

# PRINCIPLES AND INSTRUCTIONS FOR COMPLEX PROTECTION OF HISTORIC BUILDINGS WITH VAULTED STRUCTURES FROM THE EFFECTS OF DYNAMIC LOADS

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## ABSTRACT

Historic buildings located in areas exposed to dynamic effects caused by natural or technical seismicity are one of the most vulnerable types of structures. Masonry buildings often have timber-ceiling structures with insufficient rigidity and not fully functional system of wall and beam ties, therefore being extremely sensitive to the dynamic effects caused by natural or technical seismicity. Main focus of the article is the outline of possible rehabilitation and restoration design approaches for strengthening of historic buildings in terms of dynamic loads. Brief information about the research performed in the field of masonry vaults' reinforcement due to the dynamic loading is presented.

## KEYWORDS

Masonry, Vaults, Dynamic effects, Historic structures, Strengthening

## INTRODUCTION

Seismic waves due to earthquakes (natural seismicity) are usually complex continuous movements, similar to the oscillations characterized by its period, amplitude, velocity and acceleration (Figure 1a). To simplify this, the movement during an earthquake is normally assumed to be a simple harmonic motion. The effect of seismic waves in the subsoil directly in contact with the structure is first transmitted to the foundations of the building, exerting cyclical horizontal displacement of the foundation due to the repeated movements of the subsoil, which are then transmitted to above ground structure through the underground (lowest) floor. The type and magnitude of the horizontal displacement depends mainly on the shear and flexural stiffness of the individual floors' structure or the substructure (Figure 1b). The highest values of stresses or horizontal (shear) deformations related to the distribution of the load-bearing system's stiffness along the height of the building can be expected on the lowest floors between the foundations and the superstructure, or in the substructure. In this perspective, the systems with a relatively low stiffness on these floors – e.g. spacious halls, temple naves, etc. - represent the weakest, critical point, usually with the lowest resistance to seismic effects [1,2]. The movement of the Earth's surface during an earthquake in horizontal direction reaches approx. 0.3 to 0.5 times the gravitational acceleration. The horizontal component is the one that has the most severe impacts on buildings. A frequent cause of failures of masonry structures is the relatively low tensile strength of masonry and low ductility, which is the cause of considerable sensitivity of these materials (masonry structures) to the effects of forced deformations. The consequences of this property are, in many cases, manifested locally in the places of stress states with a significant tensile

component. Figure 2 illustrates this fact by comparing the working diagrams of masonry, concrete and steel.

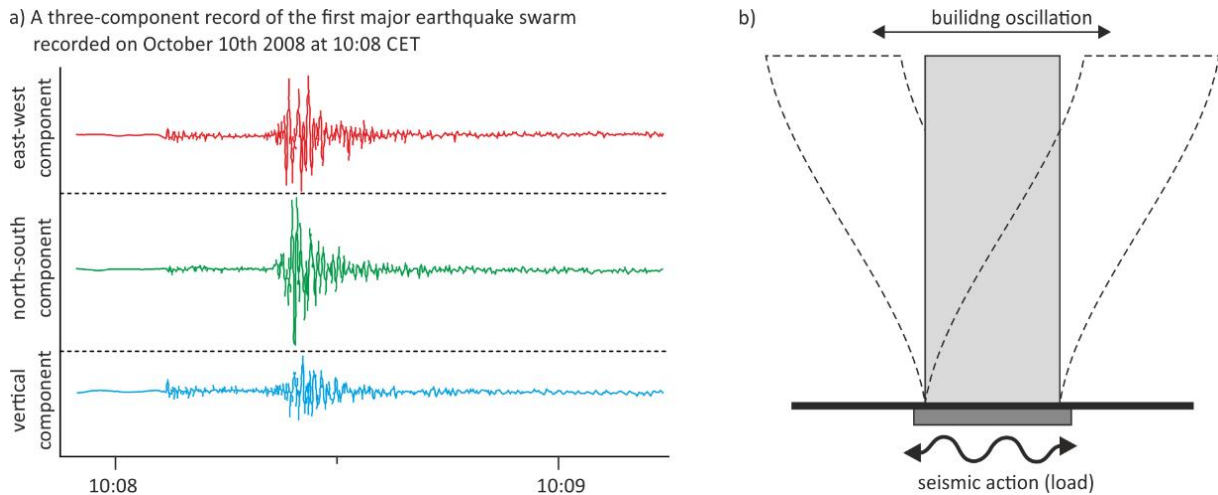


Fig. 1 – a) Record of seismic excitations during earthquake swarm in 2008 (West Bohemia, Czech Republic), b) Response of the structure to seismic loading

