Parametric Design and Isogeometric Analysis of Tunnel Linings within the Building Information Modelling Framework

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Abstract. Both planning and design phase of large infrastructural project require analysis, modelling, visualization, and numerical analysis. To perform these tasks, different tools such as Building Information Modelling (BIM) and numerical analysis software are commonly employed. 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, setup and update. In this paper, focussing on tunnelling engineering, we demonstrate a systematic and versatile approach to efficiently generate a tunnel design and analyse the lining in different practical scenarios. To this end, a BIM-based approach is developed, which connects a user-friendly industry-standard BIM software with effective simulation tools for high-performance computing. A fully automatized design-through-analysis workflow solution for segmented tunnel lining is developed based on a fully parametric design model and an isogeometric analysis software, connected through an interface implemented with a Revit plugin.

1. Introduction

The population explosion in developing countries connected with over-populated congested ‘mega-cities’ poses major challenges for urban mobility and air pollution. The use of underground transportation is an effective way to address these issues of mega-cities by effectively using underground space in highly congested urban areas while at the same time providing one of the most sustainable transport solutions in terms of CO2 emissions, energy consumption, and noise levels. Therefore, underground infrastructure is a key enabler for resource-efficient, low-carbon transportation for both people and goods in highly urbanised area. Mechanized tunnel construction, with the permanent support provided by precast segmental tunnel lining structures, has been proven as one of safest and most efficient construction technologies in terms of both costs and construction times, with minimal impact on the existing environment (Maidl, et al., 2012). In the last decades, the design and assessment of stability and robustness of the lining structure has been one of the key tasks to ensure a safe and durable tunnel structure design to withstand demanding use for 100 years and more.

Building Information Modelling (BIM) is a widely adopted concept for the design, construction and the management of buildings or industrial facilities over their entire lifecycle. However, in recent years, BIM is increasingly gaining attention also in large infrastructural projects, including urban mechanized tunnelling, where it has been used for tunnel design and construction management (Smith, 2014; Daller, et al., 2016). Some of the relevant, tunnelling-related BIM aspects recently addressed are interoperability using Industry Foundation Classes (IFC) (Koch, et al., 2017), multi-level modelling concepts (Borrmann, et al., 2015), collaborative design (Borrmann, et al., 2014), satellite-based settlement monitoring (Schindler, et al., 2016), and meta models for real-time design assessment (Ninic, et al., 2018).

Modern BIM tools have grown out of the infant stage as design tools for interactive object-based parametric design (Eastman, et al., 2008). In contrast to manual modelling of geometric details as in a generic 3D CAD approach, BIM tools allow for minimisation of direct modelling by using intelligent scripted parametric objects and algorithms with embedded knowledge about the relations between these objects. This is enabled by the extension of the BIM object-based concept with parametric modelling with embedded complex relations or intelligence between the models (Boeykens, 2012). This approach allows for automatic update of the complete model (object and constraints w.r.t. other objects) when object parameters are changed, which provides the basis for interactive design and analysis. Further enhancements of the design process are introduced by generative design, where a large number of design alternatives is generated based on input design constraints and parameters, such as materials, manufacturing methods, and cost constraints. The integration of parametric modelling and generative design within the BIM framework allows for an efficient generation of design alternatives, while the combination with other performance-based assessment methods guarantees effectiveness in generation of optimal solutions (Turrin, et al., 2011).

Another important aspect of the BIM framework is the systematic integration of assessment in the design models. In the tunnelling context, the design is evaluated using complex Finite Element (FE) simulations (Meschke, et al., 2014; Ninic, et al., 2019). In FE models, solid object is represented with trivariate polynomials of low order (usually one or two), while in design CAD models, these objects are commonly described with NURBS (Non-Uniform Rational B-splines). Therefore, to be utilised for the analysis in FE models, the CAD geometry has to be approximated using re-meshing techniques. Since FE analysis is sensitive to mesh refinement, several authors have tried to directly utilise the NURBS object definition for computationally efficient and higher-order numerical analysis by means of Isogeometric Analysis (IGA) (Breitenberger, et al., 2015; Philipp, et al., 2016) to alleviate this drawback. IGA, originally introduced by (Hughes, et al., 2005) is bridging the design process and analysis by direct use of the same shape function to represent the geometry in analysis. In addition, IGA offers additional advantages regarding the quality of the approximation, such as higher order and higher continuity of the computational mesh.

