EXPERIMENTAL RESEARCH INTO THE RESPONSE OF A MONUMENTAL HISTORIC STRUCTURE TO TRAFFIC-INDUCED EFFECTS OF TECHNICAL SEISMICITY

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ABSTRACT

The growing volumes of particularly heavy truck traffic with high road pavement loading values and, in many cases, poor quality and uneven road pavement surfaces intensify the effects technical seismicity on buildings situated in the vicinity of traffic routes.

KEYWORDS

Monitoring, Technical seismicity, Structure response, Traffic, Historic masonry

INTRODUCTION

The term technical seismicity denotes dynamic effects caused by traffic. Traffic-induced technical seismicity principally differs from natural seismicity in frequencies higher by an order of magnitude, which propagates into the surroundings, and in frequent repetitions where the material fatigue limit may be exceeded. The frequencies of traffic-induced shocks range from 10 to 200 cycles/sec, being most often in the 30 to 150 cycles/sec range, while the amplitudes of vibrations are very small reaching several tens of micrometres at the most. Natural seismicity has oscillation frequencies approximately 100 times lower and vibration amplitudes, on the contrary, by several orders higher [1]. The acceleration of traffic-induced shocks corresponds to the values of catastrophic earthquakes with a magnitude of 10 to 12 on the Richter scale. Vibrations due to road traffic propagating through the surrounding environment into the nearby development usually range in an interval of 5 – 25 Hz. By their amplitudes, the vibrations are in the 0.005 to 2 ms^2 range in accelerations, and the 0.05 – 25 mm/s range in velocities. The oscillation intensity criterion is usually the **oscillation velocity**, related to the relative dynamic deformation causing damage to buildings. The dominant frequencies and vibration amplitudes of the excitation of a building depend on numerous factors: the road type and condition, vehicle mass and construction, its speed and riding manner, the composition, compactness and moisture of the subsoil, and the distance from the building. The severity of traffic-induced technical seismicity largely depends on the condition and type of the building structure. Buildings damaged by cracks with insufficient stiffness of the floor and foundation structure are more vulnerable to failure due to dynamic effects. Oscillation velocities in the 1-2mm/s range should be the criterion for the assessment of the resistance of the building structure to the effects of technical seismicity. Masonry buildings without bond beams or beam and wall anchors, buildings with yielding (e.g. beam) floors, with vaults without bowstrings and with insufficiently deep and stiff, unbonded foundations are exceptionally sensitive to seismicity-induced dynamic effects.

BASILICA OF THE ASSUMPTION OF OUR LADY IN STARÁ BOLESLAV

The Basilica of the Assumption of Our Lady in Stará Boleslav is a Roman Catholic Parish Church from the beginning of the 17th century, the oldest Marian pilgrimage site in Bohemia (Figure 1). Today's church, built in the style of Early Baroque Roman churches according to the design by the Italian architect, Giovanni Maria Filippi, in 1613 to 1625, replaced an older Gothic structure. The northern tower was completed by Abraham Leuthner in 1675, while the southern tower and the new western façade were built according to the design by Kilian Ignaz Dientzenhofer in 1748–1749. In 1728–1732, the cloister behind the eastern chevet was added, the space in front of the Basilica was landscaped and a terrace built.

Fig. 1 - Basilica of the Assumption of Our Lady

Spatial, structural and material layout

The Basilica is a single-nave, rectangular-shaped structure with side chapels with a semi-circular apse along the longitudinal axis on the east side. The church dimensions are – 22.0 m in width, 48.0 m in length including the apse, the main nave height is 22.0 m, and the nave width 13.8 m.

The main nave is covered by a brickwork barrel vault 6.9 m high with a span of 13.8 m, with reinforcing arches 1.3 m wide in a 7.9 m spacing. The vault thickness, including plaster, is approx. 0.2 m, and the interior curve of the reinforcing arches reaches 0.3 m below the interior curve of the barrel vault. The barrel vault imposts lean against perimeter masonry 1 m thick. Below the level of pilaster heads (the upper edge of the heads is 15.15 m above the church floor), the masonry extends to 1.6 m in width and is founded on the barrel vaults of side chapels, which form the cloister on both sides of the main church nave. The crown of these vaults is 12.4 m above the church floor, their depth from the interior face of the main church nave perimeter masonry to the side façade is 3.1 m, and they are supported by pillars 1.35 m in width situated in the places of reinforcing arches. The dimension of the pillars in the direction perpendicular to the longitudinal axis of the church is 4.3 m, including the 1.2 m exterior perimeter wall forming the back wall of the side chapels. There is a gallery above the level of the side chapel vaults approx. 1.5 m wide covered by a barrel vault.