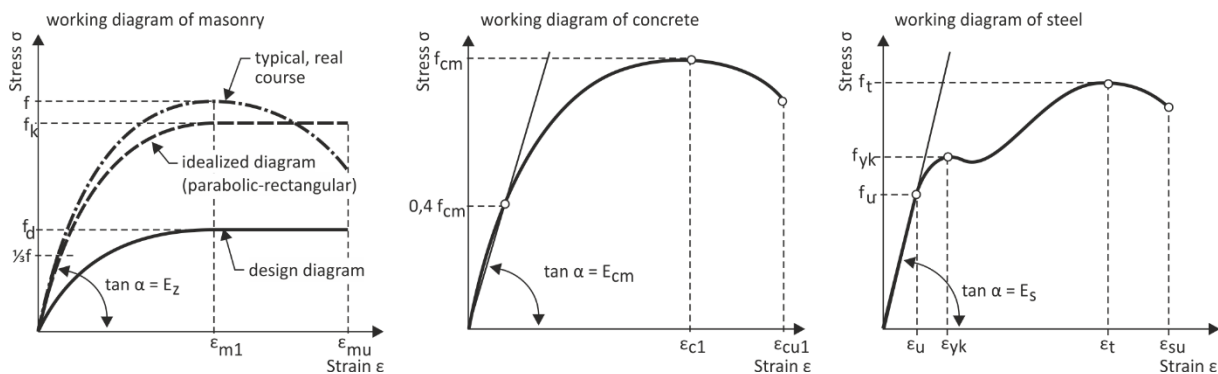


Fig. 2 – Load-displacement diagrams of masonry, concrete and steel

The severity and intensity of seismic (dynamic) effects, which spread through the soil, caused primarily by natural seismicity, depends, among other things, on the execution method and the properties of the foundation structures of the building. The magnitude of vibrations from the subsoil is mainly affected by its geological composition and mechanical properties. Propagation of vibrations through the subsoil depends directly on the natural frequencies of soils of the overlying formations on the bedrock. In the conditions of the Czech Republic, the usual thickness of soils on the bedrock is 2-4 m. In such a case, the natural frequencies of the soil may be very close to the natural frequencies of buildings [3]. Due to this, the transmission of vibrations into building structures can be amplified by the so-called resonance effect [4]. Secondary excitation of subsoil movements near non-stabilized geological conditions may also lead to failure of masonry structures.

The structures with limited spatial stiffness and insufficiently rigid foundation structures tend to be highly susceptible to dynamic effects due to technical and natural seismicity [5]. Typical masonry buildings, often without fully functional system of wall and beam ties, with beam ties anchored in degraded masonry, with an inadequately rigid vaults' supports system, buildings with "soft" timber ceilings, with shallow or non-rigid foundations and unsuitable or degraded foundation

subsoil are extremely sensitive to these effects [6,7]. The type of masonry failure under dynamic loading caused by vibrations is essentially a brittle fracture. At relatively low vibrations, the masonry breaks due to fatigue not only in the joints, but also in masonry units. Vertical cracks occurring in the perimeter walls of castle and church towers are also, in many cases, caused by seismic effects (including low-cyclic effects of temperature and dynamic effects of heavy bells) [7]. Low resistance of masonry structures to seismic effects can lead to severe damage or even collapse of these structures [8,9], many of which are buildings with national or even international heritage protection.

