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

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ABSTRACT

The issues of the response of buildings to dynamic loading effects caused by natural seismicity have become a focus of great interest worldwide. According to the latest observations and calculations, the seismic hazard for buildings, mainly in seismically active regions of the Czech Republic, has increased, together with the area of the territories where buildings must be assessed for seismic effects. It is primarily historic and listed buildings with vaulted structures, or even partially damaged ones, that are exceptionally sensitive to the deformations of the supporting structure due to natural seismicity, and their response to these effects is often accompanied by the appearance of structural failures.

KEYWORDS

Masonry, Natural seismicity, Protection, Structure response

INTRODUCTION

The territory of West Bohemia is characterized by a specific type of earthquake activity, the so-called earthquake swarms, where a series of thousands of weaker shocks occurs for a time of several days to months. Sometimes, these vibrations are strong enough to be perceived by the inhabitants, sometimes they are even able to cause material damage to buildings.

NATURAL SEISMICITY ON THE WEST BOHEMIAN TERRITORY

West Bohemia is situated in the western part of the Bohemian Massif, at the contact of three major tectonic units: Saxothuringian, Moldanubian and Teplá-Barrandian units. The Cheb, Kraslice and Vogtland (Saxony) regions are part of the north-south line of the Leipzig-Regensburg active seismic zone, characterized by earthquake swarms arising at the intersection of the Mariánské Lázně Fault and the Eger Rift. Earthquake swarms represent a special type of seismicity, occurring typically in volcanic or, potentially, in post-volcanic areas where the Cheb region also belongs (the youngest volcano there is Železná Hůrka/Iron Hill ca 150-200 thousand years old). The occurrence of an earthquake swarm can be explained by the injection of a crust fluid consisting of water and a gas of magmatic origin into a fissure zone where it pushes onto the rock in the Earth crust under the pressure of tens to hundreds of MPa gradually (i.e. not by impact) disintegrating it. In this way, the accumulated energy is released in more frequent, but smaller portions [1]. Earthquake swarms got their name and were first described at the turn of the century, at the time when the Cheb and Kraslice regions were hit by a twelve-year series of strong earthquake swarms (from 1898-9 to 1912). After very strong shocks in spring 1908, the first seismic station in the Bohemian territory was established

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in Cheb equipped with devices for seismicity measurement, which successively recorded the strongest earthquake on the 3rd November 1908. Although the seismographs recording this measurement have not been preserved, according to macroseismic records, this earthquake reached approximately level five on the Richter scale [2]. Over 90% of current earthquakes are concentrated within the north-south focal zone between Vackov and Počátky, which diagonally intersects the Mariánské Lázně Fault near Nový Kostel. The earthquake foci in this region lie at depths of 6-15 km [1]. In earthquakes, the horizontal motion component dominates over the downthrow or overthrust component [1,3,4]. Vertical movements of the Earth's surface and changes in gravitational acceleration during seismic swarms and at times between them testify to an alternative accumulation and release of tectonic stresses [1,3,5]. The activity of seismic swarms is accompanied by changes in the groundwater level in some wells. Shortly before an earthquake swarm near Nový Kostel, increased emanation rates of radon ^{222}Rn had been recorded in the Radonquelle-Wettinquelle spring in the Bavarian Bad Brambach Spa [3,6]. Moreover, the Nový Kostel focal zone correlates with the concentration of radioactive elements detected by aerial gamma ray spectrometry [3,7]. A new era of digital seismic observations in West Bohemia was only launched with the arrival of a strong swarm in 1985/1986. The Nový Kostel (NKC) first permanent digital seismic station established in the main Nový Kostel focal zone in 1989 became the basis for the present-day WEBNET network. Other WEBNET stations were gradually established from 1991 to 2004. The West Bohemia/Vogtland region currently ranks among the best monitored seismically active areas in Europe. Two decades of continuous observations from WEBNET form the background for the majority of earthquake swarm studies conducted in this area [8]. In addition to observations from the WEBNET network in West Bohemia, permanent GPS-based measurements also take place in West Bohemia monitoring soil movements in this locality [9]. For more detailed history of earthquake swarms and, in particular, their documentation based on the records of macro seismic observations see [2].