The church has two towers on both sides of the presbytery, which is situated on the east side of the church nave. The presbytery is also barrel-vaulted with a smaller span (Figure 2).

Fig. 2 - Vaulted structures in the interior of Basilica

The masonry of the Basilica is made of bricks with lime mortar, foundations of the Basilica are estimated to be under the crypt floor level, which is approx. 3 m below the church floor level. The church foundations are probably situated on terrace deposits with a significant proportion of sandy fraction. The vaults are made up of brick masonry with lime mortar and the Basilica is roofed by gable roof with king post roof truss.

The Basilica is located in the city center close to the 2nd class road II/610 at a distance of 5 – 12 m (Figure 3). This former state road no. 10 was, in the past, replaced by the D10 motorway, to which it forms an accompanying road and, in the case of motorway closure, forms a bypass. At the 2016 national traffic census [2], the total traffic intensity was set at 10948 vehicles / 24 hours, of which heavy motor vehicles (trucks, buses, etc.) amounted to 1655 vehicles / 24 hours, passenger vehicles 9188 vehicles / 24 hours and two-wheeled vehicles (motorcycles) 105 vehicles / 24 hours. Compared to the previous traffic census in 2010, the increase in total traffic intensity was 132% (with 185% for heavy motor vehicles, 122% for passenger cars and 89% for two-wheelers).

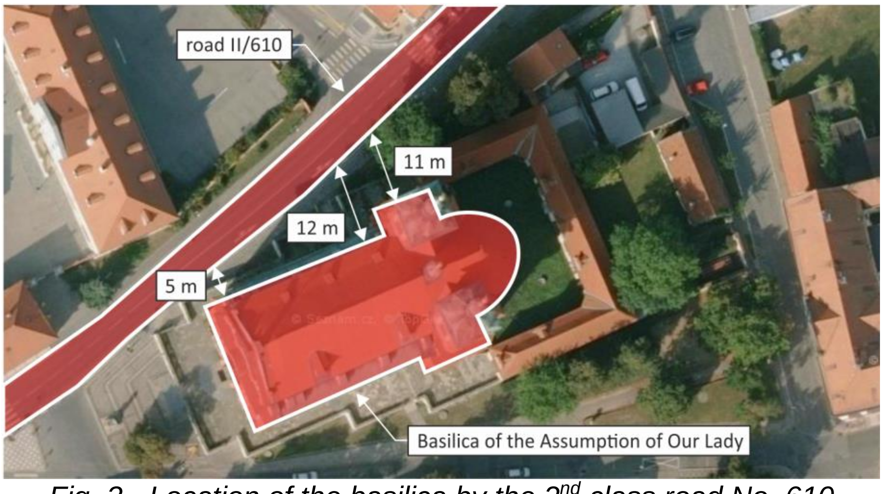

Fig. 3 - Location of the basilica by the 2nd class road No. 610

Results of a visual inspection

A preliminary (visual) survey was conducted in the Basilica aimed at the identification of the mechanical failures manifested on the surface of the load-bearing masonry, both in the interior and the exterior.

No visually observable cracks were detected in the vertical bearing walls of the perimeter and interior masonry, the masonry of the towers and the pillars. The barrel vault of the main nave and the presbytery is damaged by a longitudinal crack at the vault crown running along the entire length. It is a tensile crack up to 5 mm in width visible in the plaster on the vault face. The vault of the main nave is also damaged by cracks in the springers of barrel vault bay windows running in the same direction. The vaults of longitudinal galleries above the vaults of the main nave side chapels are damaged by cracks perpendicular to the longitudinal axis of the church and located near the main nave lunettes. The barrel vaults of the side chapels are also damaged by cracks at the crowns running in the direction perpendicular to the longitudinal axis of the church (Figure 4).

