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Influence of damage on the seismic failure analysis of masonry arches

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HIGHLIGHTS

- Defects and deterioration in masonry arches causes a decline in the structure's performance.
- Structural analysis needs to take into account, the presence of defects in the structure.
- This paper examines the influence of damage on the seismic capacity of masonry arches.
- The presence of defects reduces the seimic capacity and modifies the collapse mechanism.

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ABSTRACT

Masonry arches are typical structural elements of existing masonry constructions. Many existing masonry buildings and bridges in Europe, and indeed in many other parts of the world, are quite old and consequently may show defects and/or degradation. Such defects and degradations in masonry constructions may be caused by different factors, both environmental and human. One of the most common defects that develop over time in masonry structures involves local or uniform reduction in the thickness of the structural elements.

This paper uses limit analysis to examine the influence of local thickness reductions on the seismic capacity of masonry arches: in terms of collapse acceleration and changes in collapse mechanism.

1. Introduction

In Europe, most existing masonry constructions feature arched structural elements. As an example, most of railway bridges used in European rail networks are arched masonry bridges [1]. In past centuries, masonry arches were the most widely used structural elements in architecture and civil engineering. Indeed, as well as being able to withstand the loads applied to the structure, these also represented decorative architectural elements in the construction.

As many of these structures are very old [1] and have been subjected to: chemical and physical actions generated by the environment, the actions of man, vehicular collisions and natural hazards (earthquakes, floods, and so on), their elements may have suffered defects and degradations. For example, masonry arches may be affected by: deterioration of materials, loss of masonry blocks, loss of mortar joints, salt efflorescence, longitudinal and transverse cracking [2], ring separation [5], and so on.

The development of defects and deterioration in masonry arches causes a decline in the structure's performance. For this reason, structural analysis needs to take into account, even approximately, the presence of defects in the construction elements, in order to assess the structure's effective capacity to withstand the external loads applied [3,4]. In high seismic hazard zones, the most severe action is without doubt the horizontal acceleration generated by earthquakes. Hence the need to take defects into consideration when assessing the seismic vulnerability of structures.

This paper examines the variation in the seismic capacity of masonry arches that have undergone local reduction in vault thickness. This in fact represents a typical defect on masonry arches. On bridges specifically, local reduction of vault thickness may be a result of vehicular collision or a loss of blocks due to missing mortar in the joints or cracking [2].

Scientific literature shows that the seismic vulnerability of masonry arches can be analysed using finite element models [6], 1D fibre models or discrete element models [7]. Limit analysis [8,9], according to Heyman's hypothesis [9,10], is also a useful calculation tool for determining a masonry arch's capacity to resist horizontal acceleration [11–15].

This paper proposes an algorithm based on the construction of a thrust line to calculate the horizontal acceleration that causes collapse, and that in a simple manner takes into account the conditions of arches with local thickness reduction.

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The final part of this paper presents parametric analysis intended to describe how the results of seismic limit analysis vary according to the localisation and intensity of the defect on the arch. The results of such analysis, shown further on, highlight that the presence of defects reduces the capacity to resist acceleration and modifies the collapse mechanism.

Actual arched structures are generally composed of arch, infill material, spandrel walls, internal spandrel walls etc. Although it is known that backfill and spandrel walls have effects on arch load-bearing capacity, in this work the backfill material is exclusively considered as applied load, in accordance with the old construction practice of railway masonry bridges [15]. Furthermore, any lateral resistance contribution of spandrel walls is not taken into account, because in old arched constructions, the connection between arch and spandrel walls is generally damaged or ineffective [16].

The results reported in this work can be used for a first level of seismic assessment of masonry arches with local arch thickness reduction. The collapse multiplier values (α) are shown below for different arch geometries and different defect extents and intensities. Such values err on the side of caution, as the effect of the backfill, spandrel walls and haunch (if present) are not considered in the arch's seismic capacity. Therefore, if the results shown in this work show a negative outcome, more detailed analysis can be performed based on the results of experimental tests to determine the mechanical and geometric properties of the structural elements.

