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Static and Dynamic Monitoring of the Notre Dame de Paris Cathedral

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ABSTRACT

During the fire which took place on 15th April 2019, the Cathedral of Notre Dame de Paris underwent extensive structural damages: most of the roof was destroyed, part of the stone vaulted ceiling collapsed, and the wooden framework of the north tower was partially burned. After the fire, a list of actions was carried on in order to secure the remaining structure, prevent any further damage and start the rehabilitation. Very early on, a monitoring system was used to assist the project manager in these tasks. With the progress of site works, the monitoring system was updated to provide more insightful information. The present paper focuses on the monitoring system deployed on the towers and the stone vaulted ceiling with the objective to produce a first assessment of the current state and follow the evolution during the reconstruction phase. The monitoring campaign was carried out from December 2020 to December 2021 with two distinct sets of sensors. The first objective was to characterize the current state and identify the dynamic behavior of the structure, for that purpose 48 directional accelerometers were installed on the two towers and the two vaults lane. Acceleration measurements and analytical methods lead to the identification of the fundamental modes of these structural elements. In a second time, to follow the evolution of the vaults, 56 inclinometers were positioned on the outer side of the vaults, constituting 15 inclinometer measuring chains. Set up to transmit data continuously with a 10 min frequency, measurements allow to notify settlements or uprisings and correlate these evolutions with external factors (weather conditions or rehabilitation works).

I. Introduction

The Cathedral Notre-Dame in Paris is one of the most important heritage buildings in France, included in the UNESCO World Heritage Sites list since 1991 as part of Paris, Banks of the Seine (Unesco World Heritage List, 2021). Thus, the fire which destroyed the roof, the spire, and parts of the stone vaults on April 15, 2019, had a considerable emotional echo not only in France, but also in the world.

Immediately after the disaster, important works have been carried out, first to ensure the safety of the structure during the expertise and the dismantling of the damaged scaffolding, which was installed around the spire the day of the fire. As a part of the safety works, a comprehensive Structural Health Monitoring (SHM) system has been implemented on various parts of the building by OSMOS, including high-precision lasers to detect and anticipate movements of the damaged vaults first, and then up to more than 140 sensors.

This complex system involves several different types of sensors, measurements and data analysis tools, including an immediate alert feature based on tilt and strain measurements on the damaged scaffolding of the spire during its dismantling until November 2020, a static monitoring of the deflection of the vaults with rows of tiltmeters, and Operational Modal Analysis (OMA) performed from numerous accelerometers on both the timber structures inside the two belfries and on the vaults and pillars of the nave (OSMOS Group SA, 2020).

Such OMA are often performed on historical buildings, in particular on belfries, in order to assess structural behaviors in relation with bell swings (Metz Cathedral; Patron-Solares, 2005) or when damaged by earthquake (St Silvestro belfry in L'Aquila 2021; Capanna, 2021).

This paper focuses on two tasks of this vast SHM enterprise: first the monitoring of the vibrations of the vaults and belfries, to identify the free vibration modes of the structure, and then the continuous assessment of the movements of the vaults of the nave.

II. Vibration Monitoring

A. *Aim of the Vibration Monitoring*

The Vibration Monitoring of the Notre-Dame de Paris Cathedral was a short-term operation conceived to give inputs for structural models of the building, in view of the future reconstruction works. The monitoring system, which consists in 48 accelerometers, was in operation from December 14, 2020, to January 28, 2021. However, as the aim was only to get modal characteristics of the structure, the analysis was carried out from one single data sample of one hour, recorded on December 27, 2020.

The Monitoring System covered three separate parts of the cathedral, considered as structurally independent: the timber structure inside the North belfry, the timber structure inside the South belfry, and a sample of two vaults of the nave (Figure 1). Thus, the OMA was performed on each one of these three objects separately.

