MODERN BUILDING
MATERIALS, STRUCTURES
AND TECHNIQUES

May 19–21, 2010, Vilnius, Lithuania
The 10th International Conference

Faculty of Civil Engineering
Vilnius Gediminas Technical University
Saulėtekio ave. 11, LT-10223 Vilnius, Lithuania
Phone +370 5 2745243, Fax +370 5 2745016
E-mail: *statkon@vgtu.lt*

http://www.vgtu.lt/en/editions/proceedings

THE DYNAMIC LOADING OF VILNIUS ARCHCATHEDRAL BELFRY –INVESTIGATION AND ANALYSIS

Arūnas Jaras[1], Romualdas Kliukas[2], Rimantas Kačianauskas[3]

Vilnius Gediminas Technical University; Saulėtekio al. 11, LT-10223, Vilnius, Lithuania.
E-mail: [1]jaras@vgtu.lt; [2]pirmininkas@vgtu.lt; [3]rkac@vgtu.lt;

Abstract. The dynamic investigation of a monument of historical heritage – Vilnius Arch-Cathedral Belfry – subjected to dynamic loading, caused by the city traffic and recently installed modern bell's system is presented in this paper. The influence of the operating of the bells was evaluated by measuring the acceleration histories under the conditions, when four different combinations of bells were used. While the influence of the city traffic was estimated according to two typical sources – the conventional city traffic (natural source) and the dynamic impact, caused by heavily loaded truck moving over a localized road surface irregularity (increased risk source).
The influence of induced vibrations is recorded by accelerometers located at various levels of the Belfry's structures according to appropriate schemes. The obtained results are shown by accelerograms.
Dynamic effects are evaluated by considering acceleration magnitudes and response spectra. A comparative analysis of various dynamic loadings (operating of the bells and city traffic) is presented. The appropriate conclusions and recommendations are provided.

Keywords: dynamic investigation, building structures, historical heritage, dynamic loading, accelerations, response spectra, bells, traffic, belfry.

Introduction

The Vilnius Old Town, which is one of the largest in Eastern Europe, has many buildings of cultural and historical heritage. Most important of them is the Arch-Cathedral Basilica, with the Belfry beside. According to common practice in the world, the buildings, making historical, architectural and cultural value are protected by the state (Kačianauskas *et al.* 2004).

The preservation of buildings of historical value is a complicated problem associated with great expenses. It is important to observe the first signs of destruction in time, to identify their causes and to take effective measures to prevent deterioration.

Various theoretical and experimental investigations of the influence of the dynamic loads caused by city traffic, operation of the bells, earthquakes, etc. on the resistance and reliability of structures of cultural heritage have shown the significance of the problems under consideration (Atkinson *et al.* 1998, Gentile *et al.* 2002, Niederwanger *et al.* 1997, Sofronie *et al.* 2000, 2003).

The full-scale testing and FEM analysis are used as the main tools of dynamic investigation (Crispino *et al.* 2001, Russo *et al.* 2010, Jaras *et all.* 2005), and different approaches and techniques of strengthening the structures of cultural heritage are offered (Witzany, Cejka 2007).

All factors causing building destruction may be divided into three groups:

- natural aging of buildings in time and under long-term exposure to the environment;
- the settlement of building foundations caused by changing hydrological conditions and soil characteristics, resulting in large deformations of building structures and cracks in the walls (especially, stone-brick walls);
- the vibrations and impact loads acting on building constructions. These effects are caused by natural (e. g. earthquakes, wind, etc.), and artificial phenomena, such as human activities (e. g. explosions, traffic, bells operation, etc.).

This paper aims, to compare the behaviour of Vilnius Arch-Cathedral Belfry subjected to artificial dynamic actions induced by city traffic and operation of the bells.

The action of the city traffic was measured in two typical city traffic modes: the heavily loaded truck, moving across a localized road surface irregularity (impact loading), and the conventional city traffic (natural action).

