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COMPLEX STATIC AND DYNAMIC PROTECTION OF HISTORIC BUILDINGS FROM THE EFFECTS OF TECHNICAL SEISMICITY

Jiří Witzany, Radek Zigler, Tomáš Čejka and Jan Kubát

CTU in Prague, Faculty of Civil Engineering, Deparment of Building Structures, Prague, Thákurova 7, Czech Republic; wizany@fsv.cvut.cz, zigler@fsv.cvut.cz, cejka@fsv.cvut.cz, jan.kubat.2@fsv.cvut.cz

ABSTRACT

Numerous failures of buildings are caused by dynamic effects due to technical (or induced) seismicity. Technical, or so-called induced, seismicity is caused by the effects of traffic, building activity (machines), the effects of devices and machinery, mining and mineral extraction activity, blasting operations (in the vicinity of quarries), pressure waves, air and water jets, the effects of gusts of wind, impact waves, etc. In particular, masonry buildings with insufficiently rigid ceiling structures, non-functional wall and beam ties and foundations where the effect of settlement due to compaction of the subsoil cannot be excluded are highly sensitive to the dynamic effects caused by technical seismicity.

KEYWORDS

Masonry, Technical seismicity, Protection, Structure response, Experimental research

INTRODUCTION

Severe dynamic effects acting on buildings situated in the vicinity of traffic routes, mining and industrial zones and quarries include the effects caused by the passage of wheeled vehicles and the railway rolling stock (braking and acceleration forces, oscillations transferred by the subsoil). Dynamic effects induced by technical seismicity cause gradual compaction of the foundation bed, accompanied by additional foundation settlement. Primarily structures with a low band of elastic deformations and with insufficient spatial stiffness are highly sensitive to dynamic effects. The intensity of technical seismicity depends on the intensity of the source causing dynamic effects, its mass, the frequency and amplitude of oscillations, its distance from the place of response and on hydro-geological conditions of the foundation bed.

TECHNICAL SEISMICITY

Traffic-induced technical seismicity (Figure 1) principally differs from natural seismicity in frequencies higher by an order of magnitude, which propagate 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.

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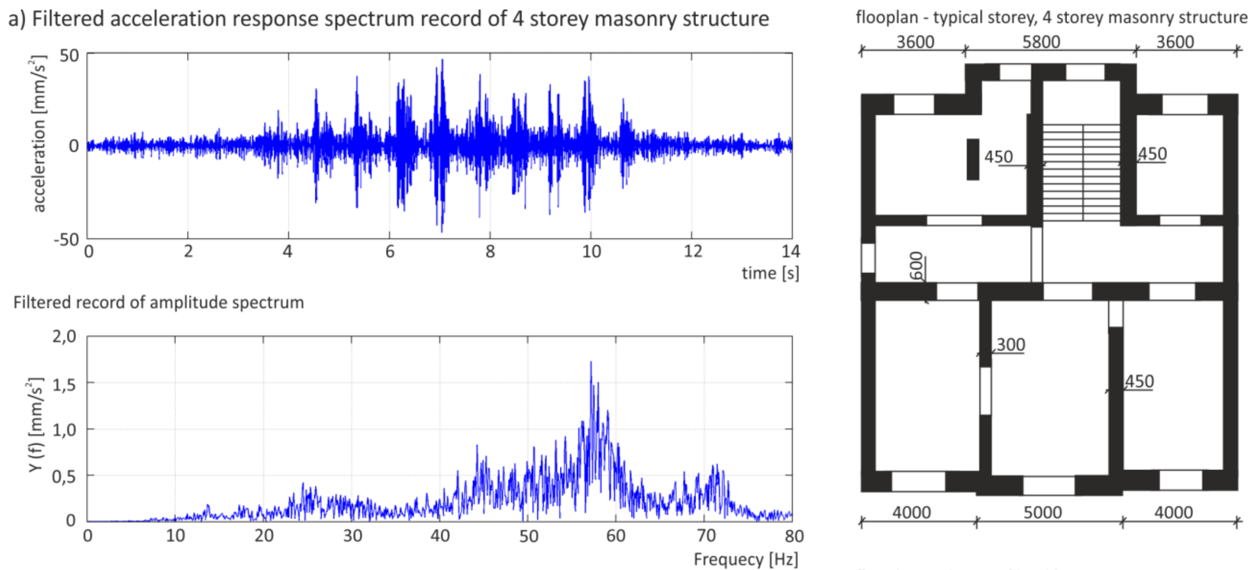