2. Seismic limit analysis of damaged masonry arches

Local reduction in arch thickness can be represented in the calculation model by defining three parameters (Fig. 1) that establish its intensity, its position and its localisation [4]. If t and S are the thickness and length of the arch, the intensity of the reduction in arch thickness can be defined using the following relationship:

$$Intensity = \frac{\Delta t}{t} \tag{1}$$

The extent of the defect can be defined using the following relationship:

$$Extent = \frac{\Delta S}{S} \tag{2}$$

and the localisation of the defect is given by the following angular relationship:

$$Localisation = \frac{\beta_{GAP}}{\beta} \tag{3}$$

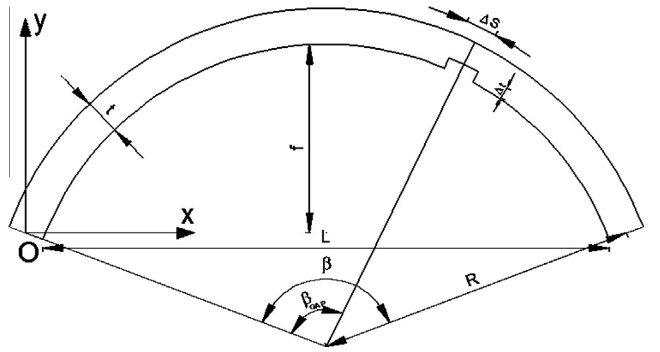

Fig. 1. Representation of the values that define the intensity, localisation and extent of the defect on the arch.

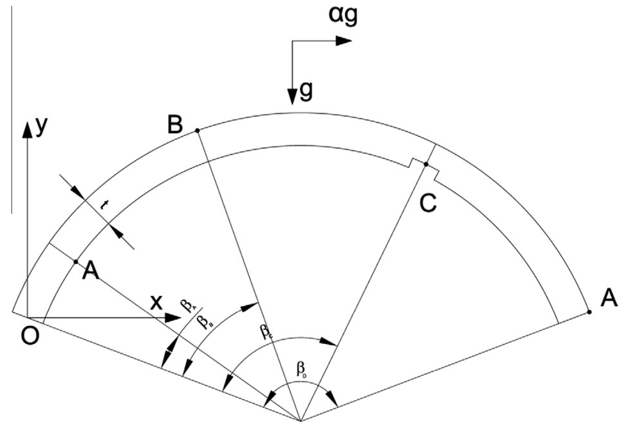

Fig. 2. Collapse mechanism and geometric parameters considered in the seismic limit analysis.

An iterative algorithm that implements hybrid kinematic and static limit analysis can be used to calculate the collapse multiplier for seismic loads. As it has been shown in scientific literature, the collapse mechanism of an arch subjected to horizontal acceleration can be represented by a kinematic model with four hinges that divide the structure into three rigid segments. For this reason, the first step in the iterative procedure involves defining the approximate position of the four hinges by expressing the following angular relationships: β_A/β β_B/β β_C/β β_D/β (Fig. 2). Once having defined the four cracking hinges, the virtual work principle can be applied to the kinematic model:

$$\alpha g\sum_{1}^{n} m_i\delta_{x,i} - g\sum_{1}^{n} m_i\delta_{y,i} = 0 \tag{4}$$

This in turn can be used to calculate the collapse acceleration α:

$$\alpha = \frac{\sum_1^n \delta_{y,i}}{\sum_1^n \delta_{x,i}} \tag{5}$$

Considering the discretisation of the arch into n blocks of mass m_i, $\delta_{x,i}$ and $\delta_{y,i}$ are respectively the virtual horizontal and vertical displacement of the centre of gravity of the i-th block, while g is the acceleration of gravity.

When horizontal loads have a value of α_{mi}, the structure becomes vulnerable and its equilibrium is unstable. In such situations, the two external reaction forces applied to the structure can be calculated using the equilibrium equation only (Fig. 3).

Specifically, with reference to Fig. 3, the structure's reaction forces can be calculated by solving the following linear system (6):

$$[Q]\{\mathbf{q}\} = \{\mathbf{R}\} \tag{6}$$

Where:

[Q] is the static matrix:

$$[Q] = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & d_{BAy} & -d_{BAx} & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{CBy} & -d_{CBx} & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 \end{bmatrix} \tag{7}$$

{**q**} is the know term: