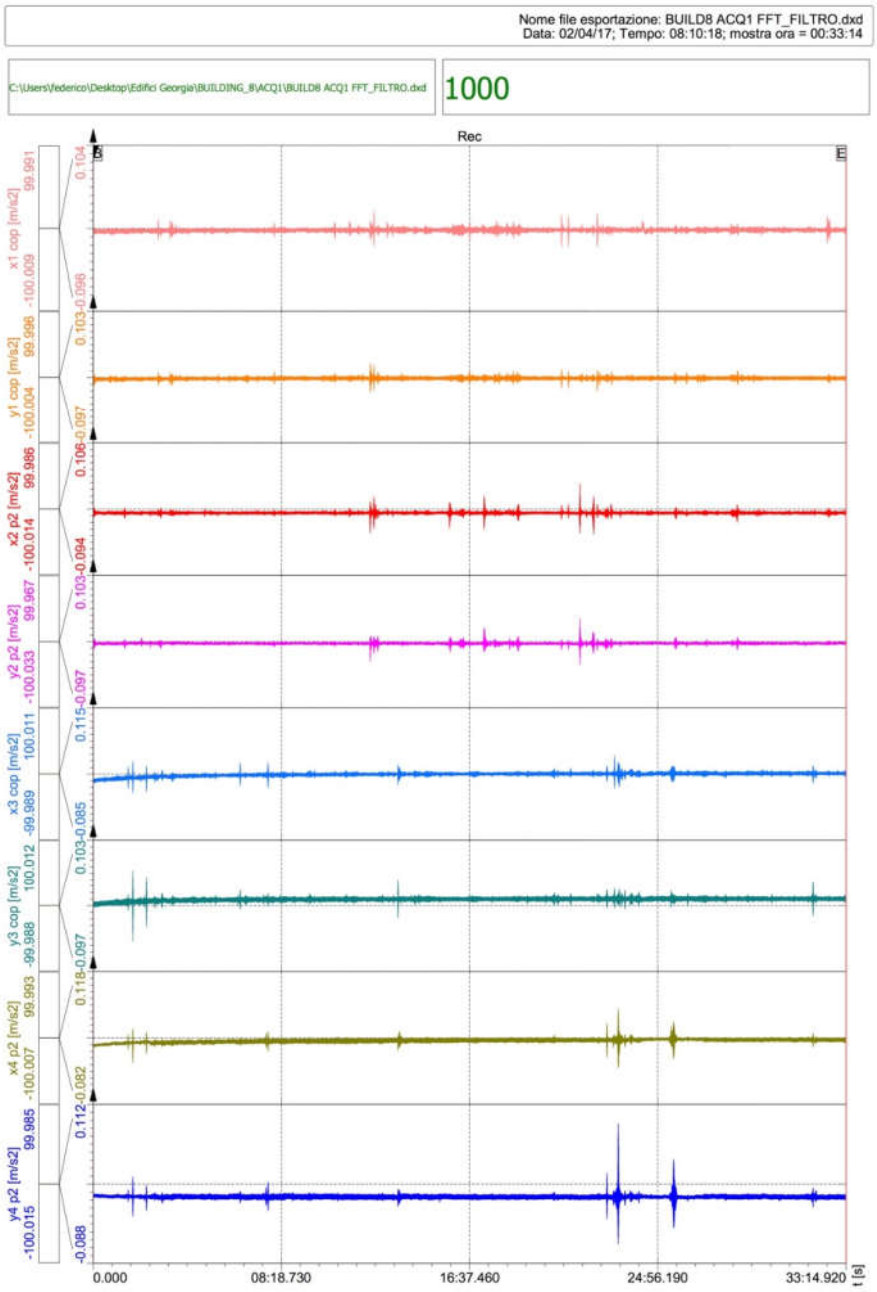


Image 132. Time histories

FREQUENCY CONTENT OF THE SIGNALS

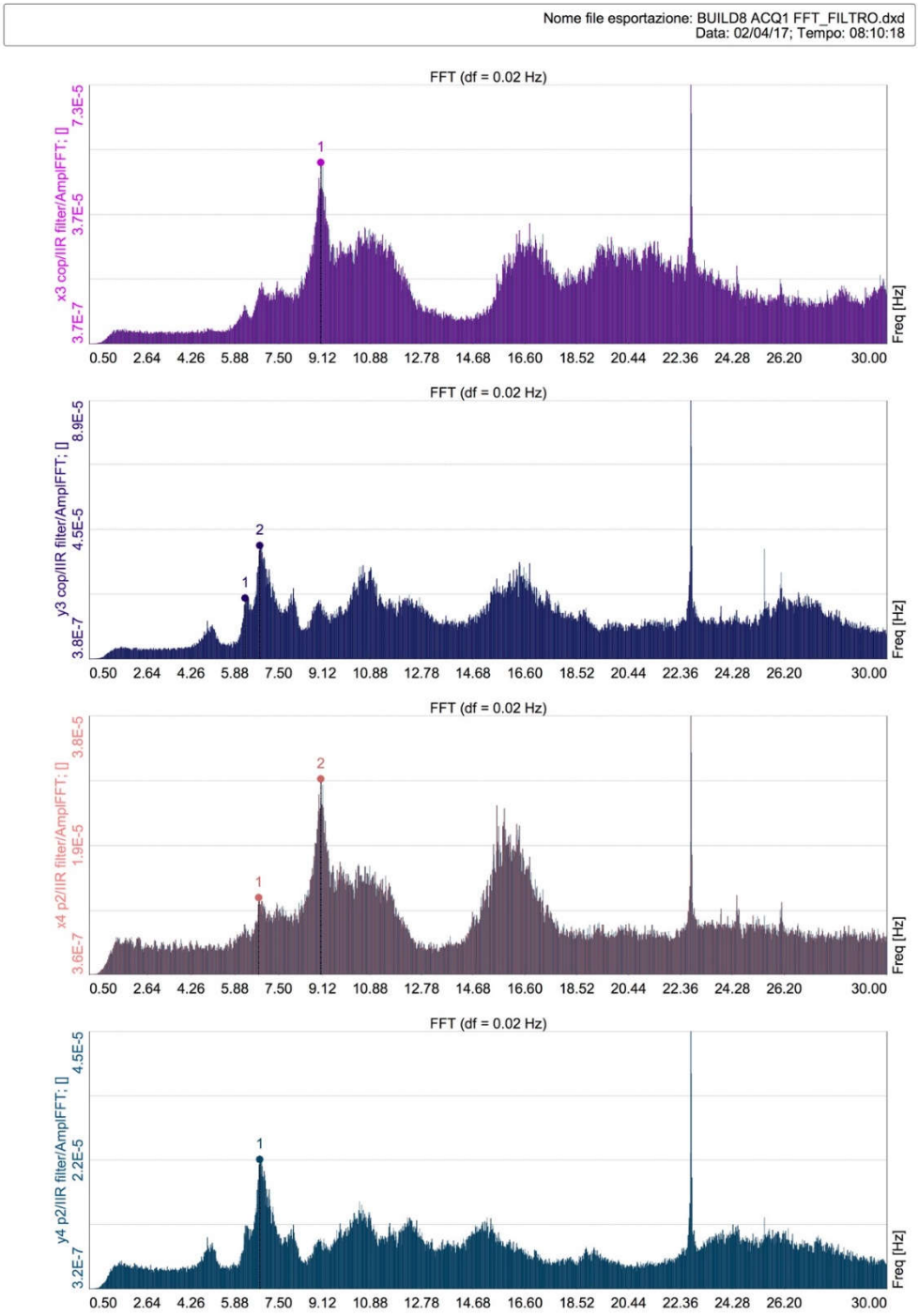


Image 133. Frequency contents

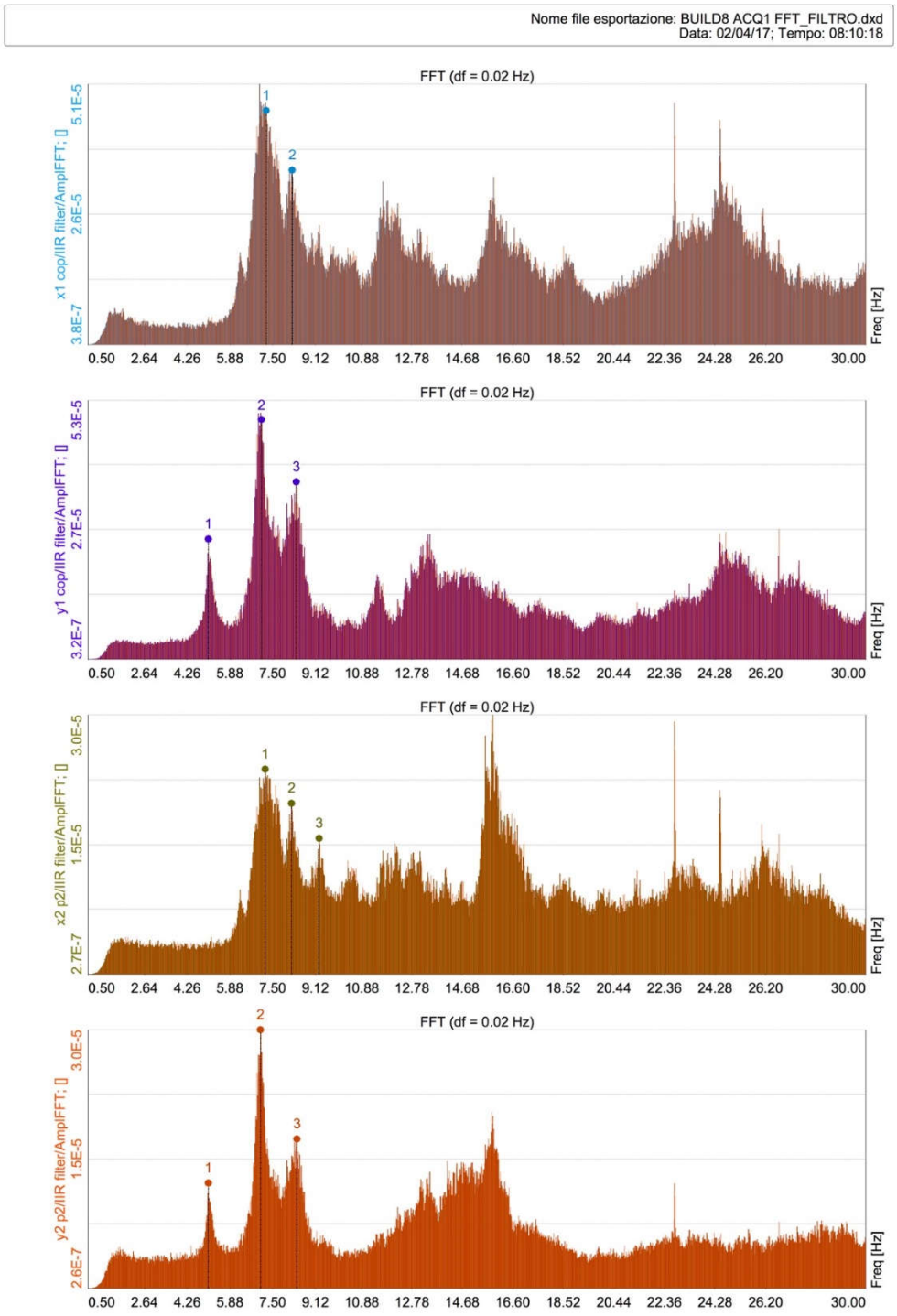
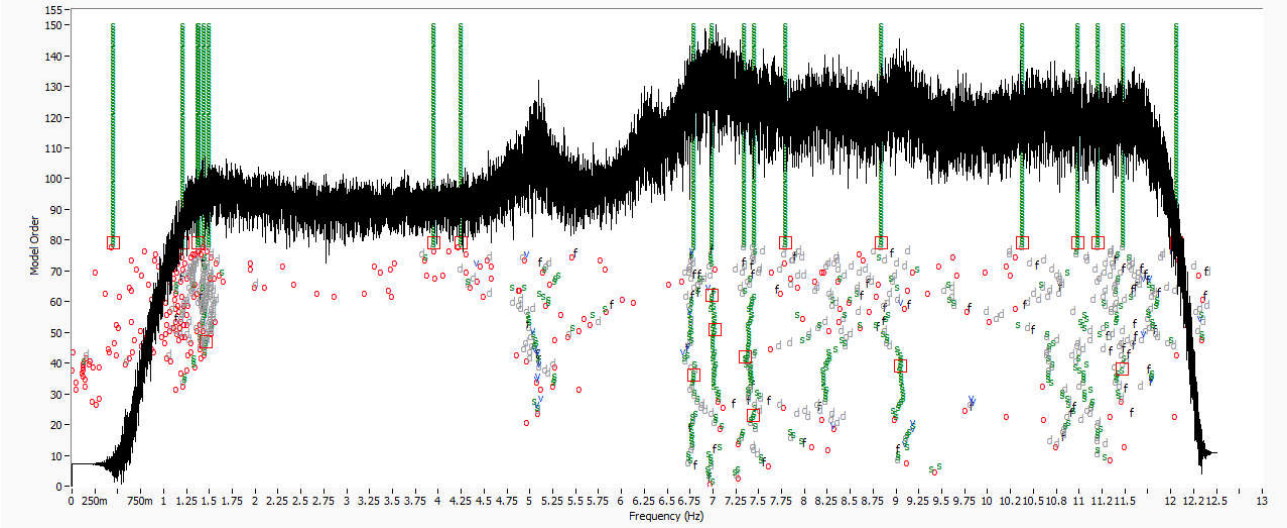


Image 134. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram

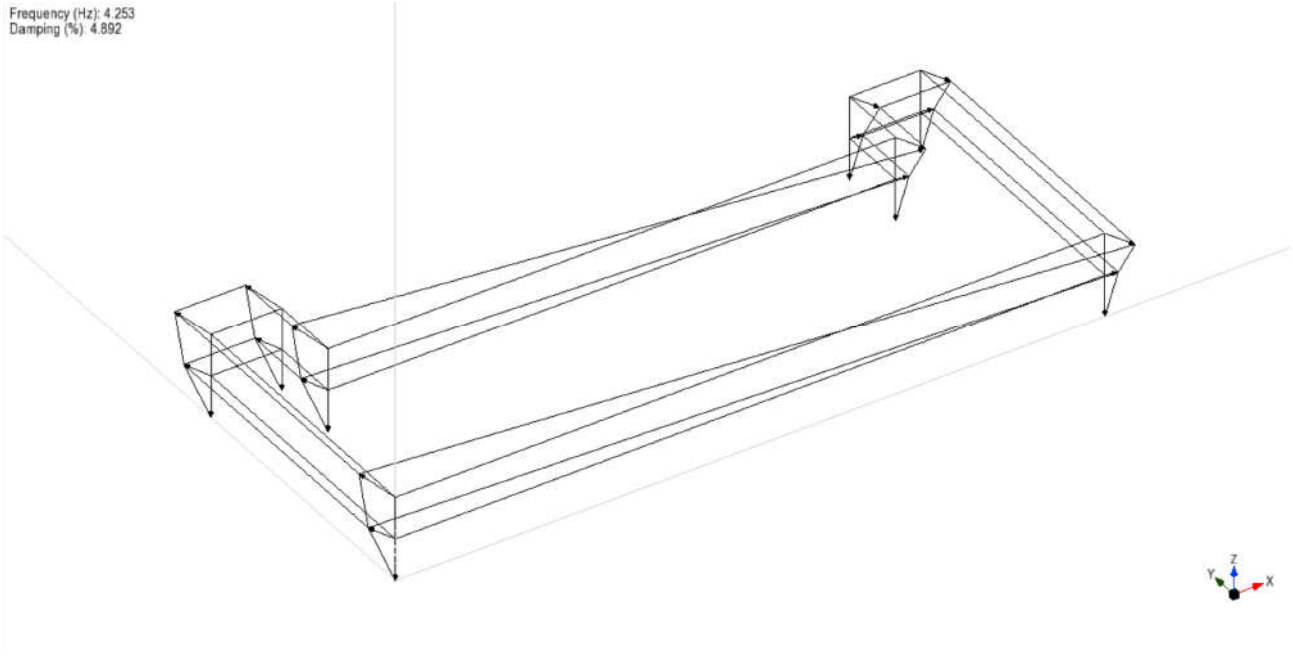


Mode n.	Frequency (Hz)	Damping (%)
1	4.25	4.892
2	6.79	2.886
3	6.99	3.066
4	8.84	2.376

