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Evaluation of the Response of a Masonry Cross Vault Subjected to Vertical Loading using the Discrete Macro-Element Method

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Abstract

This paper was focused on the application of an innovative modelling approach, known as the Discrete Macro-Element Method (DMEM), for simulating the experimental response of a ribbed masonry cross vault subjected to vertical loading. This numerical approach is based on a simplified mechanical scheme which can simulate the main in-plane and out-of-plane mechanisms of masonry structures. The numerical model of the ribbed masonry cross vault, described by approximately 1250 degrees of freedom, was subjected to an incremental vertical load aiming at simulating the experimental setup. Two different values of cohesion (0.05 MPa and 0.10 MPa) were taken in consideration aiming at assessing the influence of this mechanical property on the nonlinear response of the masonry specimen when subjected to vertical loading. The displacement of three monitored points as well as the vertical reaction of the numerical model were assessed and compared to those obtained experimentally. It was observed that the numerical model presented a slightly higher stiffness than the experimental one; however, it was possible to replicate the maximum vertical capacity of the masonry cross vault. The comparison between numerical and experimental results demonstrated the capabilities of this simplified numerical approach for assessing structural elements with a complex geometry considering a reduced number of degrees of freedom and with an acceptable level of accuracy.

Keywords: curved structures, fired brick masonry, fiber approach, numerical simulations, nonlinear static analysis, plastic damage

1 Introduction

Masonry vaults are common roofing/flooring systems for historical constructions, significantly influencing both the local and global performances of the whole structure in which they are located. Vaulted floors significantly contribute to the lateral building stiffness, therefore affecting the distribution of seismic loading to the walls. On the contrary, this structural element can be affected by brittle failures leading to a reduction of the building capacity. The numerical prediction of the seismic responses of masonry vaults constitutes a difficult task due to the complex geometry, the presence of backfill and the anisotropic nature of the material due to the internal mesoscale structure of masonry as well as possible errors during their construction. The main causes of failure that have been identified for masonry vaults are related to the lateral instability caused by the relative displacements of the supports and/or in-plane shear distortions when subjected to dynamic loading [1, 2]. In the last two decades, a significant research effort has been focused on understanding the behaviour of masonry vaults under different loading and boundary conditions, employing different modelling approaches or laboratory testing. The latter was mainly focused on the application of vertical loading such as concentrated loads or imposed differential base displacements [3-7], while numerical analyses have been mainly based on the Finite Element Method (FEM) [8-12] or the distinct element method [13-15]. However, FEM models require a refined mesh discretisation and complex constitutive laws, leading to a large computational demand to effectively describe the nonlinear structural response. In this sense, simplified macro-modelling approaches allow for a drastic reduction of the number of degrees of freedom while guaranteeing accurate results.

This paper proposes using an innovative approach known as the Discrete Macro-Element Method (DMEM) for evaluating the response of a ribbed cross vault subjected to vertical loading. The DMEM was initially developed by Caliò, et al. [16] for assessing the in-plane response of masonry walls, and further upgraded for the evaluation of the spatial responses of masonry walls [17]. The nonlinear numerical simulations were performed using the HiStrA software [18], and the results were compared to those obtained from an experimental campaign conducted by Faccio and Foraboschi [19]. A reasonable resemblance between numerical and experimental results was obtained even employing a coarse mesh refinement of the model, confirming that the proposed modelling approach constitutes an effective alternative tool for the assessment of curved masonry structures, especially for engineering applications.

2 Methods

This investigation employs the Discrete Macro-Element Method (DMEM) for the assessment of masonry vaults. The DMEM was initially conceived to analyse the in-plane response of masonry walls. It consists of the assemblage of four rigid edges by hinges and internal diagonal links. The connection between each assembly (or panel) is carried out by zero-thickness interface elements calibrated according to a fiber approach. The original formulation of the DMEM is capable of explicitly simulating the three in-plane failure mechanisms of masonry panels, namely the flexural, shear-sliding and shear-diagonal failure mechanisms. The simulation of additional mechanisms characterising non-box structures was subsequently implemented aiming at assessing the out-of-plane response of unreinforced masonry walls [17] and curved structures [20]. In this case, each panel comprises four rigid plates connected by hinges, whereas the connection between panels is given by zero-thickness plane interface elements (see Figure 1). Each panel is governed by seven degrees of freedom (DOF): six related to the rigid body motion (translations and rotations) and one that rules the in-plane shear deformability.

