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SHM Monitoring of Historical Buildings for Rapid Assessment of Structural Condition after Blast Events

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SUMMARY

Military-related blast events pose a significant threat to historical masonry structures and require rapid post-event assessment to support conservation decisions. This study presents the application of a Structural Health Monitoring (SHM) system for evaluating the dynamic response of the Church above the Economic Gate of the Kyiv-Pechersk Lavra during the missile attack of 15 June 2026. The monitoring system combines accelerometric and inclinometric sensors to record transient dynamic responses and possible residual structural displacements. Accelerometric records identified a distinct short-duration impulse with a peak acceleration of 0.05089 g, while inclinometric measurements detected transient inclination changes reaching up to 35 times the background level, although no residual deformation was observed after the event. The estimated peak particle velocity remained below commonly accepted damage thresholds for historic buildings according to DIN 4150-3. Although the blast caused severe damage to the nearby Dormition Cathedral, approximately 200 m away, no evidence of hazardous deformation or loss of structural stability was detected in the monitored Gate Church. The results demonstrate that integrated accelerometric and inclinometric SHM enables rapid post-blast assessment of heritage structures and provides objective information for emergency inspection, structural safety evaluation, and long-term conservation monitoring.

Keywords: Structural health monitoring; Heritage buildings; Blast-induced vibrations; Accelerometric monitoring; Inclinometric monitoring; Kyiv-Pechersk Lavra.

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Introduction

Heritage buildings are vulnerable structural systems because they usually combine historical masonry, heterogeneous materials, previous repairs, local defects, and long-term degradation processes. Their actual mechanical behaviour is difficult to evaluate only by visual inspection, especially under short-term dynamic impacts. Therefore, structural health monitoring and dynamic monitoring methods are widely used for historical structures, as they allow changes in vibration response and abnormal peaks to be identified from measured data (Barsocchi et al., 2021; Cabboi et al., 2017; Rossi & Bournas, 2023). Ambient vibration testing and operational modal analysis are also widely used to identify the dynamic behaviour of historical masonry structures (Degli Abbati et al., 2024; García-Macías & Ubertini, 2020; Sunara et al., 2023).

Blast-induced vibrations are a specific type of short-duration dynamic action characterized by impulse excitation and rapid energy transfer through soil and structural elements (Rodríguez et al., 2022; Rosenhaim & Koppe, 2017). This problem is especially relevant for Ukrainian heritage buildings exposed to military actions, including the Kyiv-Pechersk Lavra (Cherevko et al., 2025). The purpose of this study is to assess the dynamic response of a Lavra heritage building to a blast-induced impulse effect using accelerometric and inclinometric monitoring data.

Method and Theory

The research methodology is based on the combined analysis of accelerometric and inclinometric monitoring data, following the general principles of dynamic monitoring and interpretation of structural response from measured signals (Vabishchevych et al., 2024). Acceleration records were used to identify short-term vibration responses caused by blast-induced impulse actions, while inclination records were used to detect possible changes in the spatial position of structural elements. The data were analysed as synchronized time series for three intervals: before the event, during the impulse response, and after the event. This approach makes it possible to compare background vibrations with blast-related peaks and to determine whether the dynamic action was accompanied by residual inclination changes. At the first stage, the constant component of the acceleration signal was removed in order to analyse only the dynamic part of the response. The maximum absolute acceleration was determined for each measuring direction as:

$$\boldsymbol{a_{max} = max\,|a(t)|} \tag{1}$$

where a(t) is the measured acceleration as a function of time. In addition, the responses recorded in different measuring directions were compared to identify the dominant direction of vibration. For inclinometric data, the main parameter was the difference between the average inclination values before and after the selected event:

$$\boldsymbol{\Delta\theta \;=\; \theta_{after} - \theta_{before}} \tag{2}$$

where θ_{before} and θ_{after} are the average inclination values before and after the blast-related event. The joint interpretation of acceleration peaks and inclination changes allows short-term dynamic effects to be separated from possible residual structural changes. Such a procedure is suitable for rapid post-event assessment of historical masonry structures and for further use in long-term dynamic monitoring systems.

The monitoring was carried out using NPLUS VITTORIO sensors, including MEMS accelerometric and inclinometric measuring units, with support from UNESCO. The sensors are installed on structural elements of Building No. 82, the Church above the Economic Gate of the National Reserve “Kyiv-Pechersk Lavra”. The recorded data were processed using custom Python-based scripts for time-series analysis, peak response identification, and graphical interpretation. The monitoring data collected between May and June 2026 were analysed. During this period, the SHM system recorded the dynamic response of the structure to external loading, including impulsive events caused by missile strikes.