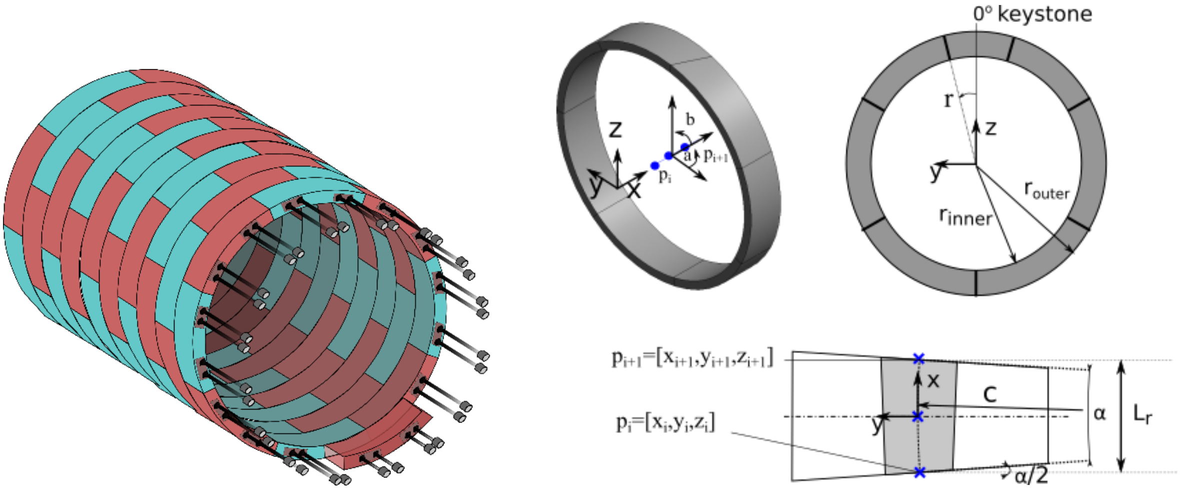
This paper presents a combination of emerging computing technologies in the area of parametric modelling and computational mechanics for the design assessment of segmented tunnel linings. Implementing an automated design-through-analysis workflow platform, we are facilitating the design process, contributing to modelling efficiency and at the same time reducing the possibility for human error. We present an extension of the recently introduced integrated SATBIM platform for information and numerical FE modelling of tunnel projects on different levels of detail (Ninic, et al., 2017; Ninic, et al., 2019), utilizing the advantages of higher-order geometry definition of the lining structure in the design software to generate higher-order and higher-continuity numerical models. By doing that, we provide a platform for the assessment and optimisation of tunnel design with high computational and modelling efficiency.

2. Methodology

The methodology for the presented integrated design-to-analysis workflow for segmented tunnel linings consists of i) fully parametric modelling of tunnel linings using the universal ring approach, ii) IGA computational framework and iii) reconstruction of the lining geometry for IGA analysis and automatic setup and extraction of computational IGA model. These three parts are briefly described in the subsequent sections.

2.1 Parametric modelling of tunnel structure

In the mechanised tunnelling process, the shield machine is digging directly into the ground, installing the precast segments at the back of the shield, so that they form the coating of the tunnel. Each ring is made of modular segments (from 4 to 10) and the narrowest spot on the segment ring is usually at the so-called key segment, which, as the last wedge element, closes and braces the ring. A complete segment ring is cone-shaped in order to accommodate curve radii from 150 m. The geometry of the entire ring and its individual segments as well as the arrangement of the joints and their sealing must be designed such that the can be easily moulded for the designed tunnel alignment. Hence, in order to have modular segments, the solution is to employ universal rings.



(a) (b)

Figure 1: (a) Segmented tunnel lining; (b) Geometry of the universal ring

A universal ring is characterized with the average ring length L_r, inner and outer radius of the ring (r_{inner} and r_{outer}), and the angle describing the tapered geometry of the ring α, which depend on the curvature c, the number of segments, and their divisions within the ring. The designed alignment of the tunnel is formed by adjusting the rotations of the rings.

Figure 2 outlines an algorithm for calculation of ring rotations, which leads to the best match between design and achievable tunnel alignment and enables the generation of the actual design model using the universal ring approach. Starting from the actual design alignment, imported as a CAD polyline, and based on the ring parameters, target points are created along the curve and ring rotations are determined based on the allowable ring rotations such that the actual ring positions have minimum discrepancy from the target design. For the calculations of the actual ring positions and $p_i(x_i, y_i, z_i)$, and spatial rotations (a, b), the following equations are derived:

$$x_i = x_{i-1} + L_r \cdot cos\left(a_{i-1} + \frac{\alpha}{2} \cdot cos(r_{i-1}) + \frac{\alpha}{2} \cdot cos(r_i)\right) \cdot cos\left(b_{i-1} + \frac{\alpha}{2} \cdot sin(r_{i-1}) + \frac{\alpha}{2} \cdot sin(r_i)\right),$$