The West Bohemian regions that can be characterized as seismically active zones are home to numerous significant historic and listed buildings. Research into the effect of natural seismicity on the degradation of historic structures involved the selection of historic structures with different degradation levels to be used for indicative observations and monitoring of cracks by means of gypsum targets, mounted measurement points (Figure 1), and detailed photo documentation ca 1 – 2 x per half a year, or immediately after major shocks (Figure 2). The monitoring is primarily focused on cracks arising due to seismic activity considering the fact that the horizontal movement component dominates over the downthrow or overthrust component during earthquakes [1,3,4]. Therefore, vertical cracks, widening in the direction towards the earth and passing into hairline cracks or hairline shear cracks in the upper part are likely to be expected (all depending on the type of building structure and its horizontal bonding).
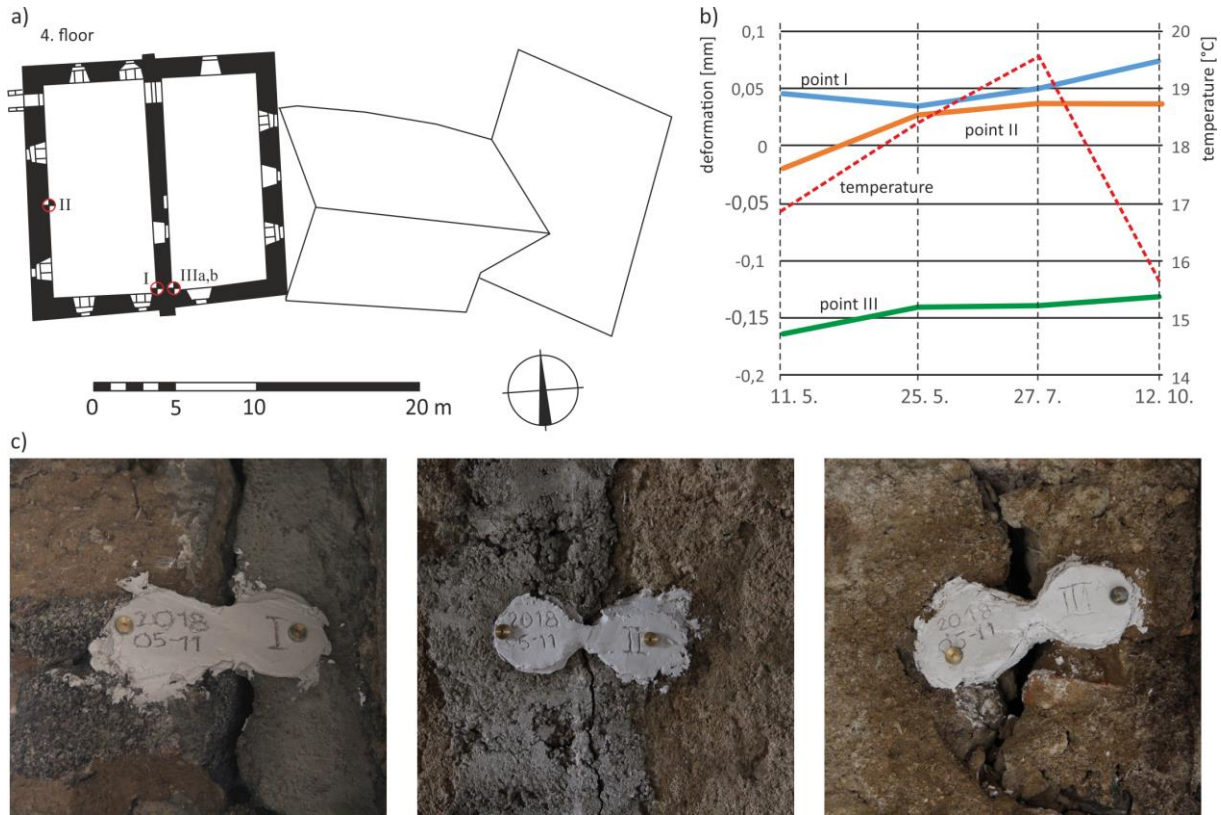
Fig. 1 – a) Floor plan of monitoring points on the Donjon structure of Bečov Castle, b) Measured time pattern of changes in the crack width within the monitored period, c) Mounting measuring points on tensile cracks
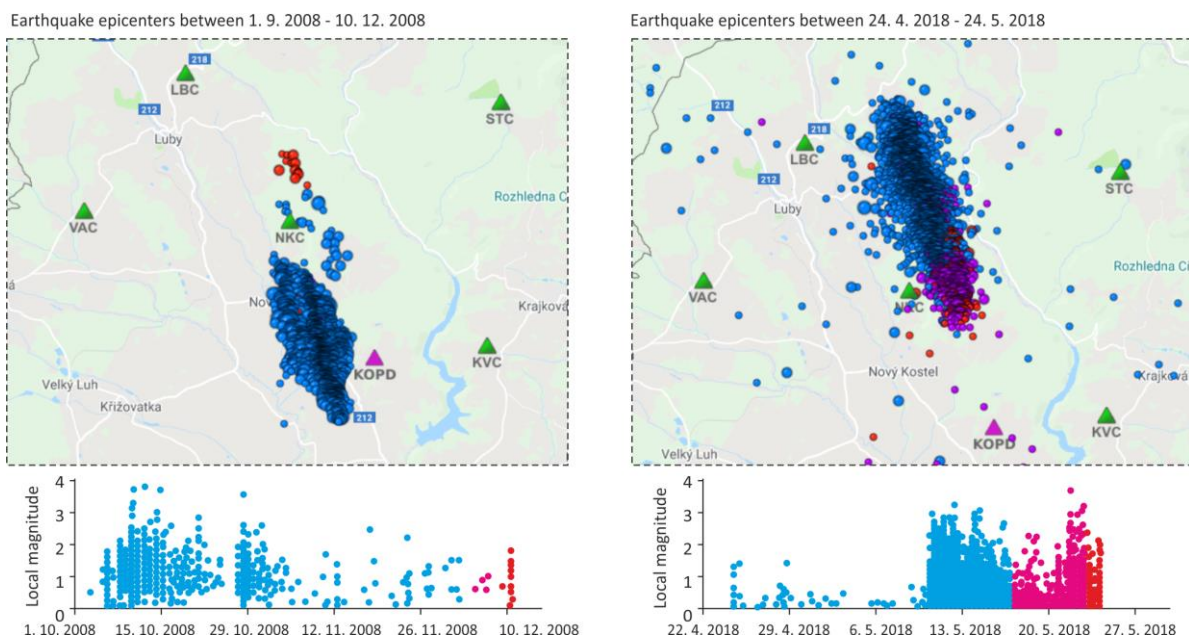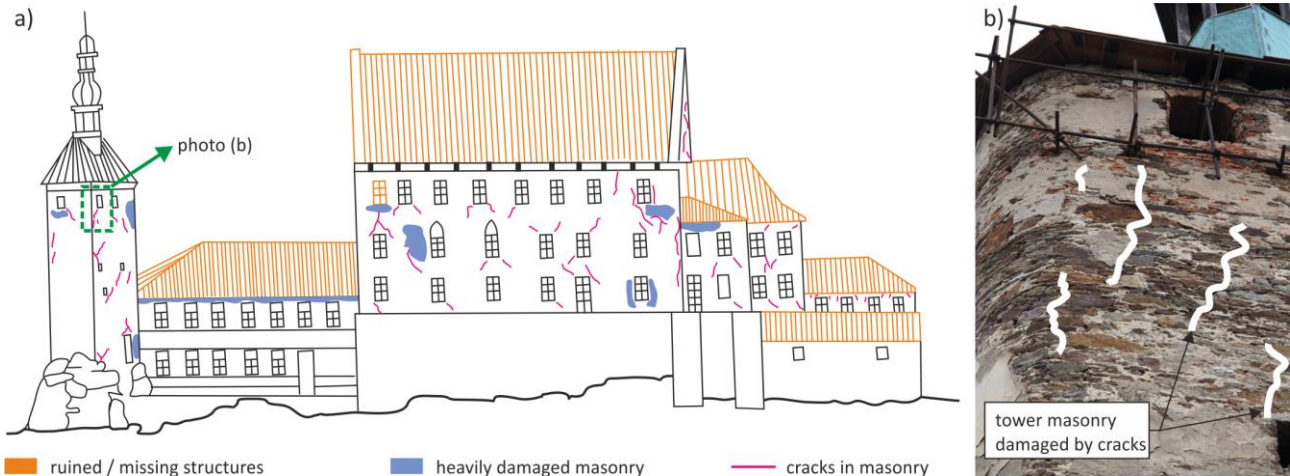

