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UK Association for Computational Mechanics

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Table of Contents

Preface	vii
Scientific Committee	viii
2024 UKACM School	ix

Conference papers organised by Technical Session

<i>Advances in Bio-inspired Computational Modelling for Engineering Applications</i>	1
Inverse design of spinodoid cellular structures with tailored mechanical-hydro-thermal performances, Jinlong Fu	2
Mechanics of 3D printed bioresorbable stents: A virtual testbed assessment., Michael Okereke	6
<i>Advances in Finite Element Modelling</i>	10
Geometric Optimization and Mechanical Analysis of Multilayer Graphene Platelet Films: A Finite Element Approach, Penghao Qi	11
Towards simulation of magnet quench using hp-FEM, Sayed Miah	15
<i>Computational Innovations in Fluid Dynamics and Material Behaviour</i>	19
Modelling the Liquid Droplet Impact Behaviour of Polymer Materials, Wei Tan	20
A numerical flume with enhanced momentum conservation for the two-phase flow simulation, Xin Wang	24
Validation of Open-source CFD Solvers for Rotating Detonation, Reuben Hann	28
Reducing Aerodynamic Drag on Flatbed Trailers for Passenger Vehicles Using Novel Appendable Devices, Michael Gerard Connolly	34
Accounting for Particle Morphology in CFD-DEM Modelling, Sadaf Marami	39
<i>Computational Methods in Heat Transfer and Hydro-Mechanical Modelling</i>	43
Overlapping improved element-free Galerkin and finite element methods for the solution of non-linear transient heat conduction problems with concentrated moving heat sources, Zahur Ullah	44
Stochastic modelling of unstable preferential flow in spatially varying water repellent soils, Evan J Ricketts	48
Mathematical modelling of pressure induced freezing point depression within soils exhibiting strong capillary pressure effect, Ekaterina Lgotina	52
Hydromechanical Modeling of CO₂ Injection in Deformable Porous Media , Farzaneh Ghalamzan Esfahani	56
<i>Computational Modelling for Material Processing and Multi-scale Analysis</i>	60
Computational Multi-scale Modelling and Inverse Design of Flexoelectric Metamaterials, Xiaoying Zhuang	61
Numerical Simulation of Nanomachining: Exploring Meshless and Finite Element Techniques for Material Removal Modelling, Rahul Yadav	65

<i>Computational Modelling of Stress Concentration and Constitutive Relations</i>	69
Metamaterials genome: progress towards a community toolbox for ai metamaterials discovery , Stefan T Szyniszewski	70
SENT specimen ductile-failure modelling via damage mechanics , Asif Ali	74
<i>Cutting-Edge Applications in Computational Engineering and Design</i>	78
Development of a Numerical Framework for Simulation of Aquaculture Systems , Shuo Mi	79
Isogeometric Analysis for BIM-based Design and Simulation of Segmental Tunnel Lining , Hoang-Giang Bui	83
A Comparative Study of Electric and ICE Vehicle Suspension System for Vehicle-Bridge Interaction Dynamics , Kaustubh Deepak Kasle	87
<i>Finite Element and Meshless Methods in Deformation Analysis</i>	91
Peridynamics: Past, Present and Future , Erkan Oterkus	92
Estimate end bearing resistance of a circular foundation using small strain and large deformation finite element modelling , shujin zhou	96
<i>Geotechnical Modelling 1: Pile Jacking to Rainfall-Induced Landslides</i>	100
Energy-based solution for stiffened slabs-on-grade on expansive soils , Abubakr E. S. Musa	101
Spatial Variability of Soil Properties in Saudi Arabia: Estimation of Correlation Length , Kun Zhang	105
Consequences of Terzaghi's effective stress decomposition in the context of finite strain poro-mechanics , Giuliano Pretti	109
A non-hysteretic simplification to the Glasgow Coupled Model (GCM) , Takudzwa M Mutsvairo	113
Comprehensive post-failure analysis of rainfall-induced landslides subjected to various rainfall patterns , Xian Liu	117
<i>Geotechnical Modelling 2: Rock Failure and Structural Interaction</i>	123
Continuum (PFEM) and discrete (DEM) modelling of pile installation in rocks , Matteo O Ciantia	124
G-PFEM numerical study of the downward trapdoor problem , Ying Cui	128
A coupled damage-plasticity DEM bond contact model for highly porous rocks , Jinhui Zheng	132
Modelling post-failure behaviour of chalk cliffs with the Material Point Method , Sam J V Sutcliffe	136
<i>Geotechnical Modelling 3: MPM, PFEM and Soil-Structural Interaction</i>	140
Simulation of strain localisation with an elastoplastic micropolar material point method , Ted J. O'Hare	141
Effects of structure and strain localization in PFEM simulations of CPTu tests in a natural clay , Kateryna Oliynyk	145
Study of Landslides through a Stabilised Semi-Implicit Material Point Method , Mian Xie	149

Dynamic three-dimensional rigid body interaction with highly deformable solids, a material point approach , Robert Bird	153
Numerical simulation of in-situ free fall cone penetrometer tests using the material point method , Debasis Mohapatra	157
<i>Innovative Computational Approaches in Composite Material Analysis</i>	161
Modelling Fracture Behaviour in Fibre-Hybrid 3D Woven Composites , Anna Weatherburn	162
A higher-order finite element framework for hyper-visco-elastodynamics of soft multifunctional composites , Chennakesava Kadapa	167
Bio-inspired cellular nanocomposite shells: stability analysis , Behnam Sobhaniaragh	171
Effects of ply hybridisation on delamination in hybrid laminates at CorTen steel/M79LT-UD600 composite interfaces , Mohammad Burhan	175
Micromechanical Computational Analysis of Debonding and Kinking in Microscale Composites , Muhammad Faiz Hamzah	179
<i>Machine Learning Applications in Engineering</i>	183
Efficient Stochastic Analysis of Landslide Post-Failure Characteristics Using Dimension Reduction Method and Machine Learning , Jianping Li	184
<i>Phase-Field Modelling for Predicting Fracture and Degradation in Materials</i>	188
Phase-field-based chemo-mechanical modelling of corrosion-induced cracking in reinforced concrete , Evzen Korec	189
A phase-field model of mechanically-assisted corrosion of bioabsorbable metals , Sasa Kovacevic	193
An Enriched Phase-Field Method (XPFM) for the Efficient Simulation of Fracture Processes , Verena Curoşu	197
Immersed traction boundary conditions in phase field fracture modelling , Bradley Sims	201
<i>Structural Analysis and Optimisation: Modelling, Characterisation, and Response</i>	205
Computational modelling of failure of welded joints in hydrogen transport pipelines , Tushar K Mandal	206
Characterisation of rate-dependent fracture in adhesive joints , Giulio Alfano	210
Robust topology optimisation of lattice structures with spatially correlated uncertainties , Ahmet Oguzhan Yuksel	214
Bayesian optimisation technique with a Gaussian process as the surrogate model for structural problems with random imperfections , Tianyi Liu	218
An analysis of stress and strain state of notched solid beams undergoing static loading , Michael T White	222
Response of a slender structure subject to stochastic ground motion and body force. , Lukman Olawale	226

Conference papers organised by Paper ID

ID	Title, Lead Author	
1	Continuum (PFEM) and discrete (DEM) modelling of pile installation in rocks , Matteo O Ciantia	124
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6	Energy-based solution for stiffened slabs-on-grade on expansive soils , Abubakr E. S. Musa	101
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10	Geometric Optimization and Mechanical Analysis of Multilayer Graphene Platelet Films: A Finite Element Approach , Penghao Qi	11
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14	Effects of structure and strain localization in PFEM simulations of CPTu tests in a natural clay , Kateryna Oliynyk	145
15	G-PFEM numerical study of the downward trapdoor problem , Ying Cui	128
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17	A coupled damage-plasticity DEM bond contact model for highly porous rocks , Jinhui Zheng	132
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29	Modelling the Liquid Droplet Impact Behaviour of Polymer Materials , Wei Tan	20
30	A phase-field model of mechanically-assisted corrosion of bioabsorbable metals , Sasa Kovacevic	193
32	Stochastic modelling of unstable preferential flow in spatially varying water repellent soils , Evan J Ricketts	48
33	A numerical flume with enhanced momentum conservation for the two-phase flow simulation , Xin Wang	24
35	A higher-order finite element framework for hyper-visco-elastodynamics of soft multifunctional composites , Chennakesava Kadapa	167
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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
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- 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 pollution; 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 infrastructure 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.