$$\mathrm{y_i} = \mathrm{y_{i-1}} + L_r \cdot sin\left(a_{i-1} + \frac{\alpha}{2} \cdot cos(r_{i-1}) + \frac{\alpha}{2} \cdot cos(r_i)\right) \cdot cos\left(b_{i-1} + \frac{\alpha}{2} \cdot sin(r_{i-1}) + \frac{\alpha}{2} \cdot sin(r_i)\right),$$

$$\mathrm{z_i} = \mathrm{z_{i-1}} + L_r \cdot cos\left(a_{i-1} + \frac{\alpha}{2} \cdot cos(r_{i-1}) + \frac{\alpha}{2} \cdot cos(r_i)\right) \cdot sin\left(b_{i-1} + \frac{\alpha}{2} \cdot sin(r_{i-1}) + \frac{\alpha}{2} \cdot sin(r_i)\right) \quad (1)$$

$$\alpha = \arccos\frac{1 - L_r^2}{2c^2} \;;\quad a_{n+1} = a_n + \frac{\alpha}{2}\cos(r_{i-1}) + \frac{\alpha}{2}\cos(r_i)\,;\quad b_{n+1} = b_n + \frac{\alpha}{2}\sin(r_{i-1}) + \frac{\alpha}{2}\sin(r_i) \tag{2}$$

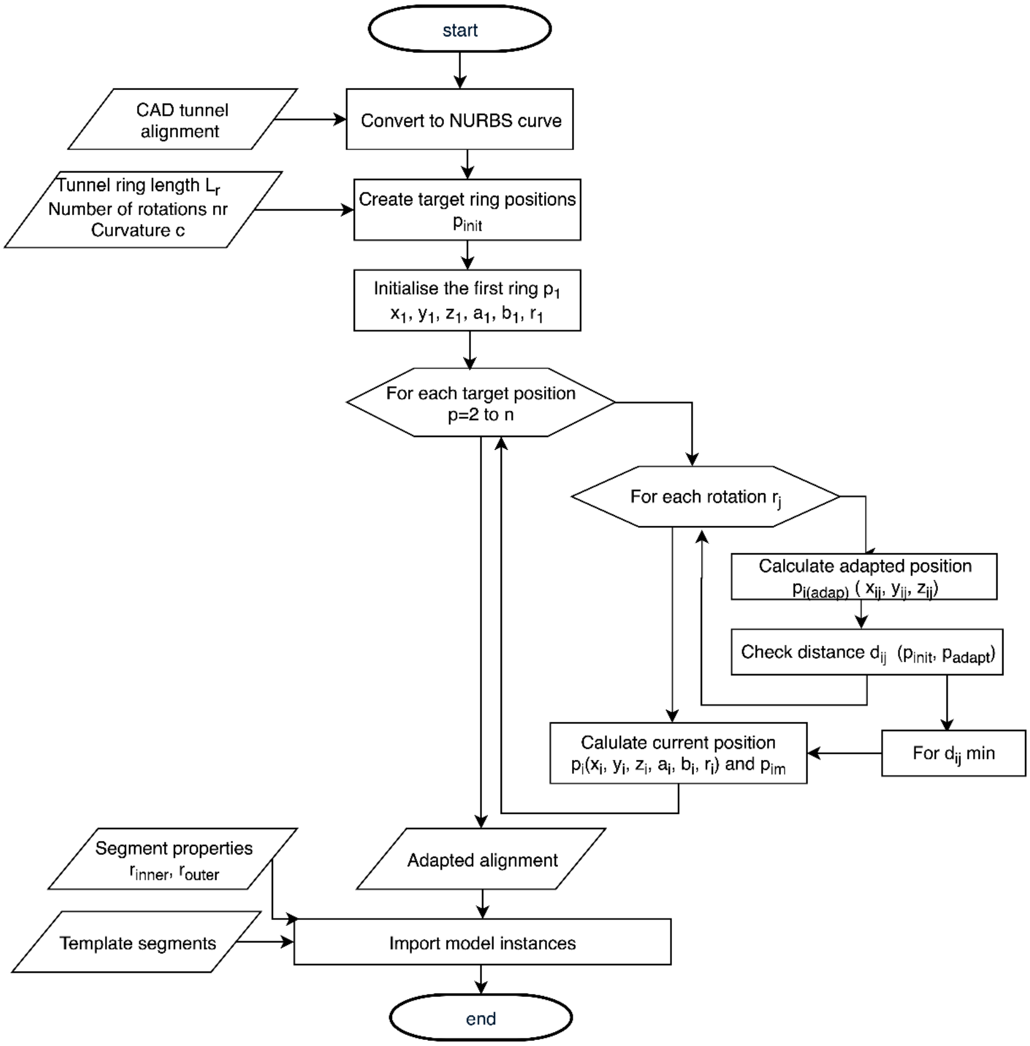
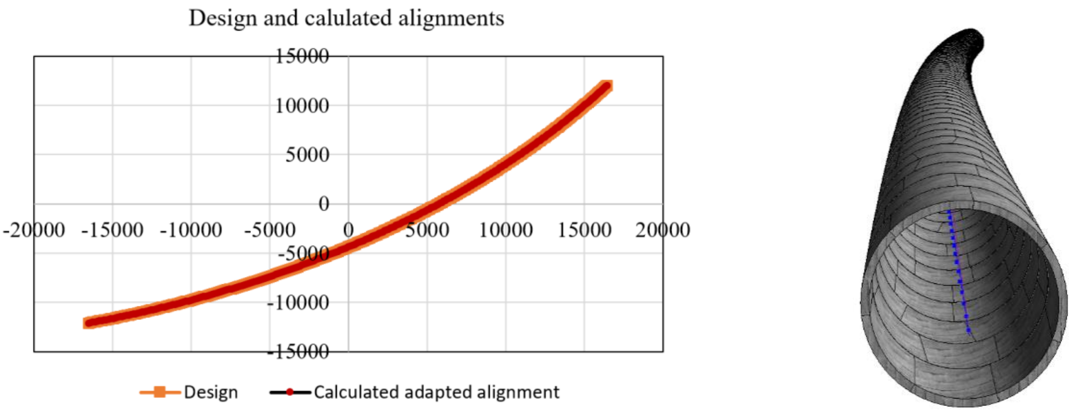