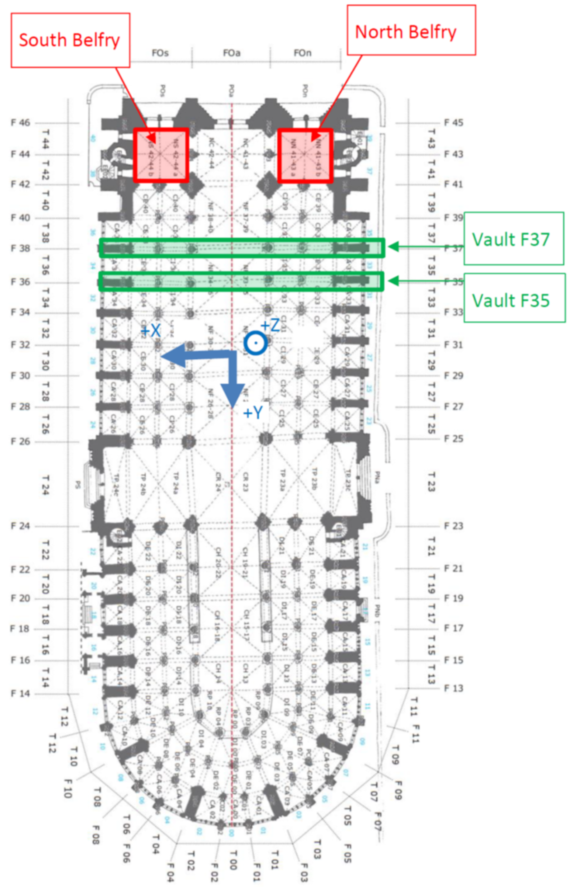

Figure 1. Plan view of the cathedral with the zones instrumented for the vibration analysis.

The results of the analysis consisted in lists of modal characteristics, including frequency, damping ratio and mode shape, directly deduced from the synchronized acceleration measurements taken under ambient noise conditions only. There was no dedicated dynamic excitation, considering the criticality of the situation of the structure, dating form the 12th century and just recovering from a catastrophic fire.

B. *Sensor layout*

The 48 accelerometers were set to catch the most significant movements due to the free vibrations of the structures.

In the case of the timber structures inside the belfries, three different levels were instrumented, each of them with three accelerometers on two different locations, to assess horizontal movements in both transverse directions and in rotation for each level. In addition, a three-axis accelerometer was installed at the location of the support of the main bell, to check the risk of resonance for future bell ringing (Figures 2 - 3, Table1).

In the case of the two stone vaults of the nave, the set of accelerometers was conceived to assess the vertical movement (Z axis) of the vault on three different locations, and the transverse horizontal movement (North-South, X axis) of the pillars at the junction with the arches of the vault and at the top (Figure 4, Table 2). In addition, the movement in both horizontal directions at the top of the buttresses was also measured, as well as the movement of the keystone in the longitudinal direction (East-West, Y Axis).

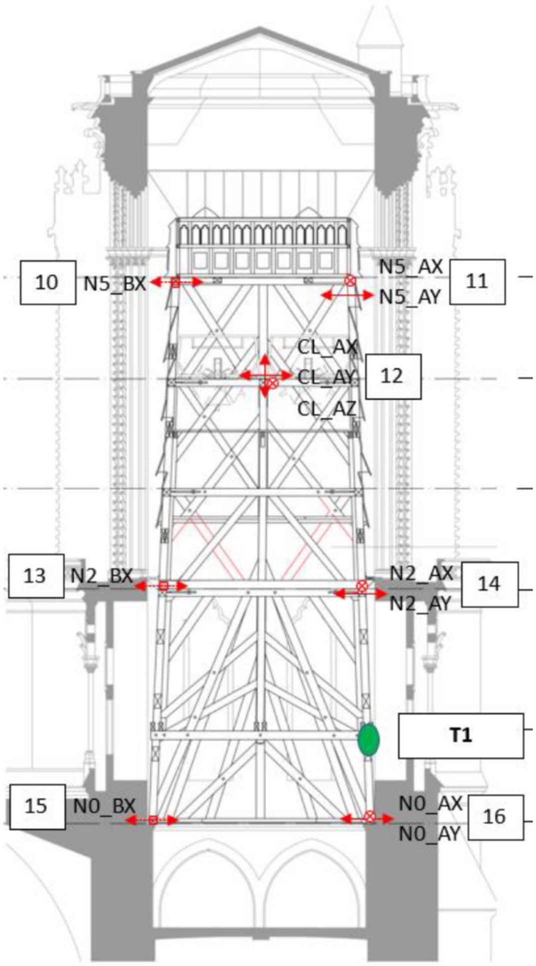

Figure 2. Accelerometer layout for the vibration analysis of the North belfry. The sensors are set on the timber structure supporting the bells inside the masonry tower.

