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Preface

The proceedings present 52 scientific papers written for the 32nd conference of the UK Association for Computational Mechanics (UKACM). The organisation was founded in 1992 with the aim of promoting research in computational mechanics and various engineering applications and establishing formal links with similar organisations in Europe and the International Association of Computational Mechanics (IACM). The conference was held in the Department of Engineering at Durham University, Durham, UK, between the 11th and 12th April 2024, with the 2024 UKACM School being held on the 10th April 2024. In total 72 technical presentations were delivered as part of the conference, in addition to four plenary lectures and three introductory UKACM School lectures.

Numerous people have contributed to the delivery of this event, but in particular the organising committee would like to thank Professor Charles Augarde, Head of the Department of Engineering, Durham University, UK, for his unwavering support. The event would not have been possible without the support of members of Durham University's Computational Mechanics Research Node, who provided scientific oversight of the submitted contributions, and the administrative support provided by Durham University's Department of Engineering and Event Durham. We would also like to thank Professor David Emerson (Science and Technology Facilities Council, UK), Professor Jon Trevelyan (Durham University, UK), Professor Xiaoying Zhuang (Leibniz University Hannover, Germany) and Dr Tim Hageman (Roger Owen Prize 2022 winner, University of Oxford, UK) who kindly accepted the invitation to deliver plenary lectures; and the three lecturers of the UKACM School, Professor Charles Augarde, Dr Robert Bird and Professor Jon Trevelyan who gave up their time to provide introductory lectures to the material point method, discontinuous Galerkin finite element methods and the boundary element method, respectively.

The papers submitted to UKACM 2024 cover the breadth of computational mechanics research within the UK and beyond. The proceedings are organised in the following sections, linked to the technical sessions of the conference:

- Advances in Bio-inspired Computational Modelling for Engineering Applications
- Advances in Finite Element Modelling
- Computational Innovations in Fluid Dynamics and Material Behaviour
- Computational Methods in Heat Transfer and Hydro-Mechanical Modelling
- Computational Modelling for Material Processing and Multi-scale Analysis
- Computational Modelling of Stress Concentration and Constitutive Relations
- Cutting-Edge Applications in Computational Engineering and Design
- Finite Element and Meshless Methods in Deformation Analysis
- Geotechnical Modelling 1: Pile Jacking to Rainfall-Induced Landslides
- Geotechnical Modelling 2: Rock Failure and Structural Interaction
- Geotechnical Modelling 3: MPM, PFEM and Soil-Structural Interaction
- Innovative Computational Approaches in Composite Material Analysis
- Machine Learning Applications in Engineering
- Phase-Field Modelling for Predicting Fracture and Degradation in Materials
- Structural Analysis and Optimisation: Modelling, Characterisation, and Response

The editor would like to thank the authors for their contributions and their willingness to consider the comments of the scientific committee when preparing their conference papers.

Will Coombs
UKACM 2024 Conference Chair, April 2024

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ISOGEOMETRIC ANALYSIS FOR BIM-BASED DESIGN AND SIMULATION OF SUB-RECTANGULAR TUNNEL

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Abstract. The design and analysis of segmental tunnel lining is today often based on empirical solutions with simplified assumptions. This work showcases the application of Isogeometric Analysis (IGA) for computationally efficient simulations of tunnel linings [1, 2]. In our past research, we developed a design-through-analysis procedure that consists of i) parametric modeling of the segmented tunnel lining; ii) development of an IGA computational framework, iii) reconstruction of the BIM lining model for IGA analysis, and iv) simulation model for lining including a reconstructed IGA model, contact interfaces between the joints, and a non-linear soil-structure interaction model based on the Variational Hyperstatic Reaction Method (VHRM) [3].In this paper, we extend our method for the analysis of sub-rectangular tunnel linings and demonstrate its efficiency using the example of the Shanghai express tunnel. The advantage of our novel method is the flexibility in adapting the tunnel alignment with the help of NURBS/CAD technology. Employing the high-order geometry definition, convergence of the mesh refinement procedure can be obtained with much faster rate. As a result, the modelling effort and computational time are reduced significantly. Moreover, this approach allows to capture the bending moment with better regularity. The combination with an existing BIM modelling approach via geometry reconstruction leads to a very efficient framework for tunnel lining analysis and design.

Key words: *Sub-rectangular Tunnel Linings; Isogeometric Analysis; BIM*

1 Introduction

With a continuously increasing population, urban planners require novel approaches to address societal problems such as congestion, noise, and polution; and underground transportation systems are an optimal solution in terms of carbon emissions, energy consumption, and noise levels. In the last decades, the design and assessment of the stability and robustness of the tunnel structure has been one of the key tasks to ensure a safe and durable underground infrastcture design to withstand demanding use for up to 100 years. Since both planning and design phase require analysis, modelling, visualization, and numerical analysis, different tools such as Building Information Modelling (BIM) and numerical analysis software are used to perform these tasks. However, in current engineering practice, there are no systematic solutions for the exchange between design and analysis models, and these tasks usually involve manual and error-prone model generation in different tools.

