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Lightweight extrados restraining elements for the anti-seismic retrofit of single leaf vaults

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A B S T R A C T

Substantial vulnerability of single-leaf vaults has repeatedly been observed in the aftermath of past earthquakes. Major vault damage or even collapse may follow the onset of mechanisms such as the indirect bending of the vault crown caused by the unconstrained rocking of the abutments, the shear failure of the vault lunettes induced by possible differential rocking of the supporting masonries, and the direct differential bending induced by the inertia forces acting as a uniformly distributed horizontal load along the vault crown. Unlike other mechanisms, which can be inhibited by traditional global retrofit interventions aimed at triggering a box-like seismic response of the existing building, limiting direct bending requires targeted measures on the vault crown. In this paper, extrados lightweight plywood restraining structures applying passive confinement actions are conceived to delay the onset of the vault direct bending failure mechanism. The reinforcement is designed as a 3-hinged arch, hinged-constrained at the springing and at the vault key section to enable small relative displacements of the vault springing, which may follow the deformation of any internal ties or roof box structure. The technique is a lightweight and dry solution that does not require specialised labour; it is reversible and minimally impairs the structure's integrity, thus respecting major restoration principles. The effectiveness of the solution is verified through an experimental study on the behaviour of a strengthened single-leaf vault, also in the case of possible relative displacements of the abutments. A special pivoting testing frame is conceived to apply cyclic, uniformly distributed inertia-like forces. The strengthened vault is shown to substantially outperform the response of an unreinforced single leaf vault, tested in a previous research study.

1. Introduction and research significance

Single leaf vaults, which are widespread over the Italian and southern European territory, are thin vaults (about 50 mm thick) made of a single layer of flat laid bricks, either running longitudinally or in a herringbone brick pattern (Fig. 1) [1–3]. Often adopted in residential and religious buildings, single leaf vaults are usually shaped as barrel, groin, and pavilion vaults and may bridge spans ranging between 3 and 10 m (3 ÷ 6 m in residential buildings; 6 ÷ 10 m as vaulting covering the main nave in religious buildings, [4]).

When adopted as walkable horizontal partitions in residential buildings, they usually feature extrados filling material, such as tightly packed rubbles or lunettes overlaid by the finishing pavement tiles. Backfill material or lunettes provide a stabilizing contribution [5]. On the other hand, in the most frequent applications, such as in churches, single leaf vaults lack any filling material and basically behave like lightweight false ceilings solely withstanding their self-weight. Unlike heavier masonry vaults that require a significant vertical stabilising load and are usually located on the building's ground floor, false ceiling single leaf vaults may also be located at the upper levels of traditional masonry buildings.

The equilibrium of masonry single leaf barrel vaults is guaranteed as long as the thrust line, associated with both static and seismic loads, lies within the vault thickness [6–8,4,9]. In single-leaf vaults the thrust line has a reduced possibility to shift and change within the small vault thickness in order to adapt to different unsymmetrical load distributions [4,10,11], or possible spreading of the supports [12], unless lunettes or spandrel walls strengthen the vault extrados against bending actions. In the case of plain single leaf vaults, the maximum shift can be attained if the structure has a catenary geometry, i.e. if the thrust line overlays the centroid axis; conversely, in the case of circular geometry, the possibility to

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Fig. 1. Typical single leaf vault with herringbone brick pattern.

shift is further reduced. As a result, these structures are particularly vulnerable even to low intensity earthquakes. Their extreme vulnerability has repeatedly been assessed after recent earthquakes, when a significant number of single-leaf vaults collapsed, regardless of the earthquake intensity and of the level of the global damage to the structure [13].

In the case of a seismic event, thin single-leaf vaults can undergo three main mechanisms, namely: (a) indirect differential bending; (b) severe shear distortion; (c) direct differential bending [13].

Indirect differential bending follows an unconstrained rocking motion of the abutment or supporting wall, which in turn induces the rotation of the vault supports (Fig. 2a). Such rotations force differential bending along the vault crown. In the case of either out-of-phase rocking or differential drift of the perimeter walls, the relative displacement of the vault springing can also worsen the indirect bending of the vault crown. Interestingly, indirect bending can be limited or inhibited through global interventions, such as roof or floor diaphragms, aimed at constraining or reducing the rotation or relative displacement of the vault springing.