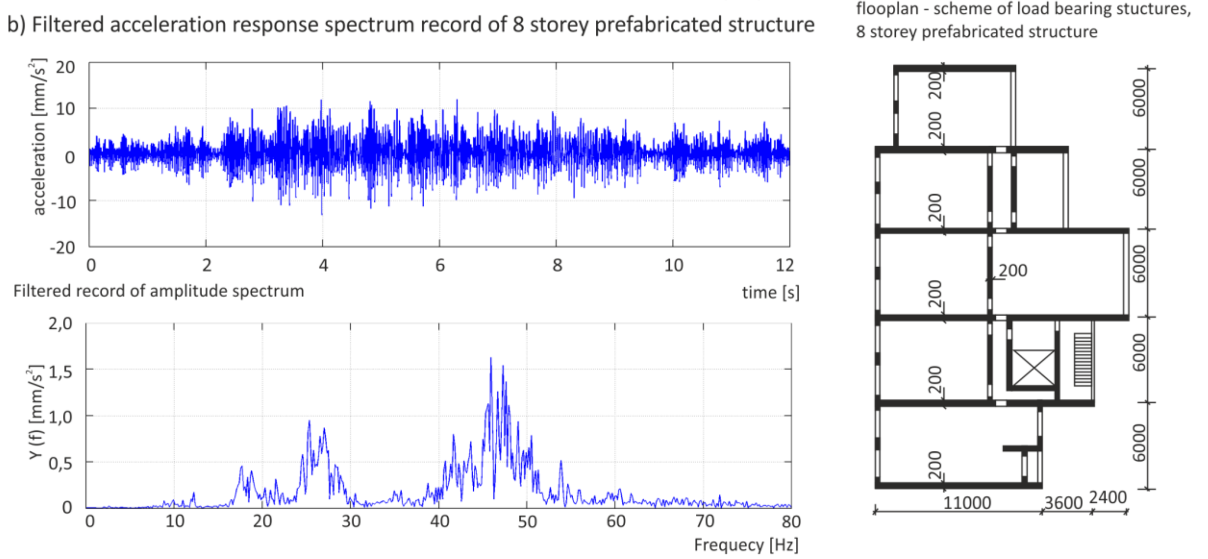

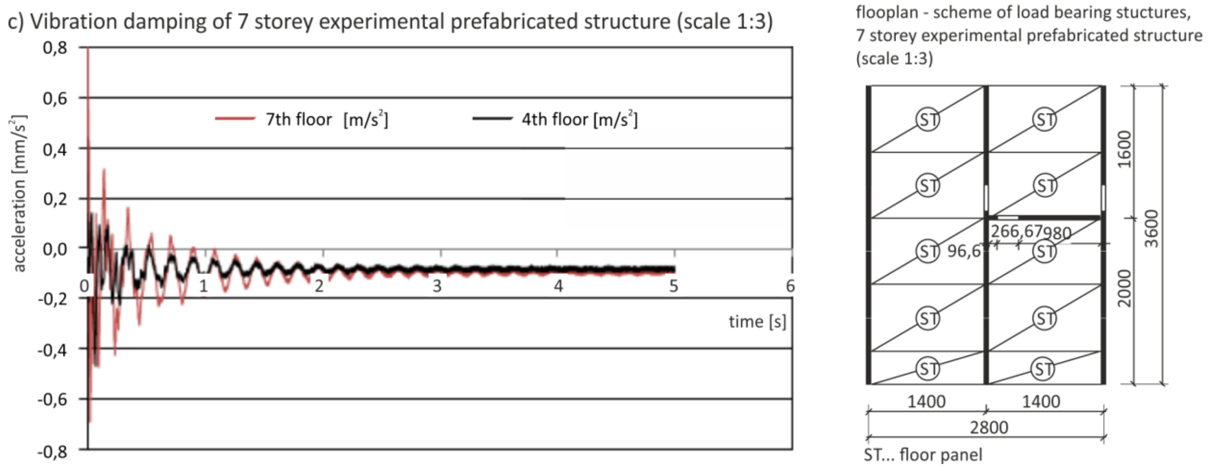

Fig. 1 – a) Response of a 4-storey masonry structure to the effect of rail traffic (tram) passage in close proximity to the building, b) Response of an 8-storey precast structure to the effects of rail traffic (tram) passage in close proximity to the building, c) Example of vibration damping of a 7-storey precast wall structure

Vibrations due to road traffic propagating through the surrounding environment into the nearby built-up areas usually range in an interval of 5 – 25 Hz. By their amplitudes, the vibrations are in the 0.005 to 2 m/s^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 the degradation of 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 structure, its speed and riding manner, subsoil composition, compactness and moisture, and 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 1-2 mm/s range should be the criterion for the assessment the building structure’s resistance to the effects of technical seismicity.

RESPONSE OF HISTORIC MASONRY STRUCTURES TO THE EFFECTS OF TECHNICAL SEISMICITY

Dynamic effects and shocks due to mining or building activity (driving-in piles, blasting rock massifs, explosions, etc.), heavy traffic on uneven road surfaces, etc. cause a gradual appearance and development of cracks and other manifestations of mechanical damage. A frequent manifestation of failures is the appearance of cracks, degradation of surface coatings, degradation of joints of built-in partitions and structures, crack formation in the joint of horizontal and vertical structures and degradation of load-bearing structures due to a change in the footing bottom shape caused by gradual compaction of the foundation bed due to technical seismicity-induced dynamic effects propagating through the foundation bed.