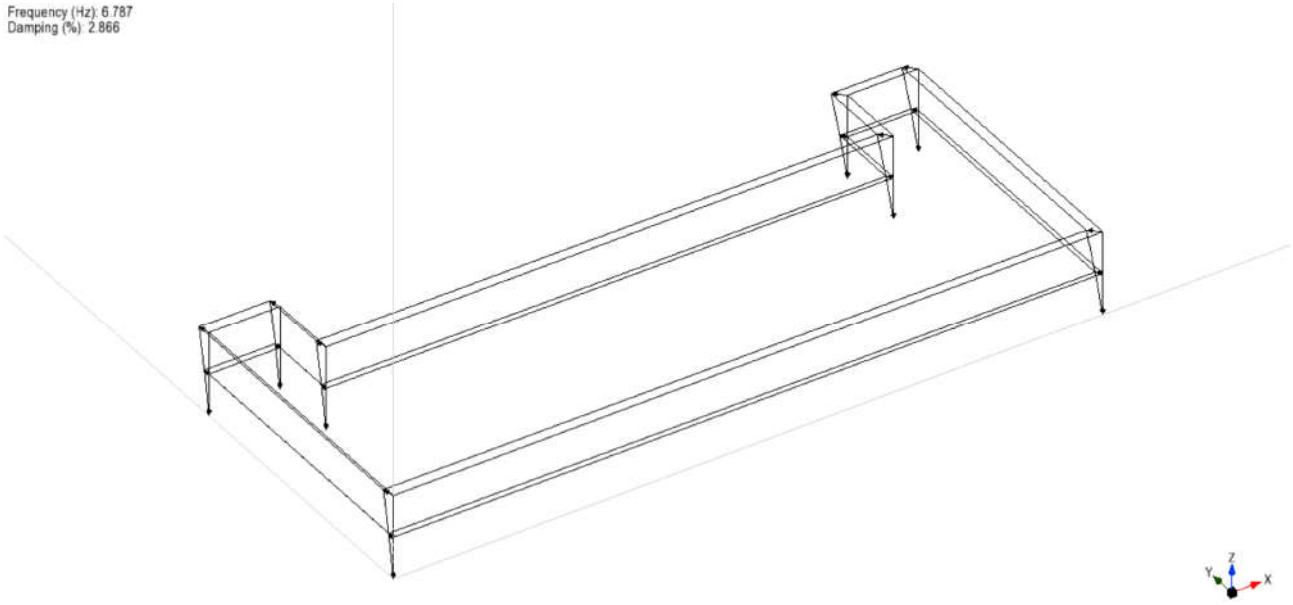
Image 135. Modal identification result

Mode Shapes

Mode1
4.25Hz - Torsional

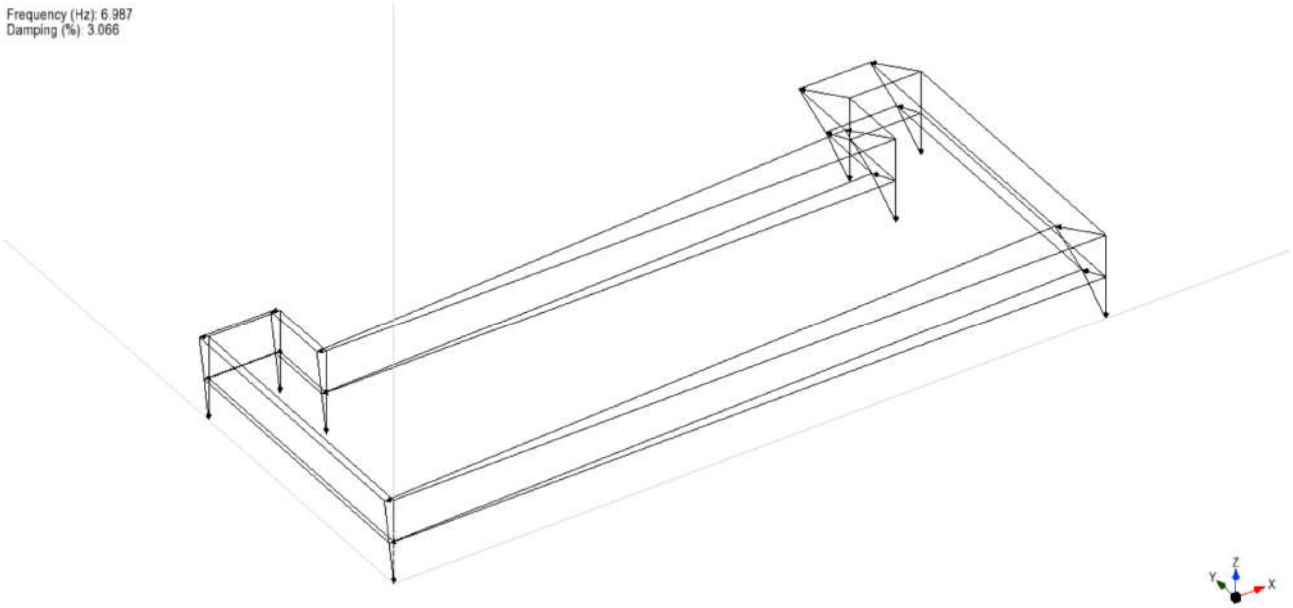


Mode2
6.79Hz – Traslational Y

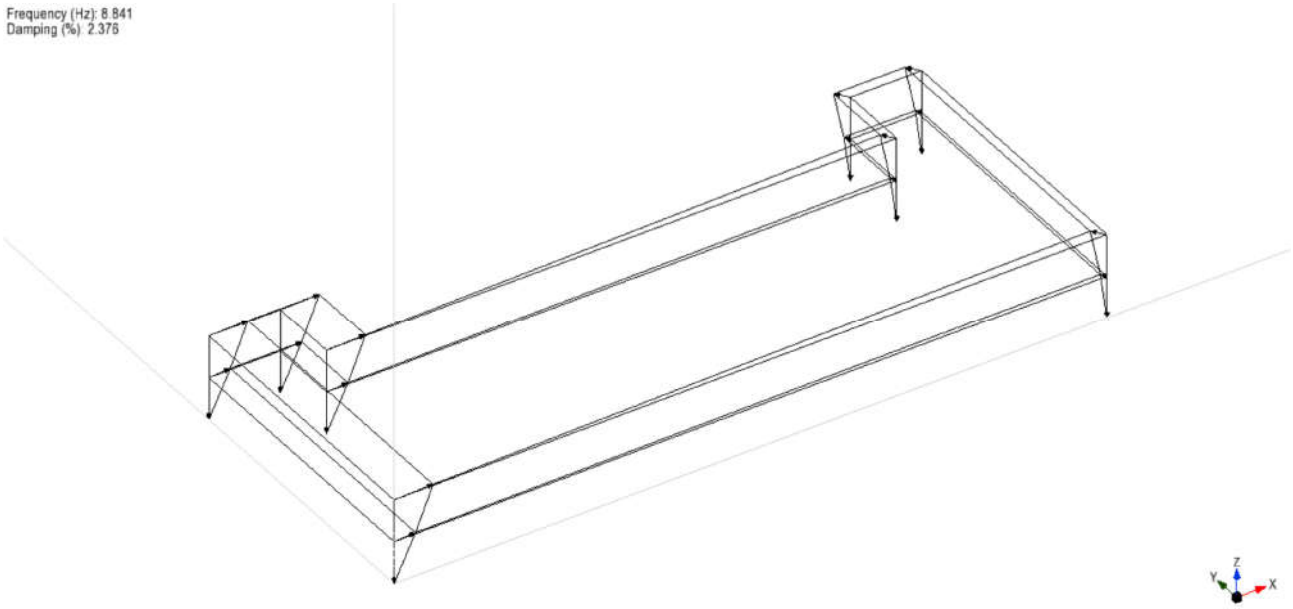


Images 136 and 137. Modal shapes

Mode3
6.99Hz – Traslational X



Mode4
8.84Hz - Torsional



Images 138 and 139. Modal shapes

BUILDING 9

Building 9 includes by two different blocks, separated by a seismic joint. Each block is disconnetted, so three different monitoring were necessary.

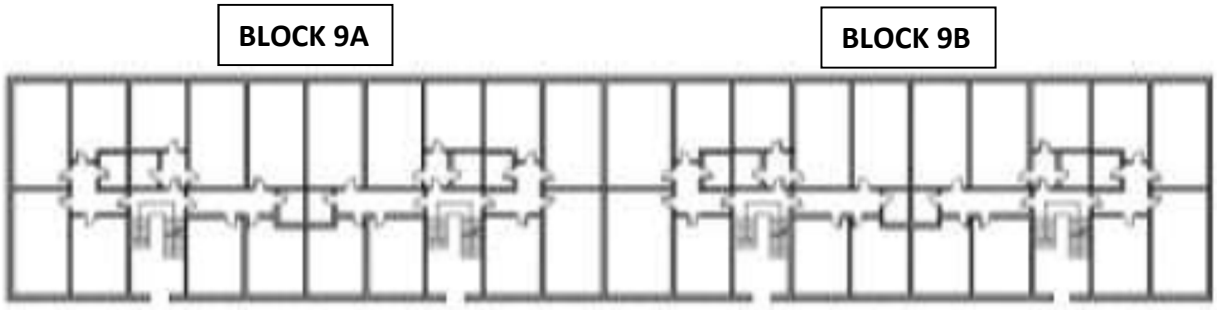
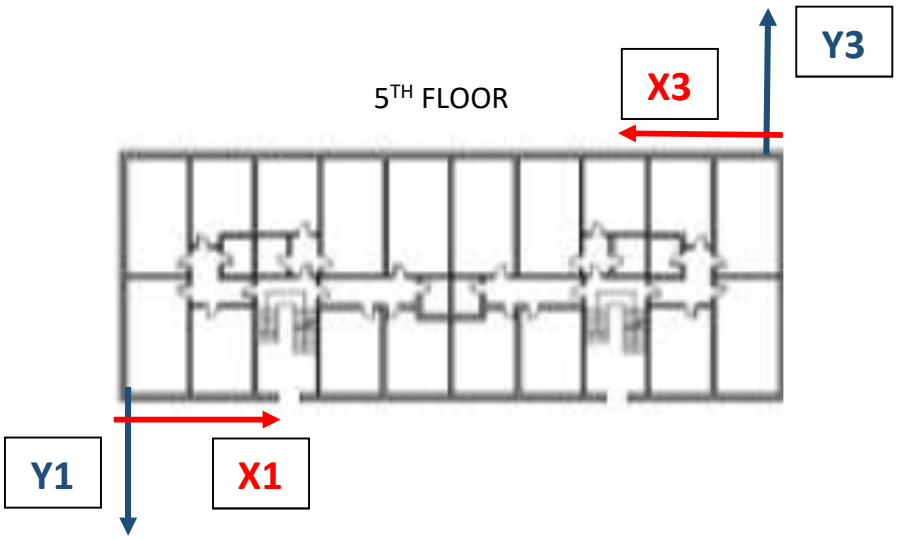


Image 140. Building n.9

BUILDING 9A

SENSORS LAYOUT

5TH FLOOR



4th FLOOR

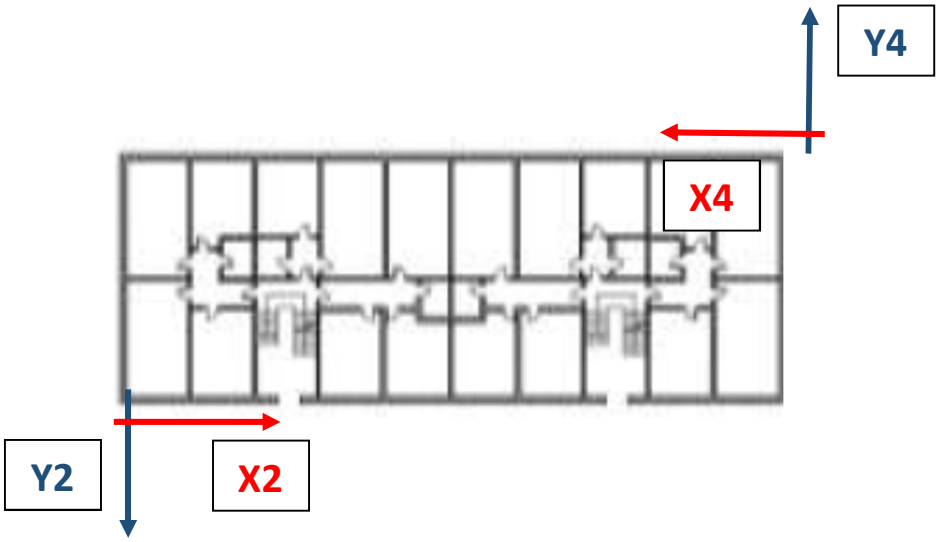
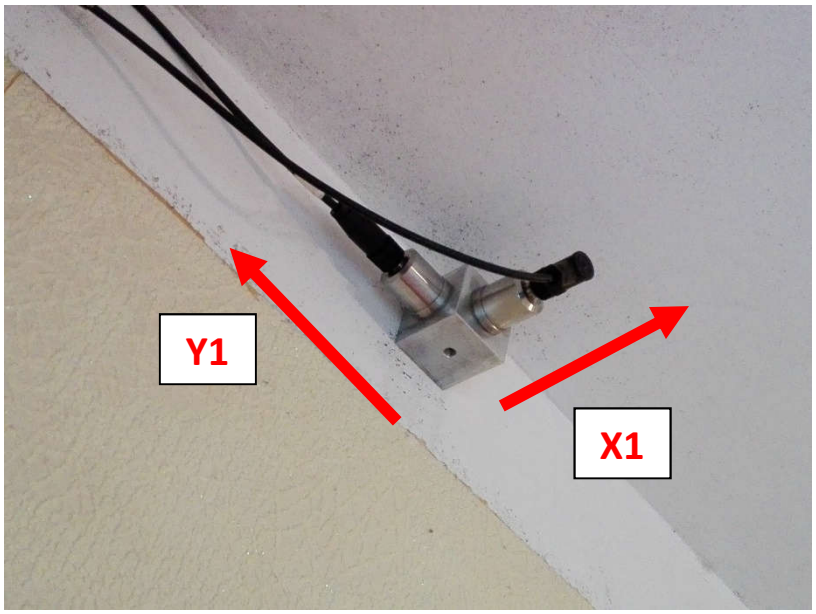
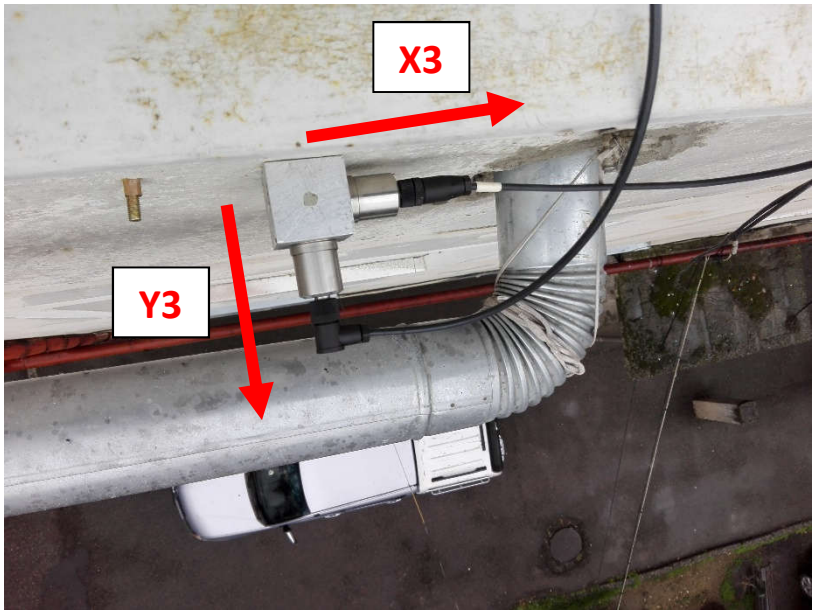
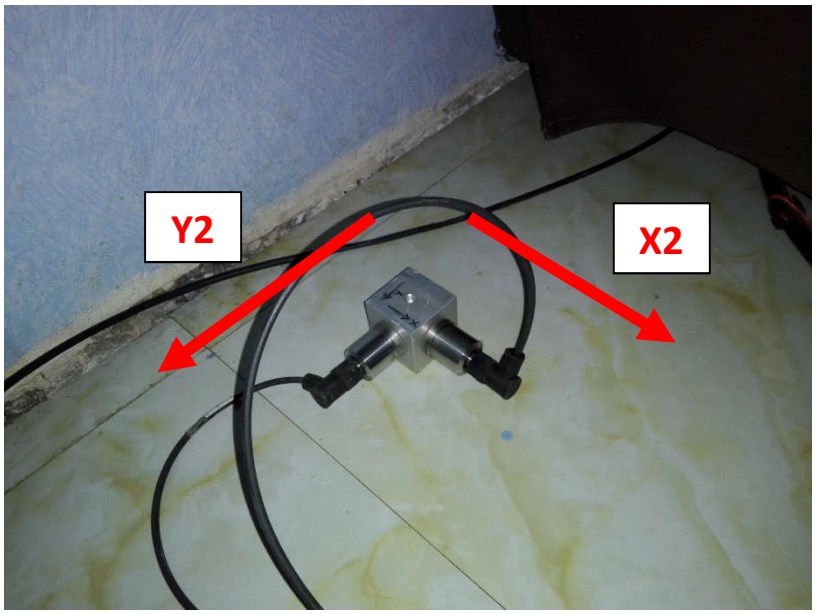


