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Full 3D homogenization approach to investigate the behavior of masonry arch bridges: The Venice trans-lagoon railway bridge

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HIGHLIGHTS

- Non-linear FE analysis of masonry bridges.
- Collapse mechanisms evaluated under vertical train loads and foundation settlement.
- Stabilizing effect of the backfill shown with different FE non-linear analyses.
- Orthotropic behavior evaluated in the non-linear range with homogenization.
- Transversal effects and loads eccentricity taken into account with 3D mesh.

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ABSTRACT

Some different procedures for the evaluation of the non-linear behavior of masonry arch bridges are here proposed. In particular, the Venice trans-lagoon masonry arch bridge is numerically analyzed by means of several 3D FE numerical strategies. The three dimensional behavior of the structure when subjected to train loads and pile foundation settlement is investigated. Focus is also posed to the stabilizing role played by the backfill.

Both a non-commercial code and a standard commercial FE software are utilized. The non-commercial code properly takes into account for the orthotropic behavior of the barrel vaults and the stone arches, and allows performing non-linear static and limit analyses on complex 3D structures. Within the non-commercial FE approach, each material of the bridge (barrel vault, external stone arches, spandrels, piers, backfill) is suitably modeled using rigid parallelepiped elements and quadrilateral interfaces exhibiting an orthotropic constitutive law with either softening or rigid-plastic behavior in the non-linear and limit analysis version respectively. In both FE codes, mechanical properties of each material of the bridge (barrel vault, external stone arches, spandrels, piers, backfill) are modeled starting from suitable homogenization procedures in the elastic range (commercial software) and also beyond the linear limit (non-commercial FEM).

The bridge is studied under service loads and up to failure for the passage of a standard train on either a single or both tracks. In the analyses, the stabilizing role played by the backfill, the strength increase obtained with stiff lateral stone arches on the barrel vault and the 3D effects induced by both load configurations are discussed. Results obtained with the incremental non-linear procedures are always compared with limit analysis predictions of collapse loads and failure mechanisms.

Finally a uniform foundation settlement of one of the piles is simulated.

1. Introduction

The Italian railroad network includes thousands of masonry arch bridges, mainly built during the XIX century, that are still in exercise. This is also common in other European countries, such as UK, France, Spain and Germany [1]. The European railway network has been almost completely built in one century, from the 1825, year of the first railway, to the 30's of the twentieth century. The first Italian railway has been realized in 1839 and the great part of bridges have been built in the fifty years from 1860 to 1910, subsequently to the unification of Italy. Thanks to their mechanical properties, thousands of masonry arch railway bridges

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have been built and, thanks to the durability of their materials, a high percentage of them are still in service, Fig. 1.

Increase in transport capacity demand, deterioration of materials and identification of a variety of defects have resulted in the recent past in the need for assessment and maintenance procedures for existing masonry bridges. As a consequence, considerable effort to develop reliable structural models based on a limited number of constitutive parameters has been made.

At present, a large amount of literature regarding the analysis up to collapse of masonry arch bridges and masonry arches in general is present [2–15]. However, such literature focuses almost exclusively on 1D/2D problems. Obviously, such structural models involve varying levels of accuracy and simplifications, which limit their range of applicability to specific cases. The most common idealizations of masonry material behavior are elastic, non-linear elastic and elastic plastic (for a detailed discussion the reader is referred to e.g. [9]), but the most diffused approach, particularly in the case of masonry arch bridges and curved structures in general, still remains limit analysis [5,10–17]. Limit analysis provides very quickly failure mechanisms and an estimation of the load carrying capacity of the structure but for serviceability purposes, as the case here treated is incapable of providing suitable information, as for instance the deflection profile under the design rail/traffic load and the crack maps, i.e. the zones undergoing inelastic deformation.

Besides the historic rules [18], the classic approach to determine the stability of arch bridges is probably due to Pippard and Ashby [19], Pippard [2] and Heyman [20]. Finally, Heyman [20] was the first to extend in a clear and explicit way to masonry arches both the kinematic and static theorems of limit analysis, according to which the structure is safe if a thrust line inner to the arch depth can be determined in equilibrium with the external loads.

The procedure may be handled without computational assistance, and fits well with experimental data for very simple arches without backfill and under specific load conditions. More recent works (e.g. Gilbert and Melbourn [3], Hughes and Blackler [21] and Boothby [4]) are based on a rigid block discretization of the arches within limit analysis concepts coupled with FEs. While such an approach is very appealing because it provides failure mechanisms and load multipliers for a variety of different 2D geometries and loading conditions, still it is based on strong simplifications, which disregard 3D effects and consider the role played by the backfill only in an approximate way.

