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MODELING AND ANALYSIS OF REAL WORLD AND INDUSTRY APPLICATIONS WITH GEOMISO ISA: A NEW HYBRID CAD/CAE SOFTWARE FOR STATIC ISOGEOMETRIC ANALYSIS WITH PLATE ELEMENTS AND ADVANCED SPLINE TECHNIQUES

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Abstract. *In this paper, we propose Geomiso ISA (www.geomiso.com), a new hybrid software for applications on static isogeometric analysis with plate elements. It is based on the IGA, the powerful generalization of the traditional FEA, which, in combination with the plate theory, has attracted increasing attention in construction industry over the last decade, as it achieves efficient design-through-analysis procedures and shows superior performance. This recently developed program is not just a plug-in, but a both on-premises and cloud-based software solution, applicable to thin (Kirchhoff-Love) and thick (Mindlin-Reissner) plates. It is used to simulate spline models of slabs and analyze their strength and behavior, while it has many features in common with both FEA software and design programs. This software solution addresses the rising industrial need for seamless integration of CAD and CAE, while it appears to be more efficient to FEA software packages with major improvements, as it facilitates the geometry modeling within analysis, and achieves superior accuracy per degree-of-freedom with shortened computational cost. This is the first time ever such a cloud-based program has been developed.*

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1 INTRODUCTION

In this paper, we introduce Geomiso ISA (www.geomiso.com), a new software for applications on static isogeometric analysis with plate elements and advanced spline techniques. This recently developed program is not just a plug-in, but a both on-premises and cloud-based software solution, applicable to simulate spline models of slabs and analyze their strength and behavior, while it has many features in common with both FEA software and design programs. This solution addresses the rising industrial need for seamless integration of CAD and FEA and for high product quality, coupled with increasingly stringent safety, while it appears to be more efficient to FEA programs, as it facilitates the geometry modeling within analysis, eliminates geometric errors and achieves superior accuracy per degree-of-freedom with shortened computational cost. This new solution empowers civil engineers to efficiently test performance and optimize durability of their structures. As it is demonstrated with several applications, the developed platform is seen to handle these situations remarkably well.

This hybrid program, used for both design and analysis, offers an innovative way to merge geometric design with mesh generation into a single procedure by designing, with its modern user interface, slabs as tensor product grids in contrast to design programs. The utilization of the exact mesh for analysis eliminates geometric errors, while there is no need of repeating the geometry design for refinement purposes. In contrast, the standard FEA technique of remeshing with more and smaller elements, not only cannot fully utilize the available data of the exact mesh, but also makes engineers unable to benefit from advanced spline techniques, which are proved a mighty tool for IGA. Geomiso ISA directly utilizes the CAD file in its solver to perform a structural analysis by using splines as shape functions. Thus, it maintains the exact representation of the geometry at any stage of the design process and eliminates geometric errors. This hybrid software provides parameterized geometries in the design, while its modern graphical user interface offers an innovative way to preserve the exact geometry at all refinement levels. Modern T-splines can accurately represent any geometry with their local refinement properties and overcome limitations inherent to NURBS, like the tensor-product topological structure, by ensuring higher-order continuity across patches.

Real world and industry applications on thin (Kirchhoff-Love) and thick (Mindlin-Reissner) plates are demonstrated with a comparison between Geomiso ISA and FEA programs, and between plate and hexahedral elements. We compare the accuracy of the numerical results, such as displacement, strain, and stress fields, for typical slab types widely used in construction. We carry out parametric investigations on the effects of polynomial order, and continuity of the basis functions, as well as the number of control points and knot spans. This viable alternative to FEA programs represents major improvements, as higher accuracy, robustness, and stability level are accomplished with reduced computational time.

This paper is structured as follows. In Section 2 we exhibit an overview on IGA with NURBS and T-splines, while Kirchhoff-Love and Mindlin-Reissner plate theory is presented. Section 3 refers to the cloud-based platform of Geomiso ISA. Section 4 introduces the workspace of the Geomiso ISA software with sample applications. A comparison between Geomiso ISA, FEA programs and exact solution is made for typical examples in Section 5, while conclusions are drawn in Section 6.