Severe shear stresses and distortion follow the onset of differential rocking along the nave ends. Differential rocking occurs as a result of the difference in stiffness between the façade and the transverse arches [13,14] (Fig. 2b). The differential rocking mechanism can be inhibited or confined by adopting a stiff roof box-structure constraining the perimeter masonries along the edge and limiting the possible shear distortion [15].

Direct differential bending is the result of the distributed seismic actions associated with the vault mass. Depending on the earthquake magnitude and the vault thickness, direct bending can be as severe as to cause the structure to collapse, characterised by the onset of a four hinge mechanism [14,16–18] (Fig. 2c). Past experimental and theoretical studies have ascertained the vulnerability of single leaf vaults with respect to direct differential bending [19]. Practical abaci for the evaluation of the vault collapse multiplier as a function of the main geometry characteristics were provided, and single leaf vault collapse was assessed to be triggered by moderate to low seismic actions, corresponding to horizontal accelerations ranging between 0.04 g ÷ 0.10 g. It is worth noting that, unlike other failure modes, and regardless of the global mitigation measures reducing the vulnerability of the whole building, this mechanism cannot be inhibited, unless special targeted interventions are carried out on the structural element.

In order to upgrade the seismic resistance of single leaf vaults, the traditional techniques developed for the strengthening of masonry vaulted structures are usually addressed. Some adjustments are needed to account for the reduced thickness of these particular kinds of vaults. For example, attention must be paid to avoid a significant increase in dead load, which in turn could result in additional seismic actions anticipating failure; also, care must be paid so as to avoid unsymmetrical load sets.

Among the possible techniques masonry spandrel walls [14,16,20,21], are worth mentioning. Spandrel walls are extrados retaining structures conceived to either constrain the deformation of the vault crown, or enforce a composite structure behaviour that allows the thrust line to migrate within the spandrel wall height. This intervention allows the substitution of the stabilising backfill material with possible reduction of the vault mass. As a main drawback, in the case of partial spandrel walls, which do not extend up to the vault key, problems may arise in the case of relative displacements of the springing.

The seismic retrofit can also be obtained through thin RC extrados slabs, which are usually secured to the vault ring through either studs, special devices, or by relying on friction so as to enable shear transfer along the vault-to-reinforcement interface. The resistance of the structure is therefore increased by enforcing a composite structure behaviour, increasing the thickness of the vault, thus allowing the ideal resisting arch to adjust within a higher thickness. The solution strengthens the vault with respect to both symmetrical and unsymmetrical load sets, but nowadays it is discarded as the concrete may induce chemical incompatibility with the masonry. The use of thin high performance natural lime mortars strengthened with inorganic fibre mesh can be regarded as an enhancement of the previous technique, ensuring chemical and mechanical compatibility [22]. As a major drawback, regardless of the material adopted, the vault mass increases and this

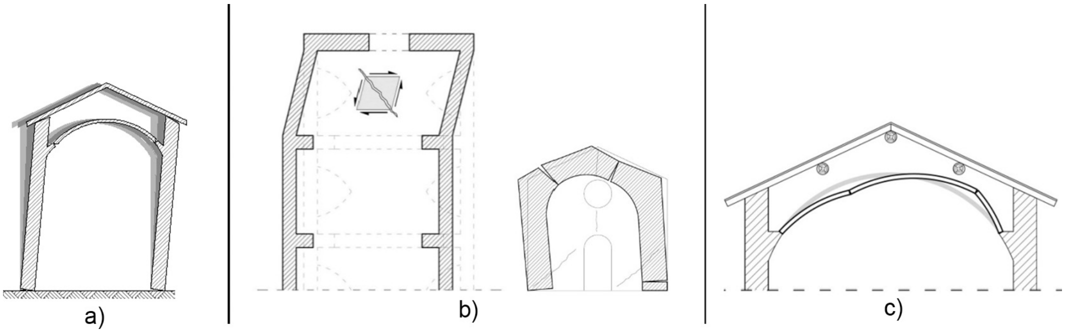

Fig. 2. Main vulnerabilities of single leaf vaults undergoing seismic actions: (a) indirect bending following rocking of the abutments; (b) shear distortion following differential rocking; (c) direct bending of the vault subject to the seismic action associated with its own mass. In the proposed strengthening approach (a) and (b) are considered as inhibited by global strengthening of the structure with roof box structures and focus is placed on the direct bending mechanism of the sole vault.