Gecko
Design for IGA-type discretization workflows

Gecko Technical Report 1

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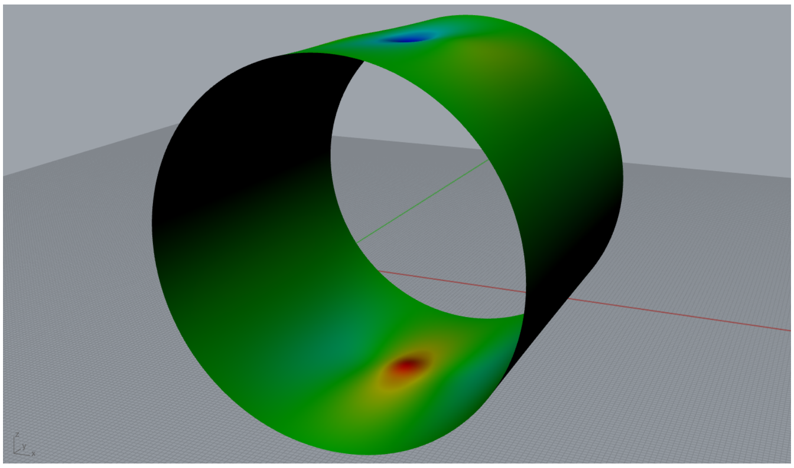

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Executive summary

This technical report presents the implementation of a Reissner-Mindlin shell element within the Isogeometric B-Rep Analysis framework as part of the GECKO project, which aims to bridge the gap between Computer-Aided Design and Computer-Aided Engineering workflows.

The research specifically addresses the implementation of structural elements for large deformation analysis, with an initial focus on shell elements. The first phase has delivered a functional Reissner-Mindlin shell element for linear elastic materials, validated through standard benchmark cases including the Scordelis-Lo roof and pinched cylinder tests all integrated within the existing Kratos Multiphysics framework.

While the core functionality is operational, challenges remain in complex geometries and the need for refined integration schemes. The next phase will focus on implementing nonlinear material models, incorporating large deformation capabilities, and developing trimming and multipatch coupling features.

This work contributes to the GECKO project's broader goal of developing an integrated CAD-CAE workflow that maintains geometric accuracy while providing efficient and reliable analysis capabilities for industrial problems. This initial implementation lays the foundation for future simulation of thin-walled structures under large deformations, with the ultimate goal of improving the design and analysis process.

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List of abbreviations

CAD	*Computer-Aided Design*
CAE	*Computer-Aided Engineering*
FEA	*Finite Element Analysis*
IBRA	*Isogeometric Boundary Representation Analysis*
IGA	*Isogeometric Analysis*
KL	*Kirchhoff-Love*
RM	*Reissner-Mindlin*

Introduction

The seamless integration of CAD and CAE remains one of the most pressing challenges in modern industrial workflows. Traditional FEA methods require extensive geometry preprocessing and mesh generation, creating an inefficient gap between design and analysis phases.

IBRA emerges as a promising framework to achieve this integration by utilizing the same geometric descriptions for both design and analysis. This approach not only eliminates the need for mesh generation while maintaining geometric exactness throughout the analysis process [Br14].

Shell elements are fundamental to this integration, as thin-walled structures dominate numerous industrial applications across automotive, aerospace, and manufacturing sectors. The Reissner-Mindlin (RM) shell element offers distinct advantages over traditional Kirchhoff-Love (KL) elements, particularly in its ability to handle varying shell thicknesses and incorporate transverse shear deformation. These capabilities are especially crucial for industrial applications where component thickness varies and accurate stress predictions are essential.

This deliverable outlines a systematic approach, starting with some research background, moving to the methodology, validation of the implementation highlighting the current work and future directions.