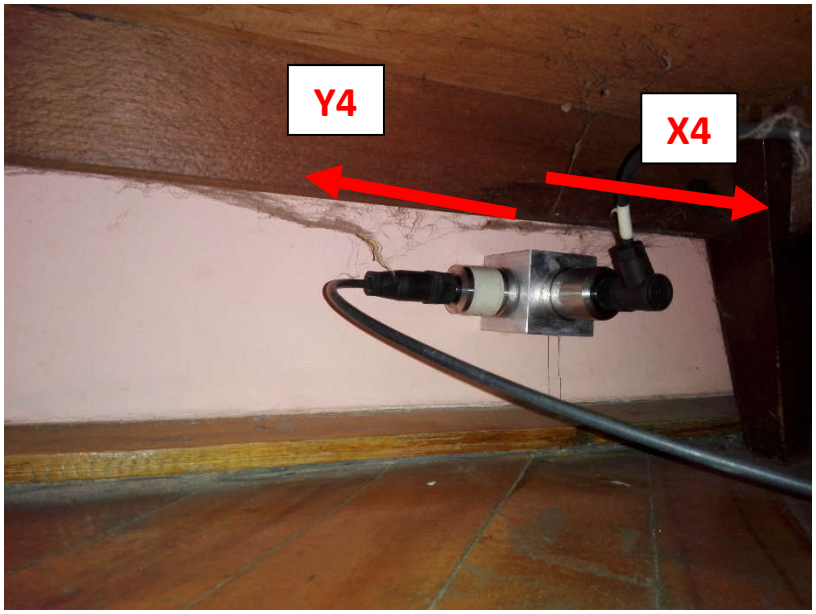
Image 141. Building n.9a



Images 142 and 143. Sensors and data acquisition system


X3
Y3


Y2
X2



Images 144, 145 and 146. sensors

ACQUISITION OF TIME HISTORIES

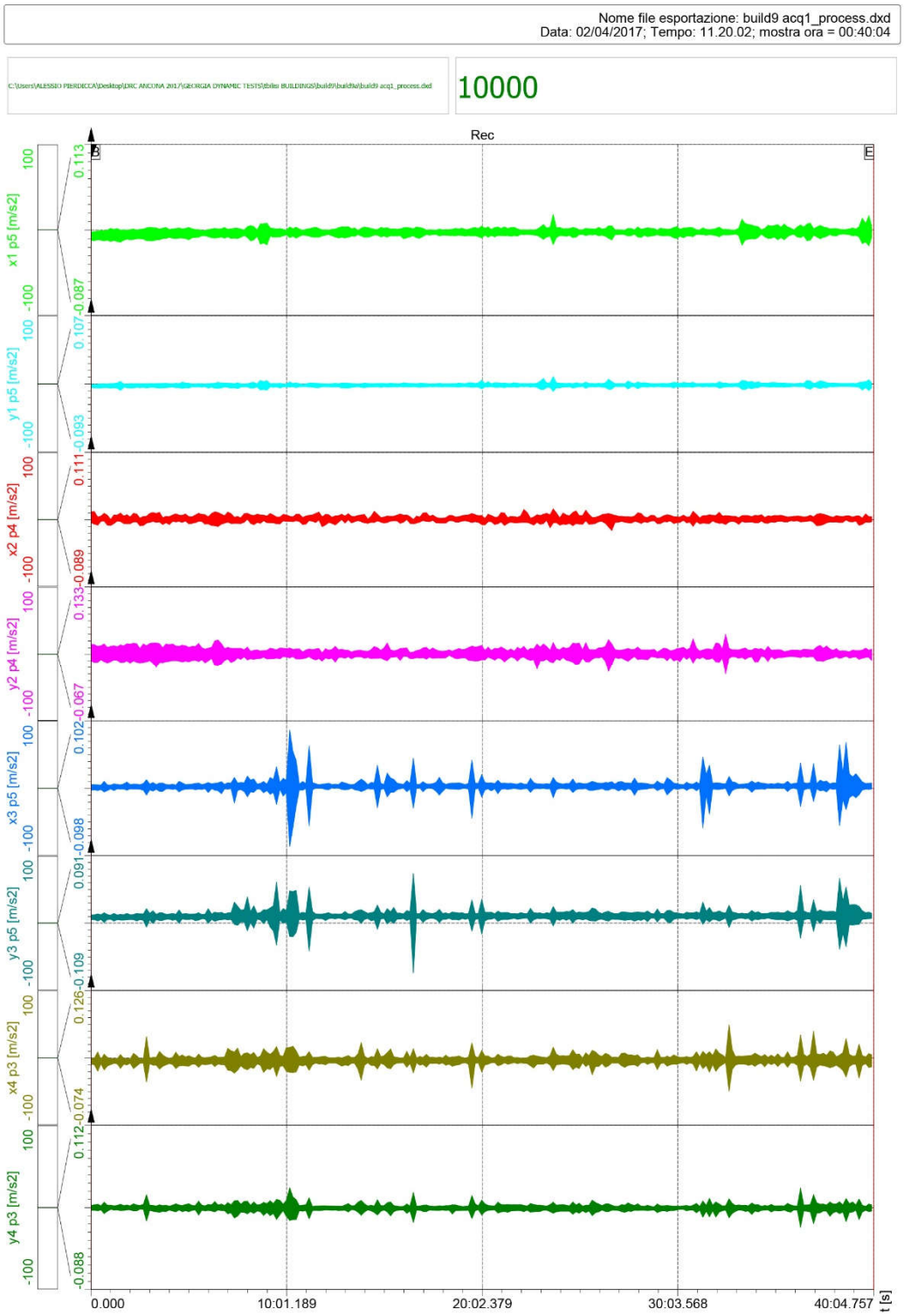


Image 147. Time histories

FREQUENCY CONTENT OF THE SIGNALS

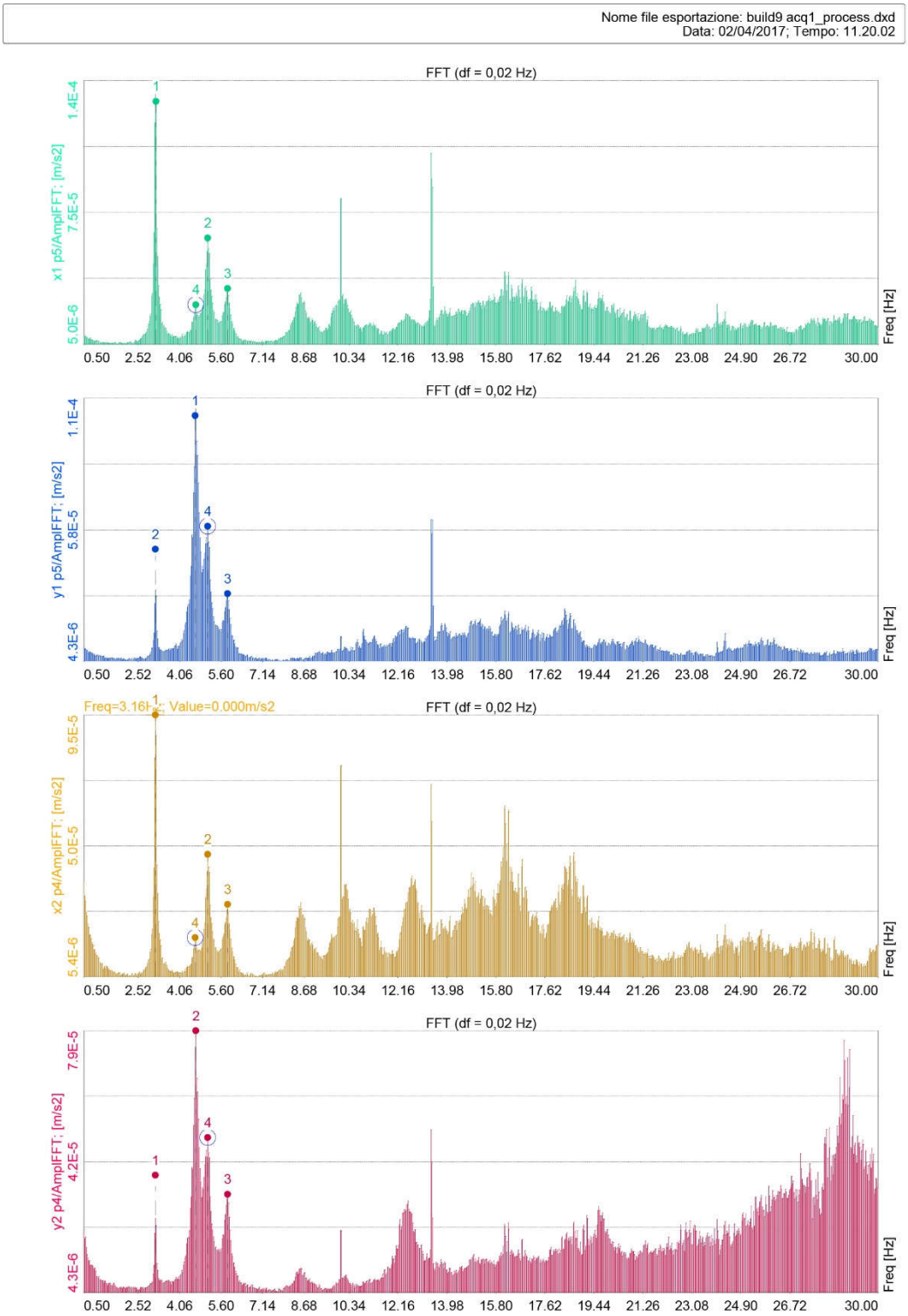


Image 148. Frequency contents

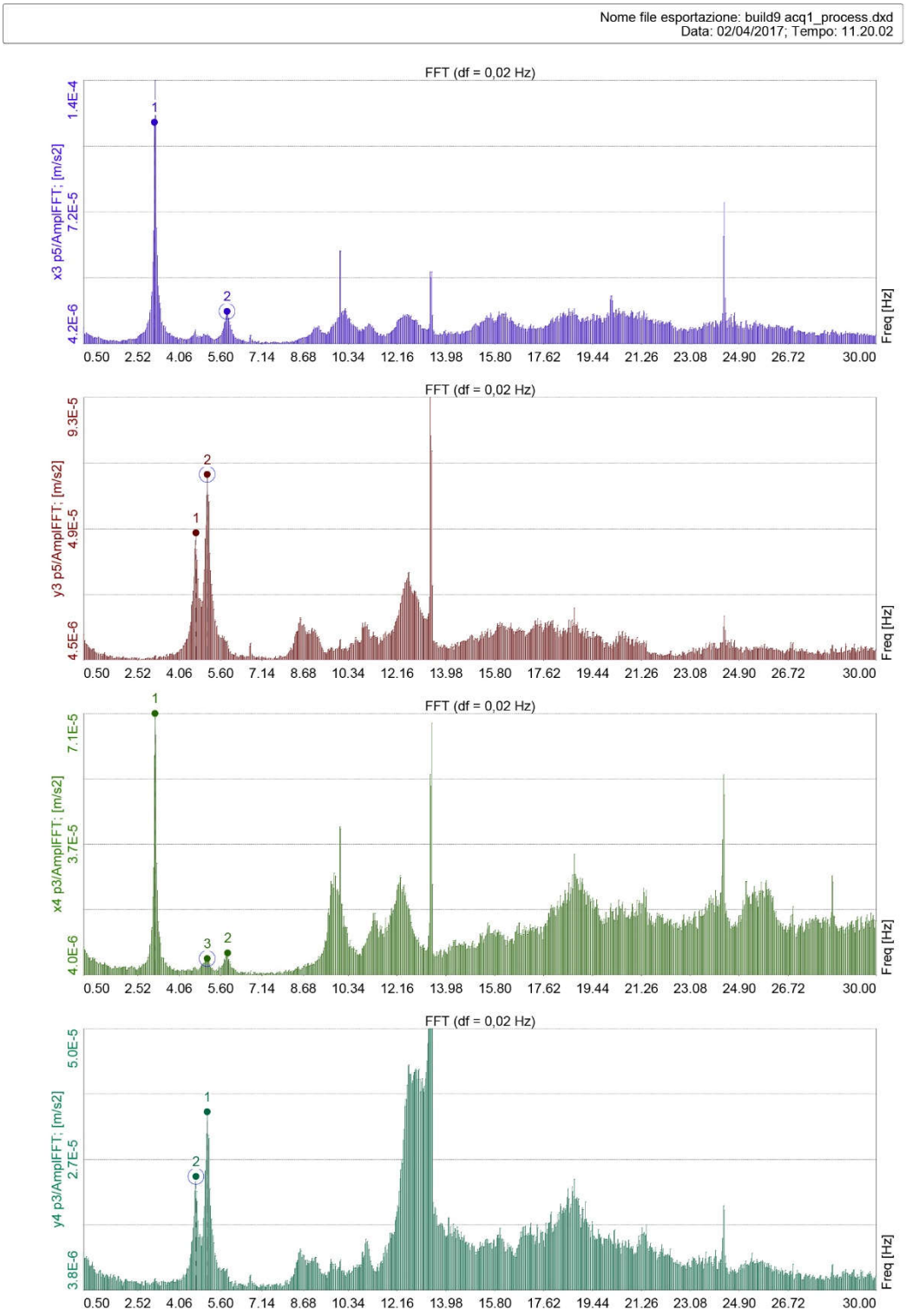
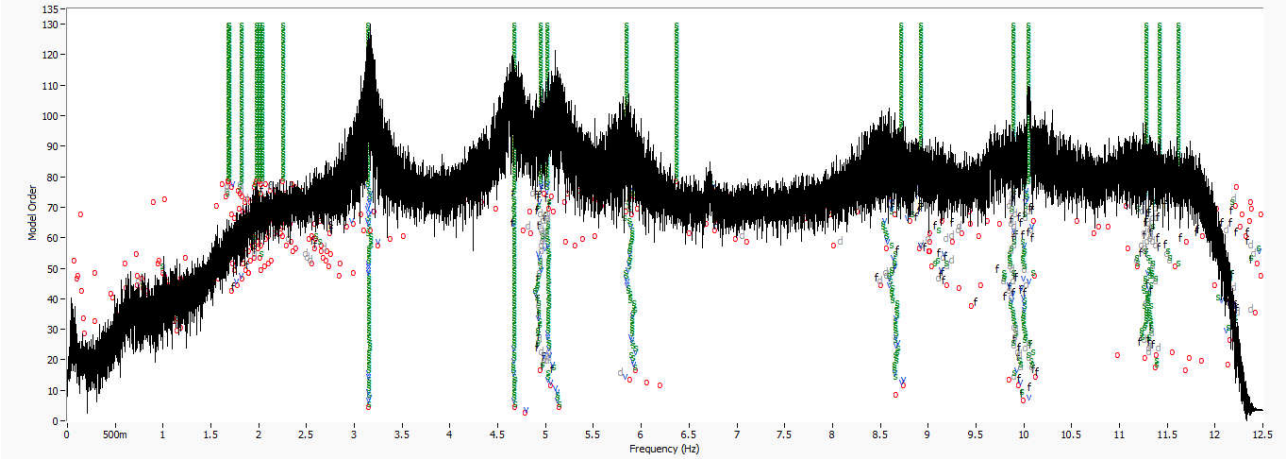