To address these shortcomings, we developed a BIM-based approach that connects a user-friendly industry-standard BIM software with effective simulation tools for high-performance computing [2, 1]. A fully automatized design-through-analysis workflow solution for segmented tunnel lining is developed based on a fully parametric design model realized as a Revit plugin and an isogeometric B-Rep analysis software (IBRA), connected through an interface implemented with the Revit plugin Dynamo (see Figure 1). In our approach, the fully parametric design model for 3D segmented tunnel lining for arbitrary tunnel alignments is developed based on the so-called universal ring approach. Moreover, we devised a higher-order finite element method based on isogeometric analysis (IGA) and employed it to analyse the forces in the lining segment with high resolution. Finally, we created a robust interface from the design model to the analysis tool for i) the reconstruction of NURBS with trivariate representation suitable for IGA analysis from the original boundary representation using the trimmed NURBS model of the lining segment, and ii) generation of the simulation script based on semantic data extracted from the BIM model (e.g. tunnel depth, material parameters, water level, etc.) and automatic execution of the analysis.

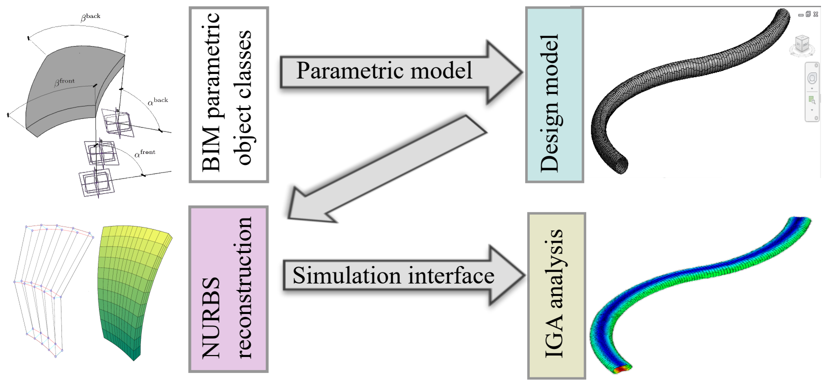

Figure 1: Design-through-analysis workflow for BIM-IGA assessment of the tunnel lining.

In this work, we extend our BIM-IGA approach to investigate the performance of IGA-VHRM for the analysis of sub-rectangular tunnel. We aim to simulate the interaction between the tunnel and surrounding soils under dynamics loading condition, i.e. seismic analysis. In the first step, the geometry of the tunnel is constructed using NURBS volumes. In the analysis phase, we employ the Isogeometric Analysis (IGA) concept in combination with the Variationally Hyperstatic Reaction Method (VHRM) approach to obtain higher computing performance and accuracy. This approach is first validated with statics analysis, in which the typical vertical geotechnical loading condition based on K_0 is assumed. For dynamics analysis, we perform validation using a simplified loading scheme based on [4].

2 Problem description

The (V-)HRM approach characterizes the interaction between the underground structure, i.e. tunnel and surrounding soils using nonlinear springs applied on the soil-structure interface. The internal forces on the springs are

$$\begin{aligned} r_n &= \chi p_{n,lim} \ln(p_{n,lim} + \eta_{n,0}\delta_n), \\ r_s &= \chi p_{s,lim} \ln(p_{s,lim} + \eta_{s,0}\delta_s), \\ r_t &= \chi p_{t,lim} \ln(p_{t,lim} + \eta_{t,0}\delta_t). \end{aligned} \tag{1}$$

In Eq. (1), the factor χ facilitates the calibration of the interaction against various factors, e.g. constitutive relationship. Moreover, it allows to match the results with classical HRM based on fixed-point iteration. The consistent linearization of the springs forces enables quadratic convergence when the Newton-Raphson iteration is used [3].

The structure and design of the sub-rectangular tunnel, including the boundary condition under statics loading condition, are presented in Fig. 2 (a). The sub-rectangular structure is characterized by segmental arcs, connected at the joints. The profile of the curve is of C_1 continuity.

