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Structural Optimization Through Parametric Design of Visco-Elastic Devices

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Abstract

This study explores the use of viscoelastic devices as supplementary energy dissipation systems for improving the seismic performance of existing structures subjected to dynamic actions. The investigated case study is a real vaulted masonry structure that forms part of the monumental complex of Santa Margherita Nuova, located on the island of Procida. Due to the historical and architectural significance of such buildings, retrofitting interventions must be both effective and minimally invasive. In this context, the introduction of viscoelastic devices offers a promising solution by enhancing the structure's dynamic response while preserving its integrity. A parametric approach is adopted to guide the design process toward optimal configurations, analyzing the sensitivity of the structural response to different mechanical parameters of the devices. Numerical simulations are conducted to evaluate the effectiveness of the intervention. The results clearly demonstrate that properly calibrated viscoelastic devices can lead to a significant reduction in displacements, internal stresses, and energy demand. This confirms their potential as an efficient and compatible retrofitting strategy for historic masonry structures exposed to dynamic events.

Keywords: viscoelastic energy dissipation, protection systems, vaulted masonry structures, dynamic response control, supplemental damping devices, parametric numerical analysis, historic structure retrofitting.

1 Introduction

Protection of historic masonry buildings against dynamic vibrations represents a significant challenge, particularly when dealing with vaulted structures subjected to dynamic loads. The need to preserve both the architectural and structural integrity of heritage buildings has led to the development of solutions aimed at controlling vibrations and improving seismic performance. Among these, the use of viscoelastic dampers installed in configurations compatible with the specific features of the structure has shown promising potential.

2 Approach and Set up of Control Configurations

The analysis was carried out using an iterative approach based on finite element modelling (FEM) to evaluate the dynamic behaviour of the structure through Fast Nonlinear Analysis (FNA), both in the absence and presence of energy dissipation devices. This type of analysis allows the dynamic behaviour of a structure to be assessed more efficiently and rapidly by separating the structural response into an elastic component and applying nonlinearity only locally, i.e., to the elements that exhibit it, the dissipative devices. Several control configurations were examined, with dampers placed laterally in different positions and in varying numbers. For each configuration, a parametric study was conducted by varying the viscous coefficients and mechanical properties of the devices in order to assess the sensitivity of the structural response.

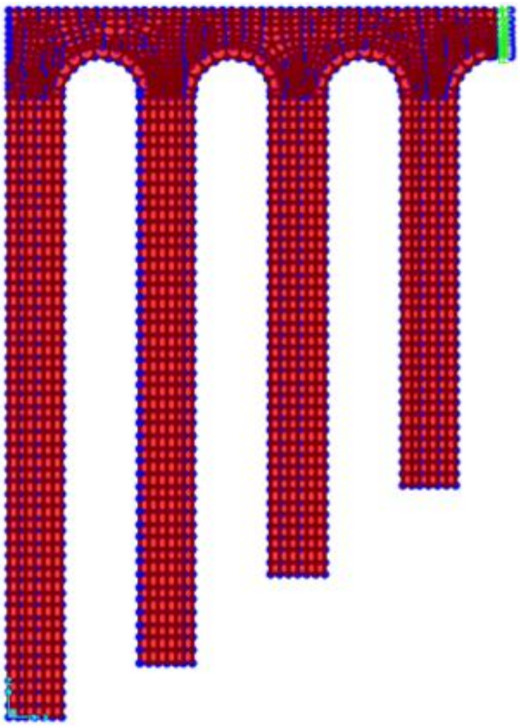

Figure 1: Finite element model overview of the vaulted masonry structure.

Before proceeding with the analyses of the various control configurations, it was necessary to accurately determine the stiffness to be assigned to each lateral constraint. To this end, the remaining portion of the structure was modelled, initially excluding the lateral constraints.
At the application points of each constraint, a horizontal force was applied, and the corresponding horizontal displacement was measured, from which the associated stiffness value for each lateral constraint was derived.
Subsequently, viscoelastic devices were introduced in parallel with the lateral constraints.

3 Results

The first configuration investigated involves the introduction of a purely viscous device, with variations in the viscous damping coefficient (c_{VE}) to assess its influence on the device's effectiveness (η), defined as the percentage reduction in input energy dissipated by the structure.