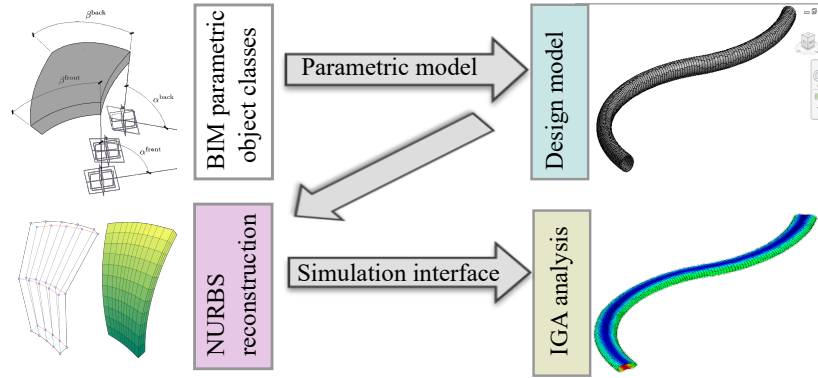


Figure 1: Design-through-analysis workflow for BIM-IGA assessment of the tunnel lining.

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.

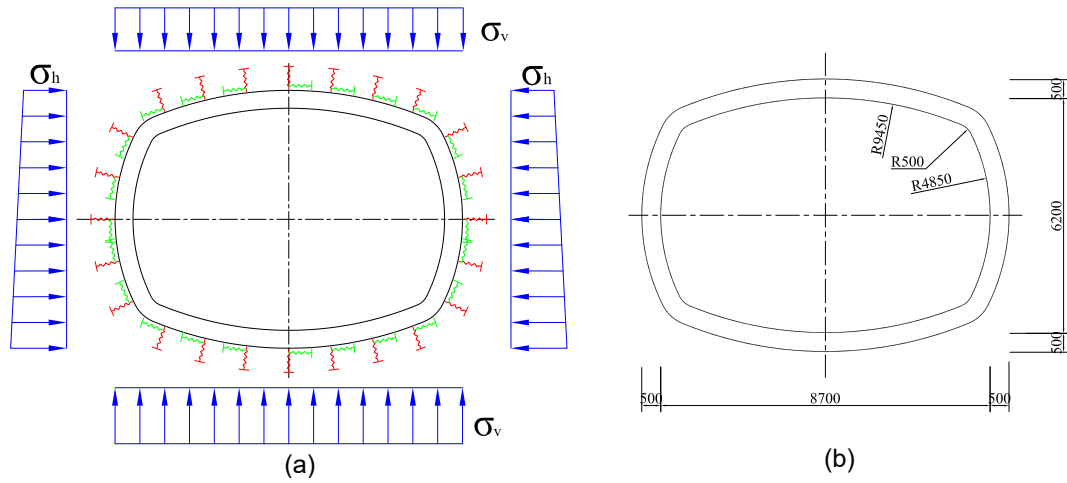


Figure 2: (a) Geometry and loading condition of sub-rectangular tunnel (b) Dimensions of the Shanghai express tunnel.

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

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

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.

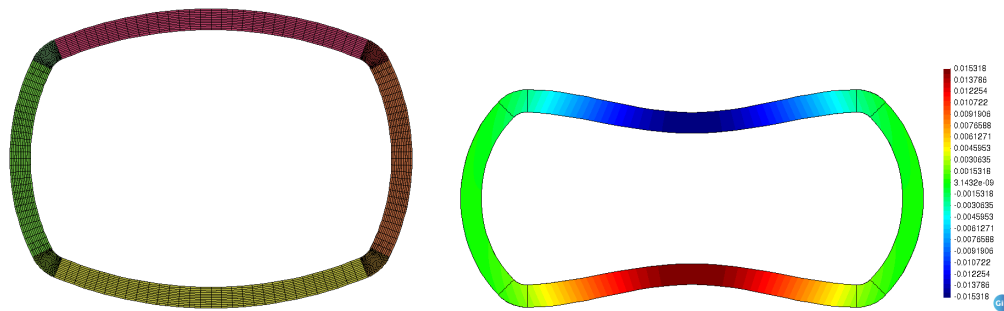


Figure 3: Displacement results of analysis with sub-rectangular tunnel. Left: undeformed structure; Right: deformed structure (scale = 100).

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 seismic 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.

Acknowledgments

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