The operation of the bells encompasses four measurements, which reflects their typical modes: the bells operate separately in consecutive order; the bells operate all together; four smaller bells operate together; the two biggest bells operate together.

The dynamic action was evaluated in terms of mass acceleration histories of Belfry structures. The obtained results were analysed and compared. The appropriate remarks and conclusions are presented.

The Materials, Geometry and the Bell system

The structure of the building is schematically shown in Fig 1a, b. It reflects two historically different parts having quite different geometry and construction styles.

The lower part, having a slightly non-symmetric annular cross-section with the external diameter ranging from 12,6 to 12,1 m and 3,0 or 2,0 m thick walls, is made of stone masonry (Fig 1c). It is 11.9 m high and has four floors. The top of this part of the building is covered by cast-in-place joist ceiling, which was constructed as a stiffened reinforced concrete slab.

The upper part of the building (Fig 1d) has an octahedral cross-section with the characteristic diameter ranging from 11,4 to 9,9 m and 1,5, and 1,3 m thick brick masonry walls. The wall of the upper part is weakened by a number of window openings. The upper masonry structure is 25,5 m high. The roof of the Belfry is a light timber dome structure covered by a thin copper shell. The total height of the Belfry is about 53 m.

The first bells were hung in the Belfry as early as in 17 th century, while later (18 th c.) the number of bells was increased. This set of bells is still operating. However, in 2002, six new bells – “Jurgis Matulaitis”, “Anna”, “Helena”, “Stanislaus", “Casimirus”, “Joachim”, with their masses ranging from 475 kg to 2600 kg (totally 7300 kg) were installed according to a modern location scheme at the sixth floor level of the Belfry (26 m above the ground level). The new bells were provided with three supporting frames, while each frame carried two bells. Their operating order was changed respectively.

The state of the Belfry structures

The initial inspection shows that the technical state of the Belfry structures is far from being perfect and the significant defects and damages can be observed. Most heavily affected are bearing wooden structures and their connections (Fig 2 a). In the masonry walls, many vertical cracks, especially prominent on the 5th floor, can be observed (Fig 2 b).

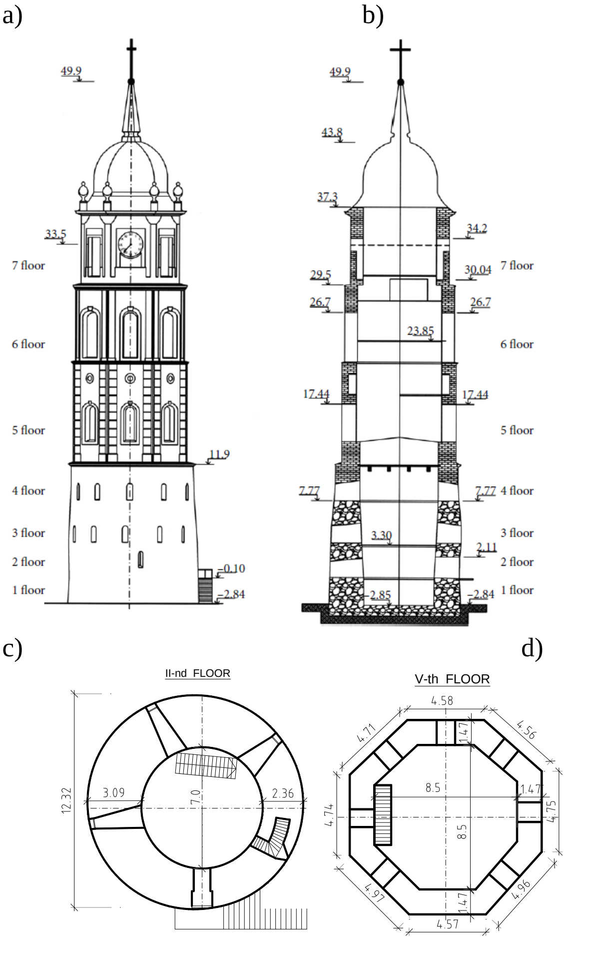

Fig 1. The Arch-Cathedral Belfry: a) a general view; b) vertical cross section; c) horizontal cross section of the lower part; d) horizontal cross section of the upper part.