Fig. 2 – Seismic activity records obtained from the network of seismic stations established by CAS Seismological Workplaces – earthquake epicentres in West Bohemia in 2008 and 2018 (source: Institute of Geophysics of the Czech Academy of Sciences)

Fig. 3 – Romanesque Hartenberg Castle with a later Baroque refurbishment built of freestone masonry – occurrence of numerous failures and cracks caused, among others, by seismic effects; a) Failure scheme, b) Failure detail (photo by M. Pospíšil)
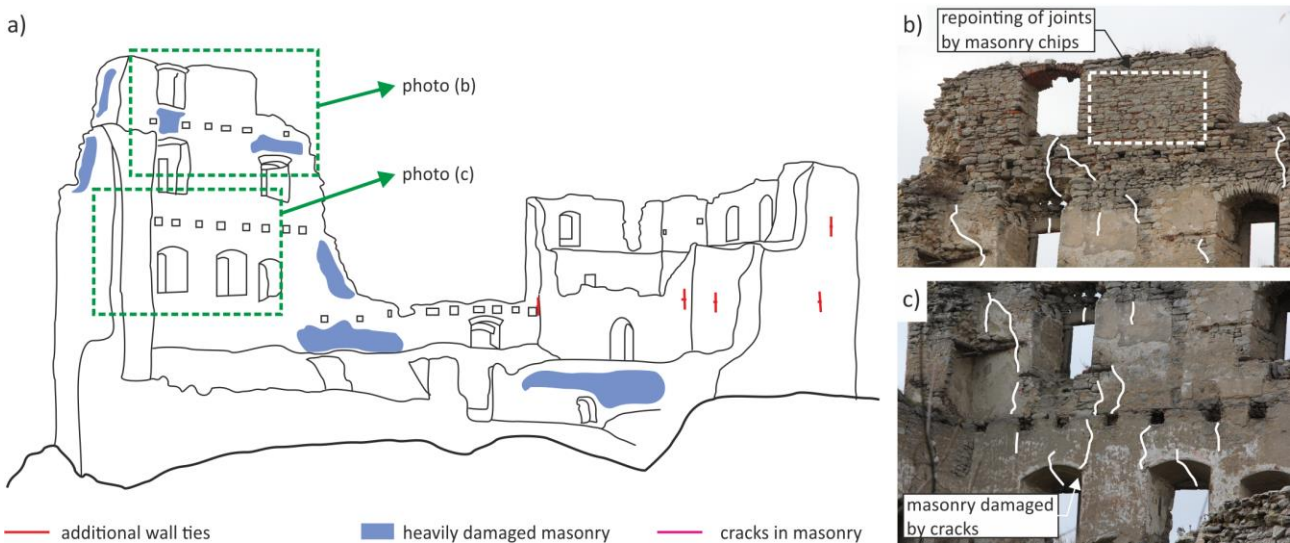

Fig. 4 – Starý Rybník ruins of a gothic castle, empire chateau and farmyard. Stone masonry of more or less worked freestone to mixed brick masonry. The complex was significantly damaged in an earthquake in 2014 when the whole eastern wall collapsed into a pond. The remains of masonry manifest numerous cracks and masonry failures; a) Failure scheme, b), c) Failure detail (photo by M. Pospíšil)

Based on the analysis of degraded buildings located in zones with active natural seismicity (Figure 3 to Figure 5), the following hypotheses and conclusions can be formulated:

a) Buildings of classical stone, brick and mixed masonry are significantly more vulnerable to seismic activity of earthquake swarms compared e.g. to wall structures of precast panel buildings built in this area in the last century.

b) The extent and intensity of damage to masonry buildings which are not continuously maintained and repaired after damage caused by the previous seismic activity is greater

compared to non-degraded buildings. The dissipation, redistribution of stresses from damaged parts of a masonry structure into undamaged parts is insufficient and, as a result, the extent and intensity of damage gradually grows – the parts of a non-degraded masonry structure that are able to absorb seismic energy without failure "diminish", and the masonry structure becomes less resistant.

c) As a consequence of greater stiffness of masonry buildings where cement mortar was used as a binder compared to buildings with a lime-based binder, and, at the same time, insufficient tensile strength of masonry, wider cracks arise there and degraded parts tend to tilt more, which makes successive masonry repairs more problematic. On the contrary, masonry with a more yielding lime binder absorbs fracture energy in the binder masonry part 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.


heavily damaged masonry — cracks in masonry
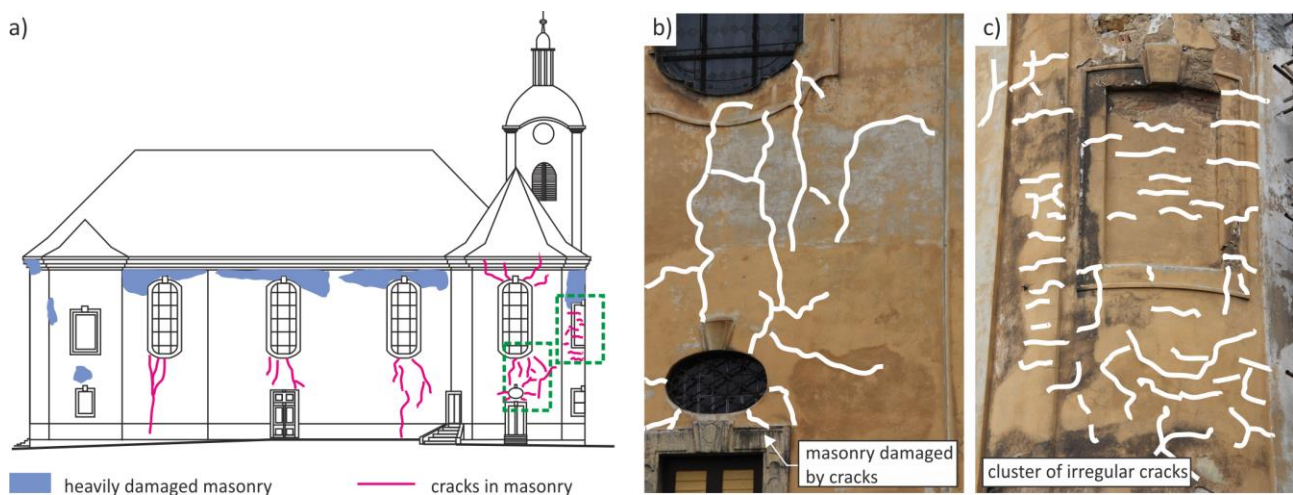
Fig. 5 – Saint Anna Church in Sedlec near Karlovy Vary from the end of 18th century with a preserved pointed arch in the sacristy from the 13th century. The church masonry shows considerable damage by all-directional tensile cracks; a) Failure scheme, b), c) Failure detail (photo by M. Pospíšil)