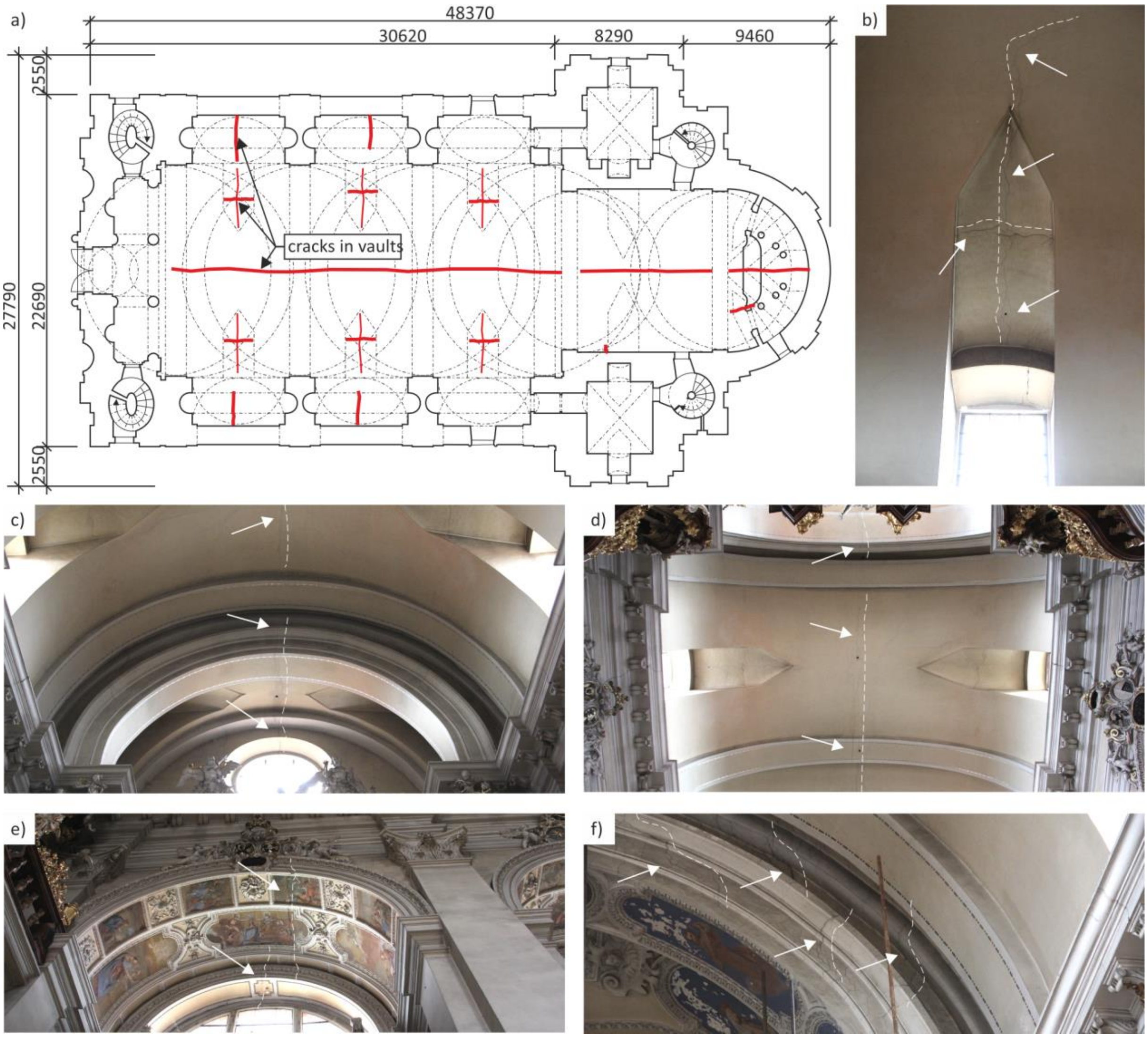

Fig. 4 - a) Scheme of the church structures' failure, b) Detail of the lunettes' failure, c) Failure of barrel vault and the arch ring at the western façade, d) Longitudinal crack in the main nave's barrel vault, e) Failure of the barrel vault of the side chapels, f) Detail of failure in arch ring footing

ANALYSIS OF THE RESULTS OF EXPERIMENTAL RESEARCH INTO A TRAFFIC-INDUCED DYNAMIC RESPONSE

The experimental measurement of the dynamic response was performed by the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences [3]. The Wilcoxon Research accelerometers, Model 731A, with a high sensitivity of 10 V/g and a noise performance of 0.5 μg RMS were used for the measurement. The dynamic response was measured at a reference point (marked by letter R) and at another three points (Figure5) in the X, Y, Z directions. Hourly records provided 5 to 12 second sections, which were computer-processed into the final effective oscillation velocities.