The composition of the geological setting and its mechanical properties affect the magnitude of vibrations from the subsoil, which can either be amplified or damped by this composition. Natural frequencies - of superficial deposit soils on the bedrock are crucial for the propagation of vibrations through the subsoil. In the conditions of the Czech Republic, the common soil thickness on the bedrock is 2-4 m. In this case, the natural frequencies of soil on the bedrock can approximate the natural frequencies of buildings and, consequently, the transfer of traffic-induced vibrations into building structures is amplified by the so-called resonance effect [2]. The failure of masonry structures can also occur due to secondarily excited movements of the subsoil in the vicinity of non-stabilised geological conditions.

The response of the structure to static loading with a dynamic component, or to dynamic (repetitive, cyclic) loads is a time-related deformation, strain or failure (a gradual growth, development and propagation of failures occurs over time up to reaching the ultimate strain and fatigue strength limit). Under dynamic loading, a material changes its mechanical properties at very high frequencies. In the other cases, the mechanical properties identified by static tests can be applied. Material fatigue occurs in the phase of a variable response of the structure (material) to loading over time. The stress at the fatigue limit decreases with the number of load cycles, but the deformation and permanent strain are increasing.

Masonry structures subjected to loading approximating the proportional limit suffer from low-cycle fatigue, a gradual growth in plastic deformations and crack development at reaching the number of cycles in the 10^2 to 10^5 order in relation to the low-cycle loading interval. First, hairline cracks appear in the plaster, in joints of different materials, in the corners and joints of mutually perpendicular walls (in cavettos), in the corners of openings to be followed by gradual spalling of the plaster and crack development in the bearing walls. The crack appearance reduces the stiffness of the masonry structure causing a gradual loss of spatial stiffness. Further repetitions of dynamic loading (e.g. repetitive mining-induced seismic events, effects of strong sound waves, etc.) and exceeding the plastic deformation limits may cause a loss in stability or a complete destruction (see

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Tab. 9, ČSN 730040 [3]). Figure 2 schematically displays examples of characteristic failures of masonry buildings due to dynamic loads.

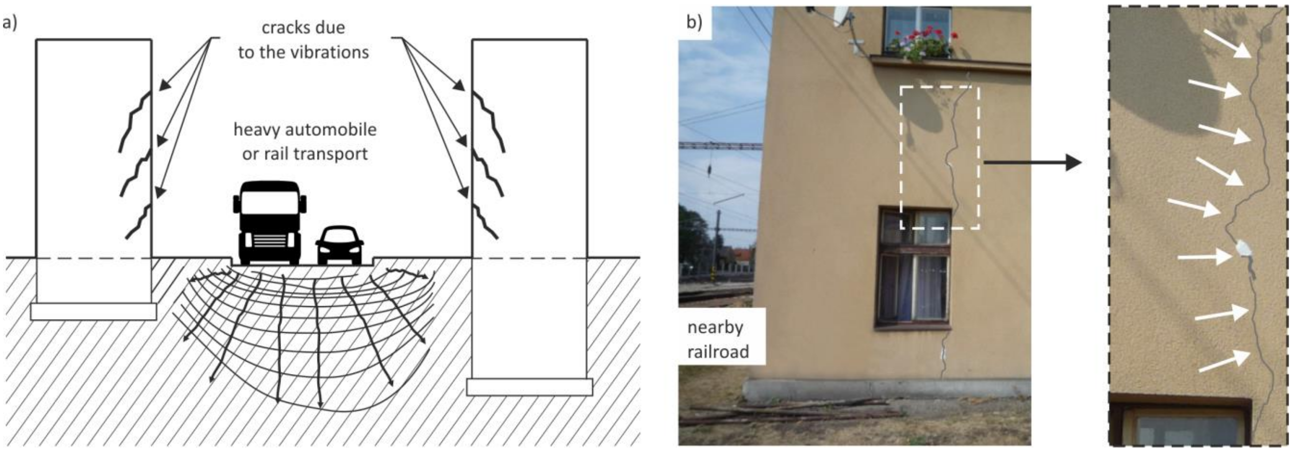

Fig. 2 – a) Failure scheme of a structure due to the effects of technical seismicity, b) Failure of a masonry building due to shocks caused by railway traffic

The type of masonry failure due to dynamic loading with vibrations basically corresponds to brittle failure. At relatively low vibrations, due to fatigue, the masonry fails not only in joints, but also inside walling units. 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.

