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Mesoscale partitioned modelling of masonry bridges allowing for arch-backfill interaction

Yanyang Zhang [a,b], Enrico Tubaldi [a,c], Lorenzo Macorini [a,*], Bassam A. Izzuddin [a]

[a] Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[b] Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu, Sichuan 610031, China
[c] Department of Civil and Environmental Engineering, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, Scotland, UK

HIGHLIGHTS

- Accurate modelling strategy for nonlinear simulations of single span masonry arch bridges.
- Masonry arches are represented using a detailed mesoscale approach allowing for masonry bond.
- The backfill is modelled employing an elasto-plastic continuum description.
- The modelling strategy is validated against experimental results on realistic bridge specimens.
- A parametric study investigates the effects of critical parameters on the bridge response.

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ABSTRACT

Masonry arch bridges exhibit a complex three-dimensional behaviour which is determined by the interaction between different structural and non-structural components, including the arch barrel, the backfill and the lateral walls. This paper presents an advanced finite-element modelling strategy for studying the behaviour of masonry arch bridges under vertical loading which combines a mesoscale description of the arch barrel with a plasticity-based continuum approach for the fill and the spandrel-walls. The proposed modelling strategy is validated against available experimental laboratory test results on masonry arch bridges. Firstly, a bridge specimen with a detached spandrel wall is analysed considering a simplified strip model. Subsequently, the influence on the bridge response of backfill and arch characteristics, loading position, arch shape and abutment movements are investigated through a comprehensive parametric study. In the final part of the paper, the results of full 3D mesoscale simulations of an arch bridge with attached spandrel walls are presented and discussed. The analysis results provide significant information on the complex interaction between the different bridge components along the longitudinal and transverse direction, and can be used to validate and calibrate simplified approaches for practical assessment of masonry arch bridge.

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1. Introduction

The realistic behaviour of masonry bridges is determined by the interaction between arch barrel, backfill, spandrel- and wing-walls, and masonry piers in the case of multi-span bridges. In practical assessment, fill material is considered as a non-structural component and its contribution is often neglected or it is allowed for by using simplified approaches. However, as confirmed by previous experimental and numerical research [1], the backfill plays a critical role spreading the loads applied on the road/rail surface to the arch barrel, and it provides transverse resistance and passive pressure to the deformed arch. Thus, a realistic representation of the fill behaviour and its interaction with the masonry arch is critical for an accurate response prediction of masonry arch bridges. For this reason, the backfill contribution has been accounted for since the development of the early 1D nonlinear descriptions for masonry bridges, as the finite element (FE) modelling strategies set out by Crisfield [2] and Choo et al. [3] using nonlinear beam elements for representing the masonry arch and nonlinear axial springs to simulate the backfill. In subsequent research, masonry arch and backfill have been represented using different 2D approaches, including discontinuous deformation analysis, discrete element techniques and nonlinear FE descriptions [4], where 1D nonlinear

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* Corresponding author.
E-mail address: l.macorini@imperial.ac.uk (L. Macorini).

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List of symbols

Latin upper case letters

C	Cohesion of interfaces
D	Parameter controlling the shape of the cap surface
E_b	Young's modulus of brick
E_f	Young's modulus of fill
E_w	Young's modulus of spandrel walls
F_1	Hyperbolic plastic surface (tension and shear)
F_2	Hyperbolic plastic surface (cap model in compression)
$F_{1,DP}$	First yield surface (Drucker Prager cap model)
$F_{2,DP}$	Second yield surface (Drucker Prager cap model)
$G_{f,I}$	Mode-I (tension) fracture energy
$G_{f,II}$	Mode-II (shear) fracture energy
G_m	Mortar shear modulus
I_1	First invariant of stress tensor
J_2	Second deviatoric invariant of stress tensor
K_n	Elastic (initial) normal stiffness of interfaces
K_t	Elastic (initial) tangential stiffness of interfaces
Q_1	Plastic potential related to F_1
Q_2	Plastic potential related to F_2
$Q_{1,DP}$	Plastic potential related to $F_{1,DP}$
$Q_{2,DP}$	Plastic potential related to $F_{2,DP}$
W_{pl1}, W_{pl2}	Distinct historical parameters (plastic works)