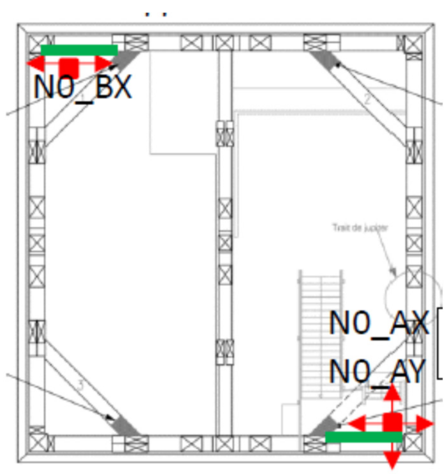

Figure 3. Accelerometer layout at a belfry level (similar arrangement for both belfry).

Table 1. Accelerometers position on the belfry (identical repartition for the north and south belfry)

Name	Height [m]	Direction	Position
N0_AX	69	+X	Bottom-Right Corner
N0_AY	69	-Y	
N0_BX	69	-X	Upper-Left Corner
N2_AX	79	+X	Bottom-Right Corner
N2_AY	79	-Y	
N2_BX	79	-X	Upper-Left Corner
CL_AX	88	+X	Bell support
CL_AY	88	+Y	
CL_AZ	88	+Z	
N5_AX	93	+X	Bottom-Right Corner
N5_AY	93	-Y	
N5_BX	93	-X	Upper-Left Corner

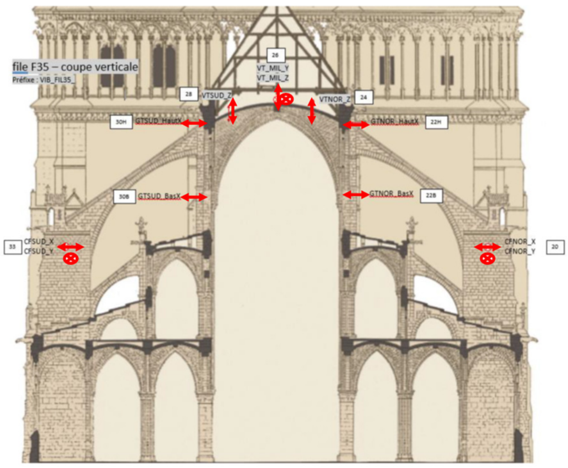

Figure 4. Accelerometer layout for the vibration analysis of one of the vault of the nave.

Table 2. Accelerometers position on the nave vault (identical repartition for the two vaults)

Name	Height [m]	Direction	Position
CFNOR_X	55	-X	North buttress
CFNOR_Y	55	+Y	
CFSUD_X	55	-X	South buttress
CFSUD_Y	55	+Y	
GTNOR_BasX	60	+X	Great transept
GTNOR_HautX	64	+X	North wall
GTSUD_BasX	60	-X	Great transept
GTSUD_HautX	64	-X	South wall
VTMIL_Y	68	-Y	Middle of the vault
VTMIL_Z	68	+Z	
VTNOR_Z	67	+Z	North Vault
VTSUD_Z	67	+Z	South Vault

The whole layout consisted in four groups of 12 accelerometers each: North belfry, South belfry, vault nb 35 and vault nb 37. The accelerometers were OSMOS AAA sensors with a measurement range of +/- 4g, a noise density of 20 µg/√Hz and 1% horizontal axis sensitivity (OSMOS Group AAA Tri-Axial Analogue Accelerometer Specifications, 2022). Each group of 12 sensors was connected to an OSMOS EDAS data acquisition system, which performed the interrogation of the sensors with a 100 Hz sampling rate and the synchronization of the measurements, necessary for the OMA.

C. *Operational Modal Analysis Methodology*

The OMA was performed on the synchronized acceleration measurements by the mean of an Eigensystem Realization Algorithm (ERA) after Juang and Pappa (1985), recently documented for applications in the identification of the vibration modes of buildings and civil structures (Bulut *et al.*, 2019). In the ERA methodology, the state-space model is obtained from a factorization of a Hankel matrix of Markov parameters using the singular value decomposition. For this application, an output-only way of using the ERA was implemented, in which the Markov parameters are obtained as correlation matrices between the output different channels, 12 for each one of the four zones.