EXPERIMENTAL MEASUREMENT OF THE RESPONSE OF SELECTED MULTI-STOREY BUILDINGS TO TRAFFIC

The experimental project (GAČR 103/09/2007 [4]) included the experimental verification of the response to traffic-induced dynamic effects performed in cooperation with the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences (UTAM AV CR) on:

- a four-storey masonry block of flats built in the early 20th century situated close to a railway line;
- a historic building from the end of the 19th century situated near an intersection with high volumes of rail and vehicle traffic;
- on two eight-storey precast panel residential buildings in the vicinity of a railway line.

Short periods of time where the most significant oscillations had occurred were selected from the records and the successive analysis only dealt with these sections. The records were obtained by filtration with a transmission band of up to 80 Hz, which is characteristic of building structures. Vibrations induced by road traffic propagating through the surrounding environment into the adjacent built-up area are usually at dominant frequencies in the 5 to 25 Hz range, while vibrations induced by overground rail traffic have dominant frequencies of ca 5 to 50 Hz. The dominant frequencies and amplitudes of vibrations causing the excitation of buildings depend, above all, on the road surface quality, vehicle mass and structure, its speed and riding manner, the composition, compactness and moisture of the pavement subsoil and the access road to the building. The distance of the pavement from the building is of major importance. The buildings subjected to experimental measurements showed partial local cracks. The geological base on the site of the investigated buildings was composed of loess loam 3 to 16 m in thickness, or gravel sands 4 to 8 m thick. The effective velocity limits (ČSN 730040 [3]), or the effective acceleration limits as the main criterion had been exceeded in none of the experimentally investigated buildings, and none of the buildings in B and C Class of resistance (ČSN 730040 [3]) and significance II under ČSN 730031 [3], therefore, required a dynamic calculation or special measures for reducing the effects of vibrations caused by the surrounding traffic. In terms of the structure reliability (Group 2 of limit states), corresponding measures to reduce the effects of vibrations on persons or sensitive devices inside the building (mainly the design of floor structures and floor finishes) usually need to be taken.

RESPONSE OF MASONRY BARREL VAULTS TO REPETITIVE STATIC AND DYNAMIC LOADS

The research project (NAKI I [5] and NAKI II [6]) included the verification of the effect of alternating static and dynamic loading on a segmental barrel vault in terms of a gradual degradation – decrease in stiffness – of a vaulted structure after individual load cycles. The verification was performed in cooperation with the TAZUS Praha a.s. Company and the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences (UTAM AV CR).

Masonry barrel vaults represent the most common vaulted structure used in all historical styles from Ancient Times to the present. Due to cyclic dynamic effects caused by technical seismicity, a gradual decrease in stiffness – growth of deformations – and damage may occur in historic and monumental structures with vaults, and, after a certain number of cycles in an order higher than 106, the deformation limit of the vaulted structure may be reached to be followed by the vault collapse.

The subject of experimental research were barrel vaults (Figure 3) with a span of 3000 mm, a rise of 750 mm and 1000 mm immovably mounted on footings anchored into the floor, or mounted on short sections of supporting walls 300 mm thick, and connected by steel tendons (2 Ø 36 mm). The vault thickness was 150 mm, of metric format bricks of P15 quality on MVC 2 cement lime mortar. A total of 3 x 6 segmental barrel vaults were investigated differing by the method and extent of reinforcement with non-prestressed strips of a carbon composite 100 mm in width, glued onto a cleaned, levelled and smooth surface. Reference measurements were performed on non-reinforced vaults exposed only to static loading. The vaults were gradually subjected to alternating static and dynamic loads in the vertical and horizontal direction.

The objective of the experimental research into masonry barrel vaults was, among others, the validation of the sensitivity of dynamic characteristics (resonance frequency) as a reliable identifier of damage to a vault and a decrease in the vault stiffness as a consequence of mechanical degradation of the vault masonry, particularly in the phase of the development of micro cracks and hairline cracks, which cannot be reliably identified by visual inspection only. For this reason, the vaults were subjected to vertical, relatively low loading values (14 – 18% of the experimentally identified limit load) in the static loading phase.

The excitation in the vertical and horizontal direction was executed with the TIRAvib electromagnetic vibration generator, type TV5550/LS weighing 550 kg with mobile mass. Its frequency range is 0 to 3 kHz, max. mobile mass stroke ± 50.8 mm. The vibration generator was fixed on the vault and set to vertical or horizontal oscillation mode depending on the loading direction.