Results

The observation objects (the Church above the Economic Gate and the Dormition Cathedral) are located within the Upper Lavra, which belongs to the Kyiv loess plateau. According to their technical condition and the type of foundation soils, these structures belong to the third priority group for restoration and repair works (Kril et al., 2024). According to engineering-geological studies of the Kyiv-Pechersk Lavra territory, this area is characterized by a cover of loess and loess-like soils, mainly loess-like sandy loams and loams, underlain by sandy and clay deposits of the Dnipro glacial complex. The response of loess soils to dynamic loading depends on slight variations in moisture content. They may exhibit positive or negative dilatancy, while moisture above the critical level causes rarefaction. Weakly cohesive soils show the highest frequency-selective sensitivity in the range of 15–45 Hz (Cherevko et al., 2025).

The analysis of monitoring records obtained during May–June 2026 showed that the blast-related dynamic effect can be clearly identified in accelerometric records as a short-duration peak that significantly exceeds the background vibration level. It was established that blast-induced vibration acceleration amplitudes exceeded the background values by approximately 20–35 times, corresponding to blast-related events located at different distances from the observation point. In all analysed records, the blast-related responses had a distinct peak character and were observed in different measuring directions, which confirms the dynamic nature of the recorded event. The representative 5 s fragment of the accelerometric record shows the structural response during the military impact on 15 June 2026, Figure 1. The peak marked by a red circle is associated with the blast effect recorded at Building No. 82, the Church above the Economic Gate of the Kyiv-Pechersk Lavra, located approximately 200 m from the affected area near the Dormition Cathedral. The peak vibration acceleration was recorded by sensor 040DAAC0 in the z-direction and reached 0.05089 g, which corresponds to approximately 0.5 m/s².

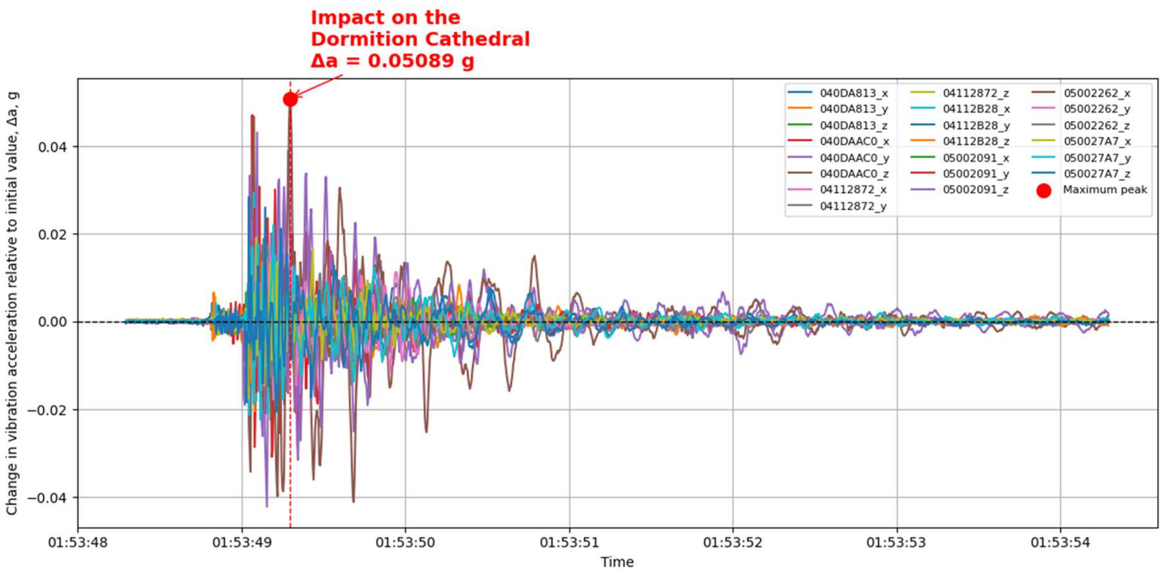

Figure 1. *Blast-induced acceleration recorded by the SHM system at Building No. 82 (Church above the Economic Gate), Kyiv-Pechersk Lavra, during the missile attack on 15 June 2026*

Taking into account approximate engineering correlations between peak acceleration and seismic intensity according to the MSK-64 scale, this value may be cautiously compared with an intensity of about VI according to DBN V.1.1-12:2014. However, this comparison depends on the spectral characteristics, duration of vibrations, and the fact that the acceleration was recorded on the structure rather than on free-field ground. Since the assessment of possible vibration-induced damage to buildings should be based on peak particle velocity rather than acceleration, a preliminary conversion was performed using the dominant frequency component of the recorded signal. For a dominant frequency of about 51 Hz, the corresponding peak particle velocity is approximately 1.5 mm/s. This value is below commonly used damage threshold values for buildings according to DIN 4150-3 (Vibrations in buildings, 2016). However, the obtained estimate should be considered preliminary, because a final assessment requires direct velocity records or numerical integration of the measured acceleration signal.