Latin lower case letters

c_f	Cohesion of Drucker Prager cap model
c_w	Cohesion of spandrel walls
D	Displacement of footing in model of Terzaghi experiment
k	Parameter controlling the shape of the Drucker Prager yield surface
k_d	Parameter controlling the shape of the Drucker Prager plastic potential

Q	Distributed load acting of footing in model of Terzaghi experiment
R	Radius of the circular cap in the Drucker Prager cap model

Greek lower case letters

α	Parameter controlling the shape of the Drucker Prager yield surface
α_d	Parameter controlling the shape of the Drucker Prager plastic potential
θ	Parameters governing the shape of the cap surface
ν_b	Poisson ratio of brick
ν_f	Poisson ratio of fill
ν_w	Poisson ratio of spandrel walls
ξ	Parameter related to I_1
ξ_c	Centre of the circular cap in the Drucker Prager cap model
$\xi_{\max}$	Maximum allowed value of ξ under isotropic tensile stresses for Drucker Prager surface
ρ	Parameter related to J_2
ρ_f	Unit weight of fill
ρ_m	Unit weight of masonry
σ	Normal stress
σ_c	Compressive strength of masonry
σ_t	Tensile strength of masonry joint
τ_x, τ_y	Shear stresses
ϕ	Friction angle of interfaces
ϕ_w	Friction angle of spandrel wall
ϕ_{wd}	Dilatancy angle of spandrel wall
φ_f	Angle of friction of Drucker Prager cap model
φ_d	Dilatancy angle of Drucker Prager cap model
χ	Cap value of ξ under isotropic tensile stresses
ψ	Dilatancy angle of interfaces

interface elements have been adopted to represent the interaction between the arch and the backfill as well as the development of cracks in the mortar joints of the arch. More recently, Cavicchi & Gambarotta [5,6] investigated the effect of the arch-backfill interaction on the structural behaviour of multi-span masonry arch bridges using nonlinear beams with an elastic-plastic no-tension material model for arches and piers, where the backfill has been simulated using a 2D plain strain FE representation with a modified Mohr-Coulomb plastic criterion allowing for material nonlinearity. These previous numerical descriptions are generally efficient as they are based on 1D or 2D reduced models, but in many cases they lead to a crude representation of the actual bridge behaviour, which is inherently three-dimensional [7]. More recently, 3D numerical models for masonry bridges have been proposed, and a continuous nonlinear FE strategy with solid elements has been employed, where the masonry components are represented using a macroscale material model which assumes masonry as a homogeneous and isotropic material [8–10], thus neglecting the orthotropic texture of masonry. An alternative advanced 3D modelling strategy has been put forward by Milani & Lourenço [11], where the masonry components are modelled using a homogenised approach with rigid solid elements and nonlinear interfaces, allowing to account for masonry orthotropy.

In this paper, a detailed 3D description is proposed for masonry bridges utilising a mesoscale strategy for brick/block-masonry [12]. In previous research [13,14], it was shown that this advanced modelling strategy enables an accurate response prediction of masonry arches, as it takes into account the actual masonry bond, including potential defects in the brickwork, without resorting to homogenization techniques as in [11]. This numerical approach is extended here to allow for the interaction between arch and backfill. Because of the significant computational cost, the proposed detailed description with solid elements for masonry units and backfill and 2D nonlinear interface elements for mortar joints is coupled with a partitioning approach previously developed at Imperial College [15,16] allowing for parallel processing on High Performance Computing systems. The mesoscale masonry model, the elasto-plastic description for the backfill and the partitioning strategy have been implemented in ADAPTIC [17], a general finite element code for nonlinear analysis of structures under extreme loading conditions, which is used in this study to perform accurate numerical simulations of masonry arch bridges. Using the proposed modelling strategy, two multi-ring arch bridges, previously tested at the Bolton Institute [18], are modelled in this paper. The two bridges are identical except for the spandrel walls, which in one case are detached providing only a transverse restraint to the backfill, while in the other case they are attached furnishing also a significant contribution to the global stiffness and resistance. Numerical predictions are first compared against test results for the case with detached spandrel walls, and the results of an extensive parametric study are then presented. This has been conducted on a simplified strip bridge model to investigate the influence of the backfill and the arch characteristics, the loading position, the arch shape and the abutment movements on the bridge response. In the final part of the paper, the results of a full 3D mesoscale analysis of the bridge model including the contribution of the spandrel walls are presented and discussed to show the unique capabilities of the proposed modelling approach for unveiling the

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