Experimental Investigation of Influences of Traffic Load on the Church of the Assumption of the Virgin Mary in Stará Boleslav

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Abstract. Long-term dynamic loads represent a serious factor which compromise the safety and durability of historical buildings. Though the daily traffic may cause only low level vibrations, which an undamaged structure could safely resist, extreme values of traffic loads over longer periods can be critical having as a consequence the initiation of cracks or the growth of existing ones, such that they may endanger the structure. Good maintenance including control measurements or monitoring can aid in early damage detection and timely planning of remedial actions. The preceding statements are supported by an investigation of the effects of ambient vibrations mainly due to traffic loads on the Basilica of the Assumption of the Virgin Mary in Stará Boleslav. Attention is aimed at a structural fault, its rehabilitation and prognosis for the future.

1. Introduction

Assessment of building structures using vibration measurements is a branch of multidisciplinary research with a long tradition that combines knowledge from mechanics, electronics, material engineering and statistics (not to mention its close relation to mathematics, physics and computer engineering). Ambient vibrations from micro seismicity or traffic are also phenomena within the focus of contemporary research. So much as to the affiliation of the presented contribution to the title of the conference.

Vibrations in general can cause problems for heritage structures, or the structural problems in heritage structures may express themselves in the form of vibrations. The primary concern with respect to vibrations is their effect on the health of people (ISO 2631) as may be the case in e.g. concert halls or theatres. In most cases, the health related limits for vibrations are far above vibrations that may cause damage to a structure. If the technical condition of monuments or historical structures is considered, the lowest damage threshold of 1mm/s (peak value) was cited in [1]. The Czech National Standard [2] considers the effective value of vibrations lower than 0.4 mm/s as a safe level for building structures. Known limits from other standards are usually higher [3].

However, usually without any reasoning, an accumulation of damage due to low-level vibrations is claimed to be dangerous under certain circumstances [3]. In the case of historical structures, it may be more serious, because the omnipresent traffic vibrations are a new additional part of loading for them.
The assessment of stresses and planning of intervention measures is a difficult task in historical structures due to many uncertainties [4, 5]: unknown parameters of historical materials, unknown history of loading events, damage and repairs, global complexity (boundaries and connections), non-linear material behaviour (very limited transfer of tension forces). The application of dynamic measurements and experimental modal analysis can provide more information about the behaviour of historical structures, thus reducing the uncertainties, and help to plan their maintenance and rehabilitation more economically.

If problems connected to excessive vibrations on historical structures occur, a number of types of solutions can be applied. Some examples of vibration mitigation measures can be found in [6-9].

The Basilica of the Assumption of the Virgin Mary in Stará Boleslav (further only the Church) is close to a busy two-lane road, but the measured vibrations only slightly exceeded the above-mentioned limit of 0.4 mm/s. The vibration measurements were initiated because of a continuous longitudinal crack in the apex of the main barrel vault. The presented results document the dynamic behaviour of a baroque church which is, in contrast to gothic churches, mentioned in technical literature more rarely [4, 10]. Vibrations of the structure were measured before and after the rehabilitation, and the level of corresponding dynamic stresses was determined using a finite element (FE) model. The results from a short monitoring period were applied for a prognosis into the future.

Figure 1. Cross section of the Church
2. The results of vibration measurement in the Church

The structure is a single nave church with six vaulted side chapels, see Figures 1 and 2. The ceiling of the nave is formed by a brick barrel vault interrupted by perpendicular window-bays over each of the side chapels.

Dynamic measurement took place on the cracked vault of the main nave in July 2018 and after the rehabilitation in April 2021. The average level of vibrations obviously decreased due to the interventions as the average measured PSD-s in Figure 3 show. In fact, the intensity of the traffic was not measured, and therefore it cannot be proved if the dynamic load was equal during the two measurements, but the differences are so significant that there are no doubts about whether the interventions were effective. A slight increase of the fundamental frequency of the vault was also noticed. The dominant movement can be observed around the frequency of ca 11 Hz. The peak values of 1s RMS for before and after the rehabilitation monitored at the same times on busy work days are shown in figure 4. The corresponding maximum vertical peak amplitude measured in the crypt of the Church was 0.047 mm/s.
In spite of the fact that the measured level of vibrations was satisfactory after the rehabilitation (\(v < 0.2\, \text{mm/s measured at the same traffic hours as before the rehabilitation}\)), the peak amplitudes from a 12-hour monitoring reached 0.54 mm/s leaving a question open: what are the corresponding dynamic stresses, and can they be harmful in the future course of time? The stress level is of prime interest in historical masonry structures because they cannot transfer tensile stresses, and tension can therefore initiate or propagate cracks.