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2 A BRIEF OVERVIEW ON ISOGEOMETRIC ANALYSIS

Isogeometric analysis is a new computational approach that has come to unify the fields of CAD and FEA. It was introduced by Hughes et al. [1] and since then it has attracted a lot of attention for solving boundary value problems as a result of using the same shape functions, means splines, functions commonly used in CAD, for both describing the domain geometry and building the numerical approximation of the solution. It directly employs spline geometry in the FEA application, which eliminates the geometric errors, while there is no need of repeating the geometry design for refinement purposes [2]. Popular NURBS and more sophisticated T-splines are proved suitable shape functions and a mighty tool for isogeometric analysis [3].

2.1 NURBS

NURBS were until lately the main shape functions used in isogeometric analysis [1]. They have been a mainstay of geometric design for many years due to their flexibility and precision, as they can exactly construct any conic section. IGA has brought them into the setting of analysis, leading to more accurate results in comparison with standard finite elements based on Lagrange polynomials [1]. Parameter space is important as all calculations take place in it, while index space plays an auxiliary role. The resulted real geometry in depicted in physical space.

NURBS geometries inherit properties, such as partition of unity, non-negativity, boundary-curve interpolation, continuity, and compact support for their basis functions. Due to their higher inter-element continuity, the overlapping is greater in comparison with polynomial shape functions in FEA. Regularity –1 indicates discontinuity, while regularity 0 is the minimum continuity for interior knots [2]. On the contrary to shape functions in FEA, basis functions in IGA are not interpolatory. NURBS are built from B-splines. Unlike in FEA, the B-spline parameter space is local to patches rather than elements. An element is defined in the physical mesh by the patch and the respective knot spans.

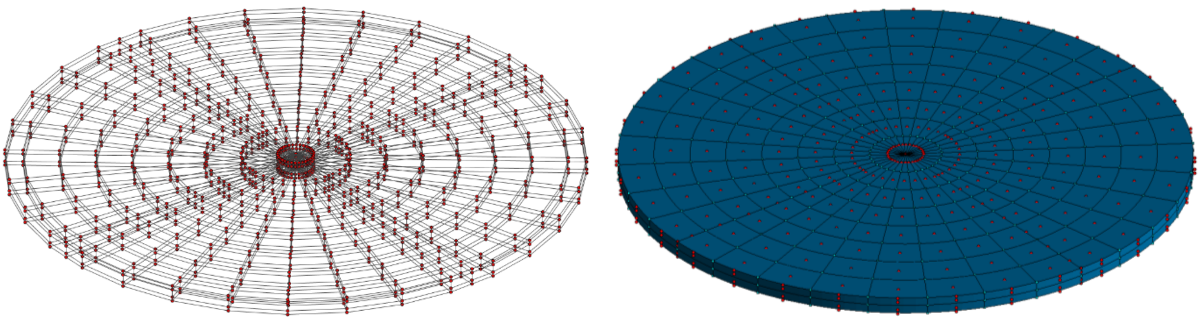

Figure 1: The control net and the quadratic NURBS mesh (p=q=r=2) for a circular plate, designed in the Geomiso ISA software. Control points are shown in red, knots in cyan, knot lines in black, and geometry in blue. This NURBS mesh consists of 1.480 control points (37 control points in the parametric axis ξ, 10 control points in the parametric axis η, 4 control points in the parametric axis ζ) and 512 elements (32 knots spans in parametric axis ξ, 8 knot spans in parametric axis η, 2 knot spans in parametric axis ζ).