Figure 2: Algorithm for generation of the adapted tunnel alignment

Figure 3 (a) shows the calculated divergence of the calculated alignment from the actual design. The two curves nearly coincide, and for this particular example, the calculated discrepancy evaluated with root mean square error (RMSE) is 2.2 mm. The actual geometric-semantic design model of the segmented tunnel lining is shown in Figure 3(b).



(a) (b)

Figure 3: Evaluation of algorithm for generation of adaptive alignment

2.2 Isogeometric analysis (IGA): From NURBS geometry to NURBS basis functions

Univariate and multivariate NURBS geometries

Univariate B-spline functions can be used to construct a B-spline curve of order p by linear combination of piecewise rational polynomials. The geometry of the B-spline curve is defined as:

$$\boldsymbol{C}\,(\xi) \;=\; \sum_{i=1}^{n} N_i^p(\,\xi\,)\boldsymbol{P}_i \tag{3}$$

where $N_i^p(\,\xi\,)$ is the B-spline basis function of order p and $\boldsymbol{P}_i$ is the list of control points. The B-spline surface and volume are described as tensor products of two and three B-spline curves, respectively:

$$\boldsymbol{S}(\,\xi_1,\xi_2) \;=\; \sum_{i=0}^{n}\sum_{j=0}^{m} \boldsymbol{N}_i^p(\,\xi_1)\boldsymbol{N}_j^q(\,\xi_2)\boldsymbol{P}_{i,j} \tag{4}$$

$$\boldsymbol{V}(\,\xi_1,\xi_2,\xi_3) \;=\; \sum_{i=0}^{n}\sum_{j=0}^{m}\sum_{k=0}^{l}\; \boldsymbol{N}_i^p(\,\xi_1)\boldsymbol{N}_j^q(\,\xi_2)\boldsymbol{N}_k^r(\,\xi_3)\boldsymbol{P}_{i,j} \tag{5}$$

The B-spline basis can be generalized to the rational case by associating each control point $\boldsymbol{P}_i$ with the control weight w_I to form the projective control points in homogeneous coordinates. Then, the NURBS geometry is described by projecting the projective B-spline geometry as:

$$\tilde{\boldsymbol{V}}\,(\boldsymbol{\xi}) \;=\; \sum_{I=\{0,0,0\}}^{n,m,l} N_I(\,\xi\,)\boldsymbol{Q}_i\,, \quad where \quad \boldsymbol{Q} = \begin{bmatrix} w_i\boldsymbol{P}_I \\ w_i \end{bmatrix} \tag{6}$$

In 3D, the NURBS basis function is defined as:

$$R_{I(\,\xi)} = \frac{w_I N_I(\xi)}{\sum_{J=\{0,0,0\}}^{n,m,l} w_J N_J(\,\xi\,)} \tag{7}$$

It should be noted, that the B-Spline shape function can represented as a linear combination of *Bézier* shape functions of the same order as in (Borden, et al., 2011), which allows an more straightforward implementation similar to standard finite element models.

