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MODELING AND ANALYSIS OF REAL WORLD AND INDUSTRY APPLICATIONS WITH GEOMISO SEA: A NEW HYBRID CAD/CAE SOFTWARE FOR INELASTIC STATIC ISOGEOMETRIC SHELL ANALYSIS AND 3D DESIGN WITH ADVANCED SPLINE TECHNIQUES

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Key words: IGA, Shell Theory, Kirchhoff-Love, Mindlin-Reissner, Spline, Software

Abstract. *In this paper, the new Geomiso SEA software (www.geomiso.com) is proposed for inelastic static isogeometric analysis with shell elements and splines. Geomiso SEA offers an innovative way to merge geometric design with mesh generation, by creating, with its modern user interface, 3D models as tensor product grids. 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 finite element technique, not only cannot fully utilize the available data of the exact mesh, but also makes engineers unable to benefit from advanced spline techniques. Real world and industry applications on both thick (Mindlin-Reissner) and thin (Kirchhoff–Love) shells are demonstrated with a comparison between Geomiso SEA and FEA programs with shell and hexahedral elements.*

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1 INTRODUCTION

In this paper, the new Geomiso SEA software (www.geomiso.com) is proposed for applications on inelastic static isogeometric analysis with shell elements and advanced spline techniques. This hybrid program is applicable to real world and industry applications, while it satisfies the rising need for technical software of dual CAD/CAA nature. It is based on the isogeometric method, the powerful generalization of the traditional finite element analysis (FEA), which, in combination with material nonlinearity and shell theory, has attracted a lot of attention for solving boundary value problems, as a result of using the same shape functions, means splines, for both describing the domain geometry and building the numerical approximation of the solution. T-spline-based isogeometric shell analysis has attracted increasing attention in automotive and aerospace industries, as it efficiently handles geometries with patches, discontinuities, and irregularities, while T-splines can design any geometry no matter how complex it is. Geomiso SEA is not just a plug-in, but a both on-premises, standalone and cloud-based software solution, which is used to simulate spline models of sophisticated structures, or machine components, for analyzing their strength and behavior.

This hybrid program, used for both design and analysis, has many features in common with both FEA software and design programs. It offers an innovative way to merge geometric design with mesh generation, by creating, with its modern graphical user interface, 3D models as tensor product grids. 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 finite element 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.

Real world and industry applications on both thick (Mindlin-Reissner) and thin (Kirchhoff–Love) shells are demonstrated with a comparison between Geomiso SEA and FEA programs, and a comparison between shell and hexahedral elements. We compare the matrix assembly and solver time, as well as the accuracy of the numerical results. Parametric tests were also performed on the effects of the polynomial degree of the basis functions, and the number of patches, knot spans, control points, and integration points. This new software represents improvements over FEA software, as higher accuracy, robustness, and stability level is accomplished with considerably shortened computational cost. This new solution empowers engineers to handle sophisticated shell structures, efficiently test their performance and optimize their durability.

This paper is structured as follows. In Section 2 we exhibit an overview on isogeometric analysis with NURBS and T-splines, while material nonlinearity in IGA is presented. Section 3 refers to shell elements in IGA, especially Kirchhoff-Love and Mindlin-Reissner shells, and the cloud-based shell isogeometric analysis. Section 4 introduces the workspace and the graphical user interface of the recently developed Geomiso SEA software. A comparison between Geomiso SEA and FEA programs is made for typical examples in Section 5, while conclusions are drawn in Section 6.

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2 A BRIEF OVERVIEW ON INELASTIC STATIC 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, 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.