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2.2 T-splines

T-splines extend NURBS to permit local refinement and coarsening, while they are very robust in their ability to efficiently sew together adjacent patches. They were introduced in 2008 as a more efficient alternative that inherits all the basic properties of NURBS and exhibits more design capabilities, like watertightness, but also sophisticated implementation, that allows better handling more complex geometries, especially when the model is irregular with hole features, and permits local refinement ensuring higher-order continuity and smoothness across patches [3]. It is not unlikely that T-splines can represent complicated shapes with only one single T-mesh. T-splines allow us to build spaces that are complete up to a desired degree, as smooth as an equivalent NURBS basis, and capable of being locally refined, while keeping the original geometry and parameterization unchanged [3]. This generalization of NURBS defined by a grid of control points, where a row can terminate without traversing the entire surface. Index space plays an important role, where junctions, anchors, local knot vectors, and elements are defined, while parameter space is auxiliary. Cartesian space represents the real geometry. Index space of a T-mesh is a rectangular tiling of a region in $\mathbb{R}^2$ such that each edge of every rectangle has positive integer value and vertices connecting three edges, referred to as T-junctions. Each anchor will be used to infer local knot vectors from a global structure, T-mesh, that encodes a topology and parameterization for the entire T-spline object. Each blending function has its own local knot vector. A line of decreased continuity does not necessarily propagate throughout the domain and thus T-splines may have different smoothness within a T-mesh [3].

The local T-spline construction warrants closer consideration, particularly as it bears on quadrature. The available T-junctions are limited in order the T-mesh to be analysis suitable and only T and cross junctions are accepted. The continuity in physical space follows directly from that of its blending functions in parameter space. The continuity of the blending functions is determined from their local knot vectors, while they influence the quadrature, therefore continuity reduction lines/faces in T-spline surfaces/volumes are necessary. These requirements of using T-splines in IGA are not met in the design process, for which there is no restriction for the junction type, means L, I and point junctions are allowed, as the linear independence of blending functions is not a requirement [3].

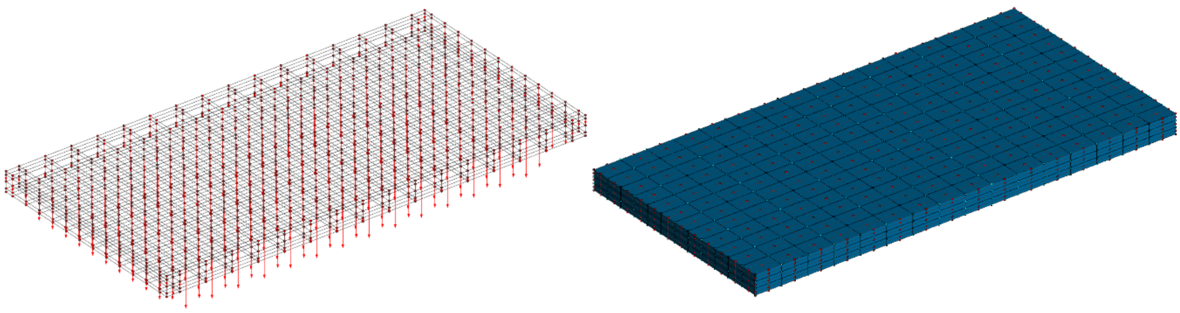

Figure 2: A T-mesh of a rectangular plate designed in Geomiso ISA, with control points in red and knots in blue. Cubic T-splines can accurately design any geometry and make the problematic and often impossible merging of patches feasible.

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2.3 Plate theory

A plate can be described as a plane structure with thickness considerably smaller than the other two dimensions. A plate structure carries loads on its plane, which lead to its bending. The theories on the deformation of plates are approximated by reducing a 3D problem into a 2D one.