CHARACTERISTICS OF NATURAL SEISMICITY EFFECTS ON MASONRY BUILDINGS

Seismic movements caused by natural seismicity are continuous movements, approximating oscillatory motion defined by the amplitude, period, velocity and acceleration (Figure 6). For simplicity's sake, it is assumed that the movement during an earthquake is simple harmonic motion. For building structures situated in high risk seismic regions, structures are also assessed for the values caused by seismic movements of foundation soil, for the effects of inertial (seismic) forces acting at various points of the structure, concentrated at various height levels (bells – bell cages, roof towers), or, in historic multi-storey buildings (palaces, castles, chateaux), concentrated at levels of individual storeys. The effect of seismic oscillations of subsoil with direct contact is first transferred into the building substructure where cyclic horizontal deformations of the foundation arise as a response to cyclic movements of the foundation bed, and then propagated to higher storeys via the underground (lowest) storey depending on the shear and flexural stiffness. The magnitude and type of the horizontal deformation depend, in particular, on the stiffness of the structure of individual storeys or the stiffness of masonry supports of the vaulted system, etc. The highest values of strain, or horizontal (shear) deformations are found on the lowest storeys situated between the foundation and the superstructure depending on the distribution of the bearing system's stiffness along the

building's height. The weakest point of the building is usually in the parts with a relatively low shear and flexural stiffness (spacious halls, church spaces, etc.) [10,11].
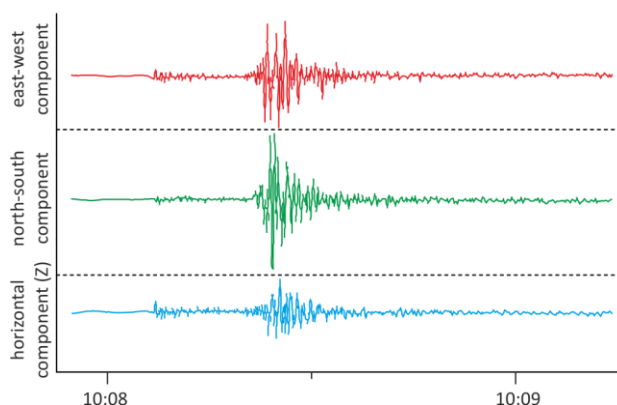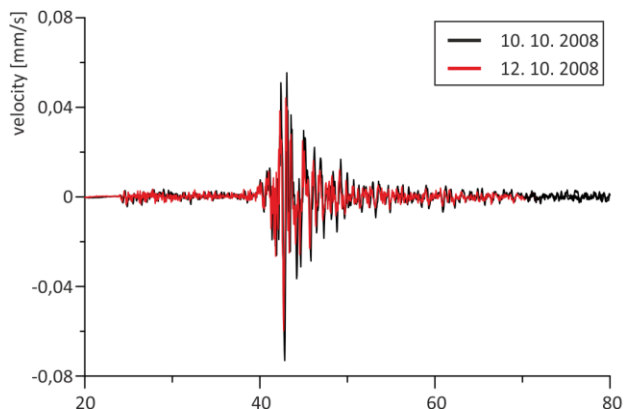

