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# Structural evaluation of historic masonry arch bridges based on first hinge formation

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## HIGHLIGHTS

- Photogrammetry data are used to create structural model for elastic frame analysis.
- Serviceability limit state at first hinge is proposed for arch bridge preservation.
- Variations in geometry, material properties, and support conditions are studied.
- Load at first hinge formation and collapse load of a masonry bridge are compared.

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## ABSTRACT

Galicia, a Northwest region of Spain, contains numerous historic masonry arch bridges but little is known regarding their live-load capacities. Several of these bridges carry modern vehicular traffic and have been surveyed using advanced geomatic techniques. In this paper, close-range photogrammetry data are used to develop structural models of a Galician bridge. Elastic analyses are performed considering variations in arch geometry and stiffness to determine the live-load capacity based on first hinge formation and aimed at serviceability and historic preservation of the bridge. Comparisons are finally made with the plastic limit load to evaluate the proximity to a collapse mechanism.



## 1. Introduction

Masonry arch bridges are one of the most intriguing bridge types due to their structural form, aesthetic appeal, historic importance, and resiliency. These historic structures have stood for centuries, have been utilized by thousands of people over many generations, and continue to provide a vital service in today's society. Numerous masonry bridges exist that are subjected to large vehicular loads which can jeopardize the structures' safety and serviceability. However, analytical methods typically focus on the ultimate capacity of masonry arch bridges and ignore serviceability issues which are critical to the preservation of historic structures.

Galicia, a Northwest region of Spain, contains numerous historic masonry arch bridges dating from the Roman and Mediaeval periods that transverse the rugged landscape. Several of these bridges have been inventoried, surveyed, and inspected but little is known regarding their live-load capacities. Recent investigations have focused on recording the physical condition and geometry of the bridges through advanced geomatic techniques including close-range photogrammetry, laser scanning, and ground penetrating radar [1,2]. These techniques have proved to be invaluable in the bridge inspection process and show great promise for monitoring deterioration and performing structural evaluations based on field measurements. The Cernadela Bridge, which crosses the Tea River in the Council of Mondariz, Galicia, has been previously evaluated based on plastic analysis methods [1,2] and will be further investigated in this paper based on an elastic analysis approach. The bridge dates from the 15th century and was likely built upon the ruins of a Roman bridge [3]. It is a five-span granitic bridge approximately 60 m long; Fig. 1 shows a side view of the Cernadela Bridge.

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**Fig. 1.** The Cernadela Bridge.

## 2. Structural evaluation: General approach

Masonry arch bridges are commonly evaluated by plastic analysis to determine the ultimate capacity of the arch following formation of the required number of hinges to achieve a collapse mechanism [4]. This analytical approach results in a unique solution based on the laws of equilibrium and does not require extensive knowledge of material stiffness properties or initial stresses [4,5]. However, plastic analysis provides no information about the structural behavior at loads below the ultimate arch capacity, in particular, the progressive formation of hinges and associated deflections which are important with regards to preservation. A masonry arch has the ability to redistribute load but the structural and historic integrity of the arch may be jeopardized by hinge formation and large deformations. The serviceability limit state is commonly taken as 50% of the ultimate collapse load since deformations have been shown to increase quickly thereafter [6]. However, limiting loads by an arbitrary percentage of the collapse load ignores the uniqueness of masonry arches. A simple elastic analysis can provide guidance for establishing load restrictions that are aimed at preserving the bridge condition based on the formation of the first hinge. Comparison of the load causing first hinge formation to the total collapse load can provide a better understanding of how close the bridge is to complete failure.

### *2.1. Structural model and loading*

The use of accurate geometric measurements plays an important part in the structural evaluation of historic masonry arch bridges. Recent advancements in geomatic techniques such as digital photogrammetry and laser scanning have made it feasible to create digital renderings of bridges to aid in inspection and evaluation [7]. A photogrammetric survey was previously conducted to produce accurate geometric models of the Cernadela Bridge that are shown in Fig. 2. To create the models, convergent photogrammetric networks were designed based on stereoscopic vision systems which allow an object to be reconstructed in 3D by solving the collinearity condition equations. These equations establish that, at the time of exposure, the perspective center (shutter in camera system), an object's point, and its impression on the image all lie in a common straight line. By knowing the image coordinates and corresponding spatial coordinates of a number of points, it is possible to compute the position and orientation of cameras. At the same time, the 3D position of all points marked in the images may be computed. The photogrammetric survey of the Cernadela Bridge involved the digital acquisition of 160 photographs in the field and topographic survey of 100 control points. With this data and the camera calibration information obtained in the laboratory, a point cloud (formed by more than 25,000 points) of the entire structure was obtained using the photogrammetric software Photomodeler Pro® and outlined to draw the contours of the masonry ashlars. The thicknesses of voussoirs at the ends of the upstream and downstream arch barrels were then measured and used to perform the structural analyses in the present investigation.

Previous studies of masonry bridges have shown that a minimum of 10 elements are necessary to attain results that accurately depict arch behavior in the elastic region [8,9]. For the Cernadela Bridge, computer-aided drafting (CAD) software was used to manage the orthophotos of the bridge geometry and determine the two-dimensional nodal coordinates for the frame elements. The nodal coordinates were located at the centerline of the arch ring (mid-depth of the voussoir). In the transverse direction, the frame was given a 1 m (3.28 ft) width representative of the middle section of the barrel. For a typical masonry arch bridge, the dead load primarily includes the self-weight of the arch and the fill material above the arch. Other elements that, if present, contribute to dead load include the roadway pavement, spandrel walls, and parapets. The self-weight of the arch was computed based on the cross-sectional dimensions and density of the voussoirs. The dead load due to the fill material above the arch ring was superimposed onto the individual frame segments. The average fill depth was defined as the midway point from the roadway to the top of the arch ring at each end of the corresponding frame segment as illustrated in Fig. 3. The product of the average depth and density of the fill material are applied as a force per linear foot over the unit width of the frame model.

The live-load pressure from truck axle loads on the roadway was assumed to be distributed over an area 30 cm (11.8 in.) long and 3 m (9.84 ft) wide, representing the width of a traffic lane [9]. The pressure was applied at the mid-depth of the arch ring voussoirs which coincides with the frame element centroids of the structural model. Live-load pressures applied to the arch ring segments were determined assuming a 2:1 (vertical:horizontal) distribution through the fill from the roadway surface as shown in Fig. 4. The area between the points of intersection defines the area of influence; that is, the members that are acted upon by the axle load. In the model, each of the influenced members has an externally applied distributed load with a magnitude correlating to the depth from the roadway. The combined effects of the internal arch ring self-weight, the superimposed loading from the fill, and the pressure from the truck axle give the total service load that the arch ring must withstand.