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A NEW SHELL ELEMENT FORMULATION BASED ON RATIONAL TRIANGULAR BEZIER SPLINES

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ABSTRACT

This report presents application of rational triangular Bezier splines (rTBS) for developing Kirchhoff-Love plate and shell elements in the context of isogeometric analysis. During last decades, structural Analysis of shells has drawn great attention, owing to its key role in structural design and the complexity in the physics of the problem. Hence, there are various numerical techniques and theories on shells and plates with respect to the finite element application. Among these theories, Kirchhoff-Love is an appealing theory for developing efficient and reliable finite shell elements formulation; this theory, however, cannot be conventionally employed in traditional finite elements as it requires high continuity between elements. In 2005, Hughes et al. [1] presented Isogeometric analysis (IGA) as a new framework for finite element analysis; the non-uniforn rational B-spline (NURBS) functions of IGA can provide higher continuity between elements; this feature has made NURBS-baded IGA a promising tool for Kirchhoff-Love shell elements. Despite its great advantages, NURBS-based IGA has some limitations; such as, representing a complex geometry might need multiple NURBS patches and imposing higher continuity constraints over interfaces of patches is a challenging issue [2] as this is required for developing Kirchhoff-Love shell elements formulation. Isogeometric analysis based on rTBS, an alternative to NURBS, has been developed by [3,4]; this method can provide C1 continuity over the mesh including elements interfaces, a necessary condition in finite elements formulation of Kirchhoff-Love shell and plate theory. Based on this technology, we use Cr smooth rational triangular Bezier spline as the basis functions for representing both geometry and physical field. Besides providing continuity for Kirchhoff-Love formulation, using rTBS elements we can achieve two significant challenging goals: efficient local mesh refinement and representation of geometric models of complex topology. We apply the current method on several examples; first, we verify the proposed technique against multiple plate and shell benchmark problems; investigating the convergence rate on the benchmark problems demonstrate that the optimal convergence rate can be achieved by the proposed technique. We also apply our method on geometric models of complex topology or geometric models in which efficient local refinement is required. In the last example, a car hood is modeled with rTBS and structurally analyzed by using the proposed framework.

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AUTOMATIC ISOGEOMETRIC ANALYSIS SUITABLE TRIVARIATE MODELS GENERATION FROM STANDARD B-REP MODELS

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ABSTRACT

We present an effective method to automatically construct trivariate B-spline models of complicated geometry and arbitrary topology. Our method takes as input a B-Rep solid model defined by its triangulated boundary. Using cuboid decomposition [1,2], an initial polycube approximating the input boundary mesh is built. The polycube can be used to approximate very roughly the geometry of a model while faithfully replicating its topology. Due to its highly regular and trivariate structure, the polycube is suitable for serving as the canonical domain of the volume parameterization required for trivariate NURBS construction. The polycube's nodes and arcs decompose the input model locally into quadrangular patches, and globally into hexahedral domains. Using cross fields and aligned global parameterization [3], the position of the polycube nodes and arcs are optimized across the surface in a way to achieve low overall patch distortion, and alignment to principal curvature directions and sharp features. Based on the optimized polycube and parameterization, compatible B-spline boundary surfaces are reconstructed. Finally, the interior volumetric parameterization is computed using Coon's interpolation and the B-spline surfaces as boundary conditions. The efficiency and the robustness of the proposed approach are illustrated by some examples.

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B-SPLINE SOLID MESH GENERATION BASED ON THE EQUATIONS OF LINEAR ELASTICITY

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ABSTRACT

In the design for civil engineering structures, such as bridges, dams, tunnels and so on, we need to understand stresses, strains, and displacements of these structures. Although solid meshes are required when we conduct these type of analysis by using IGA, needless to say, the solid model drawn by CAD does not have its internal information which is available for solid mesh generation. Recently, several approaches to generate B-spline solid have been proposed. One of the major approaches is the polycube method [1]. In some cases, even when using these methods, distorted elements may be generated. Therefore, in this study, we proposed the mesh generation method by using the equations of linear elasticity. The mesh generation technique is widely used in the fluid-structure interaction analysis [2]. The merit of using the linear elastic equations is that the quality of mesh can be controlled by adjusting Young's modulus. Out proposed algorithm and sample of a generated mesh are as follows.