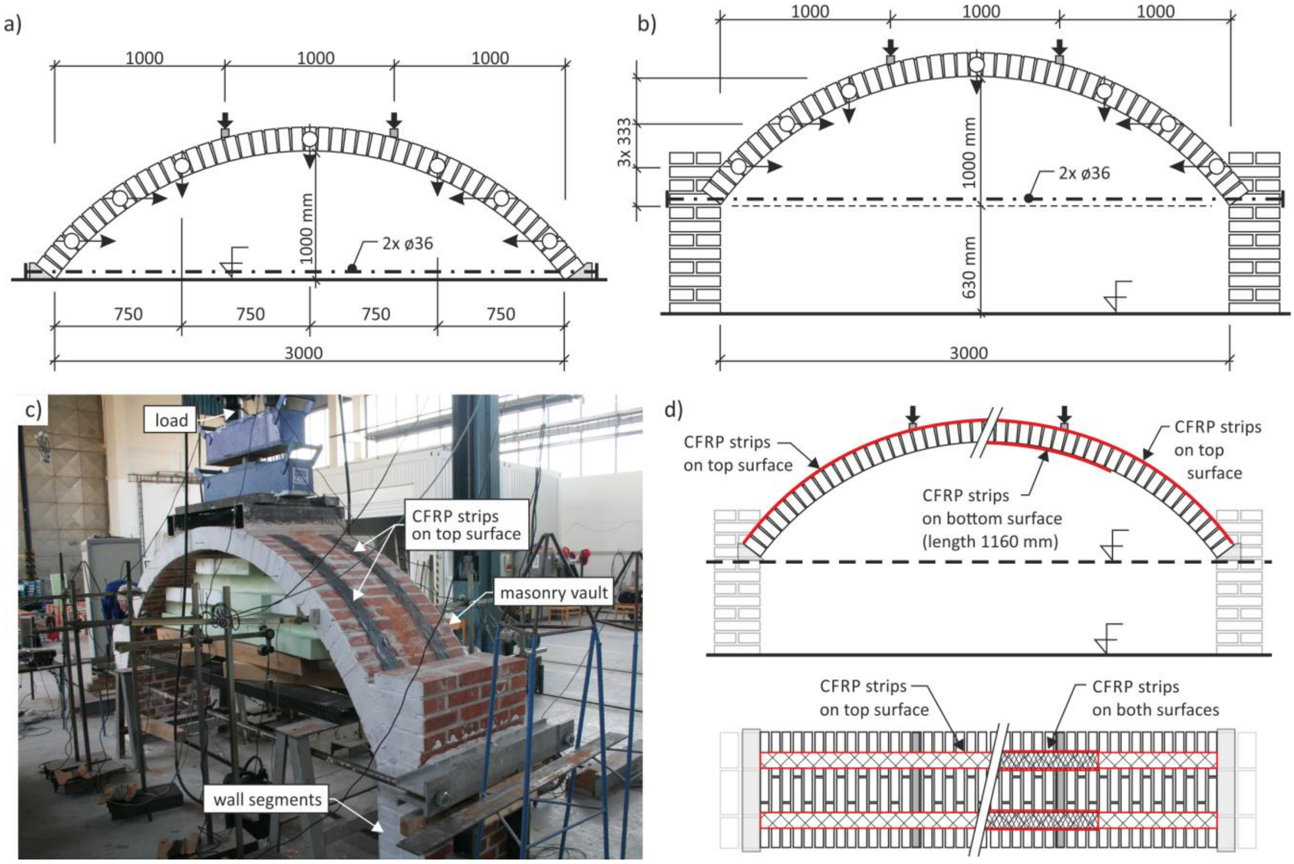

Fig. 3 – a) Scheme of a vaulted structure mounted on the floor, b) Scheme of a vaulted structure mounted on supporting wall segments, c) Reinforced vault in the testing device, d) Scheme of vault reinforcement with FRP strips

An identification test by impulse loading – an impact with a rubber mallet on the vault at point 3 was performed before each (dynamic and static) loading. The induced vault vibration (its response) was converted into frequency spectra from which frequency peaks were read. In the end, the vaults were loaded by static load until their failure (Figure 4).