Current research in the field of masonry structures' response to dynamic effects is focused mainly on experimental and theoretical analyses of the behaviour of main structural parts (walls, columns, vaults) under seismic action (horizontal loads) and on the possible methods of rehabilitation, restoration, strengthening and stabilization of these structures. The in-plane displacement capacity of masonry structures is considered one of the most important factors for evaluating their resistance to seismic loads [10,11]. In the field of strengthening, different materials and reinforcing methods are being tested. The use of high strength composites based on carbon, glass, basalt and steel fibers and epoxy resins (FRP) or cementitious matrices (FRCM) is often preferred. The experimental and theoretical research is primarily focused on the determination of optimal placement of the strengthening measures [12,13], verification of bond properties of reinforcing measures [14], verification of novel types and shapes of FRP reinforcement ( $\Omega$ -Wrap [15]), use of different materials (for example polyparafenilenbenzobisoxazole fibre reinforced cementitious matrix - PBO-FRCM [16,17], Anorganic Matrix composite Grid [18] and others) or even modification of the strengthening composite properties by nanomaterials [19]. Experimental research of masonry structures (mainly vaults) is also focused on verification of seismic performance of reinforced structures [20-23]. Integral part of the research is numerical modelling of reinforced structures using advanced, non-linear approaches and their evaluation against the experimental results [8,24-26]. The use of textile based reinforcements (TRM) and steel reinforced grouts (SRG) is often found to be favourable compared to traditional FRP reinforcement, due to the more ductile behaviour, better compatibility with historic masonry materials, reversibility, lower costs, lower diffusion resistance and better fire resistance [21,22, 27-32].

## REHABILITATION AND RESTORATION DESIGN OF A HISTORIC BUILDING IN TERMS OF DYNAMIC LOADS

The rehabilitation design of a historic masonry building situated in a seismically "hazardous" foundation soil, near the tectonic faults, in burrowed under areas, not fully consolidated made-up ground and slope covers, in the sloping terrain, in areas of geological faults exposed to dynamic effects and shocks must be elaborated with special care. It is necessary to assess the execution and condition of foundations and the substructure, the quality and workmanship of load-bearing masonry, the stiffness and effectiveness of the system of tendons, the transfer of horizontal forces exerted by vaulted structures, the stiffness of the supporting system and the stiffness of the floor structures in their planes.

Results of extensive analysis of the damaged to historic masonry buildings in seismically active regions [3] can be summarized as follows:

- a) Due to the seismic activity of earthquake swarms, the buildings made of classic stone, brick and mixed masonry are notably more endangered, compared to, for example, the wall structures of prefabricated concrete buildings erected in the same area in last century.
- b) The degree and magnitude of damage to masonry buildings, which do not undergo regular maintenance and repair of the damage caused by dynamic effects of previous seismic activity, is more severe compared to undamaged buildings. The stress redistribution and dissipation from parts of the masonry structure with damage to intact parts is too small and therefore the

extent and intensity of the damage gradually increases. The area of the undamaged masonry structure with the ability to absorb the seismic energy without failure is reduced, which leads to lower resistance of the masonry structure.

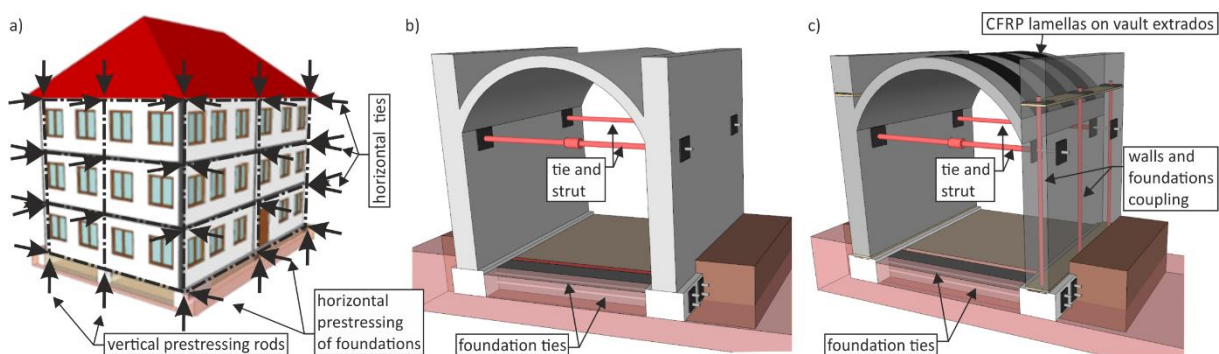
- c) Masonry buildings with binder based of cement mortar have higher stiffness, compared to buildings with binder based on lime, and, at the same time, due to the low tensile strength of the masonry, cracks of larger widths appear and a more significant deflection of damaged parts occurs, which makes subsequent masonry repairs difficult. In contrast, the masonry with a softer binder based on lime dissipates the fracture energy in the binder part of the masonry and, as a result, more frequent and smaller (thinner) cracks appear, with a less pronounced effect on the overall stability of the masonry structure.