Algorithm:

1. Draw a desired solid model which will be analyzed on CAD.
2. Extract the coordinate of control points on the surface of the desired model.
3. Make a primitive solid mesh. The primitive mesh should be a simple shape such as a cube, bar, rod and have the same number of control points to the objective solid model on its surface.
4. Calculate the difference of coordinate of control points on the surfaces between the desired model and the primitive mesh.
5. Solve the equations of linear elasticity for the primitive mesh with imposing the difference of coordinates as displacement boundary conditions.
6. The deformed primitive mesh becomes the solid mesh of the desired model.
7. If the result (deformed primitive mesh) has large distorted elements, step 5 is conducted again with control of Young's module locally.

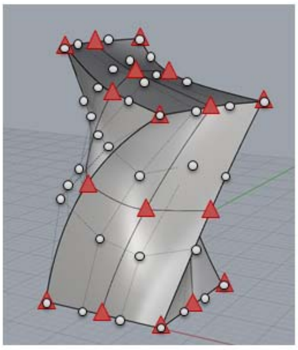

Fig 1. Sample of an desired solid model

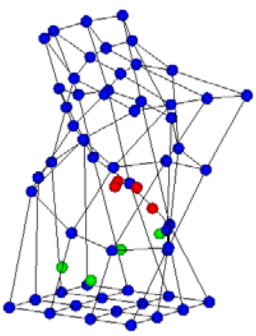

Fig 2. Generated mesh

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COST-EFFECTIVE ISOGEOMETRIC ANALYSIS OF COMPOSITE STRUCTURES BY AN EQUILIBRIUM-BASED STRESS-RECOVERY APPROACH

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ABSTRACT

This work focuses on the development of an isogeometric method for layered composite structures taking advantage of the accuracy and high-regularity properties of isogeometric analysis [1] to build a cost-effective stress recovery procedure [2]. The proposed simulation strategy consists of using 3D or shell isogeometric computations with a single element in the thickness and a layer-wise integration rule or a homogenized approach, granting an inexpensive and accurate approximation of the in-plane response. This solution is then post-processed in order to obtain also an accurate stress state through the thickness, based on the integration of the equilibrium equations in strong form. Such an approach allows to drastically reduce the number of degrees of freedom and, accordingly, the overall computational time as compared to standard layer-wise approaches where every layer corresponds to an element through the thickness. The post-processing operation is in fact very fast and its cost does not increase significantly with the number of degrees of freedom. Several numerical experiments are shown, revealing the very good accuracy-to-cost ratio of the method, which appears to be particularly effective on composite stacks with a large number of layers. The isogeometric collocation version of the approach is finally also presented.

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CURVILINEAR COORDINATES BASED IMPLEMENTATION OF KIRCHHOFF-LOVE SHELL KINEMATICS AND ITS APPLICATION TO MODELING OF NECKING PHENOMENA IN BIOLOGICAL MEMBRANES

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ABSTRACT

Numerical treatment of Kirchhoff-Love thin shell kinematics is elegant and straightforward in the framework of curvilinear coordinates and local basis. However, the continuity requirements of such formulations and the differential geometric treatment inherent to the kinematics of surfaces have limited its widespread adoption and application. Isogeometric analysis, given its C^n continuity and exact geometric representation properties, is an ideal framework for developing thin shell formulations. In this work, we present an isogeometric analysis based, finite-strain Kirchhoff-Love shell implementation and its application to a variety of problems involving biological membranes. One specific problem of interest is the necking of membranes and tubules. The formation and constriction of membrane necks as a precursor to membrane fission is a fundamental step for a variety of biological processes including endocytosis, cytokinesis, etc. Using the thin shell framework described above, we model the deformational response and instabilities in various membrane geometries, study the suitability of Helfrich like material models, and estimate the boundary conditions needed to induce preferred deformation modes. Further, extensions of this framework to problems involving mechano-chemistry on membranes will also be presented.