This method was recently applied in the frame of an experimental study on one pier of the Millau viaduct in France, from strain measurements on two different levels on the pier, under the effects of strong winds (Cartiaux *et al.*, 2021). In the case of Notre-Dame, the data used for the OMA was acceleration data, in a more classical way, however this method has been proven to be robust to other types of measurements.

The ERA gives results in the form of a stabilization diagram, from which abstract modes can be deduced. An abstract mode has the frequency and the damping ratio of an actual free vibration mode, and its shape is described by a set of factors, with one (real number) value associated with each one of the accelerometer channels.

Once the abstract modes have been identified, the actual mode shapes are built by considering the locations and directions of the accelerometer channels. The shape between two sensor locations is then interpolated according to the geometry of the structure. In the case of the belfries, the accelerometer layout allows to quantify both horizontal displacements (bending modes) and rotation (torsion modes) for each one of the instrumented levels of the timber structure.

The data used for the OMA was recorded on December 27, 2020. It is one single sample of one full hour for all 48 accelerometers, including some episodes of significant wind with a wind speed up to 70 km/h. The results have then been confirmed by a similar analysis performed on four other samples of data at different dates in January 2021.

D. *Results on the belfries*

The timber structures inside the belfries are classical objects for an OMA, similar in some way to high-rise buildings, for example. Thus, the locations and directions of the accelerometer channels were decided following usual guidelines, to assess bending and torsion modes through the movement of rigid floors, at three main levels.

However, the complexity of the timber bracings, also different between the North belfry and the South one, induced interesting dynamic characteristics with strong differences from North to South. Tables 3 and 4 summarize the results of the OMA for each belfry. X (North-South) and Y (East-West) directions refer to Figure 1.

Table 3. OMA for the North Belfry

Frequency [Hz]	Damping Ratio [%]	Shape
1.2	2.7	Y Bending
3.4	4.7	Y Bending
4.5	4.3	X Bending
4.6	3.3	XY Bending
5.6	5.4	Torsion
6.1	5.1	Torsion

Table 4. OMA for the South Belfry

Frequency [Hz]	Damping Ratio [%]	Shape
1.3	2.0	XY Bending
1.5	2.6	XY Bending
1.9	2.3	XY Bending
3.8	3.7	XY Bending
4.3	2.5	X Bending
4.7	2.2	Torsion
5.5	2.8	Torsion
5.8	4.1	Torsion

For both belfries, the first mode is a bending mode with similar frequencies around 1.2-1.3 Hz. Torsion modes appear starting around 5 Hz (5.6 Hz North and 4.7 Hz South). Differences appear mainly for the second and next bending modes, both in terms of frequencies and mode shapes: on the North belfry, bending modes mostly have a main direction X or Y, while on the South we have mixed modes combining both directions. The frequencies are also higher in the case of the North belfry, except for the first bending mode.

It is also noted that few modes, except the first one, induce movements of all the levels along the height of the belfries. Only the top half of the timber structure has a significant participation in higher bending modes and in the torsion modes, while the lower half appears to be retained by the surrounding masonry tower. The visualization of some of the mode shapes is released on Figures 5 and 6.

E. *Results on the vaults*

The stone vaults of the nave are more exotic objects for an OMA than the belfries. They are composed of very different types of masonry structures, from massive buttresses to thin pillars and light keystone. The 12 accelerometers layout is then a compromise between comprehensiveness of the measurements and economical possibility. It allows to assess the global movements of each one of the two instrumented vaults along the nave at the locations where it is expected to be the most significant, including the keystone, the top of the buttresses and of the pillars. However, some assumptions had to be accepted to deduce whole mode shapes from the limited number of measurement locations, like fixed bearing conditions at the soil interface.

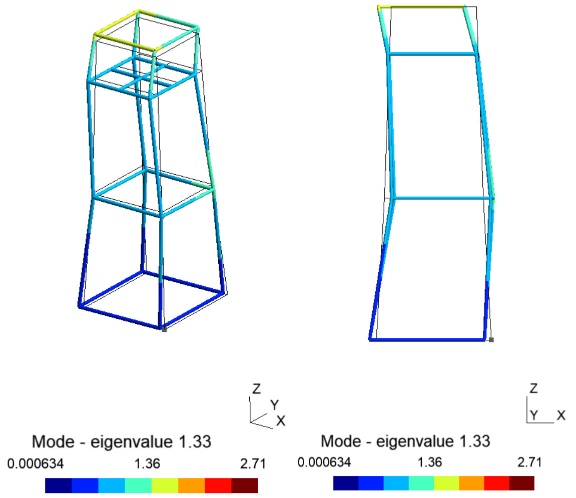

Figure 5. First bending mode of the timber structure inside the South belfry, at 1.33 Hz. The mode shape shows bending in both X and Y directions on all levels along the height of the tower.