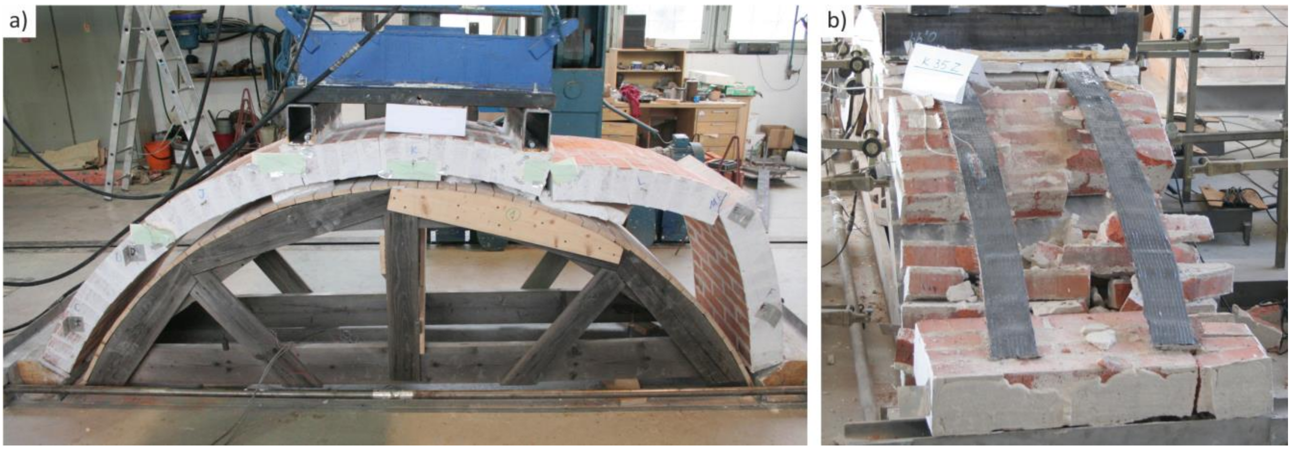

Fig. 4 – Failure mechanisms of non-reinforced vaults (a) and vaults reinforced with FRP strips (b)

To identify the natural frequencies of the load acting on the vault dynamic load tests were performed at the first resonant frequency (ca 18 Hz) and also outside resonant frequencies, namely at frequencies of 5 Hz and 50 Hz, which characterize loading due to traffic-induced dynamic loads.

Figure 5 and Figure 6 present partial characteristic results of the “stiffness” measurement expressed as the percentage of loading necessary for reaching unit deformation.

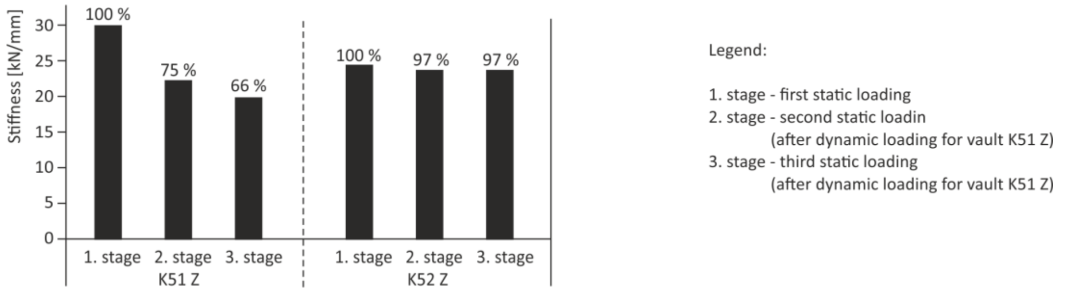

Fig. 5 – Decrease in the stiffness of a vaulted structure loaded by alternating static and dynamic loads (a) and static load (b)