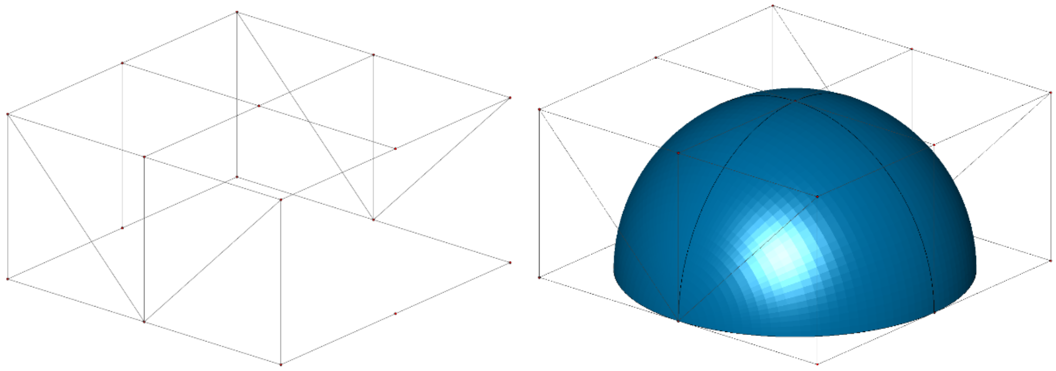

Figure 1: The control net and the quadratic NURBS mesh (p=q=2) for the dome of Hagia Sophia, designed in the Geomiso SEA software. Control points are shown in red, knots in cyan, knot lines in black, and geometry in blue. This NURBS mesh consists of 25 control points (5 control points in the parametric axis ξ, 5 control points in the parametric axis η) and 4 elements (2 knots spans in parametric axis ξ, 2 knot spans in parametric axis η).

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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 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].

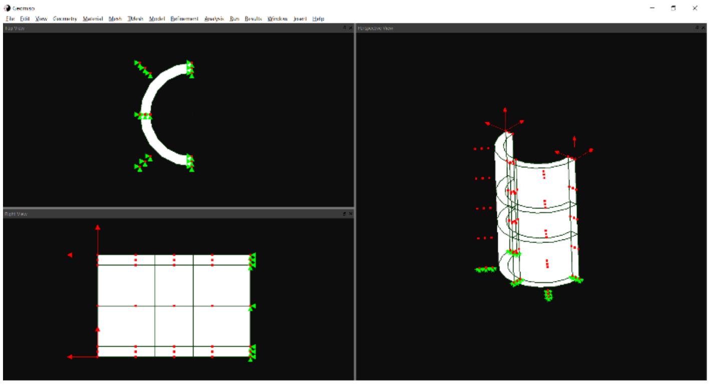
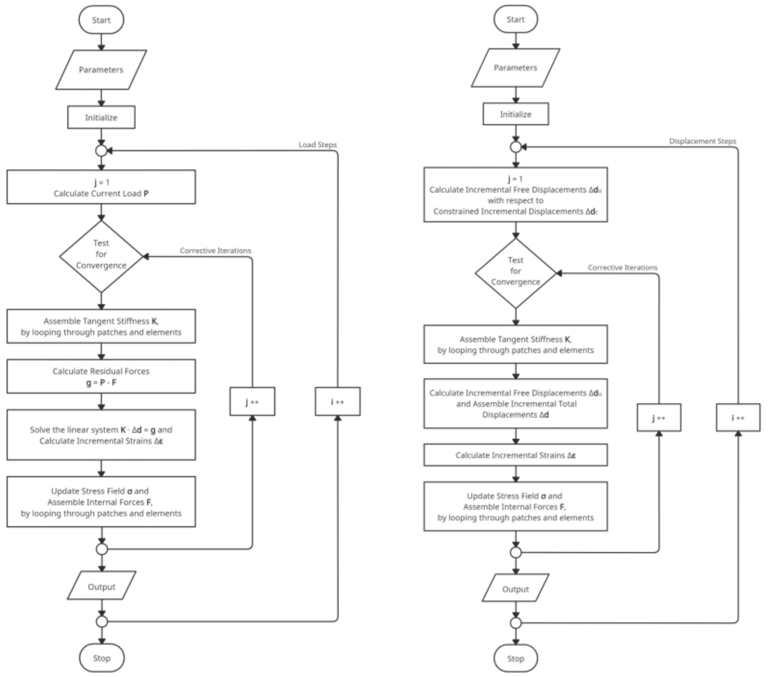


Figure 2: A T-mesh of a shell structure designed in Geomiso SEA, with control points in red, knots in blue, constraints in green and loads as red arrows.

2.3 Material nonlinearity in IGA

This paper focuses on the advantages of IGA in describing nonlinear behavior of materials, which is commonplace in many applications, such as metal forming, and vehicle crash test. Material nonlinearity represents the case when the constitutive law, means the stress-strain relation, is not linear. Once yield occurs, the material will deform plastically. The constitutive law provides the mathematical relationships that describe the material and govern the nonlinear analysis. A fundamental observation comparing elastic and inelastic analysis is that in elastic solutions the total stress can be evaluated from the total strain alone, whereas in inelastic response calculations the total stress also depends on the stress and strain history [4].