Plate elements are considered as bidimensional structural elements. In IGA, the plate's geometry can be represented using splines, such as NURBS and T-splines. In a plate that has three degrees of freedom of generalized displacements per node, an arbitrary point on the plate can be interpolated by using the shape functions of the NURBS model. It is worth noting that in IGA of a plate, the nodal displacements and rotations are treated independently by using NURBS as shape functions. Thus, they are not coupled in the governing equations such as classical plate theory and first-order shear deformation theory. Depending on the polynomial order of the basis per axis and the knot vectors $\{\Xi\}$ and $\{H\}$ being used, we need to have the associated number of control points on a control mesh. The increasing number of control points being used to construct the NURBS model will increase the degrees of freedom. Compared to the plate element in FEA, where there are only four nodes having three degrees of freedom at each node, the element in IGA can have an excessive number of degrees of freedom at the control points on the control mesh.

Numerical modeling and analysis of plates of complicated shapes has continuously been a popular research topic because of the widespread applications of plate structures in various fields. The analysis of plates can be categorized into thin plate analysis based on the Kirchhoff-Love plate theory and thick plate analysis based on the Reissner-Mindlin plate theory. The main difference between the two prevailing theories lies in the fact that thin plate analysis assumes that the vector normal to the plate mid-surface remains normal to the mid-surface during deformation and thus does not take into account transverse shear deformations, whereas thick plate analysis does. Due to the fact that Reissner-Mindlin plate elements can be joined with C^0-continuity, the use of very simple basis functions is allowed. On the contrary, in the Kirchhoff-Love plate formulation, because of the presence of second-order derivatives, C^1-continuity is demanded between knot spans which requires higher order basis functions. However, most of the plate structures in reality are thin and very thin, and the use of C^0 basis functions would usually result in various shear locking problems. The high continuity naturally inherent in NURBS and T-splines, makes IGA very appealing for plate applications.

Although the numerical analysis of thin plates is already a very mature field, to exactly describe the plate geometry can be rather difficult and sometimes inaccurate, particularly when the structures have curved boundaries or complicated cutouts are involved. The main reason for this lack of accuracy lies in the fact that the model created from standard FEA, which is represented by Lagrange shape functions, is only an approximation of the original CAD model, which is described by NURBS. By employing the same shape functions used in geometric design to approximate field variables in an isoparametric sense, the spline models possess geometric exactness. Other appealing features of IGA include high order continuity of basis functions, which further leads to more stable numerical conditioning, faster convergence of solutions, and so on.

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3 CLOUD-BASED SIMULATION PLATFORM

In this paper we propose the world's first cloud-based simulation platform for isogeometric analysis www.geomiso.cloud with plate elements that enables civil engineers to execute simulation experiments without the need for dedicated hardware. This platform has shown its potential for being a viable option, which enables engineers to test, validate, and optimize their structures' durability and performance, through IGA, via a standard web browser, more efficiently and more cost-effectively.

By harnessing the power of the cloud for simulation, Geomiso ISA is accessible from a standard cloud-browser, thus from any computer, eliminating the hurdles that accompany traditional simulation tools, such as high installation costs, and deployment of high-performance computing hardware. Engineers don't need to install any software on their computer, they just create an account on the website www.geomiso.cloud and use Geomiso ISA online. It allows users to conveniently access computing resources as pay-per-use services. The cloud version, easily accessible to every engineer, serves as an entry point for those who wish to get acquainted with IGA. Workstation computers have only limited capabilities of delivering results for large-scale simulations. This leads to the problem that many engineers must either reduce the scope of their experiments or fail to execute as many experiments as they would like in a given time frame.

The cloud version of the Geomiso ISA software enables civil engineers to automatically construct parameterized geometries and analysis-suitable spline models for plate structures online. The quality of parameterization has a great impact on the results and the efficiency. Furthermore, the convergence rate of the IGA framework is affected by the quality of the volumetric parameterization. In IGA, there are three refinement mechanisms to improve the results, means h-, p-, and k-refinement. Their common feature is that the number of control points is increased, while the geometry remains intact. Geomiso ISA combines IGA, plate theory and cloud computing, which is one of the fastest growing fields in IT industry. Cloud-based IGA represents the future of product engineering, soon to become an industry standard as development teams around the world seek to manage complexity, and further drive time and costs out of design cycle and production processes.