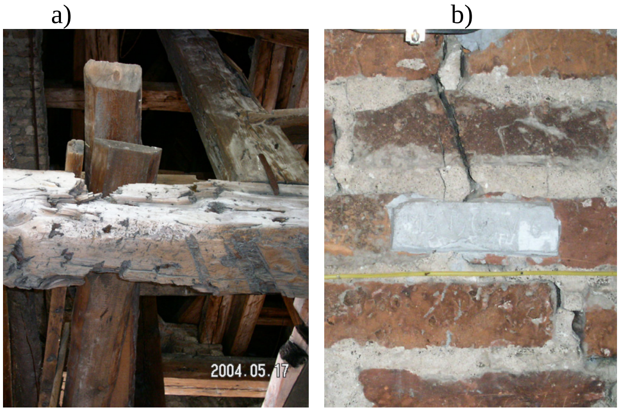

Fig 2. The damages, observed in the Belfry structures

Artificially-induced vibration does not present a direct threat to the safety of buildings, but leads to accumulation of local damages which may reach a critical value and even cause their failure. This can be particularly important for the old masonry structures, such as Belfry, having some specific defects (e. g. cracks, vertical deflections, foundation settlements, etc.).

The long-term vibrations, characterized by the steady dynamic action of various natural and artificial disturbances (conventional city traffic, operation of the bells) may cause gradual reduction of masonry strength due to deterioration of mortar and its detachment from the bricks.

While the dynamic impact, caused by a heavily loaded truck moving across a localized road surface irregularity, may be considered to be a factor of higher risk. It may cause unexpected crack propagation in the structure considered.

Dynamic loading and measurement technique

Dynamic loading

Apart from the settlement of building foundations, there are two groups of most critical factors reducing the ability of building structures to retain their original properties and serviceability:

- Natural long-term degradation of the materials under the exposure to the environment, which nowadays is often aggressive;
- Short and long term dynamic action such as vibrations or impact loads, caused by the factors of natural (earthquakes, wind) or artificial (various human activities e. g. city traffic, operating of the bells, etc.) nature.

Dynamic investigation is mainly aimed at determining the influence of the dynamic loads of artificial nature i. e. city traffic and operating of the bells.

To predict the behaviour of the Belfry structures, affected by dynamic loading caused by operating of the bells, the four modes of the bells operation were investigated:

- the bells operate separately, ringing one after another in consecutive order;
- the bells operate all together;
- four smaller bells operate together;
- two biggest bells operate together.

The dynamic loading caused by city traffic was investigated according to two typical city traffic modes:

- the conventional city traffic (natural action),
- the heavily loaded truck, moving across a localized road surface irregularity (impact loading).

The dynamic action was evaluated in terms of mass acceleration of Belfry structures.

Measurement technique

The dynamic investigation and analysis of the structures, based on the advanced measurement technique and computer-aided technologies seem to be the most powerful research tools applied to the evaluation of dynamic effects (Russo *et al*. 2010, Gentile *et al.* 2002, Sofronie 2000, 2003, Crispino *et al.* 1997 and etc.).

During the dynamic measurement, a mobile set of oscillation measuring devices was used to register vertical and horizontal oscillations caused by the operation of the bells and city traffic. The equipment used consisted of:

- a portable multifunctional analysis system „PULSE–3560C“ (12 canals), with software 7700 &7705, produced by „Bruel&Kjaer“, (Denmark);
- 12 one-directional sensors (accelerometers) of the type 7752, produced by „Endevco“ (USA);
- a standard portable personal computer „Hewllet Packard“.

The vibro sensors were rigidly fixed to the structural elements of the Belfry, according to the layout schemes (Fig 3).