Image 149. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram

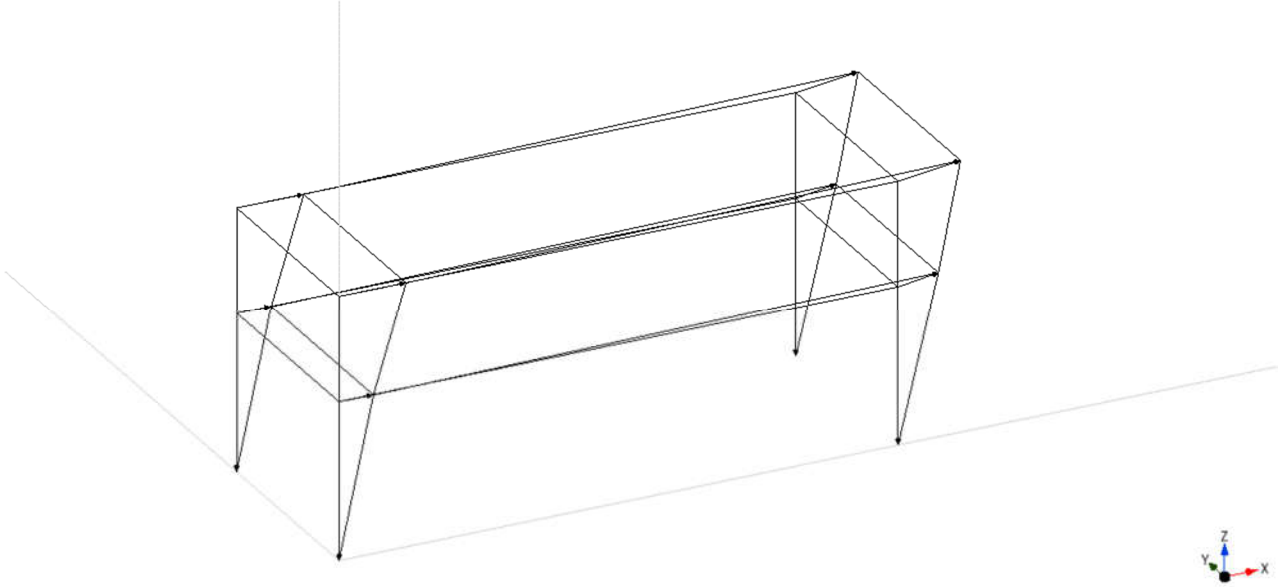


Mode Number	Frequency (Hz)	Damping (%)
1	3.156	0.9212
2	4.677	1.479
3	5.029	3.032
4	5.849	2.41

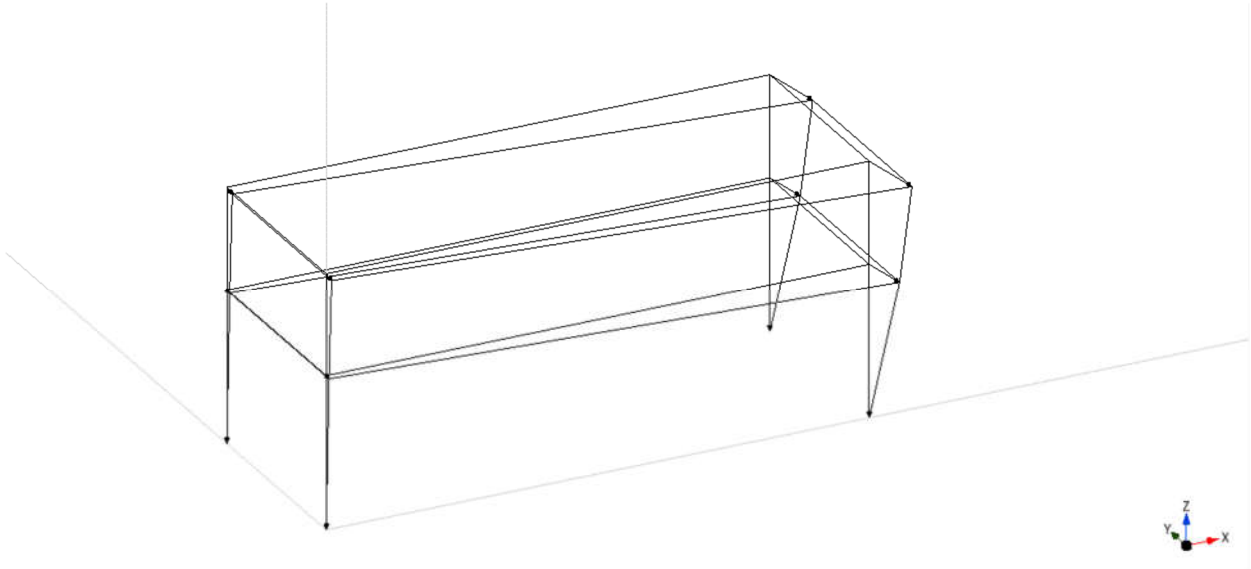
Image 150. Modal identification result

Mode Shapes

Mode1
3.156Hz – Traslational X

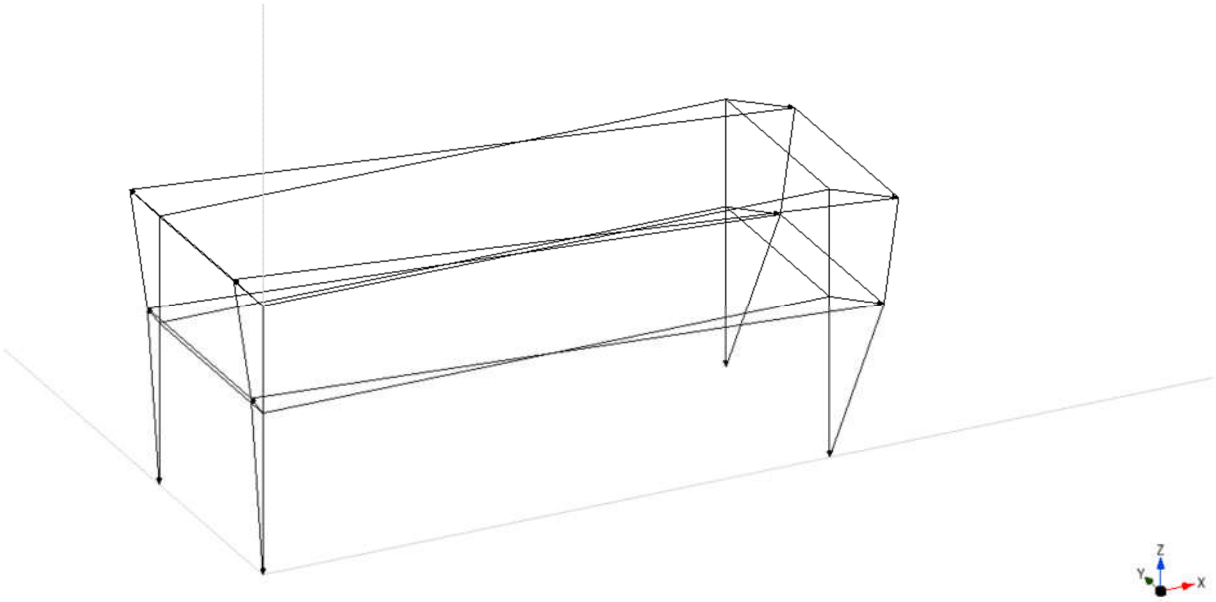


Mode 2
4.677Hz – Traslational Y

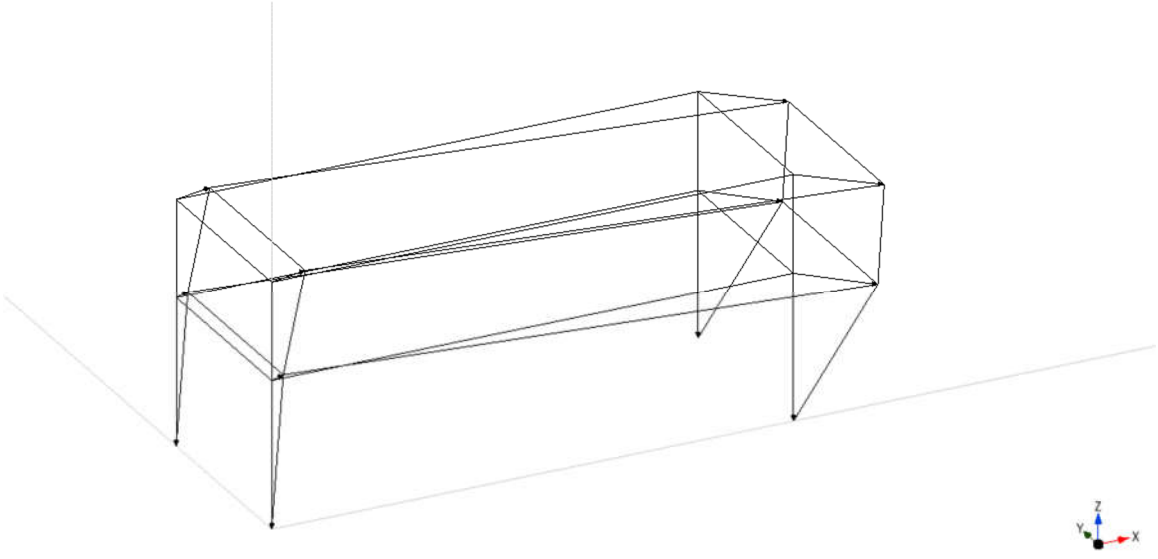


Images 151 and 152. Modal shapes

Mode 3
5.029Hz - Torsional



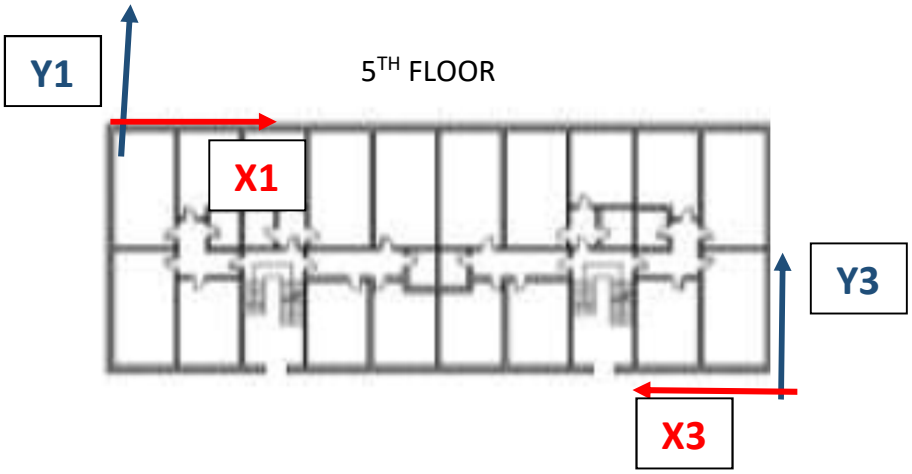
Mode 4
5.849Hz - Torsional



Images 153 and 154. Modal shapes

BUILDING 9B

SENSORS LAYOUT



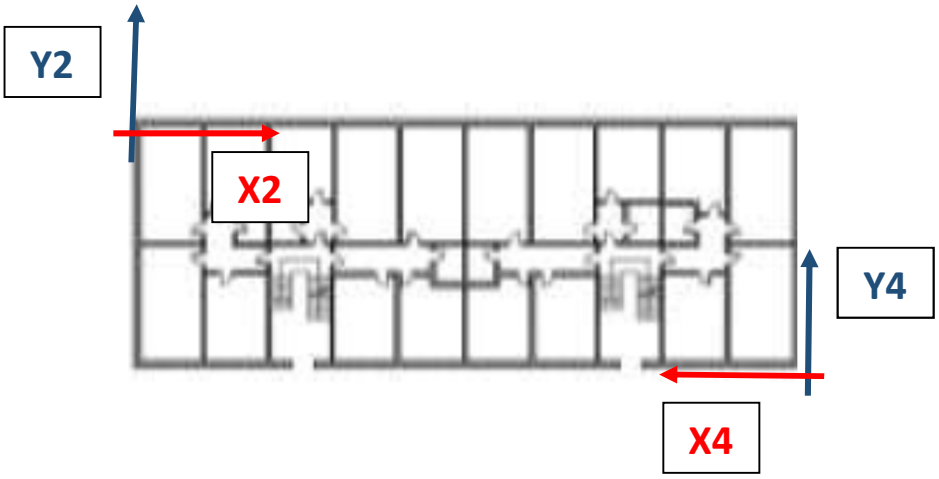
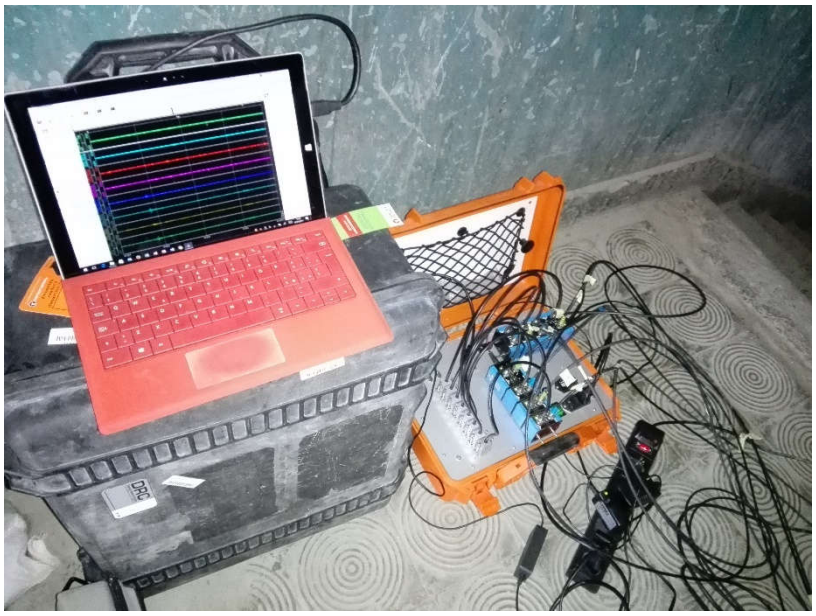
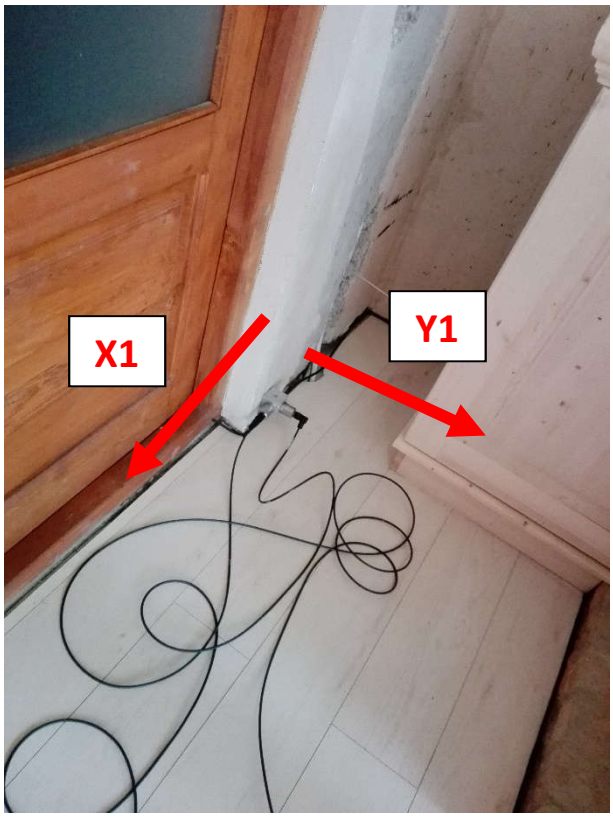
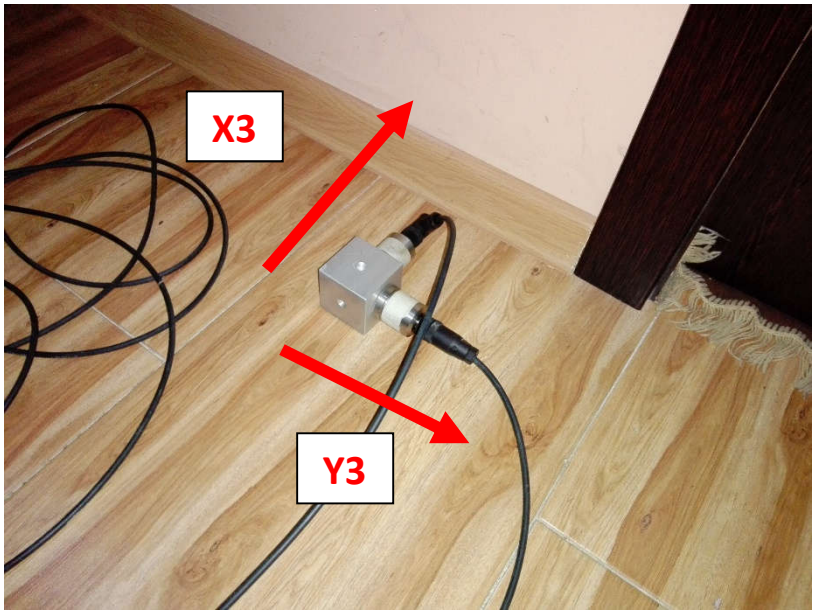