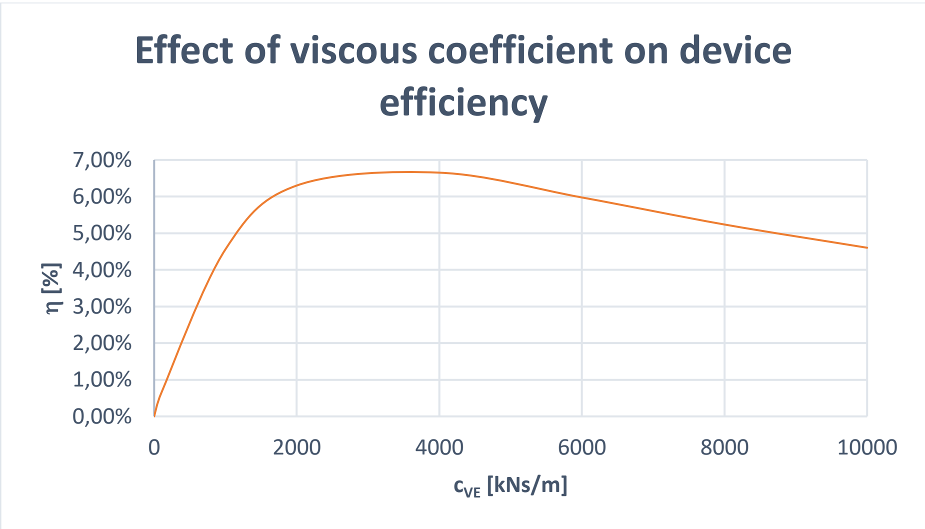

Figure 2: Efficiency of the viscous device as a function of the damping coefficient. The curve highlights the optimal range for energy dissipation.

The results obtained show that, for low values of the viscous coefficient c_{VE}, the energy dissipated by the device increases as the coefficient rises. However, for higher values of c_{VE}, a reduction in energy dissipation is observed.
When the viscous coefficient is very low, the damping effect is minimal, and the structure oscillates almost freely. As a result, the device is unable to dissipate significant energy. Increasing the coefficient allows greater resistive force to be developed, which leads to higher energy dissipation.
Conversely, when the viscosity coefficient becomes very large, the system is strongly damped, reducing deformation velocities. Since the energy dissipated is proportional to these velocities, the efficiency of the device also starts to decrease.

This observed trend suggests the existence of an optimal value of the viscous coefficient that maximises the energy dissipation efficiency of the device.
Following the analysis of the viscous component, an elastic component (k_{VE}) was also introduced.

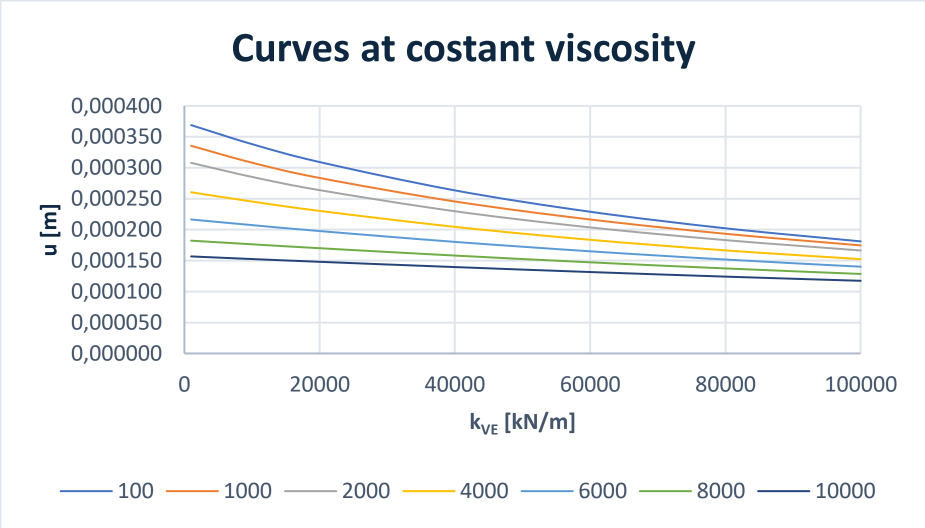

Figure 3: Displacement at the dissipative device location as a function of stiffness, for multiple curves under constant viscosity values.