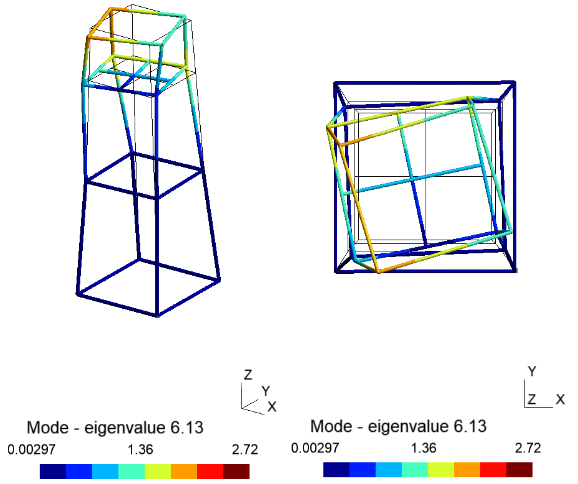

Figure 6. Torsion mode of the timber structure inside the North belfry, at 6.13 Hz. The torsion appears as a local mode of the top of the structure, while the lower part has very few movements.

Unlike the case of the two belfries, the two vaults show good similarities concerning the frequencies of the main vibration modes, but also slight differences. Tables 5 and 6 summarize the results of the OMA for each vault. X (North-South) and Y (East-West) directions refer to Figure 1.

In both cases, the first vibration modes are local vibrations of the South buttress in the East-West direction (2.1 Hz and 1.9 Hz, Figure 7), then a similar main bending mode of the whole vault in the North-South direction (2.4 Hz and 2.3 Hz, Figure 8), and then the local vibrations of the North buttress in the East-West direction (2.6 Hz for both). The fourth mode is also similar with another global bending in the North-South direction (3.1 Hz and 3.4 Hz), as well as the local vertical bending modes of the keystone at higher frequencies around 11 Hz.

Table 5. OMA for the vault nb 35

Frequency [Hz]	Damping Ratio [%]	Shape
2.1	2.8	South buttress in dir. Y
2.4	8.9	Global bending in dir. X
2.6	2.7	North buttress in dir. Y
3.1	3.1	Global bending in dir. X
3.4	3.6	Bending of North side in dir. X
4.8	6.5	Keystone in dir. Z
11.2	6.5	Keystone in dir. Z

Table 6. OMA for the vault nb 37

Frequency [Hz]	Damping Ratio [%]	Shape
1.9	1.3	South buttress in dir. Y
2.3	2.3	Global bending in dir. X
2.6	2.6	North buttress in dir. Y
3.4	4.3	Global bending in dir. X
4.2	4.0	Bending of South side in dir. X
4.7	8.1	Global bending in dir. X
10.7	4.1	Keystone in dir. Z
11.2	8.9	Keystone in dir. Z

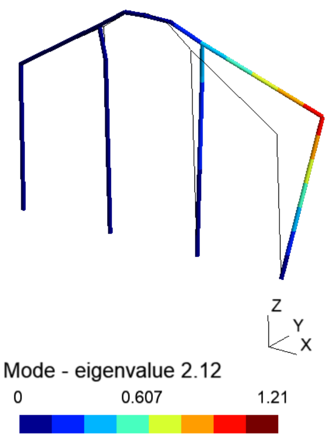

Figure 7. Local mode of the South buttress in direction Y (East-West) on the vault nb 35.

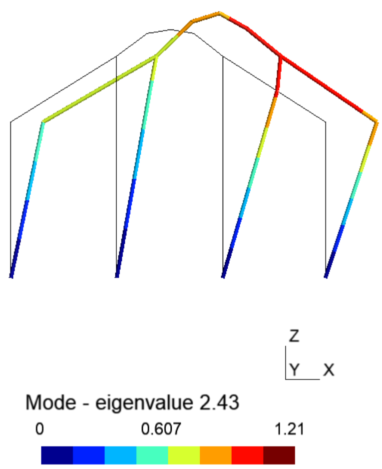

Figure 8. Global bending mode in the direction X (North-South) on the vault nb 35.