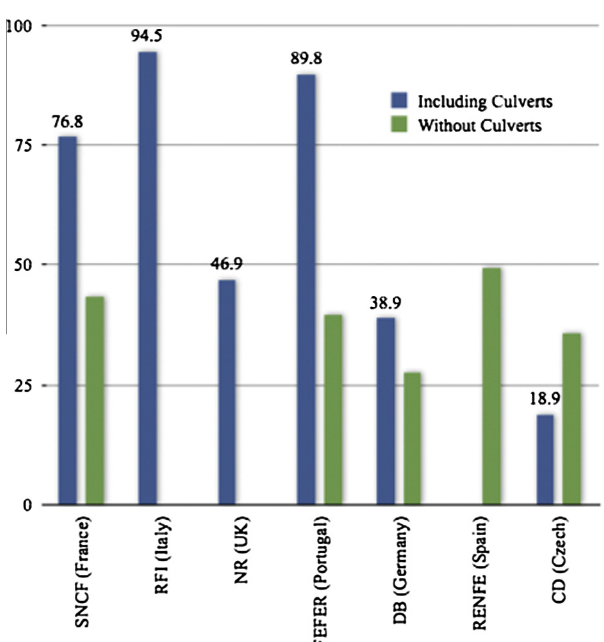

Fig. 1. Proportion in percentage of masonry arch railway bridges on the overall bridge stock of some of the main European railroad network, adapted from [1].

To rigorously investigate the role played by the backfill in the determination of the actual load carrying capacity of 2D bridges, a discretization with plane strain rigid-plastic elements and interfaces is needed, as recently proposed by Cavicchi and Gambarotta [11,12]. While this latter approach is very powerful, giving good predictions of the actual behavior of real bridges, it still has the disadvantage that it cannot be used for the analysis of skewed or straight arches in presence of eccentric loads. Transversal effects may be very important from a practical point of view, playing a crucial role in the decrease of the load bearing capacity and 3D limit analyses models seem still missing in the technical literature, essentially because of the lack of commercial programs and of the prohibitive computational cost required by refined discretizations within standard linear programming algorithms. While limit analysis is a very appealing alternative to common non-linear simulations, it is unable to give any prediction of the pseudo-ductility of the structure, because of the material hypotheses at the base of such formulation (infinite ductility of the constituent materials). To have a prediction on displacements in the non-linear range, non-linear FE approaches (ranging from 1D up to full 3D) have thus been used in the recent past [8,22–24]. For complex geometries, FEs models generally require many elements and variables, making the solution of the incremental problem difficult even for small bridges. In addition, since commercial codes are normally used, it is also difficult to adapt material models available to the actual masonry behavior, to properly take into account the orthotropy along material axes [25,26], softening behavior and separate failure surfaces for tension and compression [27–33].

Two distinct FE software are utilized in the paper to perform several numerical simulations on the Venice trans-lagoon bridge (Fig. 2), namely a macroscopic FE procedure dealing with isotropic elastic–plastic materials within the commercial code Strand7 [34], and a homogenization non-linear FE procedure recently presented in [15,16], which relies into a discretization of the structure with rigid parallelepiped elements and non-linear quadrilateral interfaces. The latter approach allows performing non-linear static simulations taking into account the orthotropic behavior and the softening of actual masonry materials by means of a Sequential Quadratic Programming (SQP) strategy recently presented in detail in [16], where the reader is referred to. When for the interfaces a rigid plastic behavior with infinite ductility is assumed, an upper bound limit analysis can be performed, which allows the estimation of collapse loads and failure mechanisms, by means of the solution of a large scale linear programming problem (LP).

For all models, a full 3D discretization is adopted in order to suitably consider the unsymmetrical response of the structure induced by live loads eccentrically applied and the always present transversal effect due to the three-dimensional geometry, even in presence of loads symmetrically disposed on the width. Furthermore, it is worth noting that the role played by the presence of lateral stone arches on the barrel vault may be estimated only using a full 3D model.

Finally, the stabilizing role of the backfill up the collapse is evaluated together with the effects induced by a foundation vertical settlement of a pile.

In Section 2, the salient features of the different codes used are summarized. In Section 3, the case study examined, namely the trans-lagoon Venice railway bridge, Fig. 2, is presented in detail and the homogenization procedures employed for the barrel vault and the stone arches are also reported. In Section 4 the results of the structural analyses performed both on service loads and at collapse are critically discussed and the effect of backfill and spandrels is highlighted. Finally the effect of the foundation settlement of a pile is presented in Section 5.