EXPLICIT ISOGEOMETRIC COLLOCATION FOR THE DYNAMICS OF GEOMETRICALLY EXACT BEAMS

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ABSTRACT

The study of isogeometric collocation (IGA-C) methods has been recently initiated in [1,2] motivated by the idea of taking advantage from the higher-order accuracy of NURBS basis functions and the low computational cost of collocation. A field where the IGA-C attributes have a high impact is explicit dynamics. Here the idea is to keep the computational advantages of one-point quadrature methods and, at the same time, achieve high-order accuracy [3].

In the present work, we extend the development of the IGA-C method to the explicit dynamics of three-dimensional beams undergoing finite motions. Unlike in linear and traditional nonlinear structural dynamics, the configuration space involves the rotation (Lie) group SO(3) where standard time integration schemes, including predictor-multicorrector methods, cannot be straightforwardly applied. Since our ultimate goal is the development of high-order accurate methods, we employ consistent mass and inertia matrices and focus mainly on the development of a SO(3)-consistent explicit time integration scheme. Following [4,5], finite rotations are represented by elements of SO(3), incremental rotations are parameterized by means of spatial rotation vectors, and configuration updates are made directly by exponentiating and superimposing the incremental rotation to the current rotation. We combine this kinematic model with one of the best-performing second-order accurate explicit central difference method for SO(3) [6]. The capabilities of the proposed formulation are assessed through a series of numerical applications.

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ISOGEOMETRIC MULTILAYER SHELLS: DAMAGE, DELAMINATION, IMPACT, AND GRADIENT-ENHANCED MODELING

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ABSTRACT

Fiber-reinforced composite materials have become increasingly popular in the past few decades for lightweight applications, in particular in the aerospace industry where high strength-to-weight and high stiffness-to-weight ratio are considered key design parameters. At the same time, new computational technologies are required to support the design process of increasingly complex structural components and to predict damage growth under nonstandard loading conditions. The unique challenges associated with modeling damage in these structures may be addressed by means of thin-shell formulations, which are naturally developed in the context of Isogeometric Analysis (IGA).

We present a novel multi-layer modeling framework based on IGA, where each ply or lamina is represented by a Non-Uniform Rational B-Spline (NURBS) surface, and it is modeled as a Kirchhoff--Love thin shell. A residual stiffness approach is used to model intra-laminar damage in the framework of Continuum Damage Mechanics. A new zero-thickness cohesive interface formulation is introduced to model delamination as well as permitting laminate-level transverse shear compliance. The Gradient-Enhanced continuum damage model is then introduced to regularize material instabilities, which are typically associated with strain-softening damage models. This nonlocal regularization technique aims to re-establish mesh objectivity by limiting the dependence of damage predictions on the choice of discrete mesh. To account for the anisotropic damage modes of laminae, the proposed formulation smoothes a tensor-valued strain field by solving an elliptic partial differential equation system on each lamina. The smoothing PDE is formulated in general curvilinear coordinates and is thus uniquely suited for Kirchhoff--Love thin shells.

The proposed approach has significant accuracy and efficiency advantages over existing methods for modeling impact damage. These stem from the use of IGA-based Kirchhoff--Love shells to represent the individual plies of the composite laminate, while the compliant cohesive interfaces enable transverse shear deformation of the laminate. Kirchhoff--Love shells give a faithful representation of the ply deformation behavior, and, unlike solids or traditional shear-deformable shells, do not suffer from transverse-shear locking in the limit of vanishing thickness. This, in combination with higher-order accurate and smooth representation of the shell midsurface displacement field, allows one to adopt relatively coarse in-plane discretizations without sacrificing solution accuracy. Furthermore, the thin-shell formulation employed does not use rotational degrees of freedom, which gives additional efficiency benefits relative to more standard shell formulations.