Intermediate modes present some discrepancies between the two vaults: bending of either the North side (Vault nb 35, 3.4 Hz) or the South side only (Vault nb 37, 4.2 Hz), and a specific mode shape at 4.7 Hz for the vault nb 37, combining a vertical displacement of the keystone and opposite bending on both North and South sides (Figure 9).

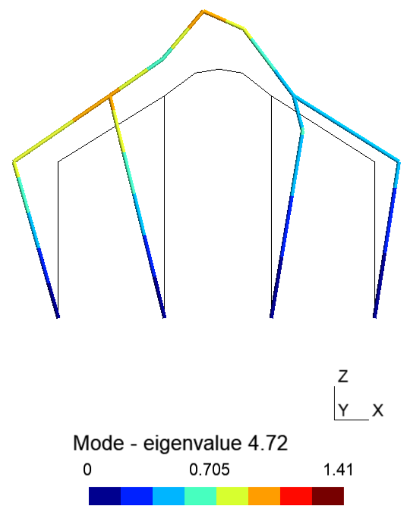

Figure 9. Specific combined mode on the vault nb 37, with vertical displacement and opposite bending of both North and South sides.

The OMA performed on the vaults from a one-hour sample of acceleration records at 100 Hz sampling rate gave consistent results in terms of frequencies and mode shapes. The damping ratio is less reliable, as it is not easy to deduce from ambient noise only. Indeed, the accurate estimation of the damping ratio by the mean of an ERA requires the assumption of pure white noise as an input, which for sure is not perfectly fulfilled under real conditions on site. However, the order of magnitude of the estimated damping ratios is still consistent with a masonry structure.

III. Settlements of the Vaults

A. *Aim of the settlement monitoring and sensor layout*

The fire of April 15, 2019, induced strong evolutions concerning the descent of loads on the vault structure: the whole roof was destroyed, and some parts of the vaults themselves did not resist to the collapse of the spire. Within the first two weeks after the fire, a first monitoring system was set up to detect any further movement of the damaged vaults, by the mean of high precision lasers (La Fabrique de Notre-Dame, 2021). This was the only option, as the access to the vault was not possible to install sensors or targets.

However, this solution faced numerous issues during the safety works, since the space between the laser and its target point on the vault is supposed to remain clear. This condition imposed to displace some lasers regularly, which troubled the continuity of the data acquisition, and eventually the configuration of the workplace imposed to seek another way to assess the settlements of the vaults.

Thus, a new monitoring system was set up in February 2021. Since it had become possible to access the cleaned vaults, the sensors could be set directly on the structure at that time. The solution consisted in tiltmeter chains along the transverse profile of the vault: each chain is composed of five high-resolution Senceive autonomous tiltmeters, fixed on the upper side of the vault with plaster.

The variations of the tilt for each one of the sensors reflects the average slope of the vault at its location, and the integration of the successive slopes allows an estimation of the settlement along the transverse profile. Four of the tiltmeters are used for the slope estimation, and the fifth one is set on a fixed point (relatively to the vault, i.e., on the next wall) and is used as a reference (Figure 10).

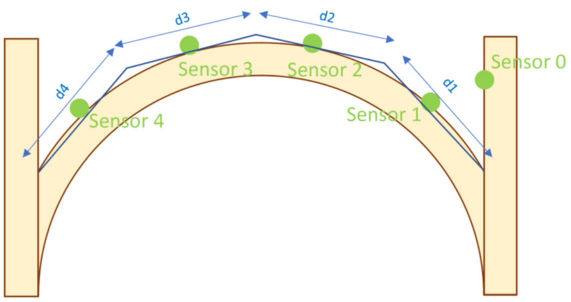

Figure 10. Schematic view of a tiltmeter chain on a vault with four slopes. Sensor 0 is the reference.

15 tiltmeter chains have been used on the vaults of Notre-Dame de Paris: six on the nave, six on the choir and three on the transept.

B. *Main results*

On the period from February 2021 to June 2021, very few movements of the vaults have been measured. Indeed, at this stage of the safety works, the structure of the whole cathedral was already strongly stabilized with additional supports.

Millimetric fluctuations are cyclically observed every day, due to the effect of the temperature variations. Apart of these variations, global trends have been assessed only for the choir, with settlements on the south part of the vaults near to the transept, where the vaults collapsed during the fire (Figure 11). The same is observed on the north part of transept, also consistent with the vicinity of collapsed vaults.