To describe a particular case of nonlinear material behavior in solid mechanics, a suitable model must be adopted. The nonlinear nature of a structural analysis problem emerges from the relationship between the applied external loads and the displacements, which are no longer analogous. This nonlinearity arises from either the geometry of the structure, where large deformations impose the equilibrium equations to be solved in the deformed shape, or the material itself, in case of inelastic materials. In each case, the stiffness matrix can be expressed as a function of the displacements; $\boldsymbol{K}=f(\boldsymbol{u})$. Nonlinear problems in mechanics are solved with incremental iterative algorithms based on the Newton-Raphson Method, such as Force Control Algorithm, in which the external load $\boldsymbol{P}$ is applied directly with load increments $\Delta\boldsymbol{P}$, or Displacement Control Algorithm, in which an effective load is applied in such a way, so that a specific degree of freedom acquires constant displacement increment.



(a) (b)

Figure 3: (a) Force Control Algorithm flow chart, combined with the Full Newton-Raphson method. (b) Displacement Control Algorithm flow chart, combined with the Full Newton-Raphson method.

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3 SHELL STRUCTURES

Shells are commonly identified as surface structures with one dimension being significantly smaller than the other two. Geometry of a sufficiently smooth shell can be uniquely identified by defining its midsurface and a thickness function. Very thin shells, like thin metal sheets, play an important role in many industrial applications, such as automotive and aerospace industry.

3.1 Kirchhoff-Love and Reissner-Mindlin shell theory

The first mathematically correct theory on the structural behavior of shells accounting for Bernoulli's normal hypothesis was derived by G. Kirchhoff in 1850, which states that normals to the mid-surface in the undeformed configuration remain normal and unstretched in the deformed configuration. With increasing thickness of the structure, transverse shear effects become more pronounced, thus significantly contributing to the total strain energy of the system. For Reissner-Mindlin models, the Kirchhoff-Love kinematics are relaxed by introducing additional rotation parameters for the director, which do not depend on the gradient of the mid-surface displacement field and thus allow for extra transverse shear effects. The main intention is to apply the Kirchhoff-Love model in regions which are dominated by membrane and bending action, whereas Reissner-Mindlin kinematics is applied in areas where transverse shear has a significant influence, i.e. in non-smooth domains of low continuity, such as folds, intersections or boundaries. Most shell structures in practical engineering applications are in the range of thin and very thin shells and most analytical solutions for shells are based on the Kirchhoff-Love theory. In contrast, the Reissner-Mindlin theory is more spread in finite element codes. This is mainly due to the fact that for Reissner-Mindlin elements only C^0 continuity is required between elements, with very simple shape functions, and more popular in finite element shell analysis. For Kirchhoff-Love elements C^1 continuity is required between elements and it is quite difficult to achieve for free-form geometries when using standard polynomials as basis functions. NURBS allow great geometric flexibility with high order continuities at the same time, and they are therefore ideally suited as basis functions for Kirchhoff-Love shell elements. As CAD design models of thin-walled structures are often constructed by surfaces rather than volumes, shell analysis appears to be the corresponding analysis method for these applications.

Over the last years, IGA has attracted enormous interest in nearly all fields of computational mechanics and the development of shell formulations. The high continuity naturally inherent in the isogeometric basis functions allows for a straightforward implementation of C^1 thin shell models. The formulation is rotation-free and purely surface-based, which means that the shell kinematics are completely described by the midsurface's curvature properties. This allows for a direct integration of IGA into CAD systems, which are usually based on surface geometry models. The lack of rotational degrees of freedom also permits a direct coupling of structures and fluids in fluid–structure interaction applications. Furthermore, this shell model has been applied to wind turbine blade modeling, isogeometric cloth modeling, explicit finite strain analysis of membranes, and for the modeling of fracture within an extended IGA approach.