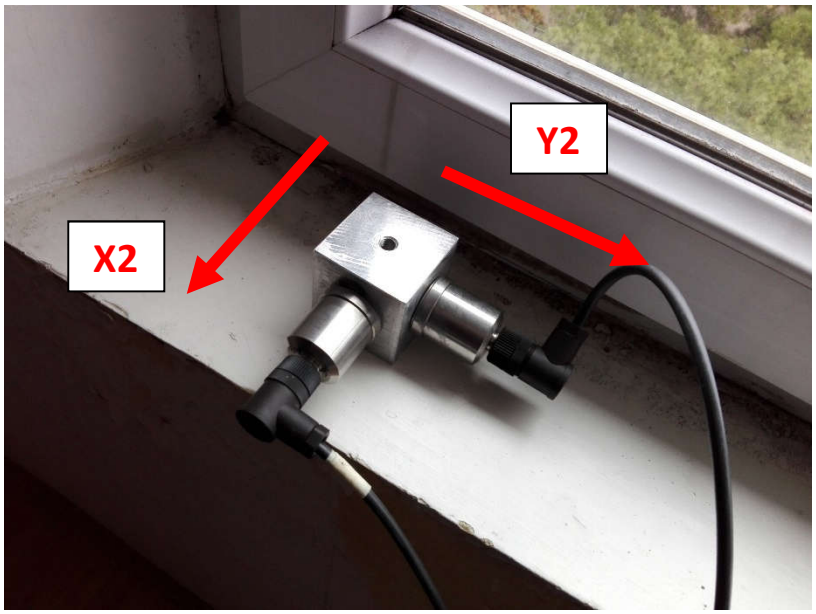
Image 155. Building n. 9B

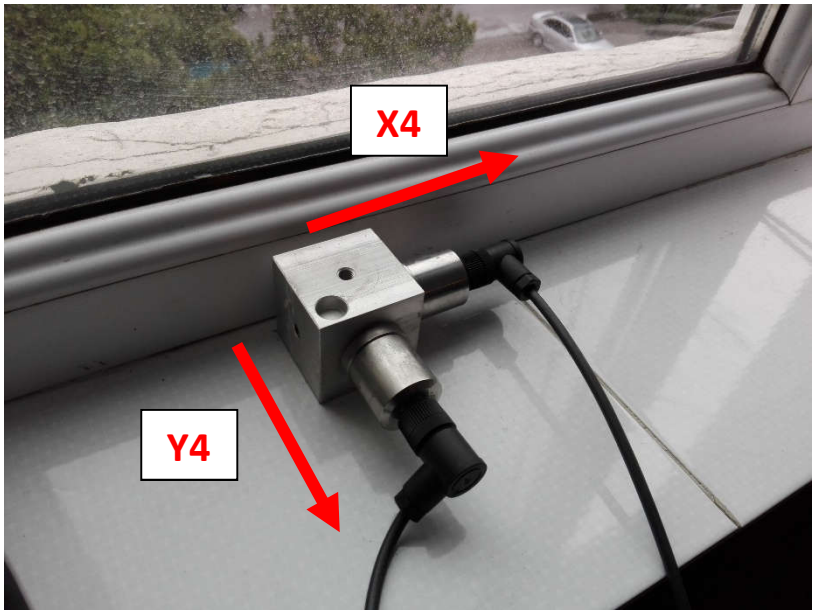




Images 156 and 157. Sensors and data acquisition system


X3
Y3


Y2
X2



Images 158, 159 and 160. sensors

ACQUISITION OF TIME HISTORIES

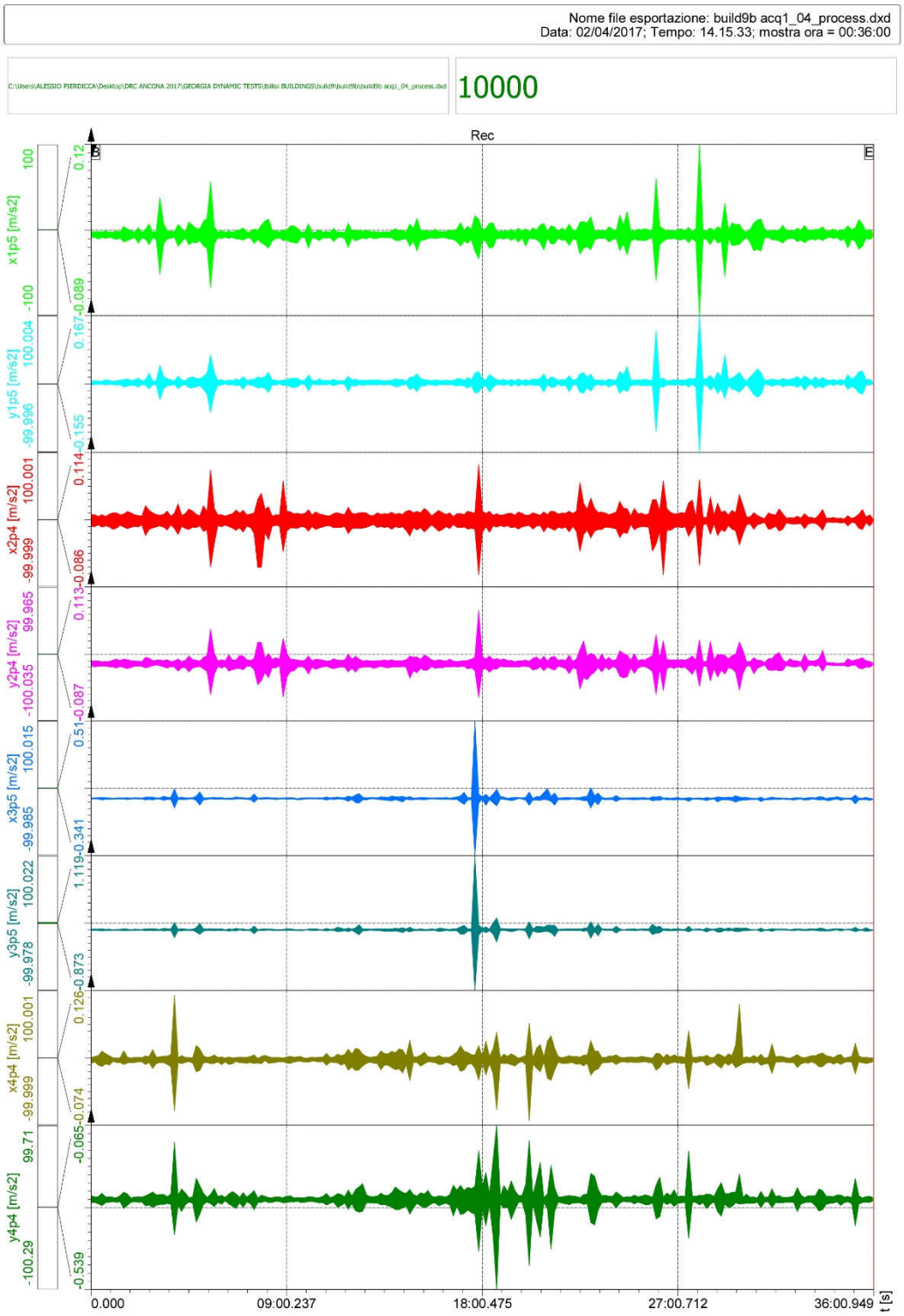


Image 161. Time histories

FREQUENCY CONTENT OF THE SIGNALS

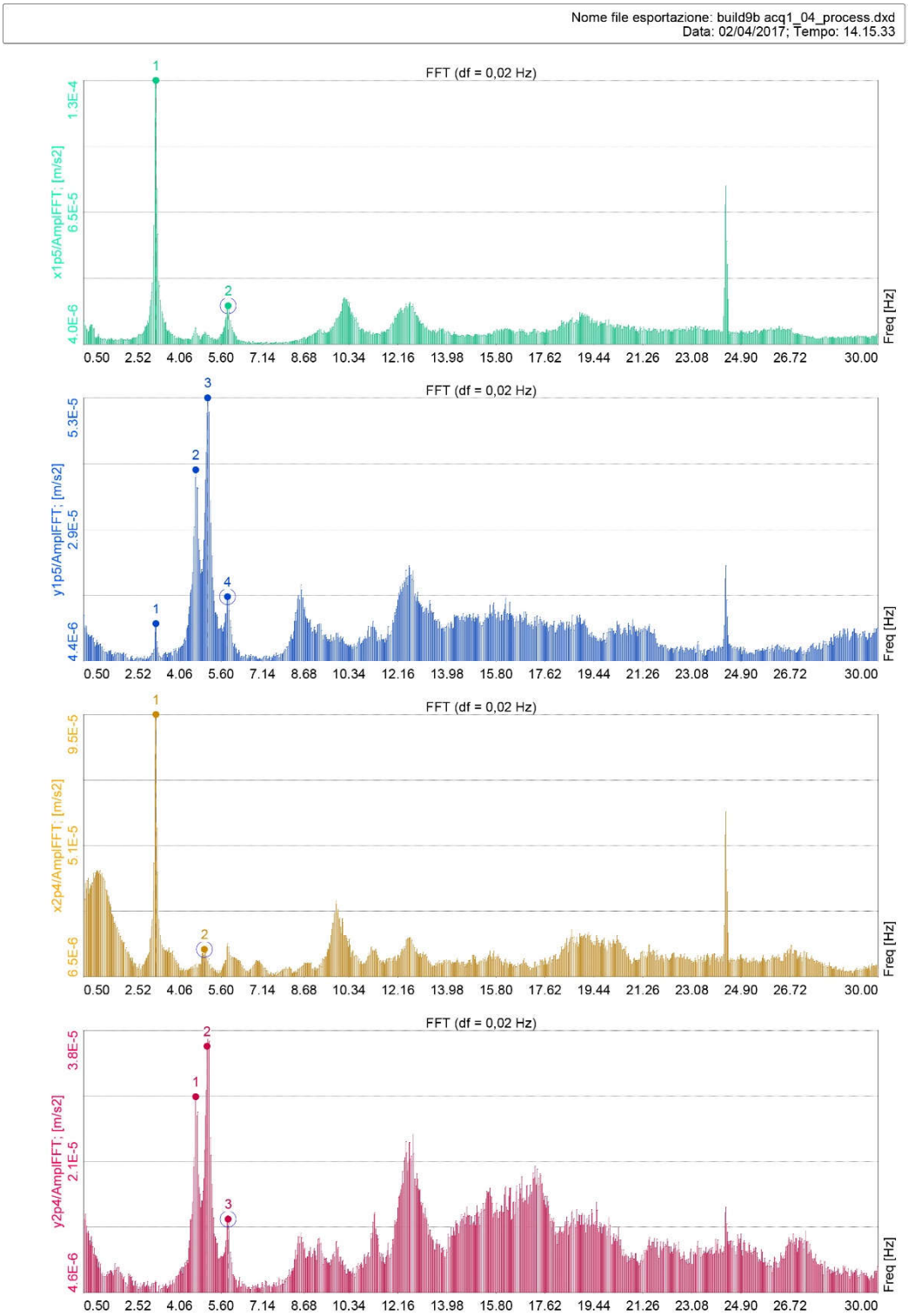


Image 162. Frequency contents

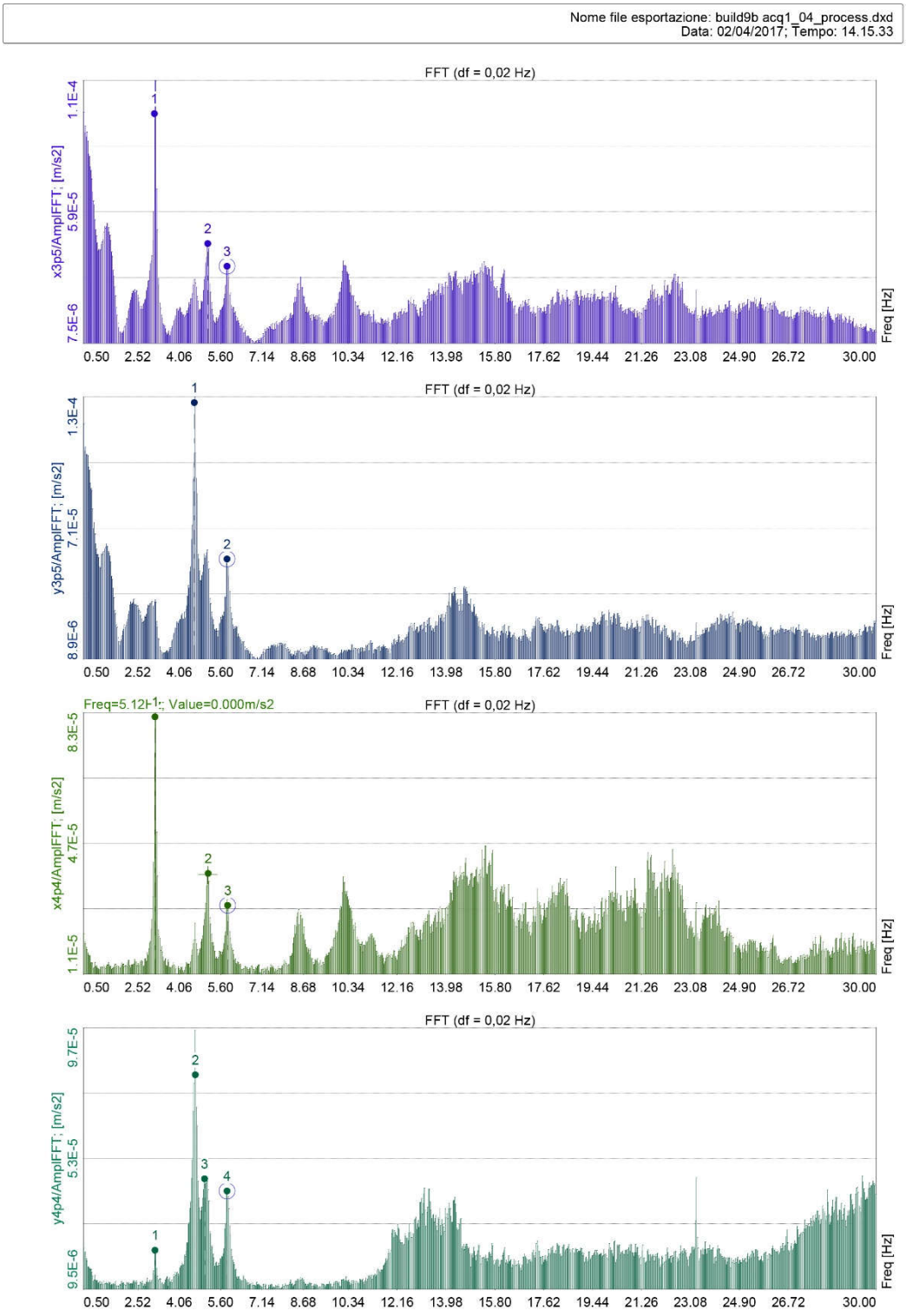
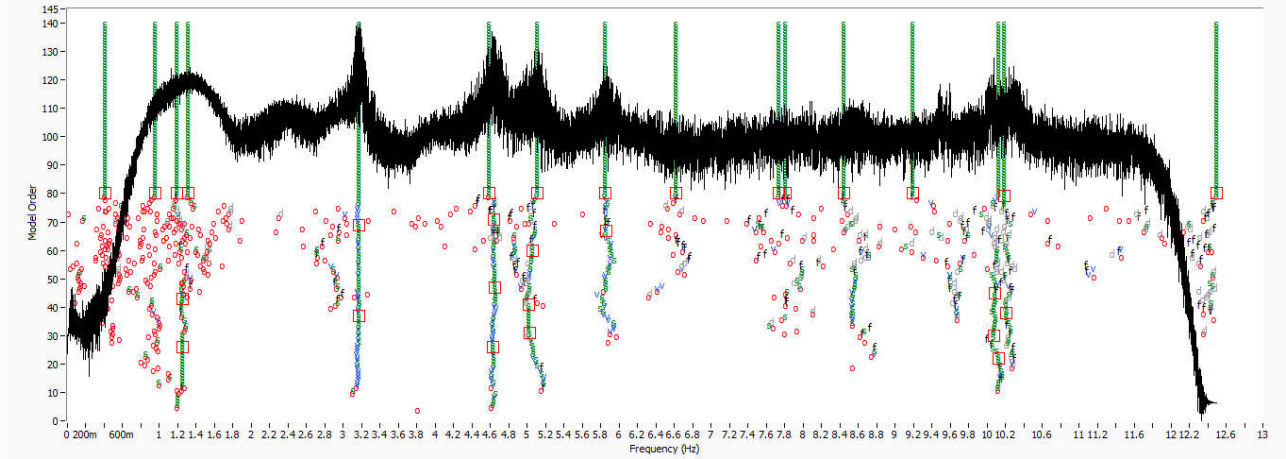