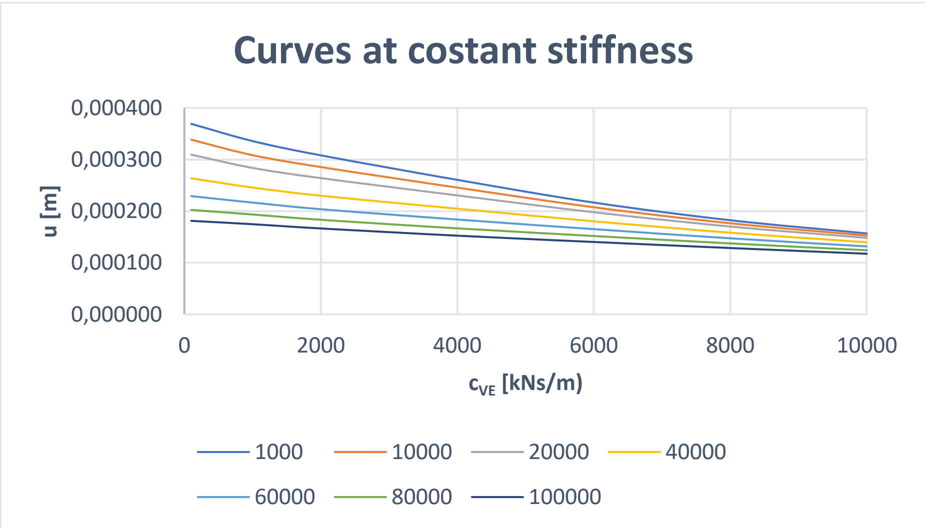

Figure 4: Displacement at the dissipative device location as a function of viscosity, for multiple curves under constant stiffness values.

To better understand the interaction between these two parameters, an abacus was developed, collecting the results of various combinations of viscosity and stiffness.

In order to refine the study of the viscoelastic device's behaviour, curves under constant viscosity (Fig.3) and constant stiffness (Fig.4) were plotted based on the numerical results, allowing a clearer interpretation of the device's dynamic response.
Below are the curves in terms of maximum displacement measured at the point of application of the viscoelastic device.
It is observed that an increase in both parameters leads to a significant reduction in the maximum displacement recorded.
In particular, a increase in stiffness offers strong mechanical resistance to deformation – especially at the local level of the device – resulting in reductions exceeding 50% for high stiffness values, regardless of the viscosity level.
However, this increase in stiffness also reduces the deformation velocities, which are essential for the device's energy dissipation mechanism, thereby lowering its overall efficiency, as highlighted by the efficiency curves (Fig.5).

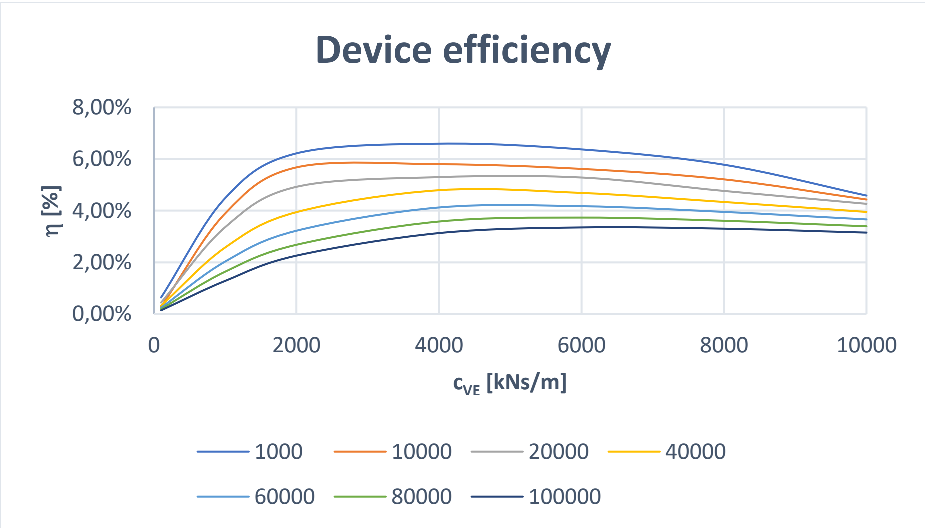

Figure 5: Efficiency of the viscous device as a function of the damping coefficient, for multiple curves under constant stiffness values.

By combining the results obtained from the parametric analysis, the existence of an optimal value for the elastic component was also identified, at which the system achieves a reduction in displacements while maintaining satisfactory dissipative efficiency.
Subsequently, an additional viscoelastic device was introduced, also in a lateral position, but placed in correspondence with the upper side constraint, opposite to the location of the previously installed device.
A similar parametric analysis was carried out to evaluate its influence on the overall dynamic behaviour of the structure.
In terms of percentage reduction of the input energy dissipated by the structure, a marked improvement is observed, with values approximately twice those of the previous configuration, while maintaining a response consistent with previous trends.

Further analyses show that beyond a certain threshold further increases in stiffness or viscosity no longer led to significant reductions in displacement, making additional improvements in performance negligible.
Also observation of the vibration modes of the structure highlights the stiffening effect and the local control of deformations induced by the devices, as well as a significant change in the distribution of maximum horizontal displacements, resulting in an overall average reduction of approximately 20% in the maximum amplitude recorded in the most stressed areas.

4 Conclusions and Contributions

The use of viscous and viscoelastic devices as supplementary energy dissipation systems proved effective in improving the overall dynamic response of the structure, while preserving the historical and architectural context in which they were implemented.
The results obtained offer practical guidance for selecting optimal parameters in future applications.

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