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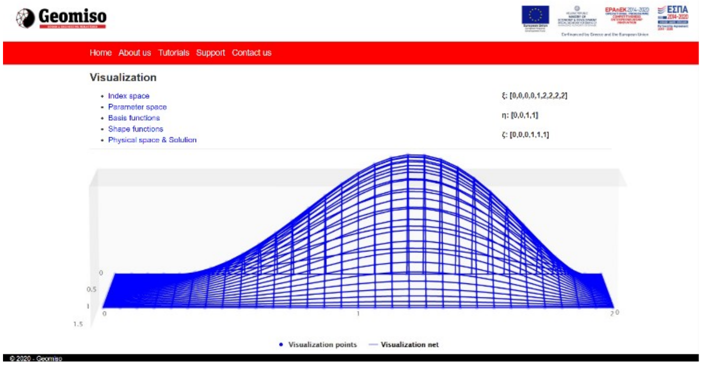
3.2 Cloud based shell analysis

Geomiso SEA is a cloud-based simulation platform for nonlinear static isogeometric shell analysis for thin and thick shells that enables users to execute large-scale simulation experiments without the need for dedicated hardware. The project, which created with this software, has shown its potential for being a viable option to be used for cloud-based modeling and simulations for shell applications. More specifically, in order to solve a problem with shell elements that involve material nonlinearity, as it is often involve sharp creases in both the initial geometry and solution, demands significant computer power, thus the cloud platform constitutes a robust efficient solution for engineers. The Geomiso SEA software enables them to test, validate, and optimize their designs and their products' durability and performance more efficiently, through IGA, via a standard web browser, more cost-effectively. Its simulation services include both CAD and CAE environment for structural analysis problems and allow engineers to move their simulations completely to a cloud-based solution.

By harnessing the power of the cloud for simulation, Geomiso SEA is accessible from a standard cloud-browser, thus from any computer. More specifically, engineers don't need to install any software on their computer, they just create an account on the website www.geomiso.cloud and utilize Geomiso SEA online. This online software solution can design and analyze structures, machines, components or objects with complex loading, geometries, or material properties. The cloud version, easily accessible to every engineer, serves as an entry point for those who wish to get acquainted with IGA. As soon as the simulation is complete, users can access the results on the platform or download them locally. Geomiso SEA also allows users to save a simulation configuration as an xml file and, also to export results into PDF format. It allows users to conveniently access computing resources as pay-per-use services. This software helps researchers concentrate on particular design issues without considering the low-level details of cloud infrastructures. It also enables a modeler to repeatedly perform simulations and to conduct a series of simulation experiments in a quick and easy manner.



ξ: [0,0,0,0,1,2,2,2,2]

η: [0,0,1,1]

ζ: [0,0,0,1,1,1]

Figure 4: 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 SEA

Geomiso SEA 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, polynomial orders, number of univariate basis functions and knot value vectors for each parametric direction (ξ, η, ζ).

Geomiso SEA 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.