Image 163. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram

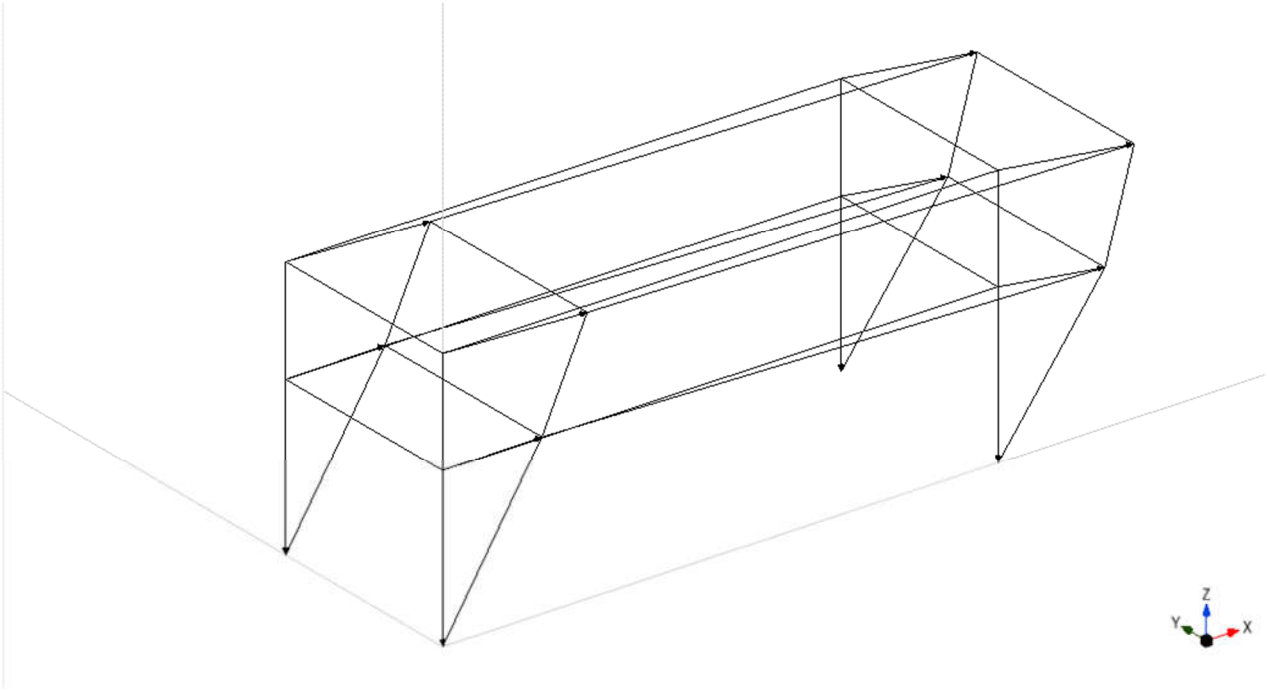


Mode Number	Frequency (Hz)	Damping (%)
1	3.169	0.6696
2	4.628	1.893
3	5.053	2.942
4	5.855	0.6868

Image 164. Modal identification result

Mode Shapes

Mode1
3.169Hz – Traslational X



Mode 2
4.628Hz – Traslational Y

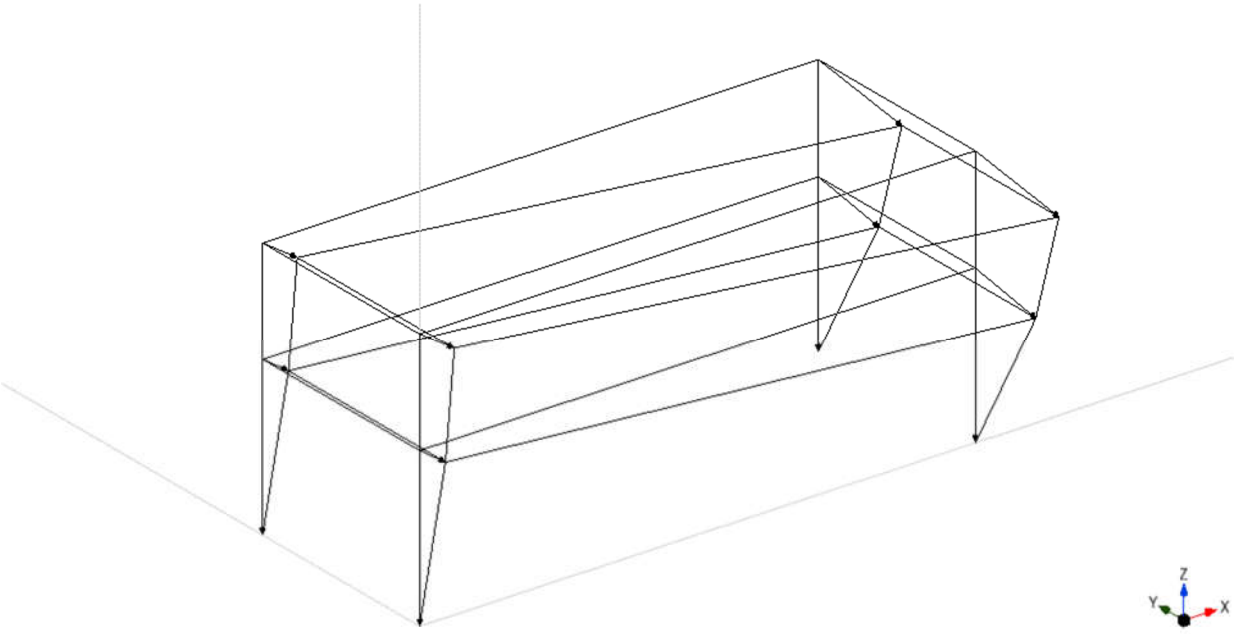
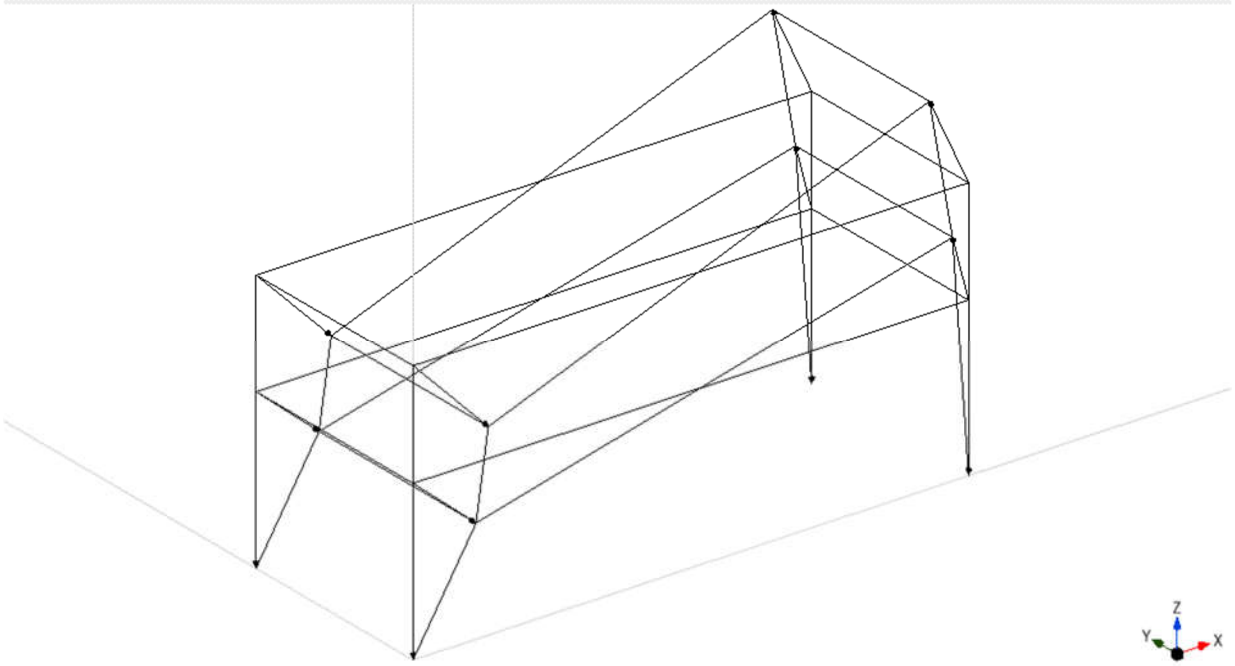


Image 166. Modal shapes

Mode 3
5.053Hz – Torsional



Mode 4
5.855Hz – Torsional

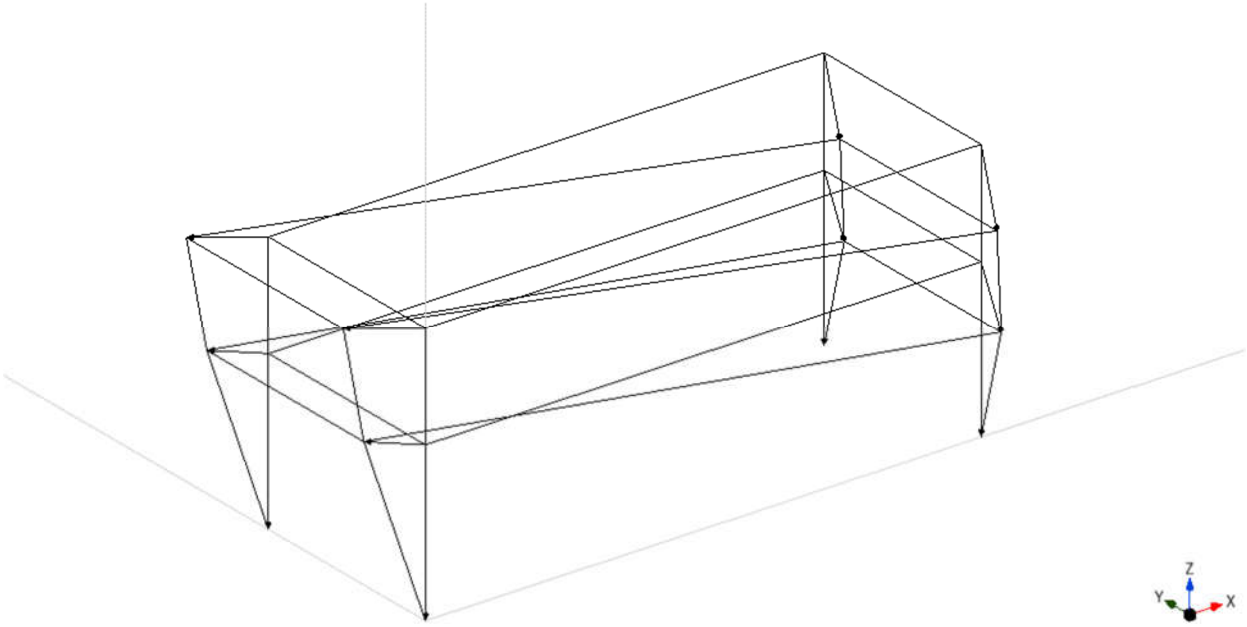
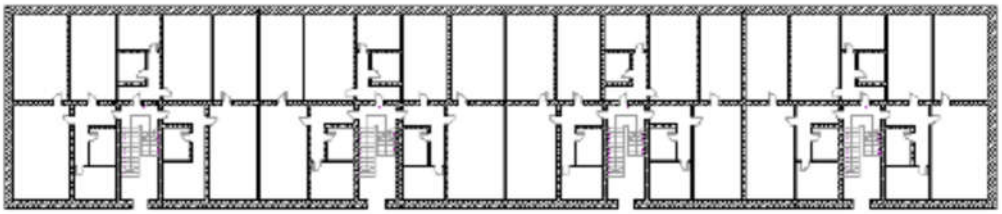


Image 167. Modal shapes

BUILDING 10



TYPICAL PLAN

Image 168. Building n. 10

SENSORS LAYOUT

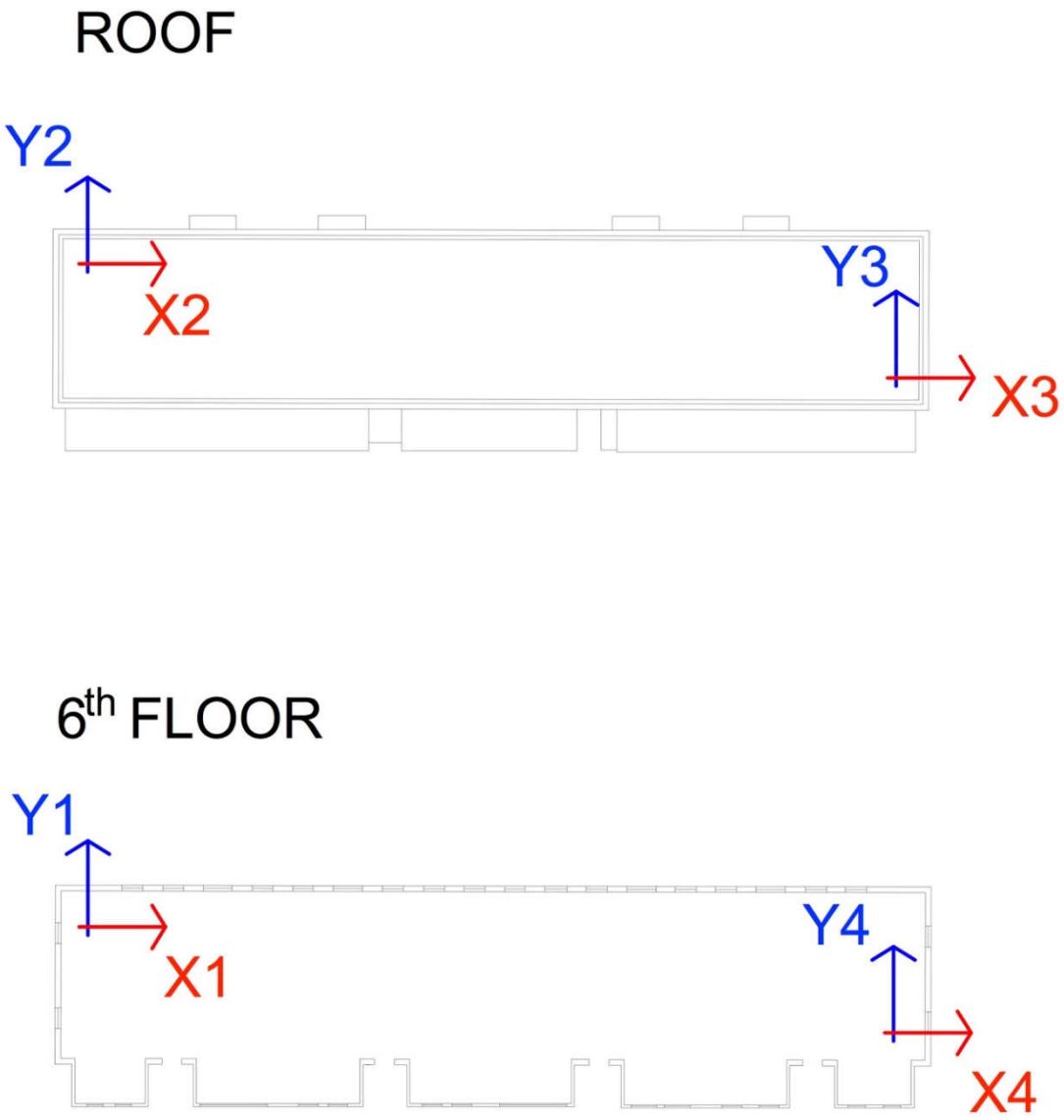
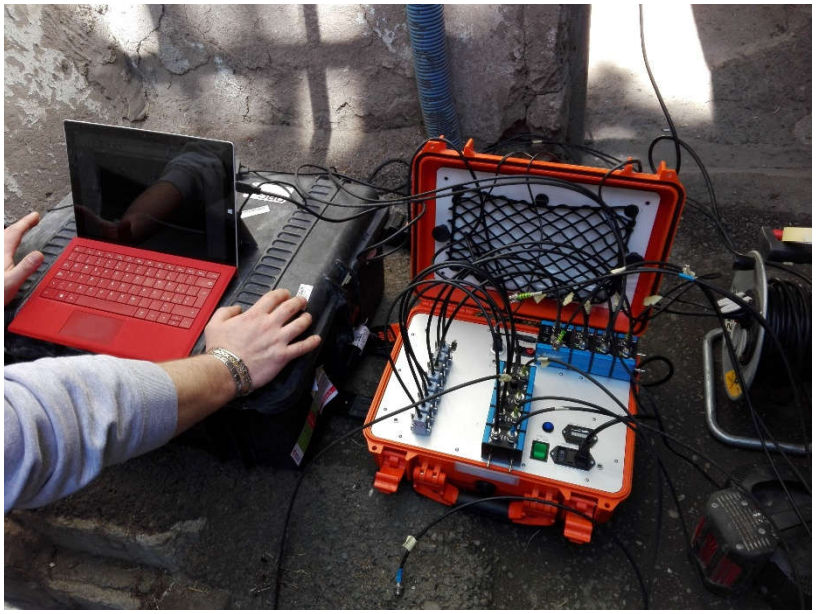
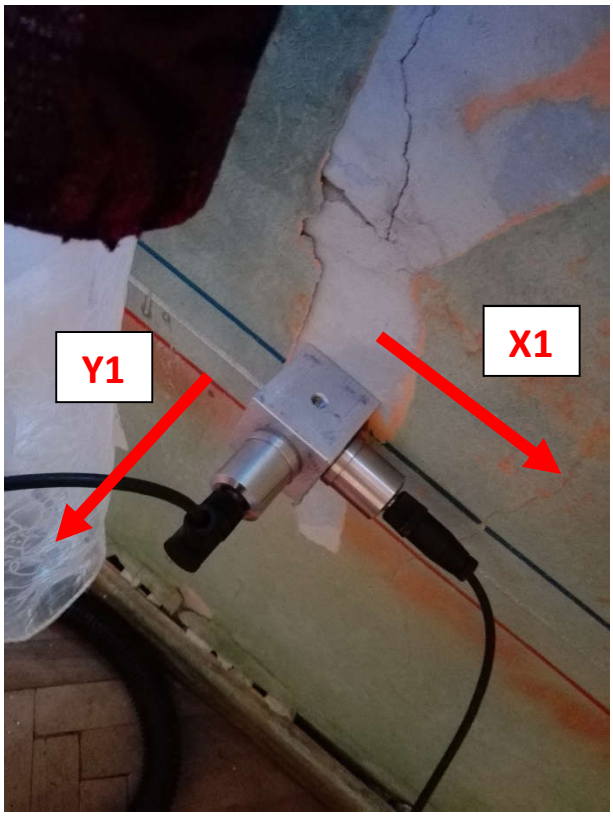
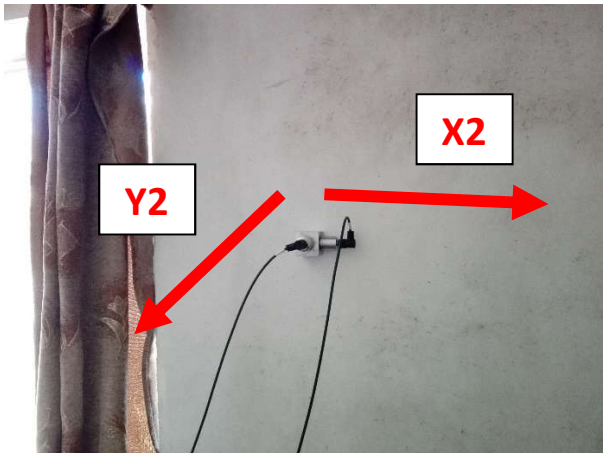