Fig 3. Accelerometer in the working position

The results. Analysis and comparison

The average values of only one measurement parameter (acceleration), allowing us to determine the harmful effect of varying dynamic loading on the Belfry’s structures, was measured during the experiment.

The comparative analysis of these actions was performed in the present investigation, based on the indication of the 8^{th} and 3^{rd} sensors, whose data reflect the most dangerous effect of the bells’ operation and the city traffic, respectively. Both sensors are located on different sides of the building in nearly the same horizontal direction (perpendicular to the road), at the altitude 21.71 m. The more extensive data on all sensors readings and their layout schemes, developed according to varying dynamic loading, are given in (Kliukas *et al.* 2008, 2008).

The dynamic experiment comprises four Belfry‘s mass acceleration measurements according to the four modes of bells’ operation (the bells are ringing separately one after another, or all at the same time; 4 smaller bells, and 2 biggest bells are ringing at the same time) and two measurements according to two typical city traffic modes (conventional city traffic, and the heavily loaded truck, moving across a localized road surface irregularity).

The signal registering step of each measurement is $7{,}8125\times10^{-3}$ s, while the measurement time-span ranges from $3{,}8399\times10^{2}$ to $6{,}3999\times10^{2}$ s (for bells’ operation) and from $5{,}119\times10^{2}$ to $6{,}40\times10^{2}$ s (for city traffic).

With the aim to eliminate the influence of random disturbances (noise, etc.), the recorded signals of vibro sensors were filtered up to 0,3 Hz and over 60 Hz. (the bandwidth was 0,3–60 Hz).

The diagrams of acceleration time histories were drawn, and the obtained results were carefully analysed, using a commercial program package DynaTool. The tools provided are based on those used for structural analysis. However, they are based on standard techniques and may be used in other areas of frequency analysis.

In Fig 4, acceleration time histories of the most characteristic (8^{th}) sensor are presented on the same scale. They reflect the situations caused by the operation of the bells. Fig 4a presents the acceleration produced by each of 6 bells ringing one after another sequentially. It shows that the effect of the bells on the acceleration value is