According to the inclinometric monitoring data, the maximum deviation during the recorded impulse event caused by the missile attack on 15 June 2026 was $\Delta\theta = 0.03498°$, which corresponds to a relative inclination of $i = \tan(\Delta\theta) \approx 0.00061$, or 0.61 mm per 1 m of height, Figure 2. For the actual height of the sensor installation h, the corresponding horizontal displacement should be determined as $\Delta = h \cdot \tan(0.03498°)$. After the impulse action, the inclination values returned to a level close to the initial state; therefore, the available data do not indicate hazardous residual inclination.

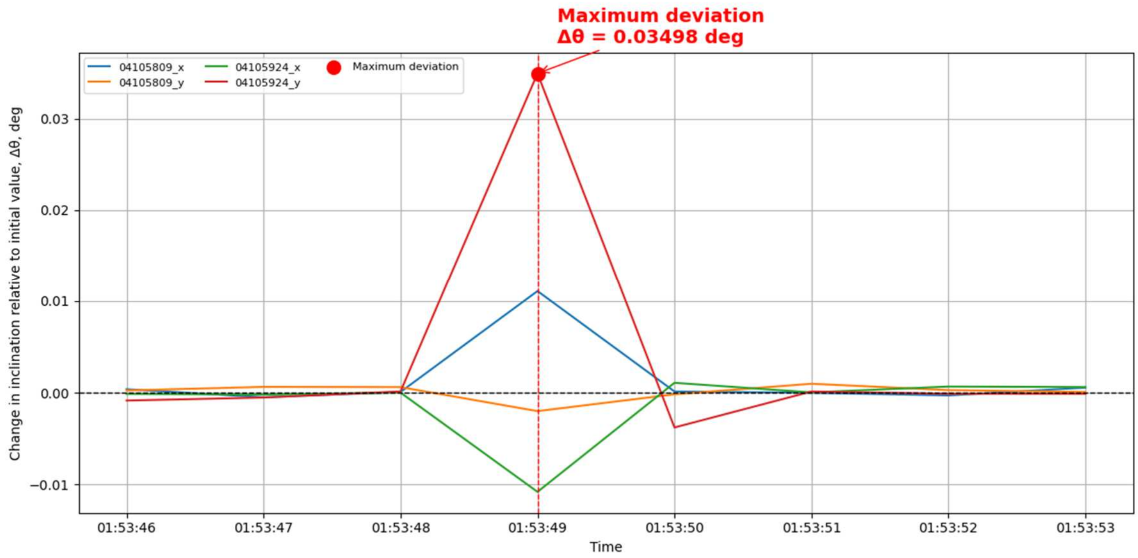

Figure 2. *Inclination changes recorded by the SHM system at Building No. 82 (Church above the Economic Gate), Kyiv-Pechersk Lavra, during the missile attack on 15 June 2026*

The obtained relative inclination value is lower than the reference limit $i \leq 0.001$, which may be used for preliminary engineering assessment of building inclination according to DBN V.2.1-10:2018. The assessment of historical buildings should also be considered in the context of DBN A.2.2-14:2016, which regulates scientific and project documentation for architectural heritage sites. However, for historical masonry structures, this comparison should be treated with caution, because their technical condition depends on existing defects, masonry condition, previous damage, and local structural conditions. Compared with the background inclination changes before the event, which did not exceed approximately 0.001° according to the graph, the maximum short-term deviation during the impulse action increased approximately 35 times.

Conclusions

The blast impact resulting from the missile attack on 15 June caused severe damage to the roof, structural elements, and interior of the Dormition Cathedral, a nationally significant architectural monument. Accelerometric and inclinometric monitoring of the Gate Church, located approximately 200 m from the explosion site, indicated that the blast effects did not result in significant changes in its stress–strain state or spatial position. The recorded acceleration values and inclination angles do not indicate the development of hazardous deformations or loss of structural stability.

The study results confirmed the effectiveness of the implemented non-destructive Structural Health Monitoring (SHM) system for the rapid assessment of the effects of extreme dynamic loads on cultural heritage structures. The integration of accelerometric and inclinometric monitoring enables rapid evaluation of the structural condition and timely detection of potential deformations.

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