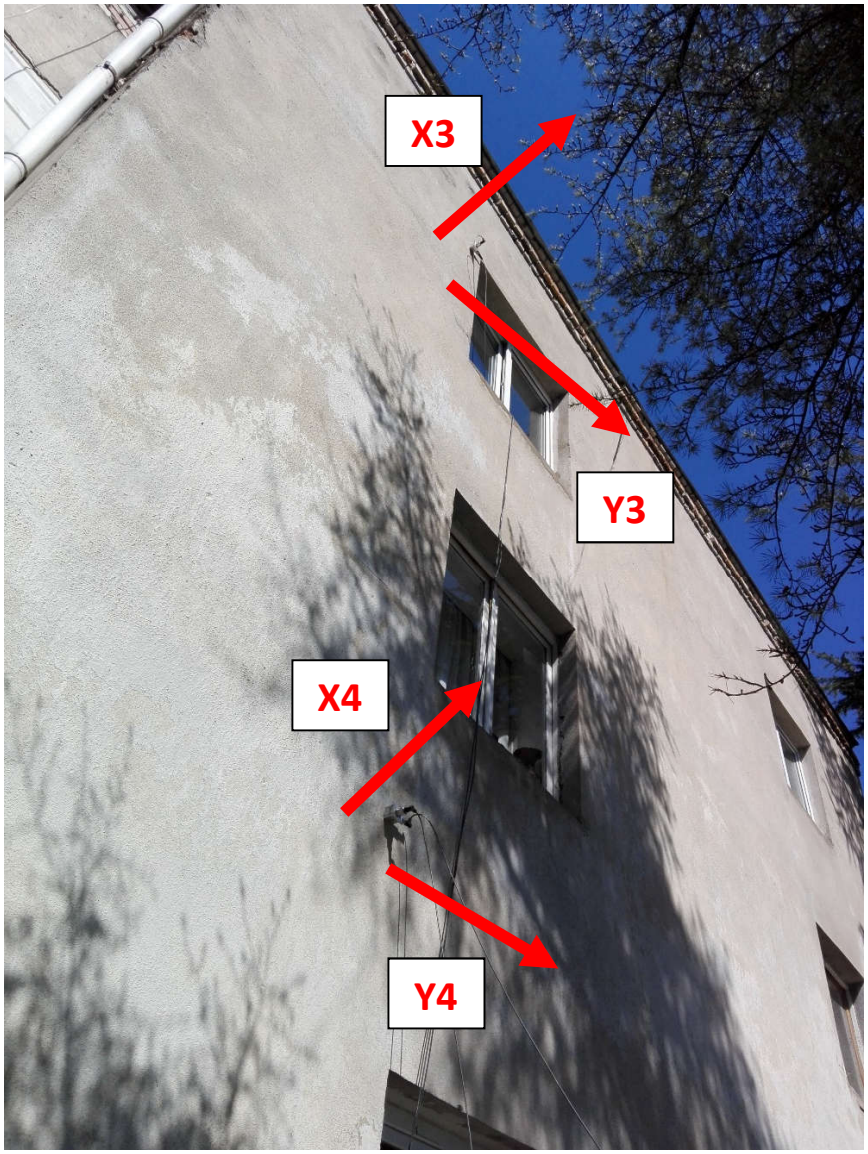
Image 169. Sensor layout





Images 170 and 171. Sensors and data acquisition system





Images 172 and 173. sensors

ACQUISITION OF TIME HISTORIES

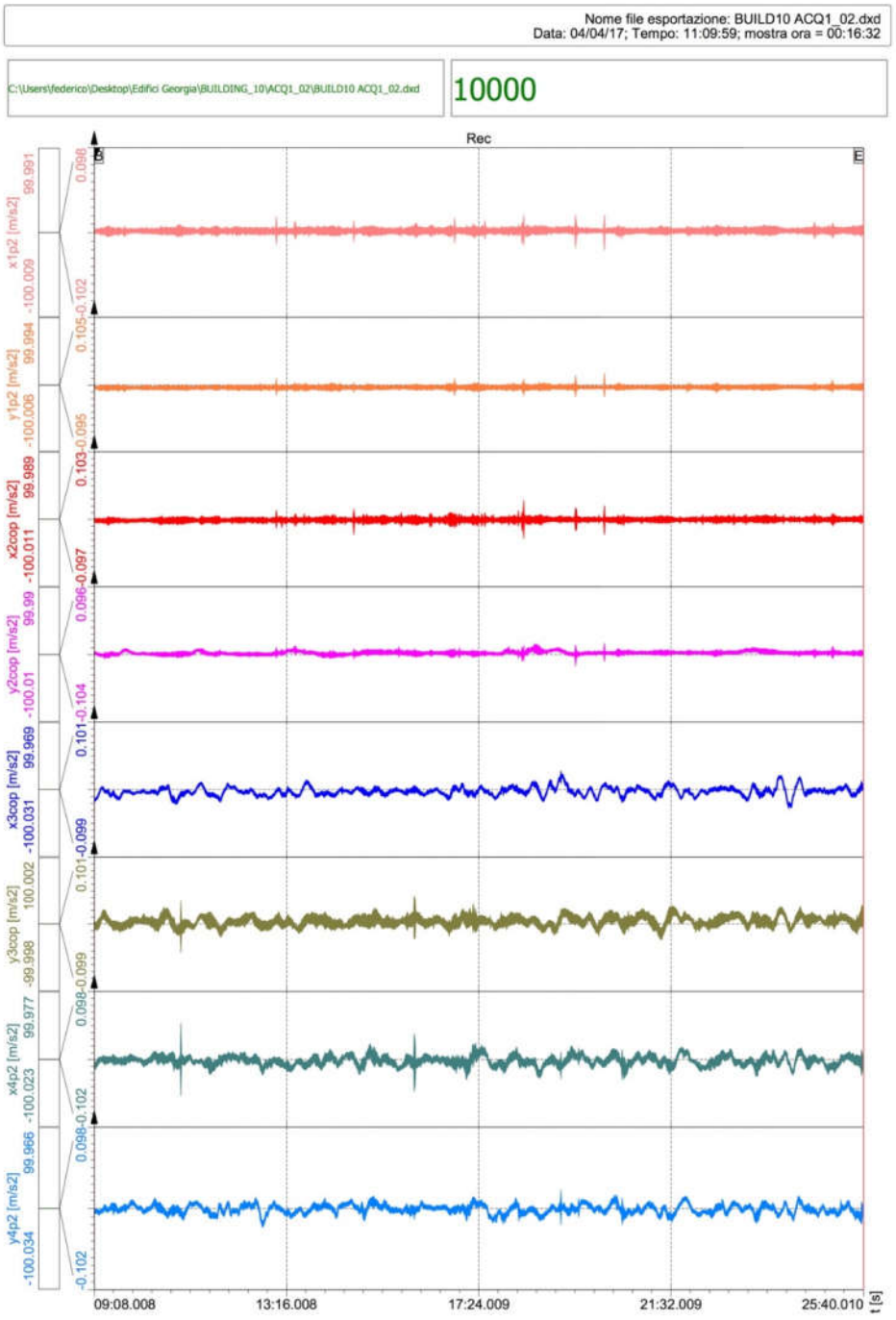


Image 174. Time histories

FREQUENCY CONTENT OF THE SIGNALS

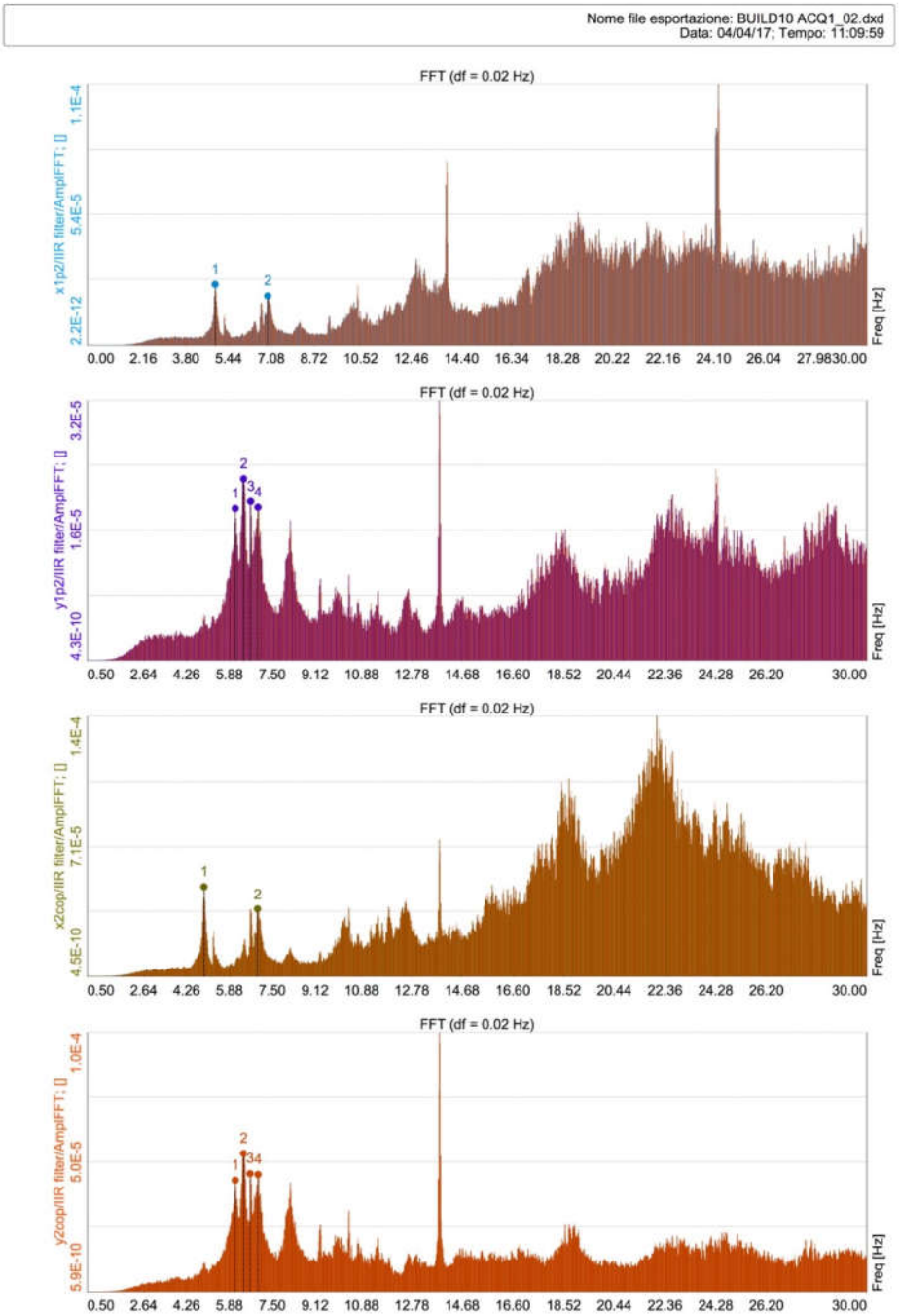


Image 175. Frequency contents

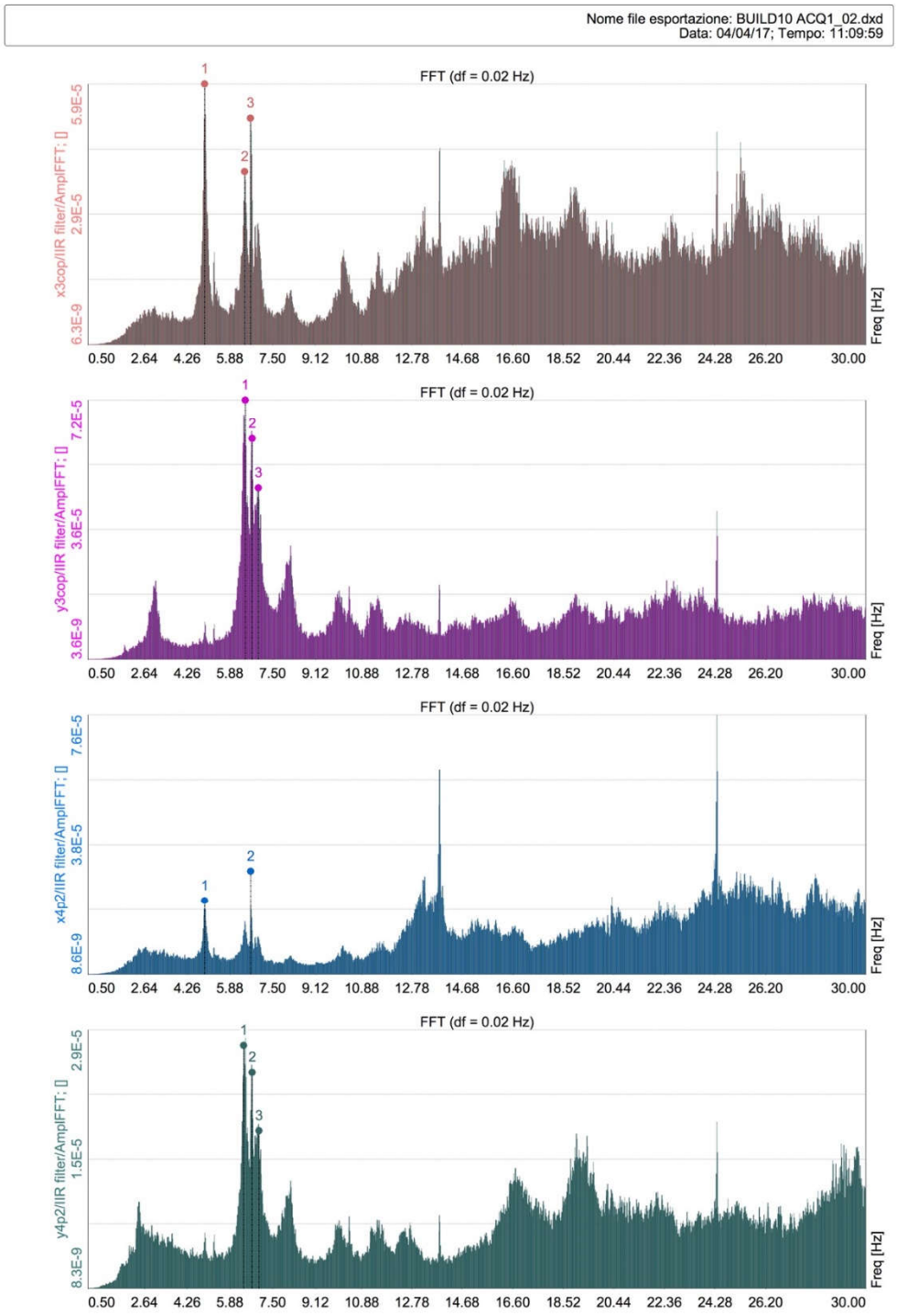
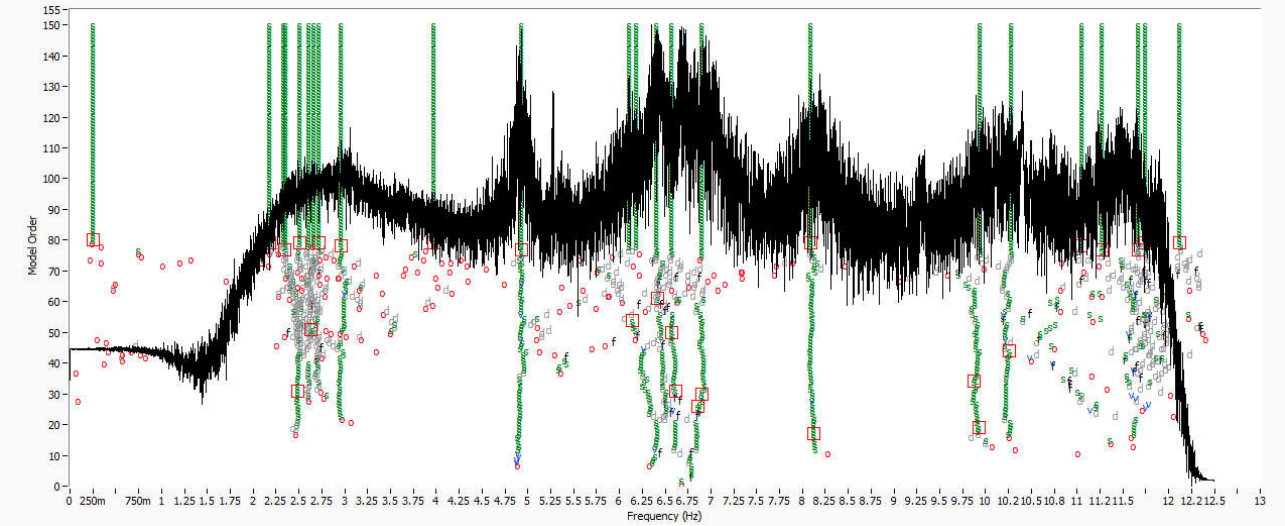


Image 176. Frequency contents

MODAL IDENTIFICATION RESULTS

Stabilization diagram

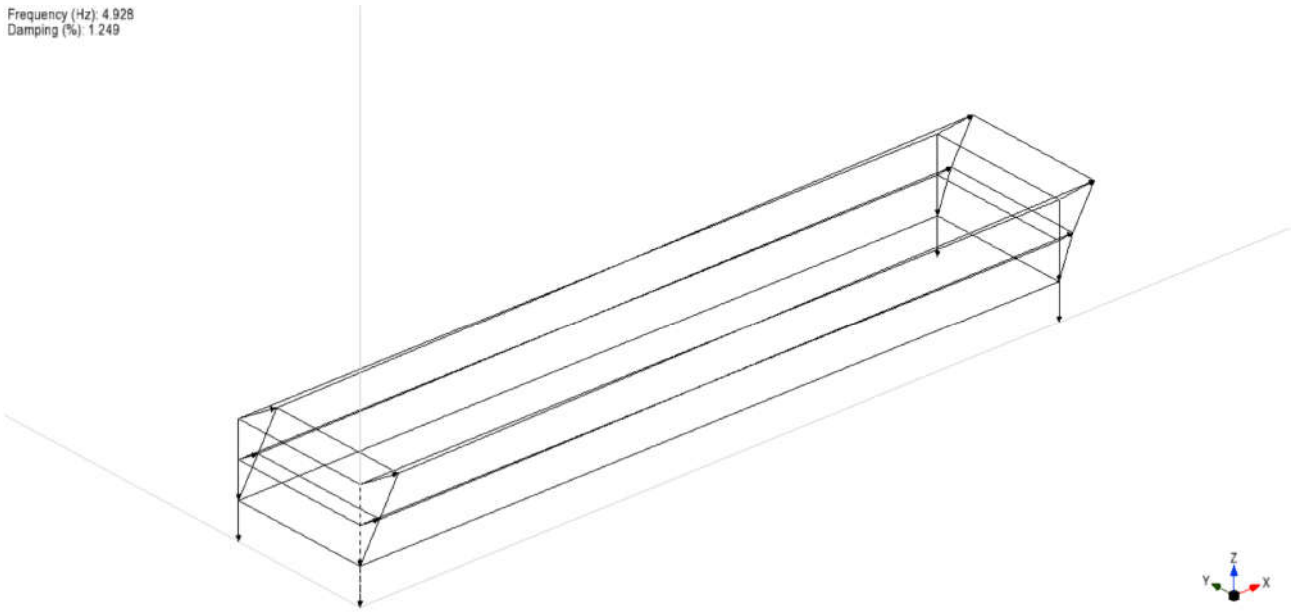


Mode n.	Frequency (Hz)	Damping (%)
1	4.93	1.249
2	6.14	1.733
3	6.42	1.775
4	6.86	1.117

Image 177. Modal identification result

Mode Shapes

Mode1
4.93Hz – Traslational X



Mode2
6.14Hz – Traslational Y

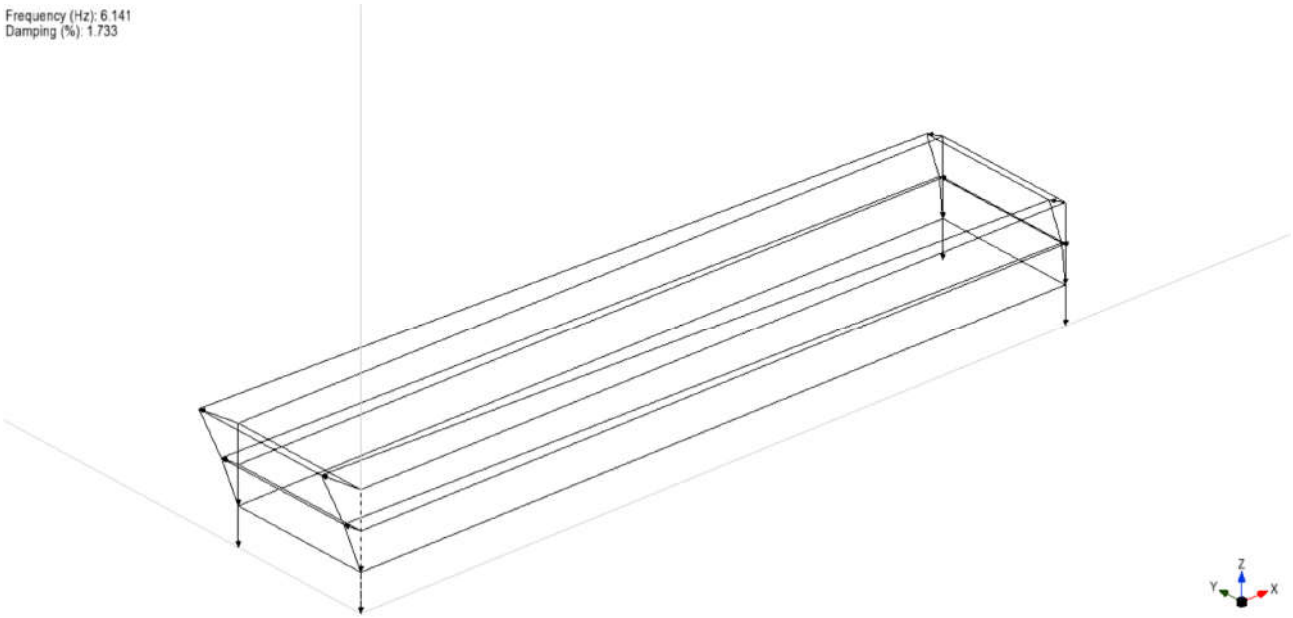
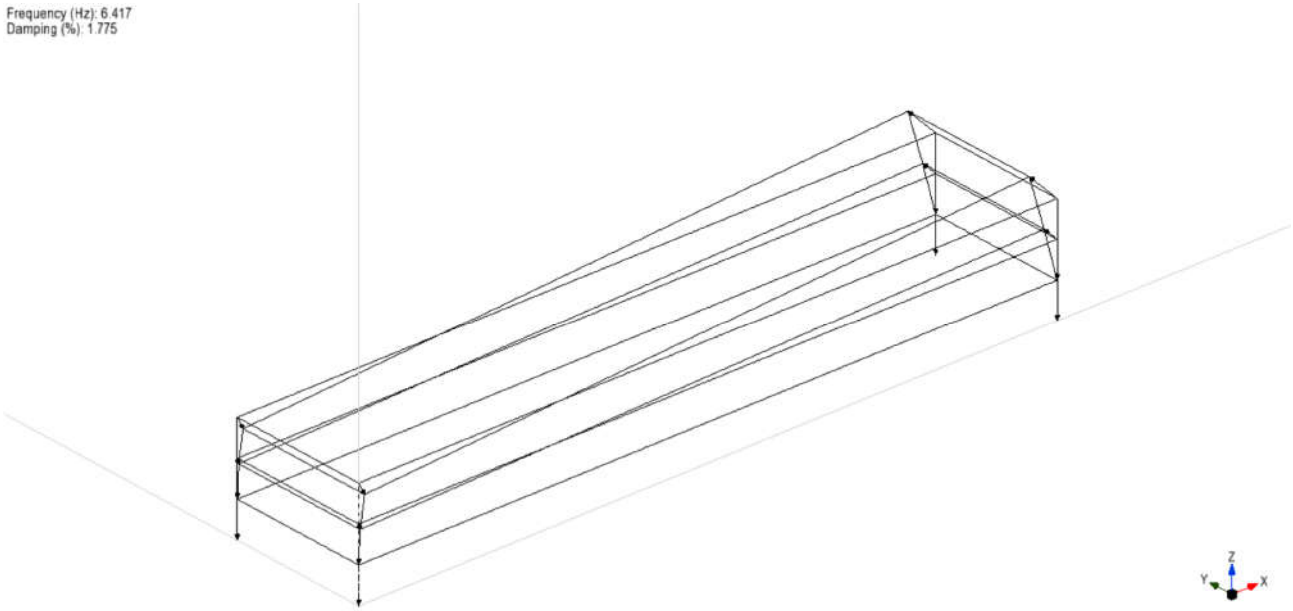


Image 178. Modal shapes

Mode3

6.42Hz - Torsional



Mode4

6.86Hz - Torsional

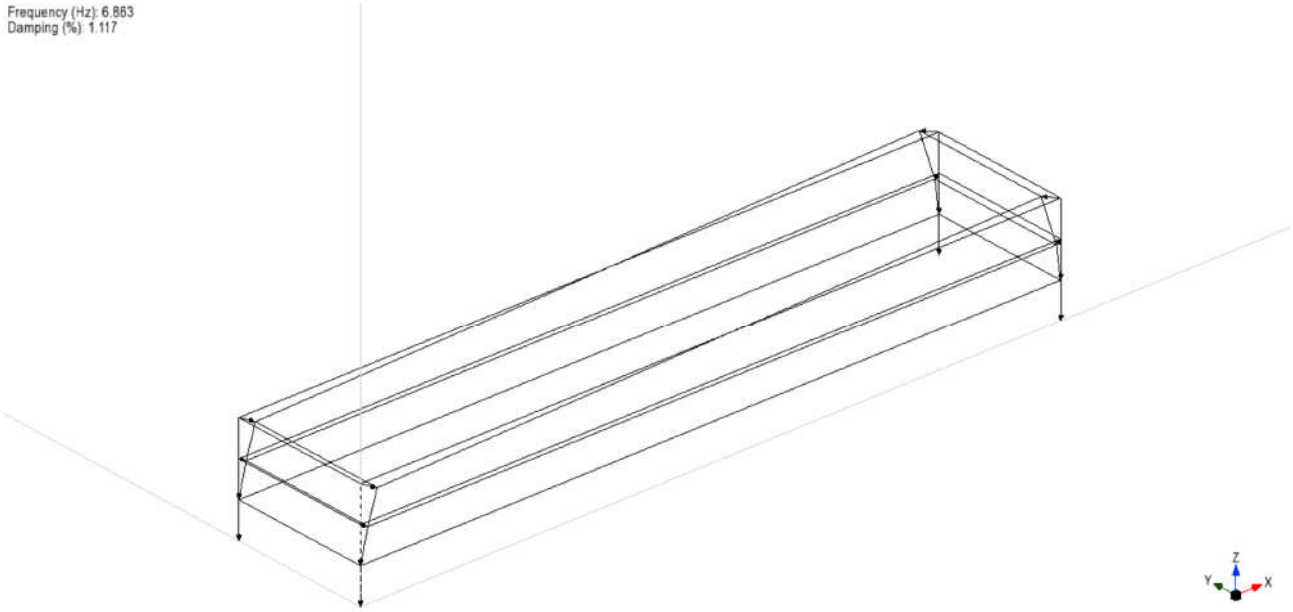


Image 179. Modal shapes

CONCLUSIONS

SUMMARY OF THE NATURAL FREQUENCIES OF MONITORED BUILDINGS

Following the monitoring works the main structural parameters of the buildings (natural frequencies, modal shapes and damping ratios) have been obtained.

The method used for dynamic identification is Stochastic Subspace Identification (SSI), working in time domain.

In the following table the mail results in terms of natural frequencies and type of mode shape are reported.

	mode 1		mode 2		mode 3		mode 4	
BUILDING NUMBER	Frequency Hz	Type	Frequency Hz	Type	Frequency Hz	Type	Frequency Hz	Type