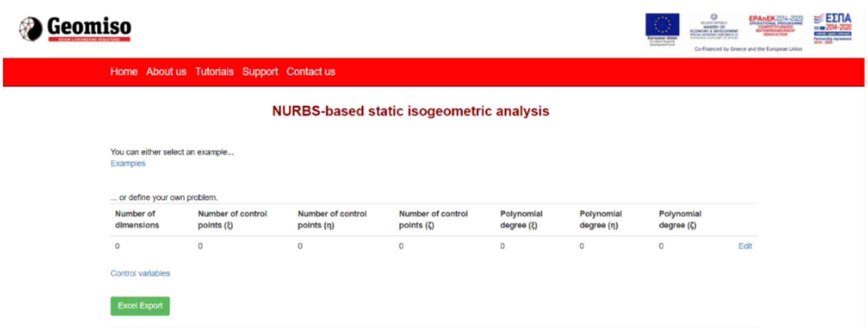

Figure 3: The world's first cloud-based simulation platform for IGA, www.geomiso.cloud. This online software solution can design and analyze structures, and products, with demanding loading, geometries, or material properties in a cloud environment. As soon as the simulation is complete, users can access the results on the platform or download them locally.

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4 THE DUAL NATURE OF GEOMISO ISA

Geomiso ISA is not just a plug-in, but a recently developed both on-premises and cloud-based software with a dual CAD/CAE nature. All the geometrical, connectivity, material, quadrature, refinement, constraint, and load data, must be given as inputs to its hybrid user interface, to calculate stiffness matrix, pseudo-displacements, and displacement, strain, and stress fields. The geometrical data include control variables (Cartesian coordinates, weights), polynomial orders, number of univariate basis functions and knot value vectors for each parametric direction (ξ, η, ζ).

Geomiso ISA helps all users leverage its simulation capabilities, while provides increasing speed and productivity for the entire product development process, as it merges geometric design with mesh generation into a single procedure, eliminates geometric errors, increases the accuracy of the numerical results, and significantly reduces the required computational cost, when compared with commercial FEA software packages.