1. Methodology

The Reissner-Mindlin shell element was selected for implementation due to its versatile capabilities in structural analysis. It effectively handles moderately thick shells, incorporates both translational and rotational degrees of freedom, and accounts for transverse shear deformation while requiring only C^0 continuity between elements. These features make it particularly suitable for a wide range of industrial applications where varying shell thicknesses and complex loading conditions are common.

The implementation in Kratos follows the approach based on [Be10], using the existing KL shell element [Ki09] as a foundation. This choice was motivated by the idea of having a user-friendly formulation compared to existing shell elements in Kratos, that also serves as an effective learning platform for the doctoral candidate while contributing to Kratos' element library providing greater flexibility.

The process began with the implementation of the shell element for 3D linear isotropic materials- but thanks to the dimension reduction possibility the shell can be represented in 2D-, initially focusing on flat geometries. Key aspects included validation through cantilever patch tests under both in-plane and out-of-plane loads, and establishment of fundamental testing procedures where implementation of basic element formulation following [Be10].

The transition from flat to curved geometries introduced several technical challenges required modifications to be made to account for the variation in normal vectors along curved surfaces during deformation, as previously it could be represented with constants. Adjustments to integration weights were made to accommodate the curvature effects on the Jacobian based on [Du24]. Knot insertion and degree elevation techniques were used to refine the control point distribution and enhance element resolution.

2. Validation

The cantilever patch test serves as an initial validation case to assess the bending and membrane effects of shell elements under both in-plane and out-of-plane loading conditions. Both elements yielded nearly identical displacement results, as shown in Figures 1 and 2. This close agreement demonstrates that the RM shell element maintains consistency with the KL formulation for thin shell geometries, despite their theoretical differences.

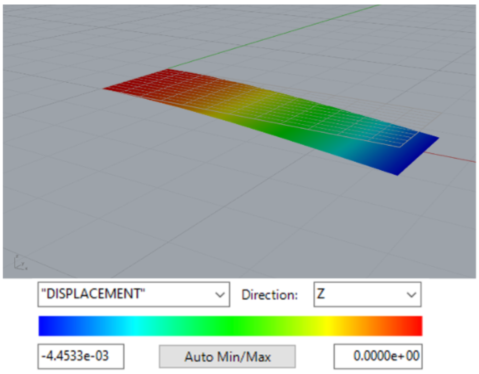

Figure 1. Cantilever with Kirchoff-Love elements

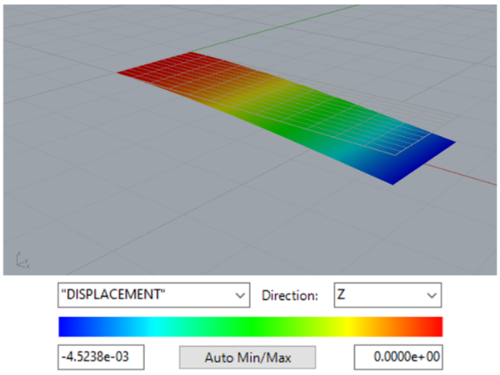

Figure 2. Cantilever with Reissner–Mindlin elements

These results validate the RM shell element's ability to replicate the performance of the KL element in thin-shell scenarios, providing confidence in its broader applicability to a wider range of thicknesses and deformation behaviours.

The Scordelis-Lo roof is a well-known benchmark for evaluating the element’s ability to handle curved geometries and coupled deformation behaviors. In this test, the reference displacement at the mid-span point u=0.3006 is compared against results provided by Kiendl et al. [Ki09]. Accurate coupling between bending and membrane behavior was observed, validating the effectiveness of the derivative-based normal vector computation.