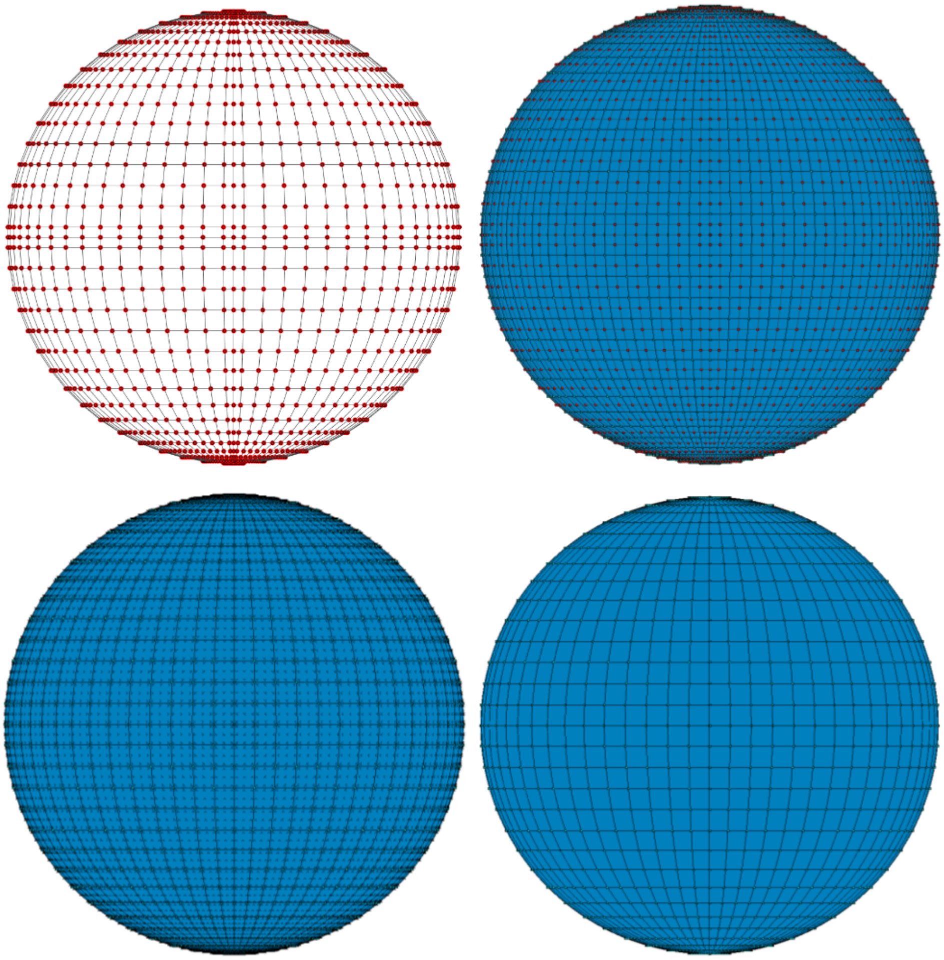

Figure 5: The dome of Hagia Sophia designed and analyzed in the new Geomiso SEA software. Control points are shown in red, knots in cyan, knot lines in black, quadrature points in gray, and geometry in blue.

5 APPLICATIONS

We present indicative shell applications of the Geomiso SEA software in structural mechanics. The numerical results, which are compared with FEA and the exact solution, exhibit that Geomiso SEA is a more efficient alternative to finite element programs.

5.1 Dome of Hagia Sophia

Figure 6 depicts the NURBS model of the dome of Hagia Sofia under gravity load at the middle of its span, designed in Geomiso SEA. The ends are supported by fixed diaphragms, while the side edges are free.