The computational analysis of the tunnel linings using isogeometric analysis is based upon the weak form of the initial boundary value problem,

$$\int_{\Gamma^t}^{h} \delta\boldsymbol{u}^{\boldsymbol{h}} \cdot \boldsymbol{t}\, dA \;+\; \int_{\Omega}^{h} \delta\boldsymbol{u}^{\boldsymbol{h}} \cdot \boldsymbol{b}\, dV \;-\; \int_{\Omega}^{h} \delta\boldsymbol{\epsilon}^{\boldsymbol{h}} : \boldsymbol{\sigma}^{\boldsymbol{h}}\, dV \;=\; 0, \tag{8}$$

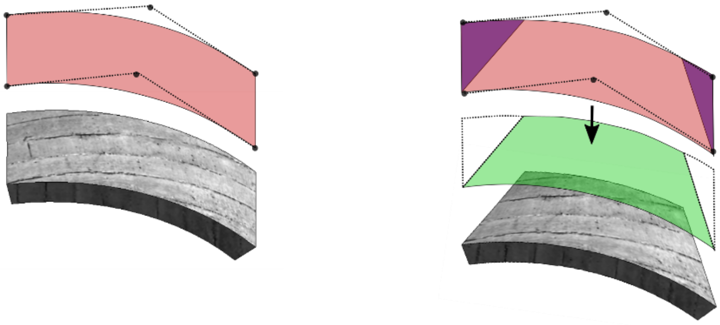
where $\boldsymbol{\sigma}^h$ is the stress tensor depending on the discretized displacement field $\boldsymbol{u}^h$, $\delta\boldsymbol{\epsilon}^{\boldsymbol{h}}$ are the virtual strains obtained from the discretized test functions $\delta\boldsymbol{u}^h$, $\boldsymbol{t}$ are the boundary tractions and $\boldsymbol{b}$ the distributed volume forces. The system of algebraic equations resulting from Equation (8) is solved for the unknown displacements $\boldsymbol{u}$. To provide a seamless connection between the CAD-based geometry description and the analysis model, the spatial discretization of the displacements $\boldsymbol{u}$ and the test functions $\delta\boldsymbol{u}$ is based on the IGA approach, where the NURBS basis functions R_I (Equation (7)) are directly employed to approximate the displacement field:

$$\boldsymbol{u}^h(\boldsymbol{x}) = \sum_I R_I\left(\xi(x)\right)\boldsymbol{u}_I \tag{9}$$

2.3 BIM-to-IGA

The main objective of integrated design-through-analysis workflows with IGA is to directly utilise the advantages of high-order geometry representations in design models to generate higher-order and higher-continuity numerical models, maximizing the computational and modelling efficiency. However, one of the biggest remaining challenges is the reconstruction of a solid model defined by boundary trimmed spline surfaces to obtain a parameterization suitable for IGA analysis (Al Akhras, et al., 2016). In the literature, different strategies have been proposed to solve this problem, such as use of tetrahedral meshes or swept volumes based on discrete volumetric harmonic functions (Martin, et al., 2009), variational approach to construct NURBS parameterization of swept volumes (Xu, et al., 2013), or a topologically equivalent solid bounded by (non-trimmed) B-spline surfaces (Xu, et al., 2013).

The geometry of tunnel segments exported in the ACIS (.sat) format is represented either with trivariate or trimmed NURBS, depending on the complexity of the segment geometry. For segments with parallel edges, the geometry is represented with trivariate NURBS surfaces (see Figure 4(a)), and for segments with inclined edges, such as keystone or neighbouring segments, NURBS surfaces are trimmed (see Figure 4(b)). In both cases, in order use the segment geometry for IGA analysis, the NURBS volumes needs to be reconstructed from surfaces according to Equation (6). Trivariate NURBS surfaces could be directly used for the generation of NURBS volumes by sweeping NURBS surfaces along the path using *Isogeometric_application* (see Section 3.1). However, a trimmed-NURBS boundary representation (BRep) is not suitable for the direct analysis using IGA, and therefore a method for NURBS reconstruction for tunnel linings along arbitrary alignments is proposed.



(a) (b)

Figure 4: (a) Trivariate NURBS surfaces; (b) Trimmed NURBS surfaces

The segment is constructed by sweeping a base surface along a tunnel alignment path with length of a ring L_r. The parametric segment is defined with the adaptive points (highlighted in red in Figure 5(a)), and the parameters $r_{inner}, r_{outer}, \alpha_{front}, \alpha_{back}, \beta_{front}\ and\ \beta_{back}$, where r, β and $\alpha,$ are the radius, arch length, and angle of the segment from the vertical axis, respectively. These parameters are used to reconstruct the trivariate NURBS definition of the segment as illustrated in Figure 5(a). The base surface is constructed as a bivariate NURBS, by defining control points ***P*** as a function of segment parameters. The bivariate NURBS is then swept along the path to generate NURBS volume as illustrated in Figure 5(b).