**Preventive measures** in historic masonry buildings with vaulted structures in regions with increased seismicity include:

The assessment or execution of adequate modifications to ensure the stiffness and strength of the foundation structure, such as the strengthening of foundation masonry, tying of foundation structures with bracing strips, tie rods, etc., securing the participation of foundations in response to the dynamic loads and stress redistribution caused by a change in the shape of the foundation subsoil.

The reinforcement of vertical masonry columns and walls (concreting, shotcreting, steel bandage, reinforcement with FRP composites), strengthening and stiffening of floor structures (reinforcement with additionally installed steel beams, tie rods, bracing, overconcreting), deepening and bracing of foundations, all these measures increase the overall resistance of masonry structures to dynamic and seismic effects.

Additional stiffening of the load-bearing structure situated at the foundation and floor slabs' levels, vertical pre-stressing of walls and columns with the foundation structure (Figure 3), activation of tie rods together with delimiting "spacers", reinforcement of vaults with pre-stressed lamellas based on high-strength fibers situated on the extrados and pre-stressing of supports or interconnection of foundations are the most effective measures.



*Fig. 3 – a) Prestressing of the load-bearing masonry structures and foundations vertical and horizontal direction, b) Additional vault ties and foundation coupling, c) Stiffening the vault structure by CFRP lamellas, vault ties and foundation coupling*

In masonry buildings with wooden ceilings, the stiffness of the floor structure must be secured, above all, by functional wall and beam ties, or by additionally executed ring beams and by masonry bracing at the floor structure level, additional masonry reinforcement (in both horizontal and vertical directions).

In addition to the horizontal bracing of the masonry structure by a system of ties (wall, vault, beam ties), the masonry can also be additionally reinforced by vertical steel ties, which vertically tie individual parts of the building – e.g. anchoring of the wooden structures of trusses, baroque

towers and domes. Wooden vertical tie rods may also be used, beam tie rods are anchored to the floor beams. Similarly, cornices, stone slabs of balconies, bay windows, suspended staircases can also be anchored by vertical steel tie rods, and the masonry can be strengthened in places where the bed joints may open.

The analysis of the response to dynamic effects in the vault structure requires special attention. The type of the vault impost mounting in the masonry of the abutments mostly corresponds to partial embedding of the vaults in the abutments. The vaults gradually or continuously enlarged in the impost cross-sections in which full embedding can be assumed may be an exception to this rule. In contrast to the “simple” mounting of a vault with a bowstring on the abutments (statically determinate system), vaults with a partial or full embedding are very sensitive to deformations of the supporting system which are transferred to the vault structure, and due to dynamic loads they may cause the vault failure (e.g. in the case of semicircular vaults most often in the crown part, but in some cases near the abutments).

Securing the vault stability requires a functional and effective tie rod, beam tie system, or a stable supporting system (massive retaining walls of Romanesque buildings, supporting system of Gothic cathedrals, etc.). Vault ties and tie rods secure the transfer of the horizontal component of the resultant support forces in the mounting of vaults onto the supporting structure and, to some extent, the vault shape. Similar to the arched supporting system of Gothic buildings, vault ties reduce the requirements for the bending stiffness of the supporting structure (columns, walls) allowing their more subtle design. Their absence, insufficient dimensions or effectiveness are the most common causes of failure in vaults.

The reinforcement (strengthening) of the vault by overall reinforcement, or by additionally installed monolithic, precast and steel strips, or strips of high-strength FRP composites installed along the whole length on the back of the vault and anchored to the vertical supporting structure increases the resistance of the vault to dynamic effects. To achieve the required effectiveness of the vault reinforcement by additionally installed strips the immovability and stability of the supports and the foundation structure is necessary (see Figure 3c).