Fig. 6 – Record of seismic excitations during an earthquake
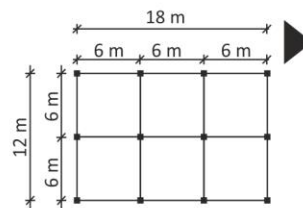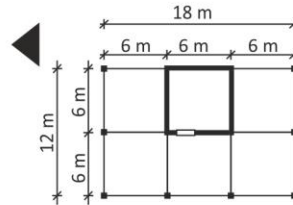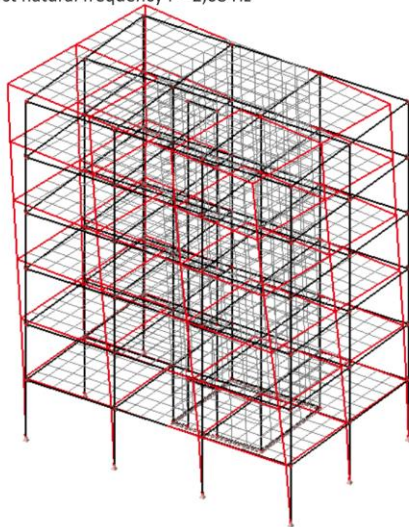*(source: Institute of Geophysics of the Czech Academy of Sciences)*

The horizontal movement of the Earth's surface reaches 0.3 to 0.5 (or even more) times the gravitational acceleration value during an earthquake – this horizontal component has the most significant consequences for buildings.

The composition of the geological setting and its mechanical properties affect the magnitude of vibrations from the subsoil, which can 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 (Figure 7) and, consequently, the transfer of traffic-induced vibrations into building structures is amplified by the so-called resonance effect [12]. The failure of masonry structures can also occur due to secondary excited movements of the subsoil in the vicinity of non-stabilised geological conditions.
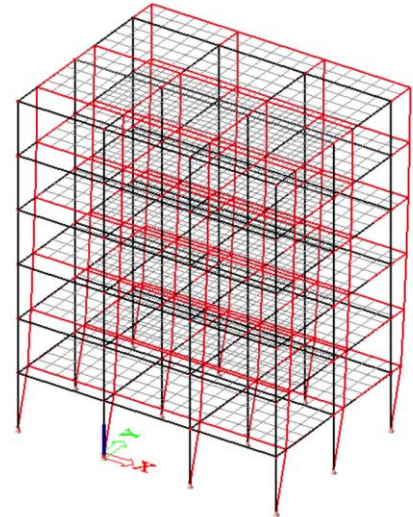
Masonry buildings without bond beams or beam and wall anchors, buildings with yielding (e.g. beam and girder) floors, with vaults without bowstrings and with insufficiently deep and stiff unbonded foundations are exceptionally sensitive to the dynamic effects caused by natural seismicity even in cases of repetitive mild intensity (such as seismic swarms with a magnitude of 1-3 on the Richter scale).

Due to frequent repetitions of dynamic effects caused by mild vibrations – e.g. the so-called seismic swarms – minor cracks arise and propagate in masonry structures. 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 propagation 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 Table 9, ČSN 730040 [13]). Figure 8 schematically displays examples of characteristic failures of masonry buildings due to dynamic loads.
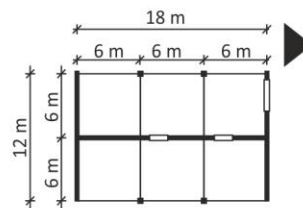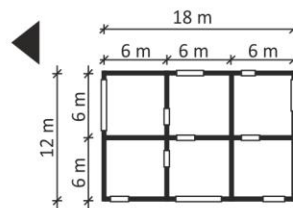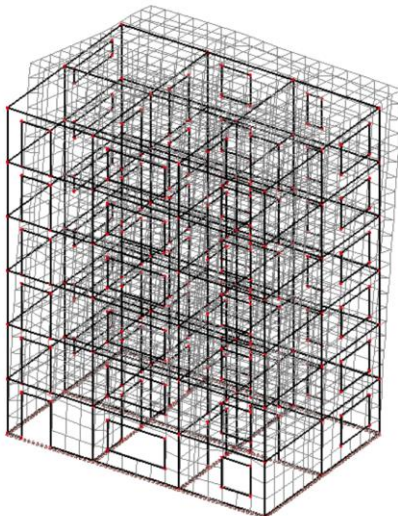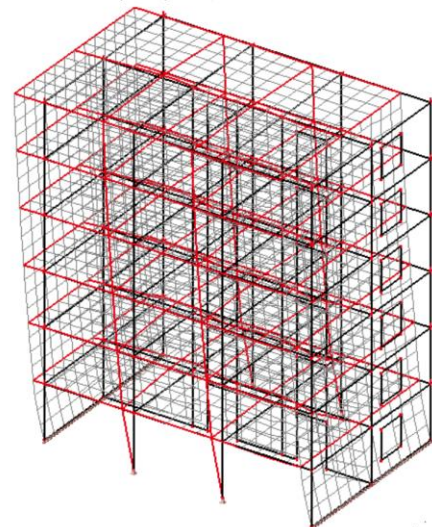
Fig. 7 – Examples of first natural frequency shapes of a precast reinforced concrete skeleton (a), monolithic reinforced concrete skeleton (b), monolithic reinforced concrete wall structure (c) and monolithic reinforced concrete combined structure (d)