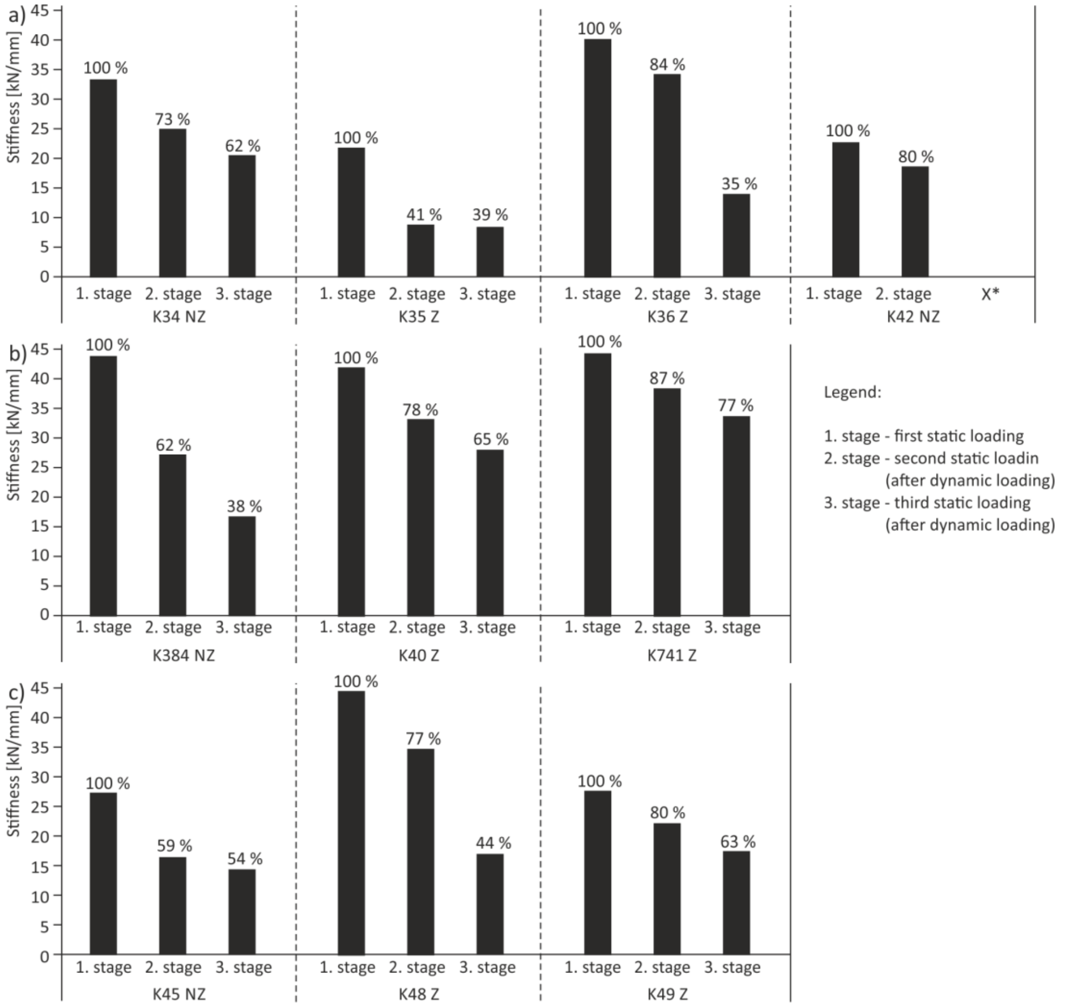

Fig. 6 – Decrease in the stiffness of vaulted structures in individual phases of alternating loading with static and dynamic loads; a) Vaults with a rise of 750 mm anchored directly to the floor, b) Vaults with a rise of 1000 mm anchored directly to the floor, c) Vaults with a rise of 1000 mm mounted on segments of supporting walls 630 mm high

*Note: *Vault K42 NZ (non-reinforced) was not loaded up to the limit load*

In agreement with the assumptions, the experimental research proved a progressive drop of stiffness (kN/mm) in individual successive loading phases. The experimentally verified intensity of the decrease in stiffness was higher in non-reinforced vaults compared to reinforced vaults. The research also manifested higher effectiveness of vault reinforcement with composite strips applied along the whole length of the vault extrados. As a result of the prevention of horizontal vault deformations in the direction out of the vault in the area of the so-called critical cross sections (ca ¼ to 1/3 of vault height), vertical vault deformations at the vault crown and, thus, the appearance of tensile cracks at the vault intrados, followed by a progressive decrease in the vault stiffness, are also prevented. In this perspective, the vault reinforcement with continuous strips applied at the vault extrados and the system of visible tendons can be considered as the most reliable method of vault protection. The case of vaults where the tendon system is replaced with an effective support system can be considered as analogical.

The research has pointed out the need to perform regular monitoring campaigns of monumental structures located near the sources of technical seismicity, and also the need to take the necessary steps to ensure stability in relation to the degree of its disturbance and the assumed intensity of technical seismicity.

PREVENTIVE MEASURES AND PROTECTION OF HISTORIC BUILDINGS FROM THE EFFECTS OF TECHNICAL SEISMICITY

The extent and intensity of damage to historic buildings in terms of hazards resulting from the effects of technical seismicity depend on the intensity and frequency of dynamic effects caused by technical seismicity, and are usually only manifested at higher amplitudes (higher than 1 m/s^{-2}) and velocities (ca 2 mm/s). Visually observable damage only occurs after the structure's response to a total number of cycles in the order of a 10^6 multiple. Masonry structures with a lime binder are characterized by the absorption of fracture energy in the binder masonry component and, as a result, the cracks are more frequent, thinner in width, with less effect on the overall geometry and the overall stability of the masonry.

Based on the analysis of degraded buildings located in zones with active technical or induced seismicity, the following conclusions can be formulated:

a) Masonry buildings with insufficient spatial stiffness, which usually have yielding, insufficiently stiff timber floors, an ineffective system of wall and beam anchors, lack stiffening tie beams and are often improperly founded are significantly more vulnerable to traffic-induced dynamic effects.

b) The extent and intensity of degradation and damage to masonry buildings which are not continuously maintained and repaired compared to non-degraded buildings are progressive and gradually grow while the parts of a non-degraded masonry structure that are able to stabilize the structure “diminish“ - the masonry structure becomes less resistant.

c) The extent of degradation of masonry buildings with a lime binder is characterized by a greater number of less prominent cracks, thinner in width – fracture energy is absorbed in the more yielding lime binder. The extent of damage to historic masonry buildings from the end of the 19th and the beginning of the 20th century with a binder of cement (cement lime) mortar with higher strength and stiffness is characterized by a smaller number of prominent, often local cracks of greater width whose stabilization requires “tying” or prestressing.