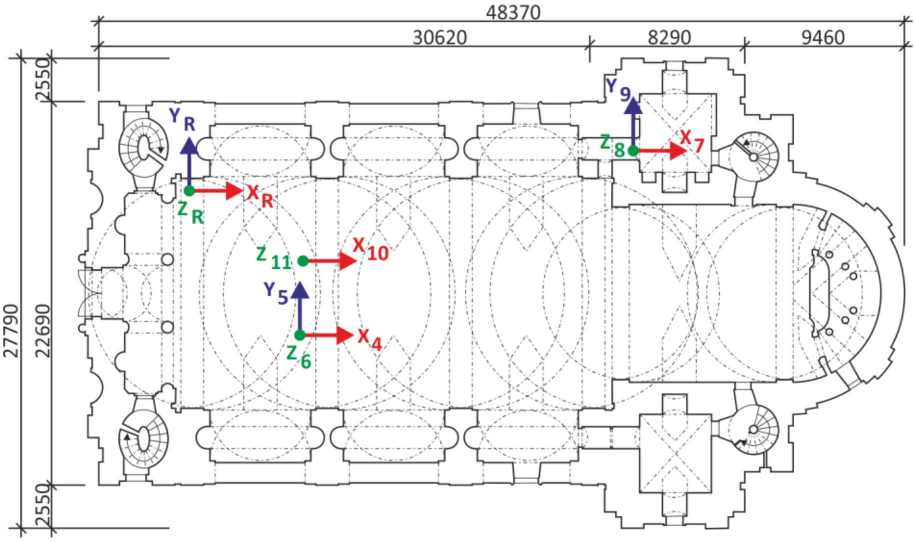

Fig. 5- Diagram of measuring points (accelerometers)

The identification of traffic-induced seismic loading is based on the analysis of the road response induced by a vehicle passing on the uneven surface of a road pavement. The response to loading by technical seismicity is usually assessed as the value of the effective oscillation velocity on the lowest storey, or in the foundation of a building – at reference points. In other parts of the structure, oscillation velocities greater than those measured at the reference point may be identified. In evaluating the propagation of technical shocks, deflections in the vertical direction *w* and deflections in the horizontal direction, in *u* and *v* components, are assessed. The deflection w_x decreases with the horizontal distance *x* from the source of seismic waves following approximately the formula valid for $x > l$:

$$w_x = w_l \left(\frac{l}{x}\right)^{1/2} \times exp[-a - l] \qquad (1)$$

where:

w_l deflection at a distance l from the source measured on the surface of the territory;

w_x deflection at a distance x from the source measured on the surface of the territory;

l horizontal distance from the source in metres at the point where the deflection w_l was detected

a absorption constant

DOI 10.14311/CEJ.2019.04.0039

Formula (1) was derived for Rayleigh waves and for a distance l > 10 m, but its indicative application for other types of waves is also possible.

The dynamic response caused by technical seismicity, except for the response to blasting operations, does not need to be further analysed in terms of the ultimate bearing capacity, unless the effective velocity of movement at the reference point exceeds the limit values for the respective resistance class (pursuant to ČSN 73 0040 [4]) and significance of a building (pursuant to ČSN EN 1991-1-7 [5]).

The analysis and evaluation of the results of the measurement of the response of the structure of the Basilica of the Assumption of Our Lady [3] are in compliance with ČSN 730040 (resistance classes of buildings) [4] and ČSN EN 1991-1-7 (classes of significance of buildings and effective velocity limits) [5].

The measured values of the effective velocity of the dynamic response (mm/s) for cases of bidirectional lorry, heavy truck, bus and tractor traffic range as follows:

vault … (0.1199 to 0.5013) mm/s, at points ACC 6 and ACC 11

tower … (0.3135 to 1.1947) mm/s, at points ACC 8 and ACC 9

reference point … (0.0400 max. ref. X, 0.0481 max. ref. Y, 0.0413 max. ref. Z).

To evaluate the detected velocities of movement at the selected points the building was classified in Class CC3 in the category of significance (ČSN EN 1991-1 [5]) and in Class A in the category of resistance (ČSN 730040 [4]).

The main criterion for the evaluation of movements (shocks) under ČSN 730040 [4] is the response to loading by vibrations assessed by the effective velocity value. Pursuant to ČSN EN 1991-1-7 [5], the Basilica building can be classified in the highest class according to significance, “Class CC3”, and if we choose the resistance of the building in “Class A” (ČSN 730040 [4]), the effective velocity limit value will be 0.2 mm/s.