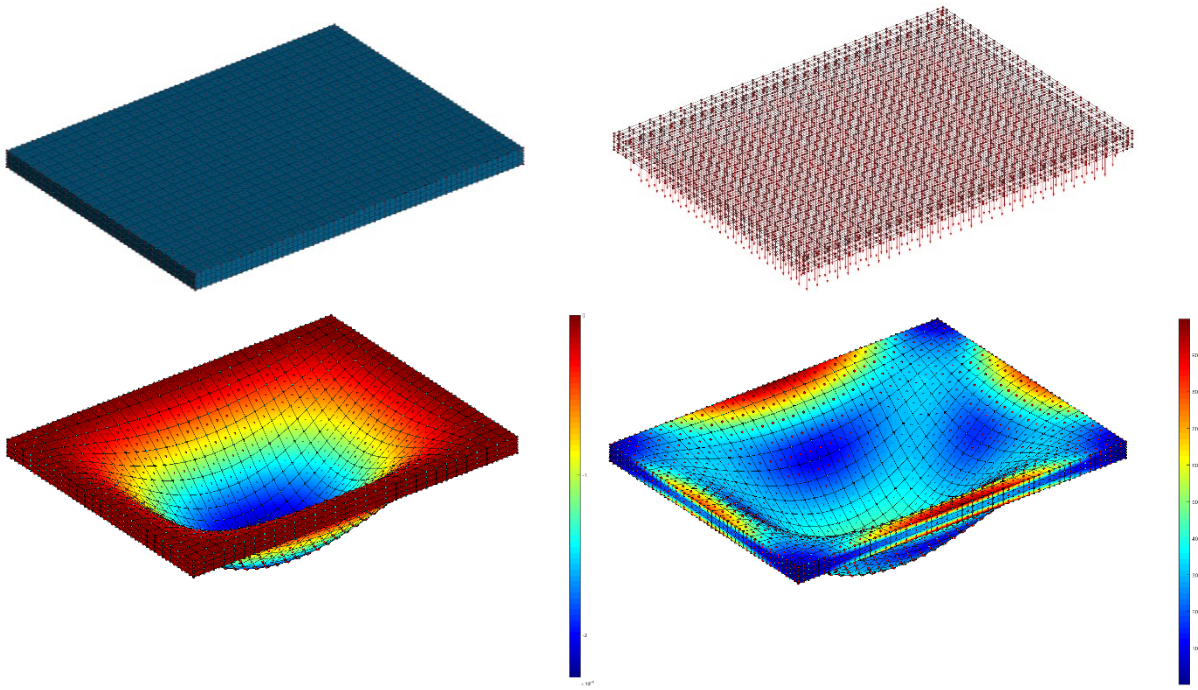

Figure 4: A rectangular plate designed and analyzed with NURBS-based static isogeometric analysis with plate elements in the cloud version of the Geomiso ISA software (www.geomiso.cloud). This NURBS mesh consists of 4.420 control points (34 control points in the parametric axis ξ, 26 control points in the parametric axis η, 5 control points in the parametric axis ζ) and 2.304 elements (32 knots spans in the parametric axis ξ, 24 knot spans in the parametric axis η, 3 knot spans in the parametric axis ζ). The control net with the loading and the quadratic NURBS mesh (p=q=r=2) for