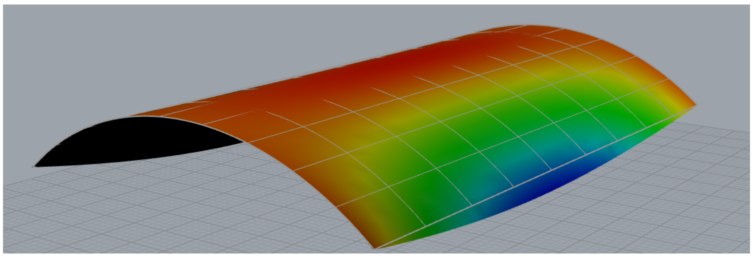

Figure 3. Scordelis Lo Roof with Reissner–Mindlin shell elements

To further analyze performance, convergence graphs were generated. These graphs indicate that while the RM shell element converges reliably, certain fluctuations were seen at certain polynomial degrees that require further investigation.

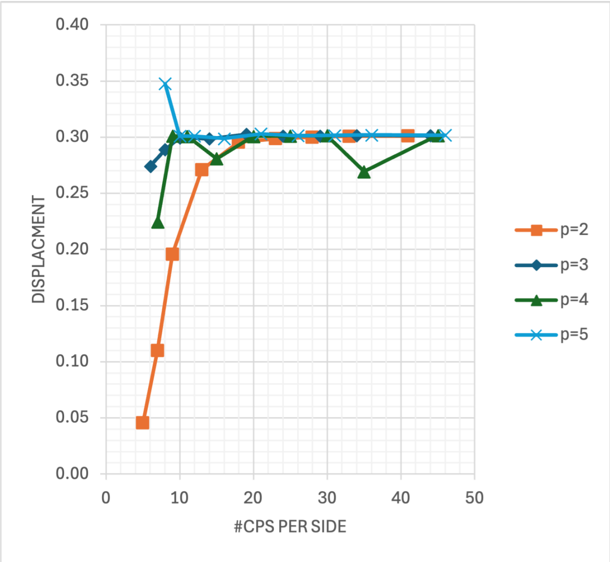

Figure 4. Convergence of the displacement for the scordelis lo roof

The pinched cylinder benchmark, a classic test for thin-walled shell structures, was used to evaluate performance under high membrane-bending interactions and symmetry loading conditions. For this case, the reference displacement at the apex point u=1.8264x10^{-5}, based on [Ki09], was used for comparison.

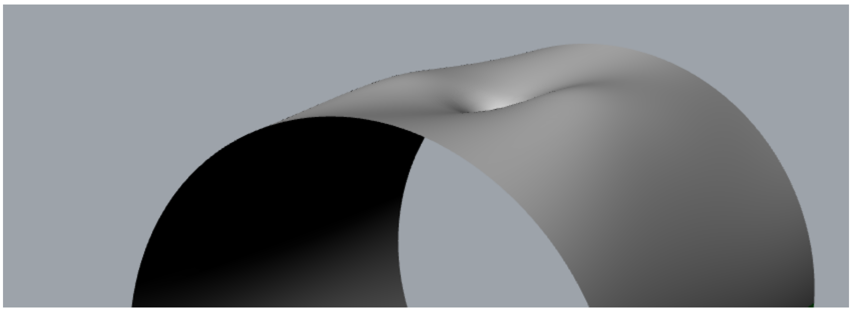

Figure 5. Pinched Cylinder with Reissner–Mindlin shell elements

It successfully captured the deformation pattern but required high levels of refinement to converge to the reference solution, indicating the presence of locking phenomena. Ongoing validation against reference solutions with areas for potential numerical efficiency improvements.