GRADIENT-ENHANCED DAMAGE MODELING FOR THIN SHELLS: APPLICATION TO ISOGEOMETRIC ANALYSIS

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ABSTRACT

Damage prediction in multilayer composite laminates is considered of primary importance for safety-critical applications. Advancements in the design of high-strength and low-weight damage tolerant components drive the demand for faster and more accurate numerical tools for structural analysis. In our recent work [1] we proposed a modeling approach for progressive damage analysis of composite laminates, in which multilayer structures are represented as individual plies connected through cohesive interfaces. The model is developed in the framework of Isogeometric Analysis (IGA) which allows for better representation of geometries, superior smoothness and a more direct link to CAD software. In addition, IGA allows to effortlessly achieve higher-order inter-element continuity, which enables the use of higher-order structural models.
The computational efficiency of the proposed analysis framework is achieved by adopting displacement-based Kirchhoff-Love shell elements for the modeling of individual lamina. In addition, a strain-softening constitutive law is coupled with Hashin failure criteria in order to simulate intralaminar damage in the framework of continuum damage mechanics. However, the use of a strain-softening damage model based on local strain measures may lead to material instability. This manifests in damage localization problems as the numerical solution of the governing equations becomes highly mesh-sensitive. Our work aims to re-establish objectivity with respect to the adopted discretization.
We introduced a nonlocal smooth strain field to drive the strain-softening damage model. The approach, which is based on the gradient-enhanced damage model [2], has been specialized for Kirchhoff-Love shell elements. The smooth strain field is obtained by solving additional sets of equations on each domain corresponding to individual plies of the laminate. The gradient-enhanced governing equations are independent of the choice of coordinates and the nonlocal damage model can be applied to smooth tensor-valued quantities, such as strains, on generic-shaped geometries in the three-dimensional space. In this work we show applications of the nonlocal damage modeling and the objectivity of results with respect to the adopted discretization.

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MODELLING FIBRIN NETWORK USING 3D SPATIAL EULER-BERNOULLI BEAM

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ABSTRACT

Thrombus is vital to our well-being as blood coagulation prevents bleeding after vascular injury. However, thrombus role is diametrical in that pathological coagulation also causes deep vein thrombosis, heart attacks, and strokes. Thrombus' propensity to detach and embolizes, and thus cause havoc, is strongly linked to its mechanical properties, which are primarily determine by its fibrin backbone. To understand how thrombus macromechanics (such as its failure behavior) are linked to its microstructure, we are developing mathematical/numerical models of thrombus' 3D microstructure. Specifically, in a representative volume element (RVE), we model each individual fibrin fiber as a 3D spatial Euler-Bernoulli beam, whose behavior is driven by St Venant – Kirchhoff material law. We have implemented this model on three benchmark problems widely used in the literature. These problems were solved with single NURBS patch and multipatch beams. Bending strip method is used to connect two NURBS patches. We have developed a method to connect more than two beams at a point, which is essential for 2D and 3D networks. All the connections in these networks are assumed to be rigid. Two different types of networks are generated, i) Networks with straight fibers and ii) Networks with undulated fibers. We have tested different 2D and 3D networks in uniaxial tension. We have made comparison between behaviour of these networks in uniaxial tension. Further we intend to test these networks in other loading scenario like compression and shear.

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THREE-DIMENSIONAL SOLID STRUCTURES SIMULATION ON ISOGEOMETRIC B-REP ANALYSIS

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ABSTRACT

Isogeometric analysis (IGA) was devised to circumvent meshing step in the design process because it uses same basis functions as CAD packages: non-uniform rational B-splines (NURBS). That NURBS information is exchangeable via Initial Graphics Exchange Specification (IGES) files, which potentially can be extracted and read for analysis purpose in IGA context. However the utilization of NURBS domains proceeding directly from CAD for analysis purposes is still not fully developed. In particular, 3D solids IGES files contain a collection of faces forming the solid boundaries, but not the solid itself. Isogeometric B-Rep analysis (IBRA) allows to generate NURBS domains in an easy manner by trimming and coupling patches. A full description on IBRA applied for shells is given in [1], where they describe application of boundary conditions /coupling to trimmed edges and analysis-CAD integration. In this work we extend IBRA for three dimensional solid structures. Although the principles are the same than IBRA on shells, there are three aspects in solids that require extra development: interpretation of 3D solids IGES files, trimming surfaces definition and domain integration. We propose a methodology for the first item, which is based on the application of certain restrictions when the solid is modeled. Trimming surface definition is based on NURBS point projection form physical to parameter space. Domain integration is carried out in parameter space by Finite Cell Method [2]. Examples provided demonstrate the accuracy of the procedure and show that IBRA on three-dimensional solids is suitable for analysis – CAD integration on that kind of structures.

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