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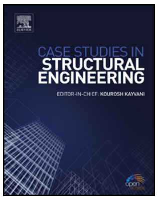

Short communication

Efficient masonry vault inspection by Monte Carlo simulations: Case of hidden defect

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ABSTRACT

This paper presents a methodology for probabilistic assessment of masonry vaults bearing capacity with the consideration of existing defects. A comprehensive methodology and software package have been developed and adapted to inspection requirements. First, the mechanical analysis model is explained and validated by showing a good compromise between computation time and accuracy. This compromise is required when probabilistic approach is considered, as it requires a large number of mechanical analysis runs. To model the defect, an inspection case is simulated by considering a segmental vault. As the inspection data is often insufficient, the defect position and size are considered to be unknown. As the NDT results could not provide useful and reliable information, it is therefore decided to take samples with the obligation to minimize as much as possible their number. In this case the main difficulty is to know on which segment the coring would be mostly efficient. To find out, all possible positions are studied with the consideration of one single core. Using probabilistic approaches, the distribution function of the critical load has been determined for each segment. The results allow to identify the best segment for vault inspection.

1. Introduction

Masonry arch bridges, still in service, represent more than 40% of bridges in Europe [1]. Most of them are century old and the degradation process is already running since several decades. Actually, the maintenance and repair continue to represent serious issues for their managers. Indeed, many repairs have been undertaken without ensuring the aimed durability. The question is: how to repair old masonry vaults while ensuring relevant actions that extend their service life? In fact, repair work is directly related to diagnosis. The more accurate the diagnosis is, the more durable and less expensive repairs are. Although several defects can be detected using non destructive tests (NDT), some defect are difficult, and sometimes impossible, to detect without coring [2]. The main difficulty is therefore to know where coring could be most efficient, in terms of information about the vault defects and the ultimate load capacity.

Several methods were developed since the fifteenth century to calculate masonry vaults, starting from the well-known empirical rules (see Table 1 in Ref. [3]). These rules allow to determine the main arch dimensions by mean of simple

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relationships developed by introducing experimentally obtained coefficients, sometimes depending on the used materials which have survived very long time in the absence of proper modeling theory. Several methods have been developed for the assessment of load-carrying capacity, such as Military Engineering experimental Establishment (MEXE) [4,5] and Railway Empirical Assessment Method (REAM) [6,7]. The first method allows the calculation of the allowable axle load on a bridge based on a so-called idealized axle load calculated with reference to an "ideal" bridge. The arch is assumed to be parabolic in shape with span/rise ratio of 4, compressive stress limit of 1400 kN/m^2, and tensile stress limit of 700 kN/m^2. This idealized axle load is then modified by factors allowing to consider the difference between the actual arch and the ideal one [8] such as the span/rise factor, the profile factor which takes into account the difference between the realistic arch line and a parabolic arch, depending on the arch rise at the haunches and the rise at the crown, the material factor depending on the material strength of the vault and filling material, the joint factor which takes into account the condition of the joint material and its thickness, and finally the condition factor which depends on the general arch condition in order to take into account the possible presence of cracks and/or deformations. The REAM method allows to obtain a preliminary arch assessment without calculations, by means of graphs for the determination of the required vault thickness based on a study conducted on different bridges with span ranging between 2 m and 25 m span/rise ratio lower than 8, filling depth above the crown between 25 cm and 150 cm and axle load is between 10 tons and 25 tons. The limit analysis method was adopted by Kooharian in 1953 for the study of arcs formed of segments [9]. The principle of this method is to determine the allowable loads under which the vault does not collapse. It is shown that if the thrust line is within the arc thickness, then the stability of the structure is guaranteed. The yield design methods [10,11] are derived from Heyman's studies on the yield design of masonry arches [12,13]. In 1976, Salençon provided the basis for this method and generalizes the limit analysis methods by replacing the perfect plasticity condition by a material strength criterion. Finally, the finite element method [14,15] and distinct element method [16] are currently considered as the main numerical methods for solving partial differential equations, through the development of computer technology. These methods are characterized by their high level of accuracy, but only when detailed input data are provided. Indeed, various software using 1D, 2D or 3D models have been developed, but most of them allow the analysis of structures without defect. In parallel, some authors have proposed methods for detecting defects [17–20]. Some others have proposed methods allowing to assess the load bearing capacity of damaged arches [1,21]. Generally, these methods provide the mechanical response assuming defect characteristics as known (position, depth, extent . . .etc.) after carrying out some ND tests, which is not always the case, and consequently destructive tests become necessary. In this framework, the present aims, in addition to assess the load bearing capacity of the vault, to identify on which segment the destructive test will be the most efficient, and presents a methodology for probabilistic assessment of the effect of defects, caused by water infiltration, on the vault bearing capacity.

One of the major reasons for building abandonment is the excessive cost of inspections and repairs, in addition to technical feasibility and reliability. Indeed, when an inspection is carried out, the observations and the assessment of the vault state are subject to large uncertainties. The vault thickness for example is an input data which is known with large uncertainties. The formulae given by Oliveira et al. [3] (in Table 1) has been used to determine this parameter and provide upper and lower bounds between which there is much disparity [24]. In addition, many of the existing bridges that were originally built for car traffic are currently being used for heavy traffic and even for trucks in some cases. From another point of view, the study of stone alterations revealed several material loss patterns and therefore changes in geometry of segments which are not visible, in most of the cases. This kind of situation requires a rigorous inspection program and associated predictive models. The first problem of the bridge owner is to know how much money he/she can spend for inspections. Depending on his/her budget allocation, the scope and extent of inspection can be defined, and consequently the uncertainties on inspection results will be high or not. The number of tests on materials, of in-situ measurements, and the NDT methods to be applied will depend on this choice. The majority of available methods for assessing the masonry vault behavior are deterministic. They can predict the load bearing capacity of the vault provided that all the variables involved in the mechanical response are assumed to be deterministic (i.e., perfectly known), which is not true because of the uncertainties involved in the geometry, materials,

Table 1
Geometrical, physical and mechanical characteristics of the studied vault.

Designation	Unit	Value
Span (s)	m	6.18
Rise (r)	m	2.50
Vault thickness (t)	m	0.58
Backfill depth above the crown (f)	m	0.85
Pavement thickness (e)	m	0.28
Segments unit weight	kN/m^3	24
Pavement unit weight	kN/m^3	21
Backfill unit weight	kN/m^3	18
Segments Young's modulus	GPa	48
Tensile resistance of segments	kN/m^2	0
Pavement Young's modulus	MPa	20
Backfill cohesion	kN/m^2	0
Backfill angle of shearing resistance	rad	$\pi/6$
Pavement angle of shearing resistance	rad	$\pi/6$