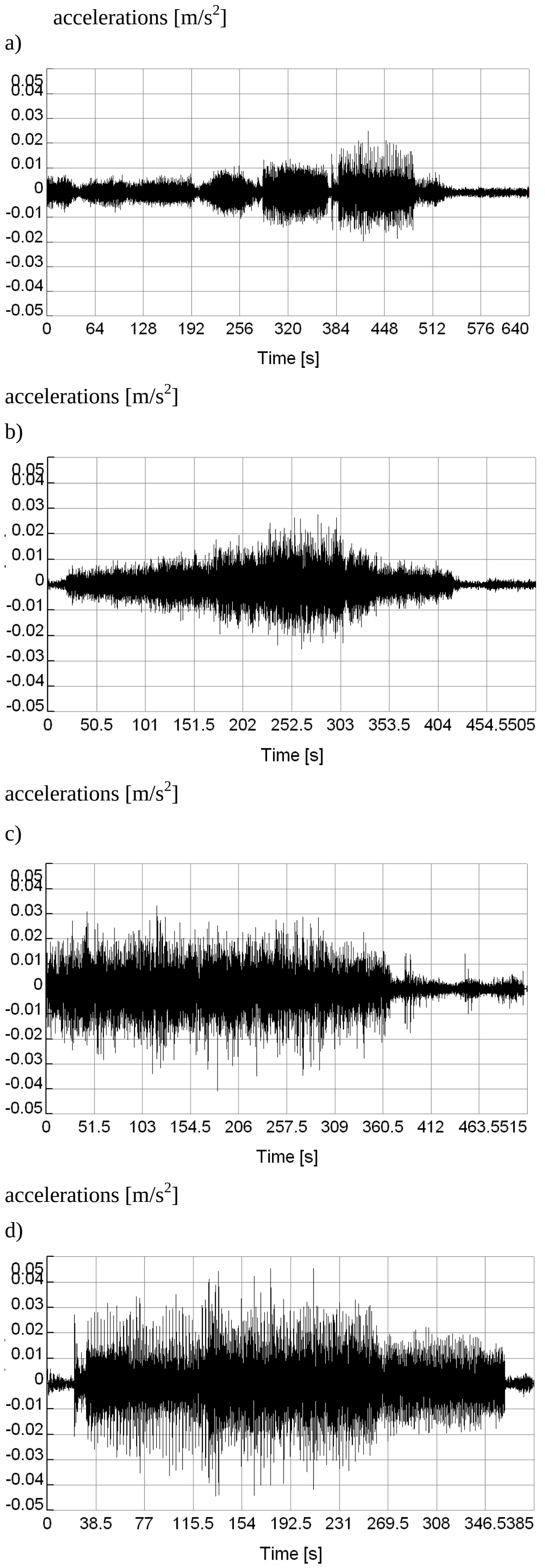

Fig 4. The accelerograms obtained by using the 8th sensor for different operating modes of the bells: a) the bells operate separately one after another; b) the bells operate all together; c) four smaller bells operate together; d) two biggest bells operate together

different (because their mass varies by about three times), ranging from 0,0084 m/s^2 to 0,0248 m/s^2.

When the bells operate all together (Fig 4b), the peak acceleration value (in modulus) at the same level is

0,0278 m/s^2. It is smaller than the value characterizing the operation of the two bigger and four smaller bells.

As shown in Fig 4 c-d, when four smaller bells are operating at the same time, the maximum acceleration is 0,04086 m/s^2, while for two larger bells operating together it reaches 0,04532 m/s^2. This can be accounted for by the fact that, when all the bells are operating at the same time, they suppress the acceleration effect of building oscillations and, thereby, the amplitudes, produced by each of them.

The comparison of the presented results shows that the bell's operating mode of two biggest bells is most dangerous (the acceleration may reach 0,04532 m/s^2).

In Fig 5 acceleration time histories of the 3rd sensor caused by city traffic is presented. Since the range of the dynamic action differs, it is presented on a different scale.

Fig 5a presents a histogram of acceleration in horizontal direction of the Belfry (at the level of 21.7 m), caused by conventional city traffic. It reflects the background dynamic effect (normal vibration level) on the building structures. In this case, the acceleration value does not exceed 0.00765 m/s^2 and may be considered insignificant.

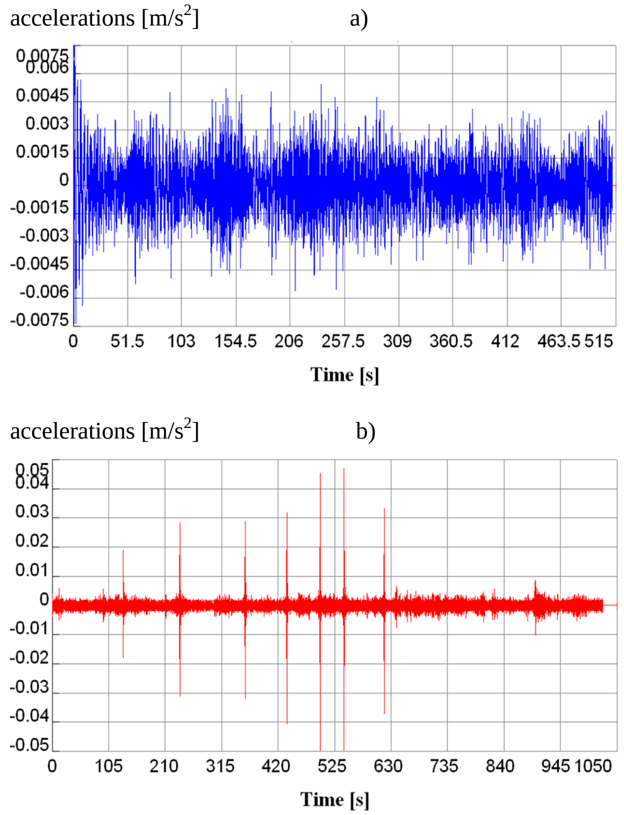

Fig 5. The accelerograms obtained by using the 3rd sensor (in horizontal direction, at the level of 21,7 m) for two typical city traffic modes: a) conventional city traffic; b) a heavily loaded truck moving across a localized road surface irregularity