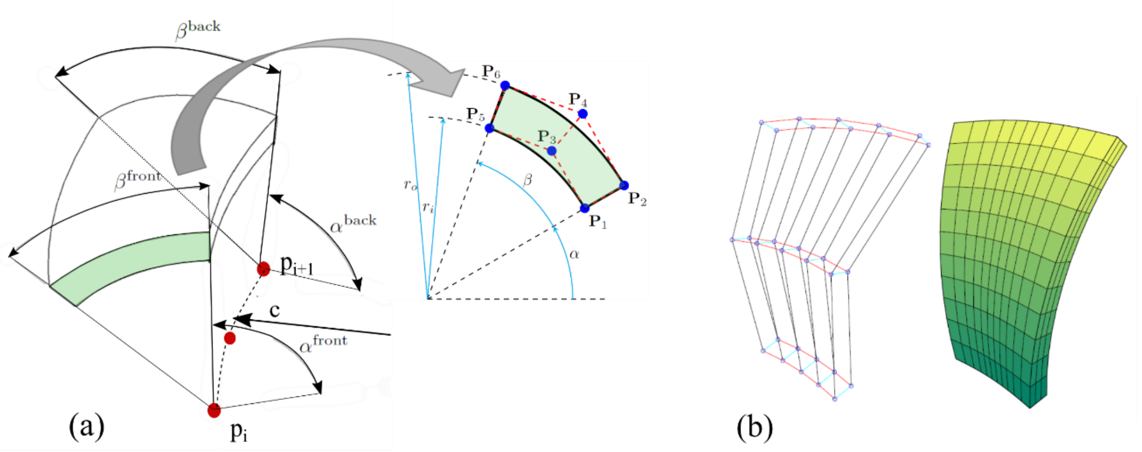


Figure 5:(a) Reconstruction of trimmed NURBS surfaces; (b) Trivariate NURBS volume

3. Implementation and Numerical examples

3.1 Implementation

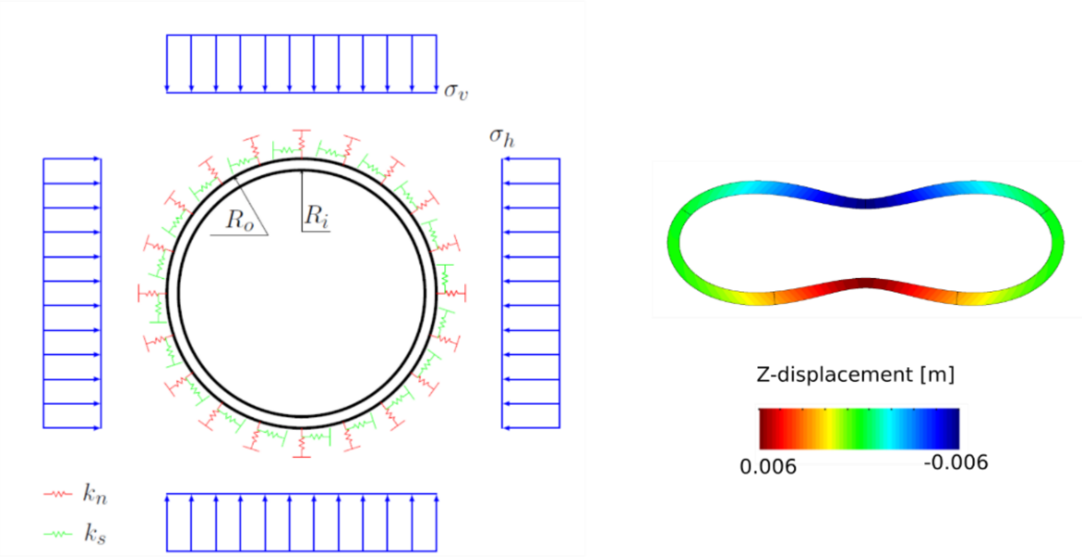
The parametric model for the segmented tunnel lining has been developed using the industry-standard tools Revit and Dynamo (AUTODESK, 2017). For the generation of the universal rings, a parametric segment family was developed as described in Subsections 2.1 and 2.3. The instances of the parametric segment family are imported to the locations calculated using the methodology and algorithm presented in Subsection 2.1. The design model is then exported to ACIS (.sat) format, and the geometrical description of the segments is used to reconstruct the bivariate NURBS volumes using the methodology described in Subsection 2.3. Two alternatives for NURBS volume reconstruction are proposed. For a simple segment geometry with parallel edges of the individual segments, Trivariate NURBS surfaces are directly utilized to reconstruct the NURBS volume using *Isogeometric_application.*