a circular plate are depicted, as well as the respective contour plots for displacement Z and von Mises stress in the deformed configuration. Control points are shown in red, knots in cyan, knot lines in black, quadrature points in gray, geometry in blue, and loading as red arrows, while scale factor is used for the deformed configuration. NURBS possess full tensor product nature. A surface element is the tensor product of two knot spans, while a solid element is the tensor product of three knot spans.

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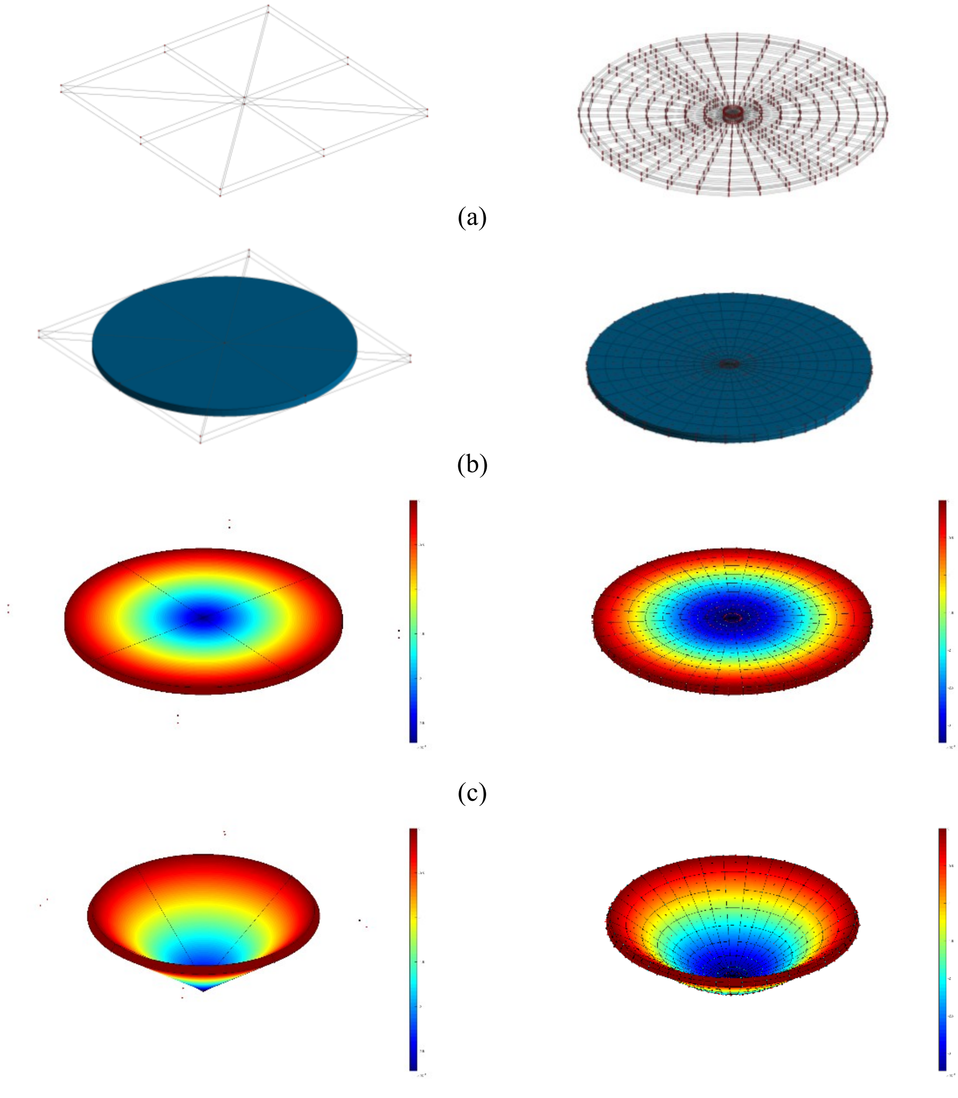
5 APPLICATIONS