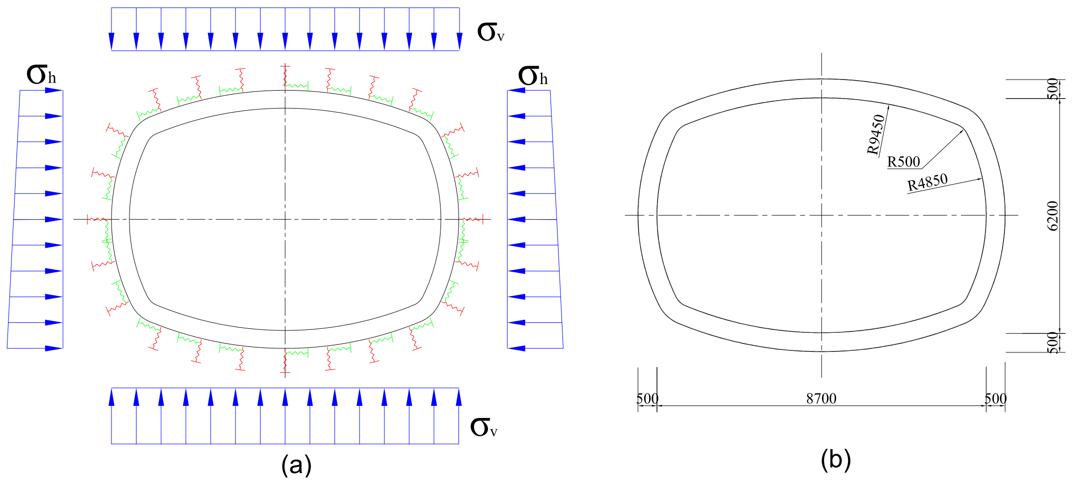

Figure 2: (a) Geometry and loading condition of sub-rectangular tunnel (b) Dimensions of the Shanghai express tunnel.

The geometry of the tunnel is constructed using NURBS volumes. The advantage of this approach is twofold: Firstly, the geometrical arcs of the sub-rectangular structure can be constructed precisely using quadratic NURBS. Secondly, the refinement of the control mesh is straightforward and does not alter the geometry; meanwhile, it improves the accuracy of the finite element solution. The NURBS volume is an extension of B-splines volume, which reads

$$\mathbf{V}(\xi_1,\xi_2,\xi_3) = \sum_{i=0}^{n}\sum_{j=0}^{m}\sum_{k=0}^{l} N_i^p(\xi_1)\, N_j^q(\xi_2)\, N_k^r(\xi_3)\, \mathbf{P}_{ijk} \tag{2}$$

in which N_i^p are the B-splines basis functions and $\mathbf{P}_{ijk}$ are the control points in Cartesian coordinates. A NURBS volume is obtained by using homogeneous coordinates for $\mathbf{P}_{ijk}$ [1].

3 Numerical results

The computational approach is used to analyse the deformation of the Shanghai express tunnel [4] under static loading condition. The dimensions of the tunnel are depicted in Fig. 2 (b).

The analysis results are shown in Fig. 3 (right). We note that due to the special design of the tunnel, there is a high degree of stress concentration at the corners. Nevertheless, the structure of the tunnel allows for better width-per-dimension usage ratio compared with a traditional tunnel using circular section.

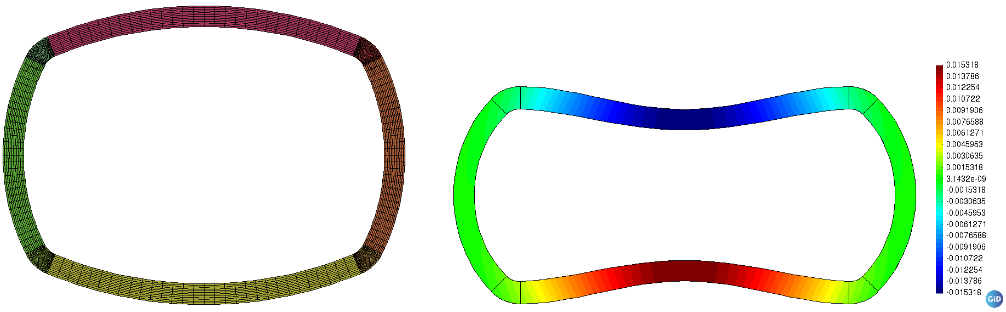

Figure 3: Displacement results of analysis with sub-rectangular tunnel. Left: undeformed structure; Right: deformed structure (scale = 100).

4 Conclusions

We propose an approach for analysis of non-circular tunnels. This approach combines the advantage of higher-order discretization method, i.e. IGA, with the simplicity and flexibility of VHRM to evaluate the deformation and internal forces of the sub-rectangular lining. In the first step, the statics analysis is performed to quantify the performance of the lining under a typical loading scenario. The extension to seismics analysis can be performed by using implicit dynamics or by using a simplified loading profile, as proposed in [4]. This is subject to further investigation. Future work includes segmental lining design and adding the interior columns.

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