Eight dominant vibration modes were identified from ambient vibrations for a chosen typical cross section of the barrel vault. Damping of two modes with dominant movement of the vault in the vertical direction was estimated using the Random Decrement Technique (see Table 1) [11].

3. Stress estimation using a finite element model
To assess the level of stresses in the vaults and the level of dynamic excitation a FE-model in ANSYS 17 was created. Aware of all the inherent uncertainties mentioned in the introduction and the prevailing longitudinal dimension of the barrel vault, a simple plane model (see Figure 5) using Shell181 element was applied. The model was tuned by trial and error to approximately fit the measured natural frequencies (see Table 1). The computed modes are presented in the Annex.
Figure 5. The Finite Element Model

Table 1. Comparison of measured and computed natural frequencies

| Mode No. | Analytical Frequencies [Hz] | Experimental Frequencies [Hz] | Estimated damping ratio [%] |
|----------|-----------------------------|-------------------------------|-----------------------------|
| 1        | 1.56                        | 1.56                          |                             |
| 2        |                             | 2.38                          |                             |
| 3        | 3.87                        | 3.50                          | 1.0                         |
| 4        |                             | 3.81                          |                             |
| 5        | 6.11                        | 5.31                          |                             |
| 6        | 9.34                        | 9.25                          |                             |
| 7        | 10.92                       | 11.38                         | 3.8                         |

A static analysis with the exclusion of tension showed that at the lower surface of the vault stresses of +14 to -160 kPa can be expected near the apex due to the dead load. It should be noted that in the case of the applied FE-model, the model uncertainty is rather high because of the unsure influence of the side bays that is difficult to incorporate into the plane model, not mentioning the nonlinear material behavior and the influence of soil deformations.

The same model was loaded by the measured displacements of the dominant mode shape 11.4 Hz normalized to the maximum amplitude achieved in a 12-hour monitoring of the vault. The results are presented in Figure 6 showing the stress amplitude of ca 1.4 kPa.
Figure 6. The vault loaded by max. displacements of the mode 11.4 Hz

Figure 7. Statistical distributions of the max. vertical amplitudes in the vault

The data collected during the 12-hour monitoring period allow for the estimation of statistical distribution of amplitudes corresponding to each mode. This was done for the dominant mode 11.4 Hz, and the amplitude distribution was extrapolated to a time exposure of one year (see Figure 7). According to this estimation an amplitude of ca 33 µm and a tension stress of ca 7 kPa can be expected once a year.

The main problem here is the uncertainty of the static analysis. If the pressure at the midspan due to the dead load is sufficiently high, the dynamic stresses will not be dangerous. But in the case of low pressure due to the dead load, or even tension, there is a justified apprehension that the longitudinal
crack in the vault at the midspan may occur again. Therefore, a more detailed analytical model is being prepared.

4. Conclusions

The contribution presents the state of the art of the investigation of the influence of technical seismicity on the baroque Church of the Assumption of the Virgin Mary in Stará Boleslav.

Maximum amplitudes in the vault were measured at the frequency 11.4 Hz, which does not correspond either to the fundamental mode of the structure nor to the fundamental mode of the main barrel vault. During a monitoring period of 12 hours, they reached 7.6 µm (0.54 mm/s), which corresponds to a stress amplitude in the vault of ca 1.4 kPa.

Statistical extrapolation to one-year extreme values expects an amplitude of ca 34 µm once a year corresponding to a stress amplitude of ca 7 kPa.

The main problem is the uncertainty of the static analysis of the stress level in the vault due to the dead load, which does not allow for a reliable estimation of the deterioration effect of the traffic vibrations.

Continuous monitoring in order to allow for a higher reliability of the statistic estimations and a more detailed static analysis were recommended to assess the effects of traffic on the Church.

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