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

Special attention must be paid to buildings exposed to dynamic effects and vibrations which are situated (founded) in seismically unsuitable foundation soils, in the vicinity of tectonic failures, in undermined areas, in insufficiently strengthened made-up ground and slope covers, in a sloping terrain, in areas of geologic faults. The foundation structures of such buildings with insufficient

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stiffness must be strengthened by a suitable remediation method so that they are able to ensure the redistribution of deformations due to changes in the response (shape) or the foundation bed.
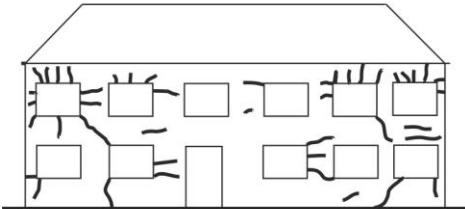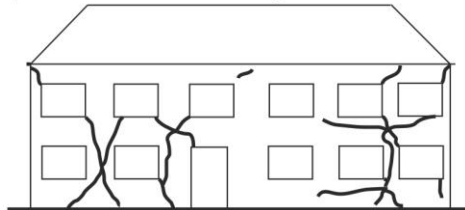
Fig. 8 – Failure scheme of masonry buildings due to dynamic effects,
a) Pile driving, b) Blasting, c) Natural seismicity

PREVENTIVE MEASURES ENSURING SEISMIC STABILITY OF HISTORIC BUILDINGS UNDER NATURAL SEISMICITY EFFECTS

The basic measures preventing the failure and stability loss of historic buildings situated in seismically active regions include:

a) Strengthening of the foundation structure – deepening, root piles, jet grouting, foundation coupling, foundation prestressing.

b) Stabilisation of vertical masonry structures – grouting, prestressing masonry and masonry supports in the horizontal and vertical direction.

c) Strengthening of masonry supports and pillars with non-prestressed strips of confining composite systems based on high-strength fibres, concreting, guniting, steel bandage.

d) Reinforcement and enhancing the stiffness of floor structures, mainly timber structures with effective wall and beam anchors, additional execution of tie beams and strengthening of adjacent masonry, additional mounting of steel or timber girders and binding joists, concrete topping.

e) Stabilisation of reinforcement of vaulted structures – reinforcement of vaulted masonry by grouting, high-strength FRP composite strips, execution of extrados strips, activation of tendons, execution of new vault ties, complementation of a tendon system with cross-braces.

The most effective measures include bracing the load-bearing masonry structure at the foundation and floor slab level and prestressing the load-bearing masonry walls and pillars with the foundation structure in the vertical direction (Figure 9).
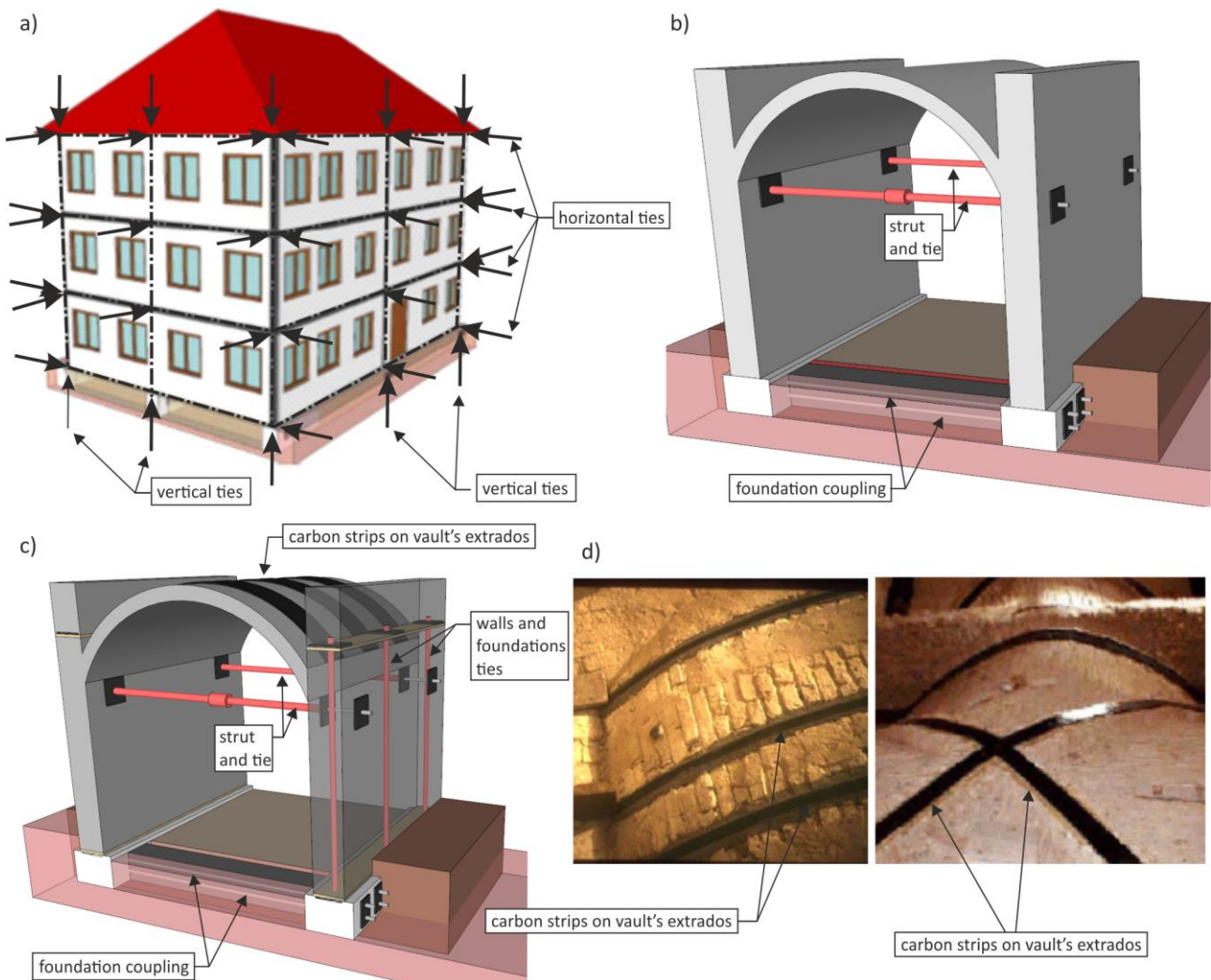
Fig. 9 – a) Enhancing the resistance of a multi-storey masonry building by horizontal and vertical bracing of masonry at the floor tie beam and inter-window pillar level, b), c) enhancing the vault resistance by bracing the supporting system and the foundation and enhancing the vault masonry tensile strength by high-strength FRP strips, d) examples of enhancing the resistance of vaults by high-strength FRP strips on the vault extrados

