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The effects of in-plane shear displacements at the springings of Gothic cross vaults

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HIGHLIGHTS

- High seismic vulnerability of masonry cross vaults in churches.
- Pseudo-static response of cross vaults to imposed shear displacements at springings.
- Experimental test on a 1:4 scaled timber bricks - lime mortar model of a cross vault.
- Significant dimensionless shear displacement levels (failure at 3%).
- Comparison between experimental results, FE numerical results and real-field data.

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ABSTRACT

Extensive damages recorded during recent strong Italian earthquakes highlighted how vulnerable masonry vaults are and what deformations they receive from the rest of the building, which can be simulated as two phenomena: (i) a dynamic response of the vault itself, above the lateral walls and piers, and (ii) a pseudo-static response of the vault to imposed displacements at its springings, triggered by significant movement from the lateral walls and piers. This paper aims at improving knowledge in this field by simulating the second of these phenomena as static shear deformation at the springings. An experimental programme was set on a model of a typical quadripartite square Gothic cross vault (from the aisle of the Holyrood Abbey in Edinburgh). The test on a 1:4 scaled model had the shear displacement applied by moving two abutments in the longitudinal sense until failure, recording the crack pattern evolution and displacements of the ridges, identifying the diagonal cracks normal to the shear displacement that cause the damage and collapse in the vault. The crack pattern was validated with linear and non-linear numerical models, confirming particular observations like the uplift of the ridges and concentration of damage along the notional shear diagonal. Non-linear models are capable of capturing not only the crack pattern evolution, but also the vertical and horizontal displacements of the structure.

1. Introduction

Damages and collapses observed in Italian churches after many recent earthquakes (Umbria 1997, L'Aquila 2008, Emilia 2012) pointed out the vulnerability of their masonry cross vaults [1] (e.g. the San Francesco Basilica in Assisi, the San Marco church in L'Aquila, and the Modena Cathedral), so understanding their behaviour is crucial for the assessment of the seismic safety of the entire structure [2–4]. However, the evaluation of their seismic response is quite complex and depends on several factors, such as understanding fully the three-dimensional geometry, determining the mechanical properties of the constituent materials and assessing the effect of the behaviour of the underlying vertical elements (lateral walls and piers).

A vault under earthquake excitation is subjected to two main phenomena:

- dynamic response of the vault itself to acceleration of its springings;
- pseudo-static response to displacements imposed at its springings from the horizontal movements of the structures underneath (walls and piers).

Several advanced computational techniques have been developed to investigate the weakness of arch and vault structures,

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including Limit Analysis, Trust Network Method, Finite Element Method and Discrete Element Method approaches [5–9]. In recent times, computer developments based on limit analysis methods have been developed, such as the Thrust Network Method which is grounded on lower bound theorems [10,11], whereas FE limit analysis approaches with infinitely resistant elements and dissipation on interfaces used the concepts of the upper bound theorem [12–14]. In addition, FE commercial software combined with either elastic-plastic or damaging models, developed to study steel or concrete structures are often used in the technical literature to model masonry vaults [15–17]. Specific software have been also developed to account for the mechanical behaviour of the masonry curved structures, for instance DIANA by TNO Delft [18] and NOSA ITACA by ISTI-CNR Pisa [19,20]. However, the aim of the paper is to explore the benefits of methods directly accessible by practitioners, embedded already in all-purpose commercial software, not specialistic for masonry.

Many experimental studies analysed the structural behaviour of arches and vaults under static [21–23] and seismic action, mostly focusing on the dynamic response [24–26], while some performed displacement-controlled tests at the springings [27–31].