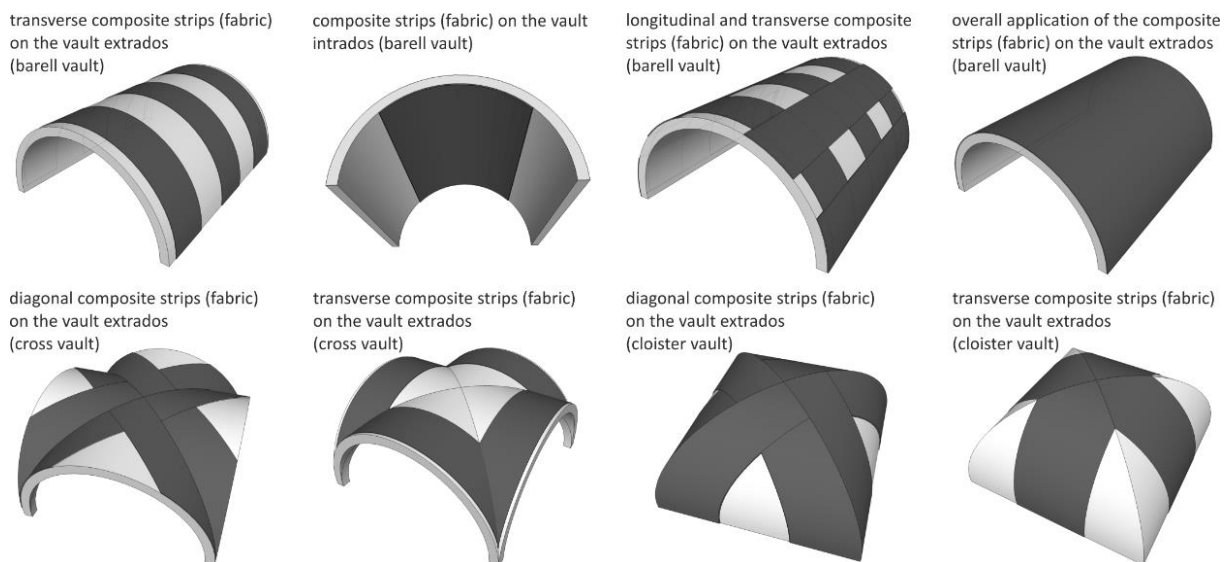


Fig. 4 – Schematic representation of the reinforcement of vaulted structures using carbon (glass, aramid etc.) fabrics based composites

By applying FRP composites based on high-strength fibers, the resistance (load-bearing capacity, stability) of reinforced vaulted structures to dynamic effects can be increased. This property may be advisably used to increase the resistance of mainly historic vaults of e.g. sacral

buildings exposed to dynamic effects due to technical and natural seismicity in seismically active regions, or to increase the resistance of structures to the effects of extreme loads (Figure 4 and Figure 5). Composites (strips of fabric made of CFRP or GFRP fibers, or carbon lamellas bonded and glued with epoxy adhesives) should be applied on the back of vaulted structures along the whole length of the vault, or locally on the face of the vault in areas of tensile stresses (Figure 6). Similarly, the overall stiffening of the system of supports or the building can be achieved by carbon lamellae situated around the perimeter of the building, installed flatly in shallow grooves or inserted in grooves in the masonry (e.g. in places of bed joints).