The basic measures for the protection of historic buildings from the effects of technical seismicity include (Figure 7):

a) Direct measures

- Rehabilitation of foundation structures – deepening, strengthening of foundation masonry, grouting, bracing, root piles and jet grouting, coupling of foundations
- Strengthening of masonry degraded by cracks – grouting, bracing
- Activation, strengthening and additional mounting of horizontal tendons and beam ties, execution of additional tie beams, bracing of masonry in the vertical direction
- Modification of the joint of horizontal and vertical structures – strengthening by grouting or loosening, including the execution of corresponding modifications and grooves for controlled cracks, etc.
- Activation or reinforcement of vault tendons and cross-braces, strengthening of vault masonry – grouting, high-strength FRP composites.

b) Indirect measures

- Landscaping of the surrounding terrain to limit the transfer of traffic-induced dynamic effects through the soil adjacent to the foundations and the underground part of the building (e.g. a ditch along the building perimeter with non-compacted backfill, or an absorber of dynamic effects, etc.)

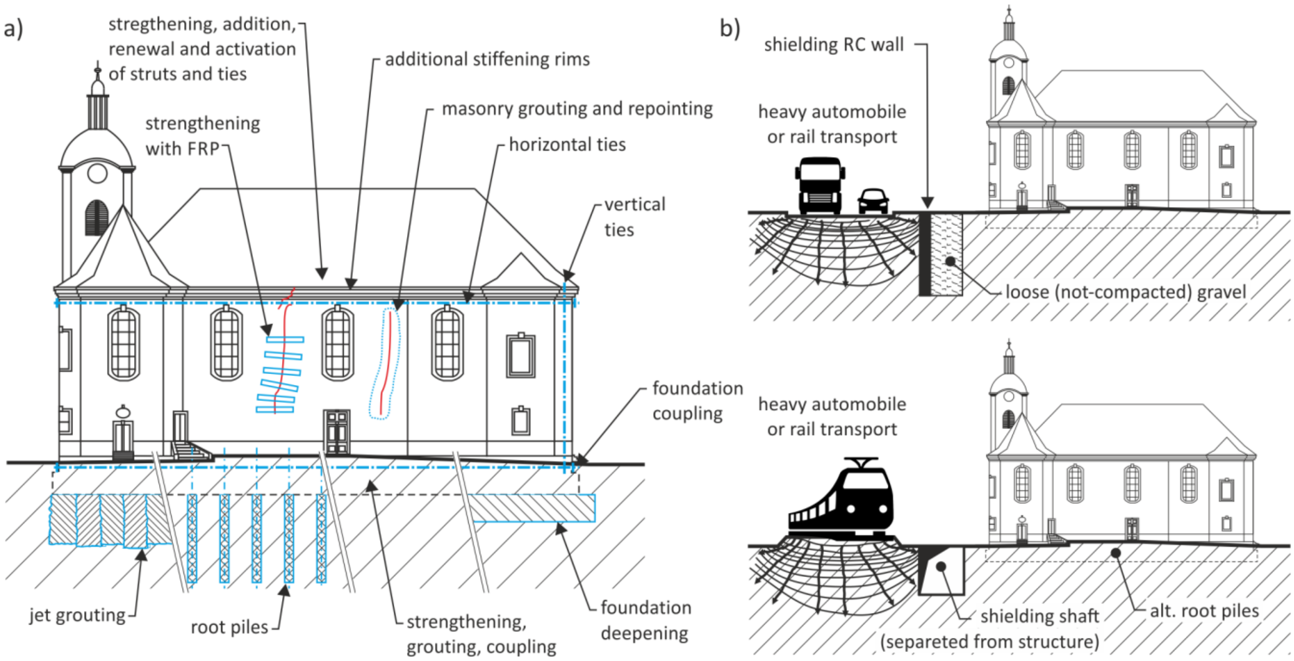

Fig. 7 – Protection of historic buildings from the effects of technical seismicity; a) Direct measures, b) Indirect measures

Apart from physical measures, an integral part of the protection of buildings from the development of mechanical failures and degradation are continuous observations and monitoring and regular maintenance and repair interventions.

The principal measure preventing the appearance and development of mechanical degradation consists in increasing the spatial stiffness of buildings located in zones with increased technical or induced seismicity, the rehabilitation and strengthening of the masonry of load-bearing walls, rehabilitation and reinforcement of floor structures and foundations (floor tie beams, tendons, bracing, deepening, coupling of foundations).

CONCLUSION

The major preventive measures to protect historic buildings from dynamic effects of technical or induced seismicity include an effective system of tendons and beam ties, bond beams, the reinforcement and rehabilitation of degraded load-bearing masonry of supporting structures and foundation structures, or excavation of “compensation ditches” and taking measures to absorb lateral seismic vibrations.

The measurements and indicative monitoring have manifested a relatively low occurrence of buildings degraded by the effects of technical seismicity, except for extreme cases of a high intensity and frequency of dynamic effects and insufficient stiffness of the buildings exposed to such effects. However, special attention must be paid to degraded buildings with insufficient spatial stiffness and buildings founded a foundation bed whose long-term consolidation due to dynamic effects of technical seismicity cannot be excluded.

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