Nonetheless, only few specific studies on the pseudo-static response of masonry cross vaults to imposed shear displacements at the springings (Fig. 1a) are available in the scientific literature [31–33]. In a multi-nave church, such a shear deformation mechanism can occur due to the large difference in the lateral stiffness between the nave and the perimeter wall or the façade (Fig. 1b). For instance, damages traced back to this mechanism were observed in the Modena Cathedral after the 2012 Emilia earthquake [4]. Rossi et al. (2014) [32] performed tests on a 1:5 scale model of a groin vault made of 3D printed plastic blocks with dry joints, by applying an incremental horizontal differential displacement between two couples of opposite abutments. Consequently, Gaetani (2016) [33] performed different experimental tests reproducing in-plane horizontal shear distortion and longitudinal opening/closing of the abutments on the above model [32]. In the shear test, the maximum force was attained at about 3% of the shear displacement-to-span ratio, a little more than half of its collapse value. Milani et al. [31] presented the simulation of a wide and diversified set of laboratory tests on a small-scale model (1:5) representative of a brick masonry cross-vault. The model was made by plastic blocks with dry joints. Two types of displacement/rotation controlled tests were simulated: DSA (Direct Seismic Action), representative of the inertial horizontal actions induced by the earthquake, and ISA (Indirect Seismic Action), corresponding with shear displacements imposed at the abutments due to the differential deformations of masonry walls. ISA tests mainly showed the great ductility of the system, the maximum force being attained at about 3% of the shear displacement-to-span ratio.

This paper describes an experimental research that aims to start understanding this pseudo-static response. The first stage discussed here is a test conducted on a Gothic cross vault from the aisle of the Holyrood Abbey church in Edinburgh (UK). The layout of the church and the geometry of the quadripartite vault are representative of a wide range of medium-sized Gothic churches and a detailed physical model of the vault exists that could be adapted to the aims of this project [34]. This model is a 1:4 scaled replica built with timber blocks and lime mortar and the shear displacement is applied by moving two abutments in the longitudinal axis until failure (Fig. 1a). Linear and non-linear numerical simulations are performed to interpret further the results of the test and complete the insight to the phenomenon.

2. The prototype vault from Holyrood Abbey

The vault investigated here is located on the surviving south aisle of the Holyrood Abbey church in Edinburgh. The church collapsed in 1768 after an unreasonable substitution of the decaying timber roof trusses with equally closely-spaced masonry walls which produced huge transverse thrusts that could not be contained by the badly maintained buttresses [35]. The performance of the vault in such conditions was studied earlier [28,30] and the model from that research could be easily used for further studies on movement spread. The aisle vault considered is quadripartite and spans over an almost squared bay, with dimensions (4.9×3.78 m and height of 3.03 m) representative of many aisle vaults. While walls and piers were built with regular shaped stones, the vault webs are constituted in rubble masonry made of long thin blocks of irregular thickness (Fig. 2a). The mechanical properties of the stone are assumed to be: (i) unit weight of 23.7 kN/m^3, (ii) elastic modulus 27.1 kN/mm^2 and (iii) compressive strength 42.8 N/mm^2 [36].

The survey of the fourth bay vault highlights its typical proportions and particular geometrical characteristics. The longitudinal, nave arches are wide enough to support the lateral wall from the triforium and have a compound cross-section made of various deep mouldings. The ribs and the transverse arches share the same plain cross-section. The transverse arches follow the quite typical

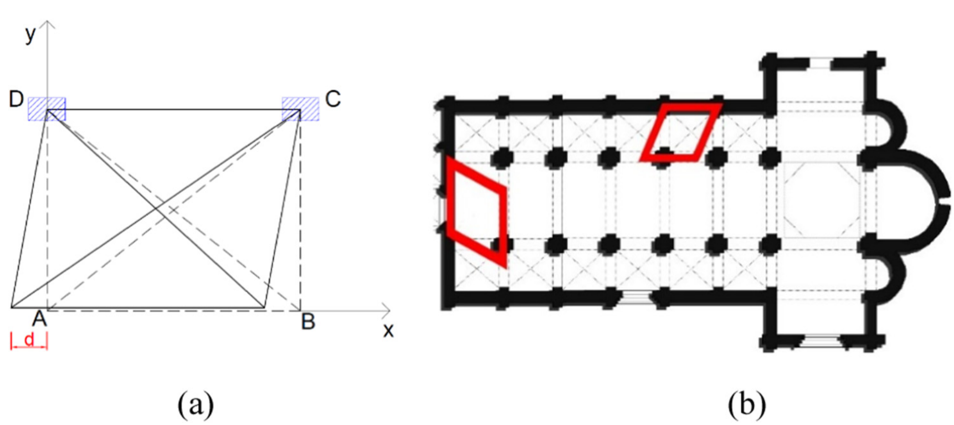

Fig. 1. (a) Imposed shear displacements at the springings A and B of a cross vault against the stiffer edge C-D. (b) Origins in possible shear displacements in a church (e.g. plan view of the Modena Cathedral, Italy).