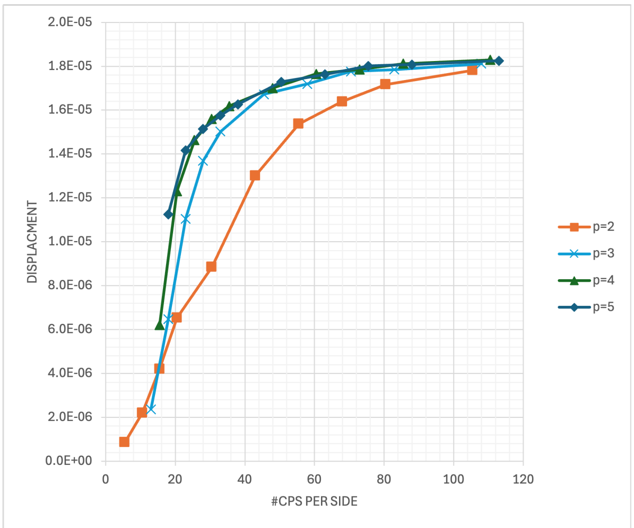

Figure 6. Convergence of the displacement for the pinched cylinder

A partially trimmed hemisphere subjected to uniform pressure was modeled, implementation demonstrated, as expected, the need for trimming and multipitch coupling to accurately represent the geometry which is still in progress.

3. Current and Future Work

The current implementation supports linear elastic material behaviour and can analyze both flat and curved geometries. However, several challenges have been identified during the process, including sensitivity to refinement in certain test cases, computational efficiency concerns, and the need for addressing locking phenomena in specific scenarios.

The immediate development path begins with the implementation of damage models, chosen as our entry point into nonlinear material behavior. While Kratos already includes robust material models, these were primarily developed for solid elements. We will start with adapting the existing 3D damage models, as they provide a suitable foundation for shell element implementation. Following this, we plan to extend the framework to include plasticity models, though this presents additional challenges as the current Kratos implementation is limited to 2D solids. Both implementations will require careful adaptation of the existing constitutive laws to ensure proper application within the shell element framework while maintaining computational efficiency and accuracy.

Efforts are centered on integrating large deformation assumptions, adidng a corotational formulation approach, and modifying strain calculations to account for geometric nonlinearity. Validation testing will involve complex material behaviors to ensure robustness.The development of advanced features such as trimming capabilities and multipatch coupling within the shell element framework is underway.

Long-term plans include applying insights from shell element development to beam formulations, integrating them within the existing IBRA framework, and creating a unified approach for structural elements. Other areas of enhancement include exploring locking treatments and implementing local refinement procedures for improved accuracy and contributing to expanding Kratos' capability in handling intricate geometries.

4. Conclusion

This research is paving the way in the development of robust structural elements for large deformation analysis within the IBRA framework, specifically focusing on the implementation of Reissner-Mindlin shell elements. The work contributes to the broader GECKO project goal of bridging the gap between CAD and CAE workflows in industrial applications.

This work marks the development of a functional RM shell element in Kratos, validated through standard benchmark cases. The implementation successfully transitions from flat to curved geometries, incorporating derivative-based normal calculations for curved surfaces. Validation efforts are ongoing for additional benchmark tests.

While the current implementation provides a good foundation, it has identified challenges such as mesh sensitivity and integration point handling, offering clear direction for future improvements. Planned advancements include: Development of trimming and multipatch coupling features to address complex geometries. Implementation of nonlinear material models, starting with damage and plasticity. Integration of large deformation capabilities, leveraging corotational formulations and refined strain calculations.

This research not only contributes to the GECKO project's overarching objectives but also reinforces the value of integrating computational mechanics with industrially relevant workflows, laying the groundwork for future innovations in isogeometric analysis.

5. References

[1] [Br14] Breitenberger et al., 2014. Analysis in Computer-Aided Design: Nonlinear Isogeometric B-Rep Analysis of Shell Structures
[2] [Be10] Benson, D.J., Bazilevs, Y., Hsu, M.C., Hughes, T.J.R., 2010. Isogeometric shell analysis: The Reissner–Mindlin shell.
[3] [Ki09] Kiendl, J., Bletzinger, K.-U., Linhard, J., Wüchner, R., 2009. Isogeometric shell analysis with Kirchhoff–Love elements.
[4] [Du24] Du, X., et al., 2024. Isogeometric Shape Optimization of Reissner–Mindlin Shell with Analytical Sensitivity.