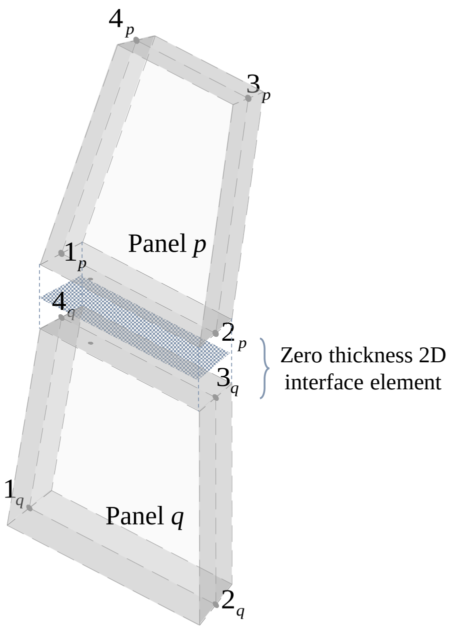
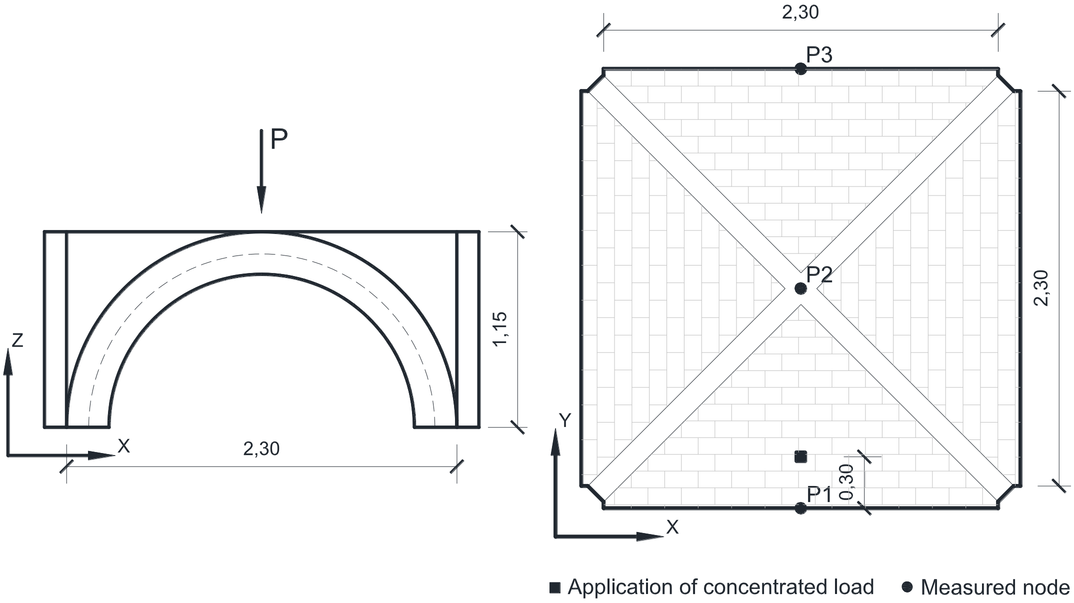


Figure 1: Representation of two adjacent DMEM irregular panels connected by a zero-thickness interface, discretising a portion of a masonry vault.

The DMEM was employed for assessing the response of a masonry ribbed cross vault experimentally investigated under vertical loading. The masonry specimen was composed of four lateral and two diagonal arches with 0.12 m of thickness and a height of 0.25 m. The external distance of the lateral arches corresponded to 2.30 m and the total height of the specimen was 1.15 m (see Figure 2a). The masonry specimen was subjected to a concentrated load which was applied 0.30 m from the external edge of a lateral arch. Due to the application of the load, the vertical displacements of three points were measured (see Figure 2b).



(a) (b)

Figure 2: Geometrical characteristics of the square ribbed masonry cross vault: (a) front and (b) plan views (adapted from Milani, et al. [21]).

The numerical model of the vault (see Figure 3) presented 1244 DOFs. The boundary conditions consisted of fixed restraints at the base of the masonry arches, whereas the application of the vertical load was defined aiming at simulating the experimental setup. According to the DMEM strategy, masonry was described by an isotropic homogeneous material with parabolic and linear softening curves in compression and tension, respectively, an elasto-plastic model for shear-sliding, whereas the shear-diagonal was assumed elastic. To assess the influence of shear-sliding behaviour on the response of the masonry specimen, two values of cohesion (0.05 MPa and 0.10 MPa) were taken into consideration. A summary of the mechanical properties is reported in Table 1.