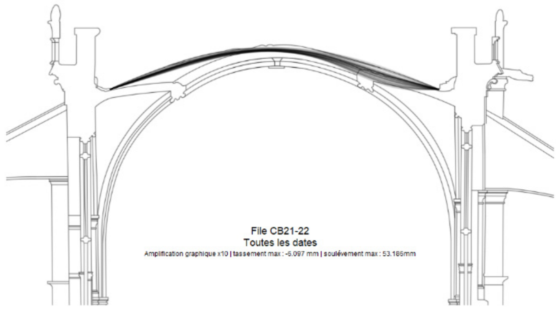

Figure 11. Envelop of the settlements of the vaults of the choir, near to the collapsed vaults of the transept, February 2021 to June 2021 (amplified 10 times).

IV. Conclusion

The very complex and challenging operation to ensure the structural safety and then restore the Notre-Dame de Paris cathedral involves a comprehensive continuous SHM system for this iconic heritage, with various problematics, sensor types, and methods for data analysis.

Among the numerous missions for which the SHM enables to give an immediate and consistent knowledge about the evolution of the structure, including real time alerts, if necessary, the two examples described in this publication show relevant applications for two very different purposes at different time scales.

As part of the diagnosis, in view of getting reliable inputs for a structural model, the natural vibration modes of different important elements of the cathedral have been efficiently identified through the use of OMA on relatively short samples of records (one hour) at a high sampling rate, using a combination of numerous accelerometers.

At the other hand, the stability of the vaults has been assessed on a long period with static tilt measurements every hour, which enabled to estimate the shape of the vault settlements on several parts of the nave, transept, and choir.

All the data collected during this exceptional project and the resulting analysis may be further used by scientists to enhance the knowledge about the wonderful and living witness of the human heritage that is Notre-Dame de Paris. As a research perspective, the obtained modal analysis may be compared with theoretical models (as finite element model) of the cathedral to assess the actual structural properties, accounting of aging and damages. These results could be also compared with further modal analysis after the reinforcement of the cathedral, in particular for the vaults.

V. Acknowledgements

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References

Bulut Y., Unal B., and Bernal D. (2019) Performance Evaluation of System Identification Al-gorithms for Structural Health Monitoring. In: *5th International Conference on Earthquake Engineering and Seismology, Ankara, 8-11 October 2019*.

Capanna I., Cirella R., Aloisio A., Alaggio R., Di Faio F., and Fragiacomo M. (2021). Operational Modal Analysis, Model Update and Fragility Curves Estimation, through Truncated

Incremental Dynamic Analysis, of a Masonry Belfry. *Buildings*, 11, 120. DOI: 10.3390/buildings11030120.

Cartiaux F.B., Le Corvec V., Cachot E., Vayssade T., and Servant C. (2021) Continuous Static and Dynamic Strain Measurements on Civil Infrastructures: Case Study on One Pier of the Millau Viaduct. In: Rizzo P., Milazzo A. (eds) *European Workshop on Structural Health Monitoring. EWSHM 2020.* Lecture Notes in Civil Engineering, vol 127. Springer.

Juang J. N., and Pappa R. S. (1985). An eigensystem realization algorithm for modal parameter identification and model reduction. In: *Journal of guidance, control, and dynamics,* 8(5), pp. 620-627.

La Fabrique de Notre-Dame, (2021). Available in: https://fr.calameo.com/read/00557636894eb0332971f?authid=TW18VI9mAvBC, consulted 2022/01/25.

OSMOS Group SA, 2020, https://www.osmos-group.com/en/news/osmos-group-heart-notre-dame-de-paris, consulted 2022/01/25.

Patron-Solares A., Cremona C., Bottineau C., Leconte R. and Goepfer F. (2005) *Experimental Vibration Analysis for Civil Engineering Structures,* Bordeaux France, 26-28 October 2005.

OSMOS Group AAA Tri-Axial Analogue Accelerometer Specifications http://www.sanlien.com.tw/product/aaa-tri-axial-analogue-accelerometer/, consulted 2022/05/10

Unesco World Heritage List, (2021). Paris, Banks of the Seine: Available in: https://whc.unesco.org/en/list/600, consulted 2022/01/25.