In special cases of exceptionally significant historic and listed buildings, the risks of damage or a collapse of a building due to a strong earthquake can be mitigated by the application of some of the so-called passive elements:

- *The group of the so-called **passive elements** includes devices and units (elements) usually embedded between the substructure and the superstructure to prevent direct contact of the load-bearing system and the foundation bed, eliminate or limit direct transfer of the seismic wave motion of the subsoil onto the building structure. There is currently a series of devices and units (elements) available for this purpose based on the so-called elastomeric bearings (natural rubber, neoprene, special rubber), viscose dampers and slide bearings. Some systems combine elastomeric and slide bearings. A characteristic feature of these devices – embedded units (elements) – is the ability to return back to the original shape to some extent even after a preceding considerable horizontal – shear deformation, where it is assumed that*

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the vertical deformation of the bearing does not occur due to a relatively high stiffness of the superstructure. This applies up to a certain range of the movement and deformations of the superstructure due to the effect of seismic waves. The stiffness of elastomeric bearings is increased by embedded steel plates. The bearings mounted between the foundation and the superstructure deform in the horizontal direction due to the effect of seismic waves thus absorbing the kinetic energy generated by the subsoil vibration. The so-called slide bearings are made of specially shaped stainless steel (concave and convex shape) and coated e.g. with teflon.

- *The group of the so-called **active elements** includes damping systems based on active mass dampers, represented e.g. by a physical weight placed on the top storey whose horizontal movement excited by seismic effects does not coincide with the movement of the building (is not identical to the building resonance) onto which part of the building's kinetic energy is transferred, which causes vibration damping.*

Additional embedding of devices and elements e.g. between the foundation structure and the masonry superstructure is very difficult to apply in existing buildings. For this reason, the basic measures used in historic and valuable listed buildings to protect them from the effects of seismicity are passive systems including numerous measures aimed at strengthening the structure so that it does not suffer any damage.

CONCLUSION

The preventive execution of some of the above measures ensuring the safety and stability of historic buildings exposed to the effects of natural seismicity requires, in many cases, substantial financial resources. For this reason, a potential design and extent of applied measures must necessarily correspond to the significance of the historic building and an objective assessment of the hazard and intensity of natural seismicity in the respective area.

Due to the frequent occurrence of natural seismicity with a relatively low intensity (up to ca level 4 on the Richter scale), it is important to perform regular observations and monitoring and, based on them, regular maintenance and repair interventions or rehabilitation measures reducing the risks of a progressive development and propagation of failures and on-going processes.

ACKNOWLEDGEMENTS

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