The velocity of movement (oscillation shocks) values at the reference point do not exceed the limit values specified by ČSN 730040. However, at points ACC6, ACC11, ACC4 (on the vault) and at points in the tower, they exceed the limit values, which complies with the note under ČSN 730040 [4]: at points other than the reference point, the oscillation velocity is usually greater. In the case of the response in the tower, where the velocity is by 100% greater than the velocity at the reference point REF, it is necessary to verify the loading by a dynamic calculation using the computational model under ČSN 730040, Art. 5 [4].

The analysis of the effect of velocity on the damage rate of a building is significantly affected by the oscillation frequency. It was manifested that frequencies higher than 100 Hz (characteristic frequencies of technical seismicity), as a rule, do not cause such failures as frequencies lower than 10 Hz (characteristic frequencies of natural seismicity). This is caused by the lag of deformations behind the stresses.

SUMMARY OF THE RESULTS OF EXPERIMENTAL RESEARCH INTO A TRAFFIC-INDUCED DYNAMIC RESPONSE

In monitoring the response of a structure to loading by technical seismicity, the value of the effective oscillation velocity (RMS) on the lowest storey, or in the foundation of a building, at the so-called reference point, is usually assessed. The effective velocity values at the reference point measured in two horizontal directions X, Y and in the vertical direction Z are rather small, the traffic passages were evident, but their manifestation was insignificant. The standard also admits that in other places of the structure, the oscillation velocities may be higher. This is the case of monitored structure, as in some places the measured values are above the limit. Based on the results of oscillation velocity measurements at selected points and the monitoring of a potential movement of the crack on the vault, we may conclude that the load-bearing structure of the church is not at risk due to traffic-induced technical seismicity on the adjacent road. After reaching a certain number of cycles in the order of magnitude larger than 10^5, very high frequencies may cause material fatigue with a subsequent growth in deformations and permanent strain preceding major failures of the vaulted structure.

STABILISATION OF THE EXISTING STATE OF DAMAGE TO THE BASILICA STRUCTURE IN TERMS OF STATIC AND DYNAMIC LOADING

Although the experimental measurements of the effect of traffic-induced technical seismicity show that the load-bearing structure of the Basilica is not at risk due to traffic-induced technical seismicity on the adjacent road, it is recommended to take preventive measures to protect the load-bearing structure of the Basilica. It is evident from the type and pattern of cracks on the vaulted system, considering the results of the experimental measurement of the dynamic response [3], that the most likely and the main cause of the existing damage to the barrel vault and arches over the Basilica main nave, the damage to the barrel vault in the springers of bay windows and the vaults of longitudinal galleries above the vaulted spaces of chapels is insufficient absorption of horizontal forces exerted by the barrel vaults. The barrel vaults over the main nave and the adjoining vaults lack visible bowstrings, and horizontal forces – particularly the forces exerted by the effects of the barrel vault with a span of 13.8 m over the main nave – are mostly transferred by the massive structures of the supporting system. The relatively very small horizontal deformations of the supporting system in the order of magnitude of 10^{-3} of the vault span may be the cause of the appearance of tensile stresses at the vault crown, which exceed the vault masonry strength in tension and are the cause of tensile cracks. In the case that a solution with a visible bowstring system cannot be used, the following solution is recommended as the main rehabilitation measure of the existing damage to the vaults:

- execution of vault beam ties at a level above the vaults;
- execution of inclined bowstrings suspended on an additionally mounted stiff girder;
- execution of a prestressed steel strip on the outer curve of the vault made up of prestressed partial segments prestressed by a composite strip (for example according to patent application no. 2018-608 [6]).

To increase the overall efficiency of the proposed solution, it is desirable to prestress the supporting walls of the vaults in the horizontal and vertical direction by prestressed carbon lamellas, or by carbon composite strips fitted in thin horizontal grooves in the area of vault imposts on the outer side of the supporting walls and in thin vertical grooves with anchoring zones at the crown and near the footing bottom of the supporting walls.

Based on an additional survey, a modification enhancing the stiffness of the footing should be designed and executed. An inseparable part of enhancing the stability of the Basilica and preventing further crack propagation is continuous monitoring, the application of simple methods of measuring changes in crack widths and, last but not least, monitoring the quality of the road pavement surface on the adjoining road.

ACKNOWLEDGEMENTS

The article was written with support from the NAKI DG16P02M055 project “Development and Research into Materials, Procedures and Technologies for Restoration, Conservation and

Strengthening of Historic Masonry Structures and Surfaces and Systems of Preventive Care of Historic and Heritage Buildings Threatened by Anthropogenic and Natural Risks".

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