Fig 5b presents the histogram of acceleration at the same level in the same direction caused by the heavily loaded truck seven times moving across a localized artificial road surface irregularity. The respective seven peaks of acceleration can be observed. It shows that the effect of heavily loaded trucks on the acceleration value at the level of 21.7 m exceeds normal vibration level by about 6.5 times, reaching 0.0498 m/s2.

According to the above considerations, we may state that the strongest dynamic action on the Belfry structures at the investigated level is produced by the dynamic impact of the heavily loaded truck moving across a localized road surface irregularity. In this case the dynamic action may be up to 1,1 times that produced by bells' operation and up to 7 times that of the dynamic loading caused by conventional city traffic.

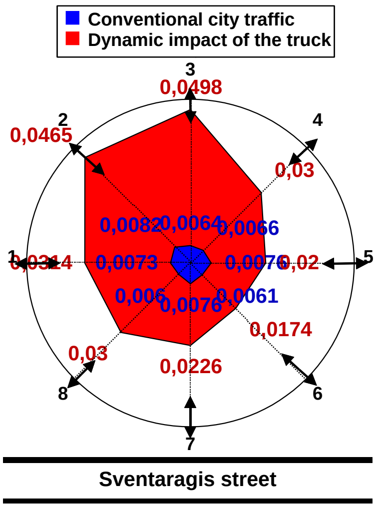

Fig 6. Radial distribution of peak acceleration in two city traffic modes

For the sake of visualisation and comparison radial distribution of acceleration according to two typical city traffic modes, i. e. conventional city traffic and a heavily loaded truck moving across a localized road surface irregularity are presented in Fig 6. Stronger dynamic action (values of peak acceleration) in the direction perpendicular to the road and a weaker effect in parallel direction are demonstrated.

The histogram in Fig 7 illustrates horizontal peak accelerations at various altitudes of the building (in the direction perpendicular to the road) caused by a heavily loaded truck moving across a localized road surface irregularity, conventional city traffic and the operating of the two biggest bells, respectively.

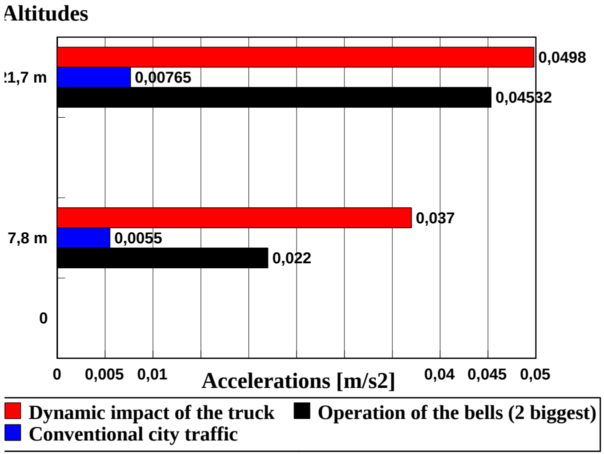

Fig 7. The histogram of acceleration distribution along the vertical axis of the Belfry

The processed investigation data describe the harmful effects of varying dynamic loading in absolute values. They allow us to assess the performance of the particular parts of the building and to determine the damages.