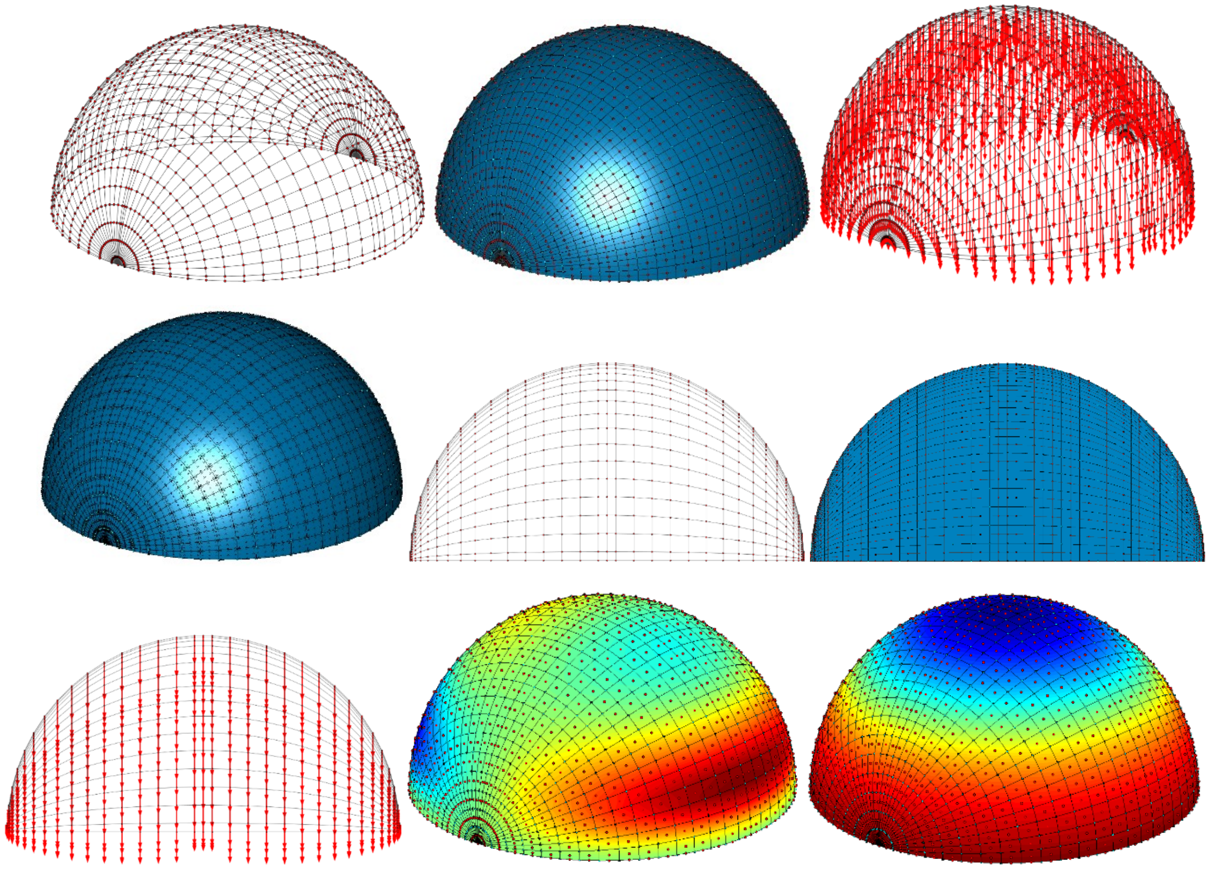

Figure 6: Dome of the Hagia Sofia, designed in the Geomiso SEA software.
The NURBS model of the dome of Hagia Sophia was analyzed with NURBS-based shell isogeometric analysis in Geomiso SEA. Control net, NURBS model in physical space, and contour plots for displacement and stress fields are depicted. Control points are shown in red, knots in cyan, knot lines in black, quadrature points in grey, 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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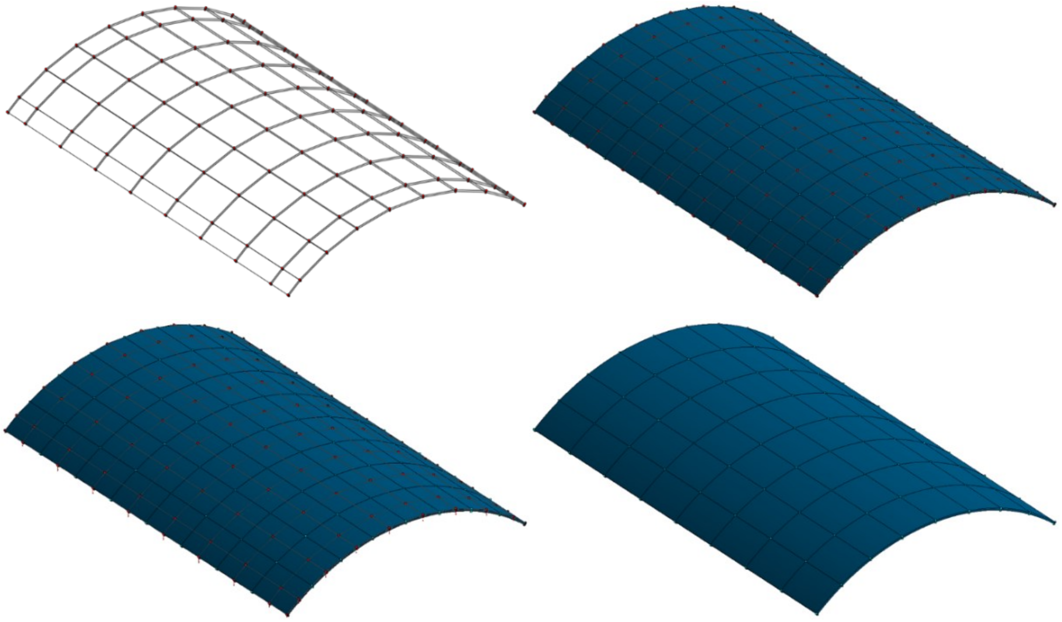
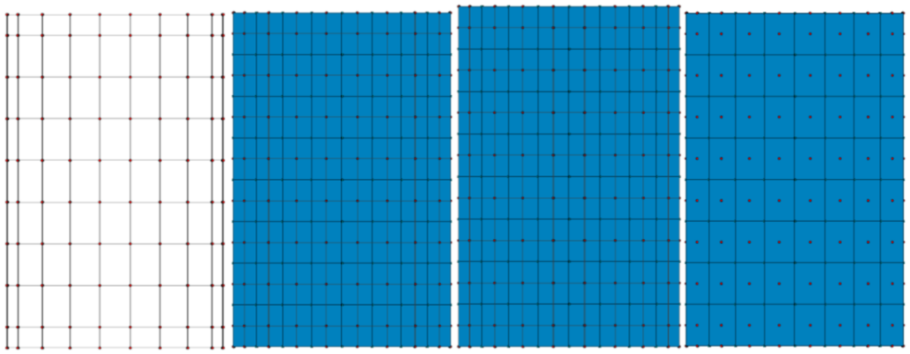
5.2 Scordelis Lo Roof