We present a comparison between Geomiso ISA, FEA programs and exact solution for typical examples. The numerical results indicate that Geomiso ISA is a more efficient alternative to FEA programs.



(a)

(b)

(c)

(d)

Figure 5: Circular plate under loading. The coarse NURBS mesh consists of 36 control points (9 control points in axis ξ, 2 control points in axis η, 2 control points in axis ζ) and 4 elements (4 knots spans in axis ξ, 1 knot span in axis η, 1 knot span in axis ζ). The fine NURBS mesh consists of 1.480 control points (37 control points in axis ξ, 10 control points in axis η, 4 control points in axis ζ) and 512 elements (32 knots spans in axis ξ, 8 knot spans in axis η, 2 knot spans in axis ζ). (a) Control net, (b) NURBS model in physical space, (c) contour plot for displacement Z field in (c) undeformed and (d) deformed configuration, for both coarse and fine mesh.

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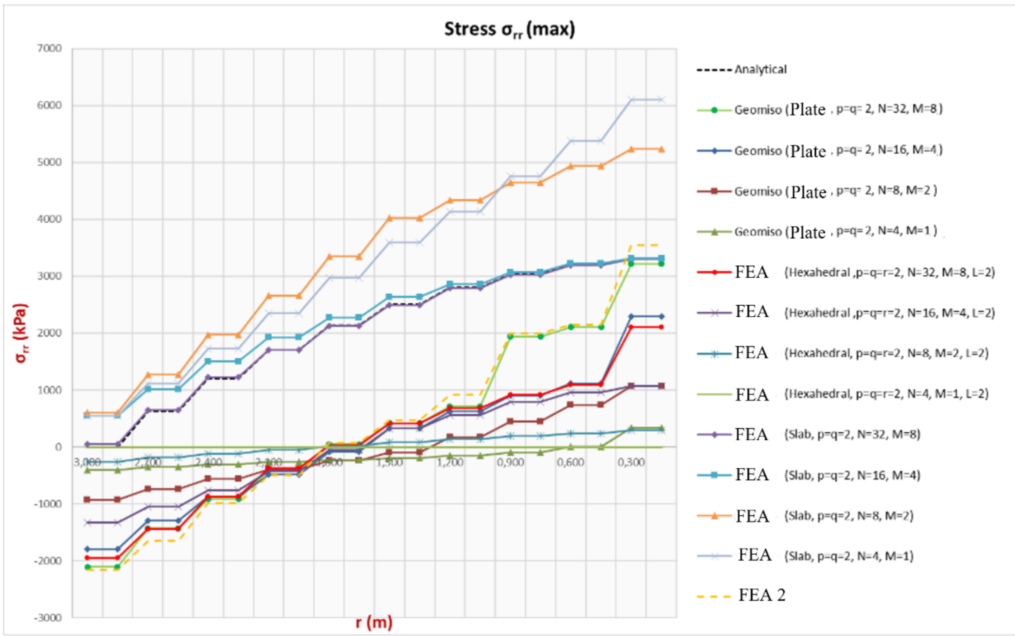
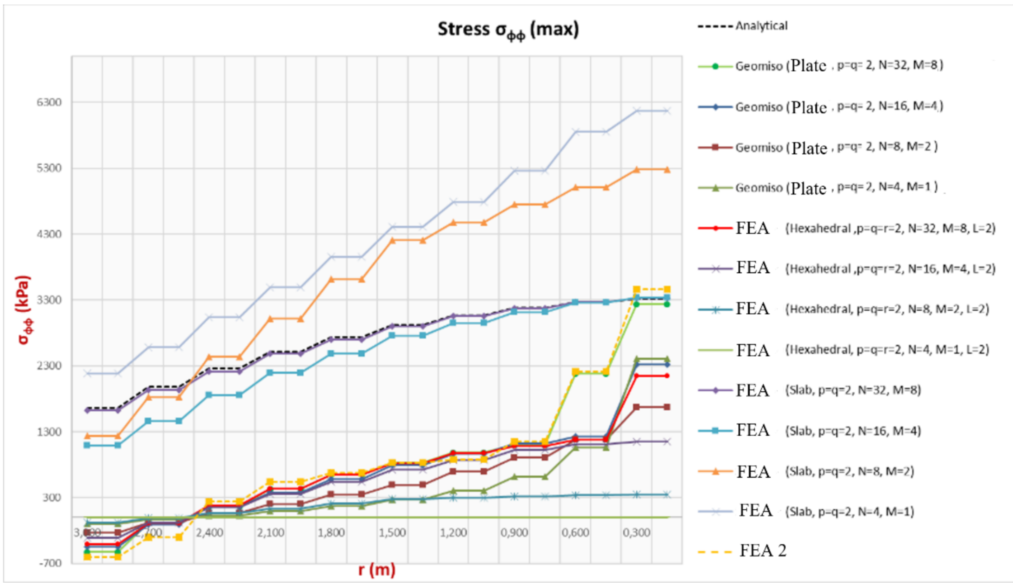
We compare the stress field σ_{rr} and $\sigma_{\varphi\varphi}$ from Geomiso ISA with FEA results and the analytical solution. Both the on-promises and the cloud-version of the Geomiso ISA software was used to design these plates, and then to analyse them using IGA with plate elements.



(a)



(b)

Figure 6: Geomiso ISA achieves accurate results with significantly fewer elements in comparison with FEA software. Numerous meshes are used in this analysis with Geomiso ISA and are compared with two commercial FEA software packages and the analytical solution.

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6 CONCLUSIONS

- The new Geomiso ISA software, which is the world's first cloud-based program for isogeometric analysis with plate elements and advanced spline techniques, is considered to be a comprehensive answer to today's simulation challenges and a viable alternative to traditional finite element software packages, as it removes the barriers between design and analysis and represents major improvements, such as superior quality numerical results, robustness, stability level, cost-efficiency and instant access from a web browser.
- This hybrid software solution utilizes the CAD file in its solver to perform structural analysis without any intermediate steps of geometry clean-up or further mesh generation by using the same shape functions, namely splines, for both describing the domain geometry and building the numerical approximation of the solution. This is the first time ever such a hybrid cloud-based software has been developed.
- Applications to typical plates have proved successful. Superior accuracy of IGA over FEA has been shown in all applications, and indications of significantly increased robustness and stability level in analysis have been noted, with drastically shortened computational cost.

ACKNOWLEDGEMENTS

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