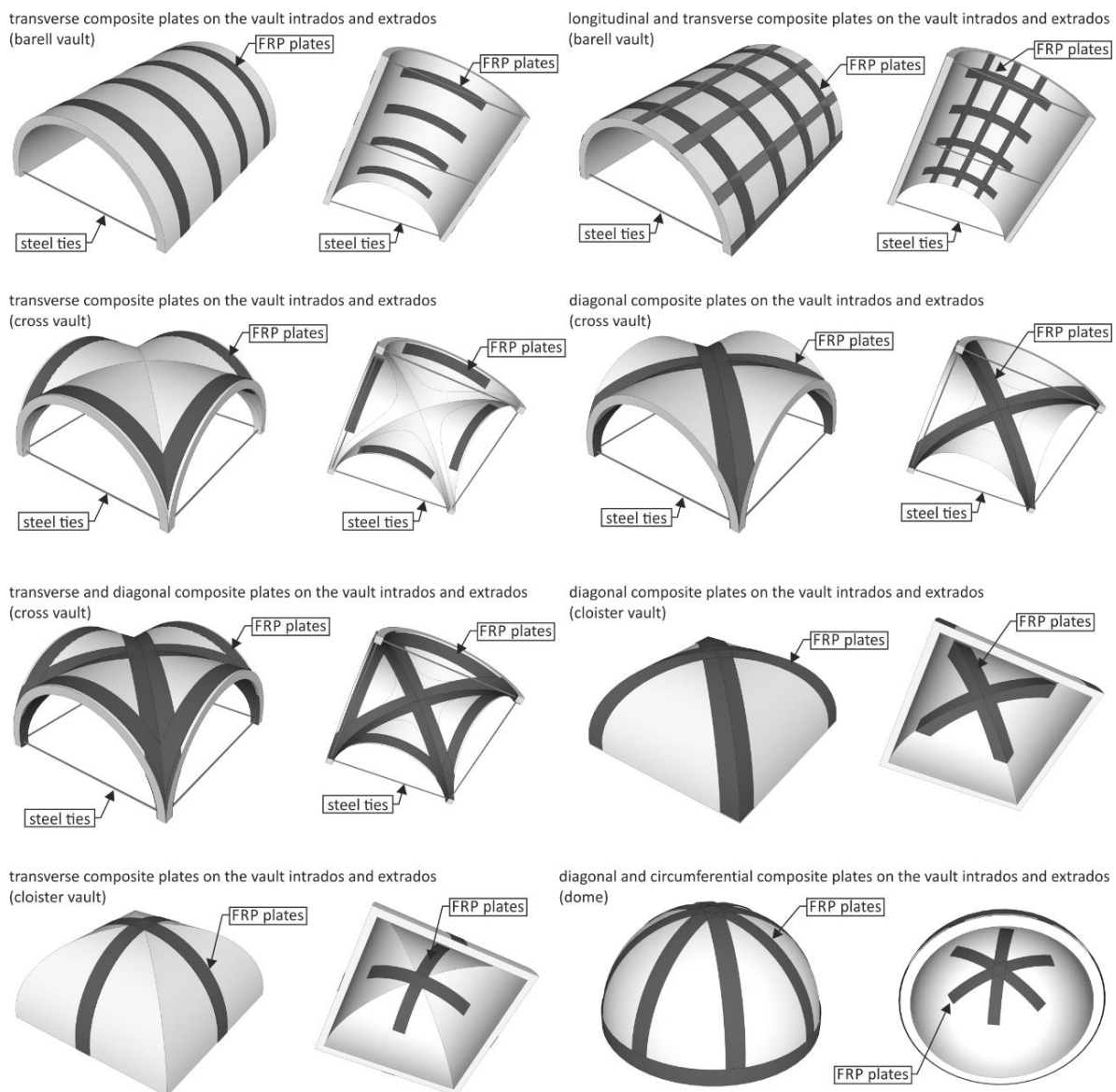


Fig. 5 – Schematic representation of the reinforcement of vaulted structures using carbon plates and steel ties due to the seismic loads and extrados using high strength strips (plates, lamellas)