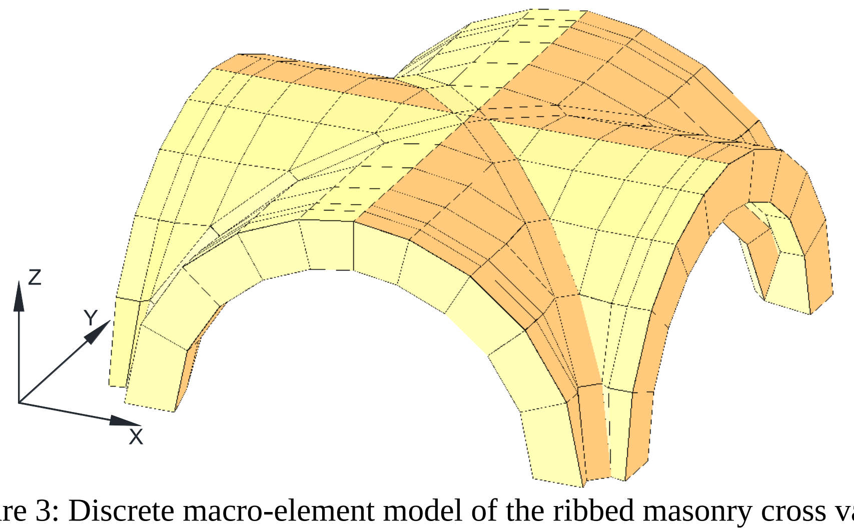


Figure 3: Discrete macro-element model of the ribbed masonry cross vault.

Elastic parameters			Flexural parameters				Sliding diagonal parameters	
E	G	γ	f_t	G_f	f_c	G_c	c	μ_s
[MPa]	[MPa]	[kN/m^3]	[MPa]	[N/m]	[MPa]	[N/m]	[MPa]	[-]
1200*	400	18	0.05*	0.65*	2.30*	3680	0.05 – 0.10	0.45
*values taken from [22]								

Table 1: Mechanical properties for the DME model of the masonry ribbed cross vault.

3 Results

The numerical load-displacement curves of three monitored points (P1 is the keystone of the arch next to the loaded point, P2 is the keystone of the vault (intersection of both diagonal arches) and P3 is symmetric to P1) were plotted and compared to those obtained experimentally.

In the numerical simulations, two different values of cohesion characterising the joints were considered to evaluate the influence of this parameter on the global response of the vault. Figure 4 reports the comparison between numerical and experimental force-displacement capacity curves adopting a cohesion of 0.05 MPa in the simulations. In this case, the numerical model predicted a lower load-carrying capacity when compared to the experimental results (approximately 12 kN). The numerical model predicted an ultimate vertical load equal to 10.2 kN, leading to an absolute error of approximately 15%. Furthermore, it was observed that the numerical curve was stiffer than the experimental one, with a reduced displacement capacity, especially for point P1.

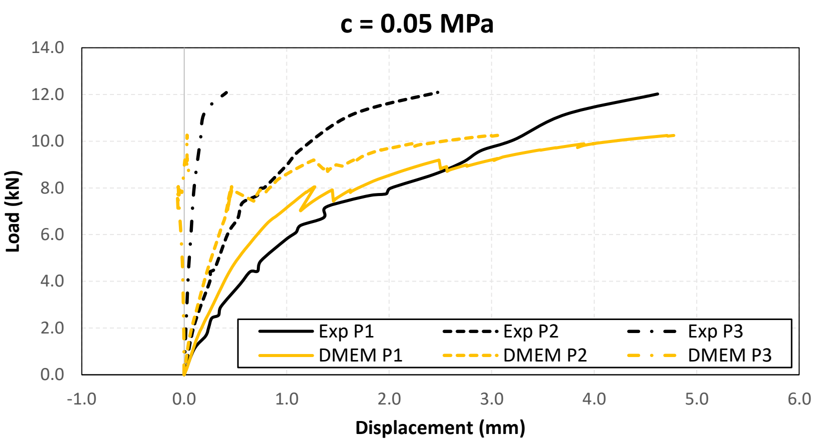


Figure 4: Comparison of vertical load vs displacement considering a cohesion equal to 0.05 MPa.