If a more accurate representation of the curved segment geometry is required, which is characterized by a trimmed-NURBS BRep due to non-parallel edges according to the universal ring arrangement of segment joints, NURBS surfaces are reconstructed using same parametric rules used to generate the individual segments. For this purpose, a utility is developed in C++ with an interface to call it from Python. This utility reads in the geometrical description of the segment and performs the necessary geometric operations to form the NURBS volumes (see Section 2.3) exactly as computed from the parametric model in Subsection 2.1. It also supports the extraction of the surface information required for applying boundary conditions (load and interaction with soils), and setting the joint conditions using elastic springs between the segments.

The computational framework used for the implementation of IGA is the open source FE simulation software KRATOS (2017). KRATOS provides the necessary components to manage the components of the finite element model, such as the finite elements, boundary conditions, etc. Furthermore, it supports multiphysics simulations via a plugin mechanism, in which the *Isogeometric_application* is developed as a special plugin supporting IGA modelling and analysis.

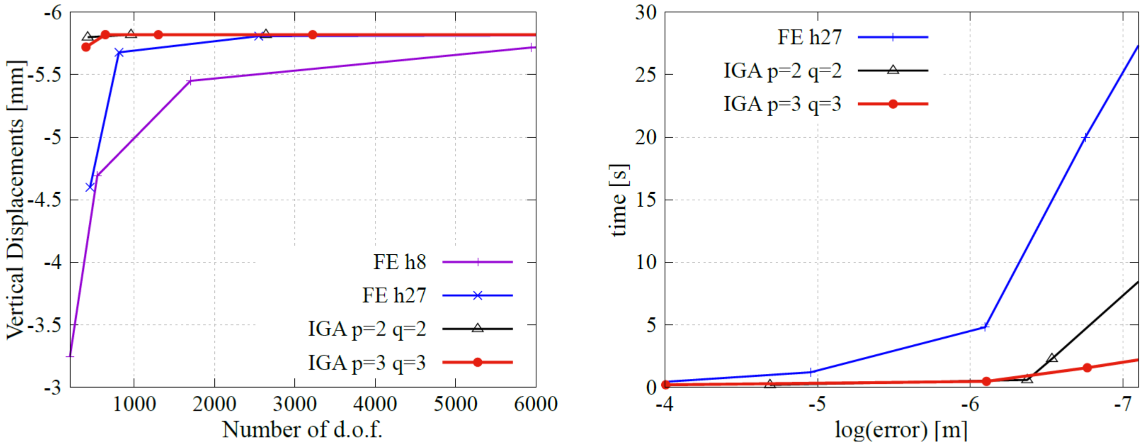
3.2 Computational efficiency

The efficiency of the proposed framework compared to standard Finite Element analysis is demonstrated by means of the analysis of a segmented tunnel ring shown in Figure 6. In this example, a tunnel lining of 4.7 m outer radius and a thickness of 40 cm is assumed to be composed of 5 segments, which are connected using a surface joint model. The distance from the centre of the tunnel to the surface is 20 m, which accounts for an overburden of 15.3 m. The interaction between the soil and the tunnel is considered by means of nonlinear springs, and is characterized by the Variational Hyperstatic Reaction Method (Bui, et al., 2019). The nonlinear springs model and the loading conditions are illustrated in Figure 6(a). The resulting deformation of the lining from the earth pressure is shown in Figure 6(b). Although the joint opening is not adequately visible in the figure, it is measured to be in the range of 1° -2° between each segment.



(a) (b)

Figure 6: (a) Boundary conditions of the numerical model; (b) Deformation under earth pressure [400-fold magnification]



(a) (b)

Figure 7: Comparison of performance of IGA and standard FE models: (a) Convergence of vertical displacement with mesh size, (b) Computational time required to reach a certain accuracy of the solution

The performance of the proposed methodology for the assessment of the tunnel lining design is verified against the performance of a standard FE model discretised using Lagrange basis function in terms of model size, i.e. the number of degrees of freedom (DOFs) required to reach a converged solution (setting the error tolerance for displacements to 10^{-7}). In Figure 7(a), it can be clearly observed that using IGA the solution is reached immediately, with only a very small number of DOFs (<500). In contrast, the FE solution shows the typical convergence behaviour depending on the polynomial degree of the shape functions. For linear interpolation functions, the solution does not even converge for the considered maximum model size of 6000 DOFs; for quadratic shape functions, approximately 3000 DOFs are needed. In Figure 7(b), FE and IGA are compared in terms of computational time needed to achieve the same accuracy of the numerical solution. The time is measured from start of the simulation until the end, without including the pre- and post-processing time. For IGA analysis, the time includes generating the NURBS mesh and computing the Bezier extraction operator. Figure 7(b) clearly shows that using IGA, high accuracy of the solution can be achieved without affecting the computational time. In other words, a sufficiently accurate numerical solution using a standard finite element model requires approximately 10 times more computational time than the IGA model.