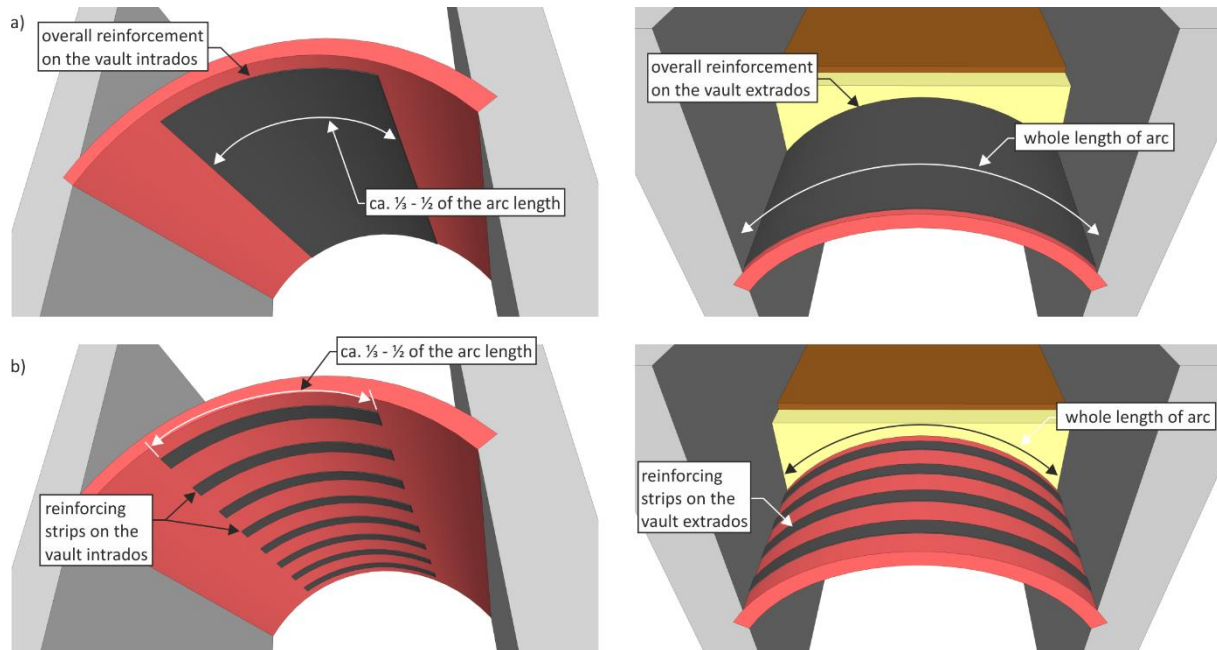


Fig. 6 – Optimal arrangement of reinforcing composites based on high-strength fabrics and lamellas on barrel vault, a) Overall reinforcement of the barrel masonry vault on the intrados and extrados (using high strength fabrics), b) Reinforcement of the barrel masonry vault on the intrados

Partial reinforcement of the vault can be achieved by additional execution of vault backings. Vault backings built, as a rule, to 1/3 to 2/3 of the vault extrados height, especially at higher vaults, favourably affect the pressure line course and effectively secure the foot joint and hazardous cross-sections at the back of semicircular barrel vaults against opening and deflection (transforming the vault with a rise  $v/l > 0.3$  into a vault with a lower rise, e.g.  $v/l < 0.2$ ). The backing must have sufficient stiffness and strength to be able not only to withstand but also to react immediately to horizontal deformations of the vault in the so-called hazardous cross-section areas, and, particularly, to an increase in the horizontal force at the “toe” of the transformed vault due to the effect of dynamic loads and thus enhance the vault stability and resistance.

Additional insertion of dampening devices and elements between the foundations and the masonry superstructure (systems with a controlled response) requires very complex technological solution when applied on existing buildings. Therefore, passive systems are often used as the basic protective measure against the effects of seismicity in historic and heritage buildings, including a number of measures focused on preventive strengthening of the structure to avoid its damage.

*Note: Load-bearing systems with a “controlled response” (stiffness of individual floors), with inserted elements and devices for the dissipation of energy and reduction of dynamic effects caused by dynamic loads can be designed:*

- on the principle of passive or active elements reducing the risks of structural damage or a complete building’s collapse during an earthquake,
- by inserting active elements and components which detect (record) the foundation subsoil movement induced by seismic or extreme wind effects (wind blasts) and actively respond to it.

### BEHAVIOR OF BARREL VAULTS UNDER SEISMIC LOADING

A frequent cause of vault failures in regions with increased risk of natural seismicity is their inelastic response to dynamic effects (Figure 7). Experimental research [13, 33] has manifested a decrease in the vault stiffness due to repeated dynamic loads - seismicity, traffic impacts, mining, etc. - which, in the interaction with e.g. a permanent vertical load, gradually cause the appearance and development of microcracks and cracks, the growth and propagation of cracks arising usually due to other permanent and cyclic loads, up to the failure of the structure – by a gradual increase in deformations in individual load cycles. The velocity of this process, the gradual decrease in the vault stiffness, depends on the intensity of the vaulted structure response during the occurrence of repeated dynamic loads. The decrease in the vault stiffness (Figure 8a) due to the growing vault damage is accompanied by a decrease in the vault natural frequencies (Figure 8b).



Fig. 7 – Examples of the failure of a barrel masonry vault with vaulted openings and cross vault of a historic building (Loretto near Bor u Tachova, West Bohemia, Czech Republic, 17th cent.)