Finally, the comparisons considering a cohesion equal to 0.10 MPa are reported in Figure 5 In this case, the model predicted an ultimate load equal to 11.6 kN corresponding to an absolute error of 3.3%. Despite the good resemblance in terms of vertical load, a slight overestimation of the initial stiffness of the vault was also observed, especially for point P1.

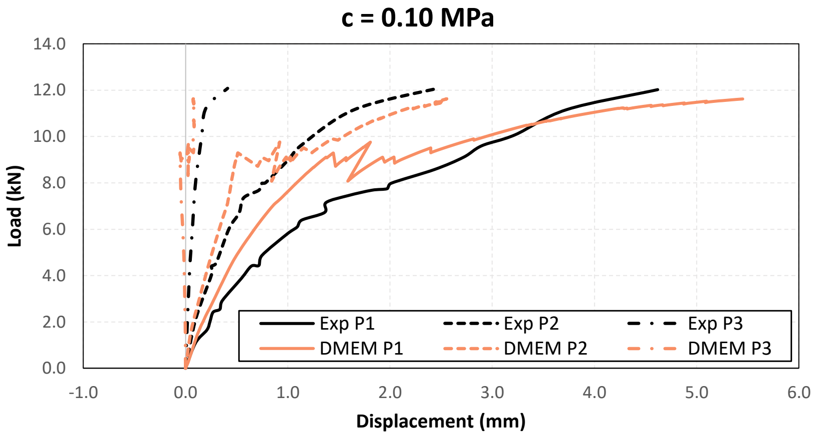


Figure 5: Comparison of vertical load vs displacement considering a cohesion equal to 0.10 MPa.

Regardless of the value of cohesion adopted for the shear-sliding behaviour, the failure mechanism obtained with the numerical model consisted of plastic damage in the frontal arch at which point P1 is located. Additional concentration of damage was identified in the loaded web in accordance with the plastic areas that were generated in the arch close to P1. It was also evidenced that the central part of both lateral webs, as well as the diagonal arches, were also characterized by damage concentration. The failure mechanism of the numerical model considering a cohesion equal to 0.05 MPa is illustrated in Figure 6.

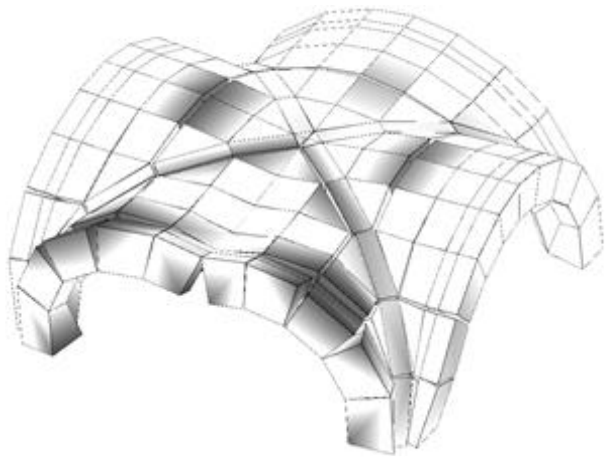


Figure 6: Damage concentration of the DMEM model of the ribbed cross vault.

4 Conclusions and Contributions

This study focused on the application of an innovative numerical approach for the assessment of a curved masonry structure, namely a ribbed masonry cross vault, subjected to vertical loading. This numerical tool, known as the Discrete Macro-Element Method, is characterized by a simplified mechanical scheme and a reduced number of DOFs, leading to a limited computational burden compared to sophisticated Finite Element of Discrete Elements approaches. The numerical model of the masonry cross vault was characterized by 1244 DOFs. A sensitivity analysis was carried out aiming at assessing the influence of the shear-sliding behaviour on the response of the cross-vault. For this purpose, values of 0.05 MPa and 0.10 MPa were taken into consideration. The comparison between experimental and numerical results was performed in terms of vertical load vs displacement curves. In the case of cohesion equal to 0.05 MPa, the numerical model provided a lower vertical load (error of 15%). The discrepancy between experimental and numerical results was reduced when considering a higher cohesion value (c = 0.10 MPa). It was evidenced that the proposed modelling approach can reasonably reproduce the experimental results regardless of the coarse mesh refinement defined for the numerical model. In terms of collapse mechanisms, the one numerically obtained is consistent with the application of the load. In this sense, the DMEM constitutes an alternative tool for assessing masonry vaults considering a reduced number of elements, especially when considering practical and engineering applications. Further investigations will be performed to evaluate the influence of the mesh discretisation on the overall response of masonry ribbed cross vault subjected to three-dimensional vertical or lateral loadings.

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