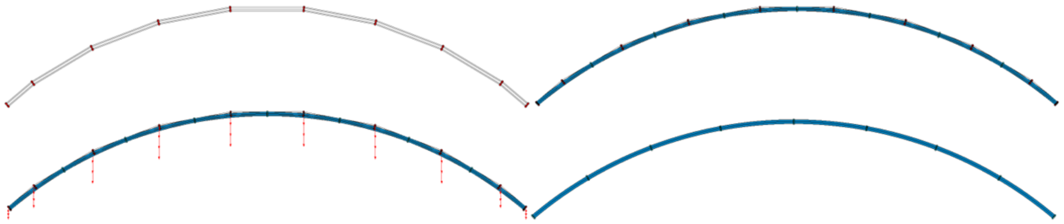
Figure 7 depicts the NURBS model of Scordelis Lo roof designed in the Geomiso SEA software.



(a) Control net and NURBS model.



(b) View XY



(c) View XZ

Figure 7: Scordelis Lo roof, designed in Geomiso SEA.

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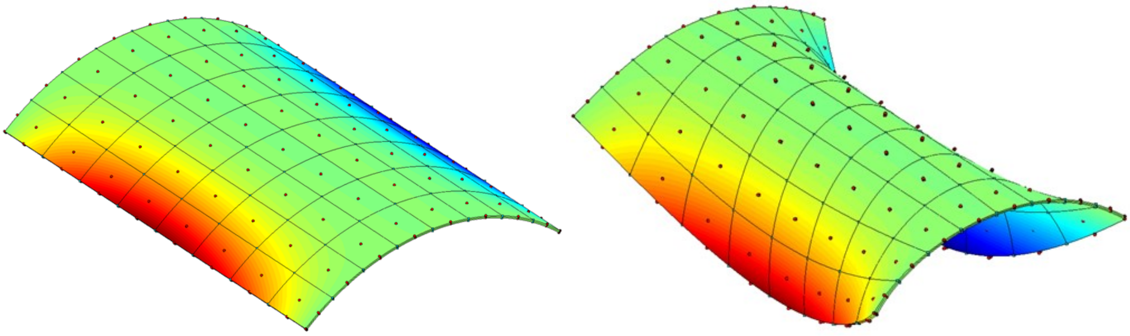
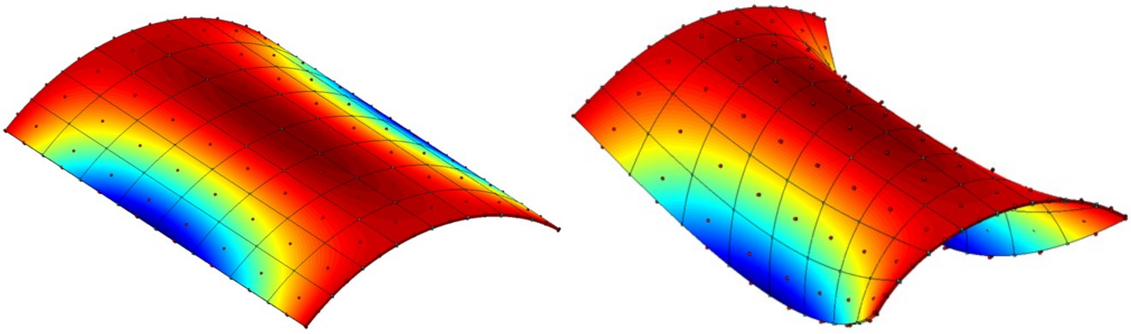
Figure 8 depicts the NURBS model of the Scordelis Lo roof designed and analyzed in the Geomiso SEA software.



(a) Contour plot of horizontal displacements (undeformed, deformed – scale factor).



(b) Contour plot of vertical displacements (undeformed, deformed – scale factor).

(c) Comparison

Figure 8: Geomiso SEA achieves accurate results with significantly fewer elements in comparison with FEA software. Different meshes are used in this nonlinear isogeometric analysis with Geomiso SEA and are compared with three FEA meshes (one for each of three commercial FEA software packages) and the analytical solution.

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6 CONCLUSIONS

- The new Geomiso SEA software, which is the world's first cloud-based program for isogeometric analysis with shell 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 shell structures 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.

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