3.3 Numerical example

In this example, we demonstrate how the proposed framework can be used for the efficient generation of the design and automated assessment of any arbitrary 3D tunnel structure.

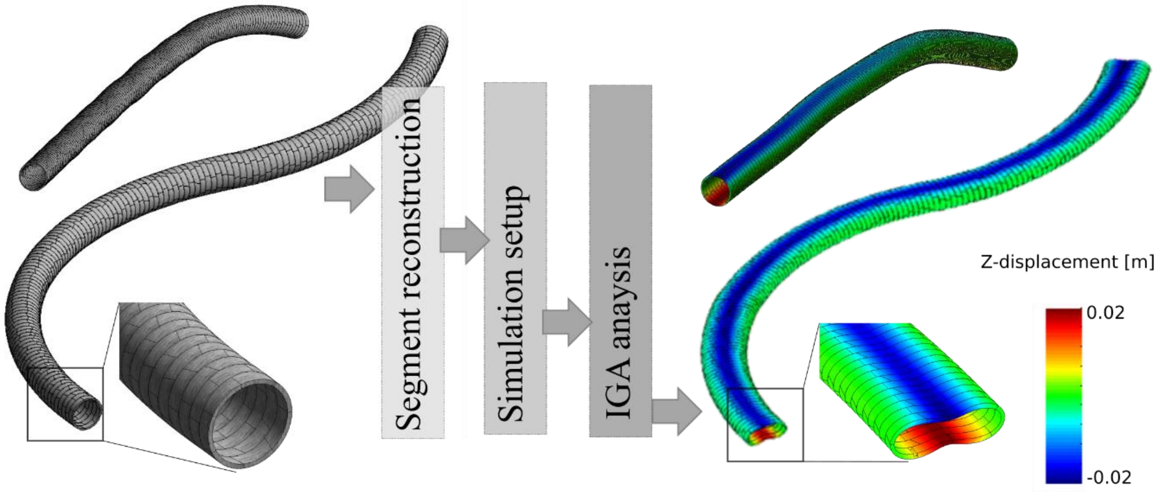


Figure 8: Automatized design-through-analysis workflow for the segmented tunnel linings

The only items defined by the user in the user-friendly interface are the designed tunnel alignment, the parameters defining the tunnel lining geometry, and the semantic parameters describing the lining and soil materials. The remaining workflow for generation of the optimal arrangements of tunnel rings, generation of the tunnel structure, and the reconstruction of the design geometry, simulation set-up and execution of IGA computational kernel, is fully automatized, with two “clicks”; one for start of the design and the other for the analysis. In the presented example, two tunnel alignments of approximately 300 m length are generated and analysed using the proposed concept. In both cases, the design-through-analysis workflow takes less than 10 min, considering the time needed for geometry generation, reconstruction and calculation of the model (which is approximately 3-4 minutes of the overall runtime).

4. Conclusions

In this paper, we demonstrated a systematic and versatile approach to efficiently generate a digital tunnel design model and analyse the tunnel lining in different practical scenarios. To this end, a BIM-based approach is developed, which connects user-friendly industry-standard BIM software with effective simulation tools, supporting high-performance computing and parallel simulation. Firstly, a fully parametric design model for the segmented tunnel lining is proposed. Secondly, a computational framework for the analysis of tunnel lining using high-order, high-continuity numerical representation by means of isogeometric analysis (IGA) is developed. Finally, an automatized design-through-analysis workflow solution for segmented tunnel lining is developed based on a fully parametric design model developed as a Revit plugin and an IGA B-Rep analysis software, connected through an interface implemented with the Revit plugin Dynamo. For the case of simplified lining geometry with straight segments, lining NURBS surfaces are directly utilised for the reconstruction of NURBS volumes, while for more complex geometry, where segment rings are described with trimmed NURBS surfaces, a reconstruction is required. The reconstruction procedure is not overly complicated and requires a few parameters, which are directly extracted from the design model. Overall, the prosed framework enables the investigation of tunnel alignment alternatives for very long sections in a user-friendly and computationally efficient way, reducing the manual modelling work substantially.

Acknowledgments

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