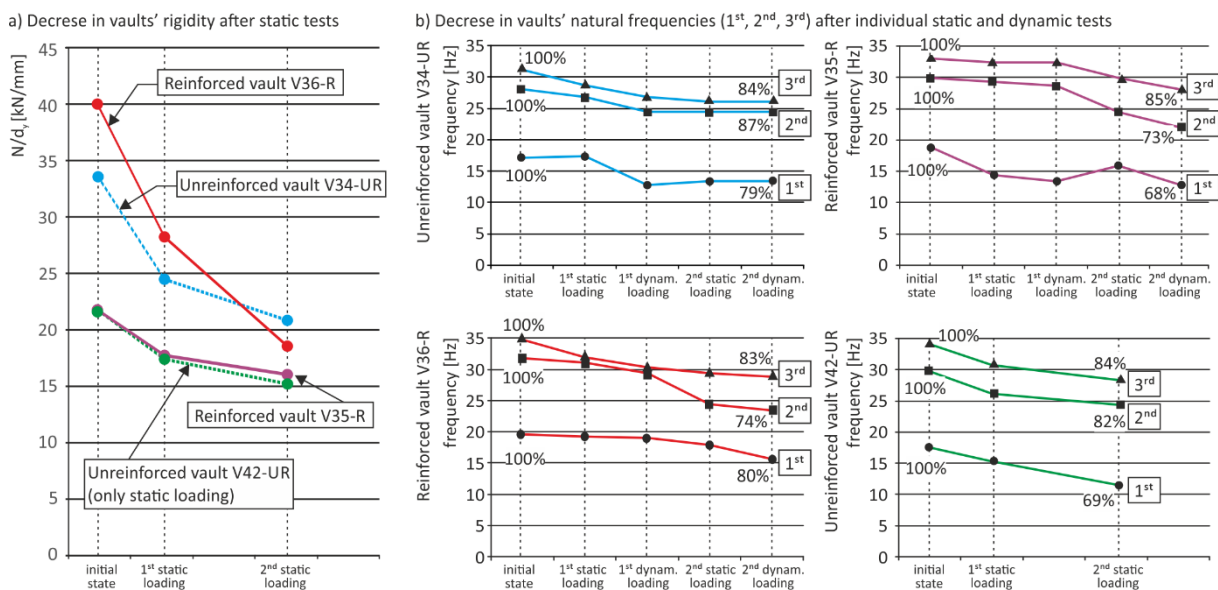


Fig. 8 – a) Experimentally determined decrease in the stiffness of vault structures, b) Experimentally determined decrease of natural frequencies (1<sup>st</sup> – 3<sup>rd</sup>)



The results of experimental research [13,33] have shown a decrease in the stiffness of a masonry barrel vault with a tendon after each load “cycle” of static and dynamic loading, which was reflected in the overall increase in deformations and a lowering of natural frequencies and, in some cases, even in an increase in internal damping. The cause of a change in the vault stiffness was the formation of microcracks, the development and propagation of cracks and, in the first load cycles, also the vault consolidation, especially by additional compression of contact joints (mortar - masonry unit) in the bed joints of the vault masonry. The obtained results are extremely important for the evaluation of the residual life of primarily the vaults of historic buildings located in seismically active regions or in places with intensive technical and induced seismicity (mining activity, quarrying, traffic etc.).

*Note: The dynamic response can be utilized to determine potential damage to the structure that may be complicated to detect in other ways. Assuming a low level of dynamic (i.e. non-destructive) excitation, the principle of such tests is to compare the dynamic characteristics of the structure. The characteristics most often refer to resonant frequencies and their respective oscillation shapes. A change in the frequency, most often a decrease, may be a sign of the appearance of internal cracks in the tested vault. A change in the shape of the oscillation then indicates its global failure.*

## CONCLUSIONS

The rehabilitation design of a historic masonry building with vaults exposed to dynamic effects in terms of its overall protection against the occurrence of failures and damage requires a detailed analysis of the supporting system of the historic building, including its adjoining structures, and, based on the overall assessment, the execution of appropriate modifications, rehabilitation and additional measures to secure the supporting system. The analysis and design of complex measures for the protection of the building must be preceded by a detailed survey. The scope of individual protective measures depends on the specific situation, design and condition of the historic building

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