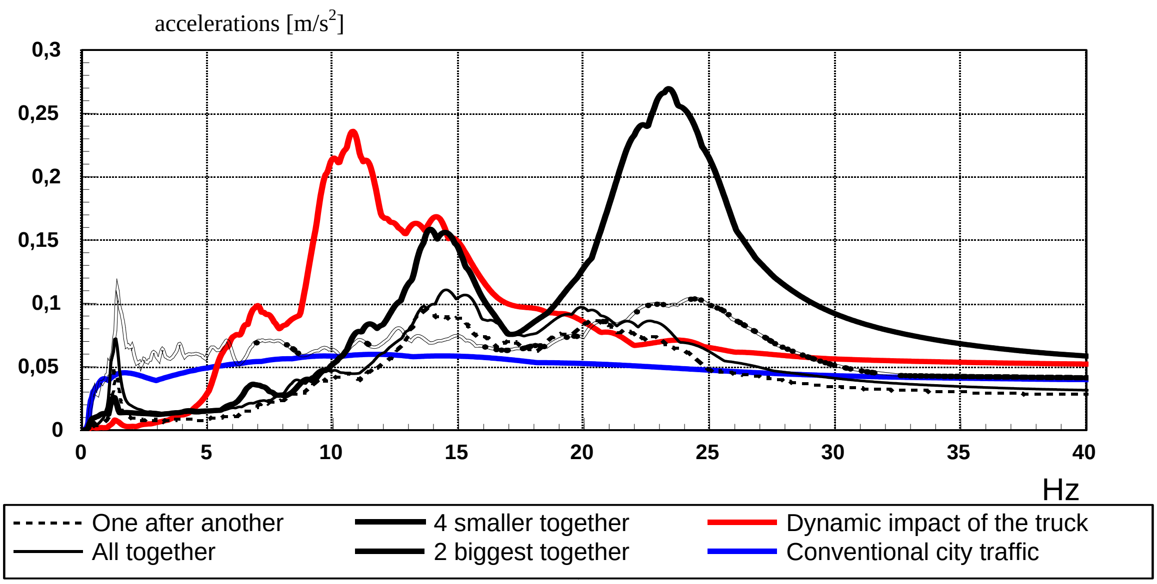

Fig 8. Response spectra obtained for various loading (with 5 % damping)

In order to determine the dynamic effects, the measured acceleration time histories were transformed in to frequency domain (Clough 1993). The acceleration response spectra were calculated by using a commercial software package DynaTool. This program provides a collection of tools for transformation from time to frequency domain, which are used by engineers and scientists involved in vibration analysis.

As shown in Fig 8, the first resonance observed at 1,25 Hz (for all types of dynamic loads) is attributed to natural frequencies of the Belfry structures, while the second resonance frequency of 10,8 Hz is attributed to the influence of the dynamic impact of the truck. Two further resonance frequencies, 13,7 Hz and 22,8 Hz are attributed to the influence of the bell system. They are produced by the operation of 4 smaller and 2 bigger bells, respectively.

Remarks and conclusions

The dynamic investigation of the Vilnius Arch Cathedral Belfry allows us to make the following remarks and conclusions:

1. The measured maximal accelerations indicate that the most dangerous dynamic loading on the Belfry structures is caused by the dynamic impact of a heavily loaded truck. However, the above dynamic action is insignificantly stronger than operating of the bells, but up to 7 times that of the dynamic loading caused by conventional city traffic.
2. The influence of the bells' operation is observed only in the local zone (the upper part) of the building's structures. The most significant dynamic effects of high acceleration magnitude are produced by the two largest bells "Joachim" and "Casimirus". The investigation demonstrated that accelerations in the vicinity of the bells' supports exceed the ultimate value of 0.1 m/s^2.
3. The details of dynamic effects are described in terms of the response spectra of accelerations. In particular, four resonance frequencies were identified. The first resonance occurring at 1,25 Hz can be attributed to natural frequencies of the building structures, while the second resonance frequency of 10,8 Hz is attributed to the influence of the dynamic impact of the truck. Two further resonance frequencies, 13,7 Hz and 22,8 Hz, are attributed to the influence of the bell system, i. e. the operation of 4 smaller and 2 bigger bells, respectively.

Acknowledgement

This research was supported by Vilnius City Municipality. The dynamic experiment was performed in collaboration with the Centre for Urban Construction and Rehabilitation (CURE) of Gdansk University of Technology. Their support is acknowledged.

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