#2	6.66	Tors.	7.28	Trasl X	7.73	Trasl Y	8.48	Tors.
#3	1.89	Tors.	2	Trasl X	3.28	Trasl Y	5.77	Trasl X
#4	1.74	Tors.	2.09	Trasl Y	2.95	Trasl X	5.45	Trasl X
#5a	3.19	Trasl X	4.56	Trasl Y	4.71	Tors.	5.54	Tors.
#5b	2.98	Trasl X	4.53	Trasl Y	4.75	Tors.	6.63	Tors.
#5c	3.05	Trasl X	4.52	Trasl Y	4.86	Tors.	5.68	Tors.
#6	3.33	Trasl X	3.85	Trasl Y	4.05	Tors.	4.97	Trasl Y
#7	5.17	Tors.	6.06	Trasl X	6.35	Trasl Y	6.75	Tors.
#8	4.25	Tors.	6.79	Trasl X	6.99	Trasl Y	8.84	Tors.
#9a	3.15	Trasl X	4.67	Trasl Y	5.02	Tors.	5.84	Tors.
#9b	3.16	Trasl X	4.62	Trasl Y	5.05	Tors.	5.85	Tors.
#10	4.93	Trasl X	6.14	Trasl Y	6.42	Tors.	6.86	Tors.

SUMMARY OF THE NATURAL FREQUENCIES OF MONITORED BUILDINGS WITH ADDITIONS

Several structures, in addition to their core structure as built originally, include additions, built in different periods of time. In order to understand the structural behavior of the monitored buildings, both, core structures and additions were monitored placing the sensors also in the additional blocks.

The following table below reports the main results obtained for those two buildings.

It is worth to remark that the structural additions show a different structural behavior. It is evident in the modal shapes reported above.

	mode 1		mode 2		mode 3		mode 4	
BUILDING NUMBER	**Frequency Hz**	**Type**	**Frequency Hz**	**Type**	**Frequency Hz**	**Type**	**Frequency Hz**	**Type**
#5b	**3.05**	**Trasl X (original structure)**	**4.54**	**Trasl X (added block)**	**4.8**	**Trasl Y**	**6.85**	**Tors.**
#5c	**3.1**	**Trasl X (original structure)**	**4.51**	**Trasl X (added block)**	**4.88**	**Tors.**	**5.78**	**Trasl X**