Explicit Isogeometric B-Rep Analysis on Trimmed NURBS-Based Multi-Patch CAD Models in LS-DYNA

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1 Introduction

A volatile and highly competitive market forces automotive Original Equipment Manufacturers (OEMs) to speed up their vehicle development processes. A key component in this process is structural design through Computer Aided Design (CAD) and Finite Element Analysis (FEA). Although the efficiency of this process has been significantly improved over the past years, the necessary conversion of NURBS-based CAD models into (linear) polynomial-based FEA models turned out to be a persistent challenge. Generating FEA models usually involves time- and labor-intensive clean-up, de-featuring and meshing steps leading to vehicle model generation times of several weeks. During the iterative vehicle development process, such model generations are even performed multiple times. It is furthermore current practice to apply design changes motivated by structural analysis results directly on the FEA model, which then diverges more and more from the initial CAD model. Adapting the CAD model to the modified FEA model for the next design cycle again requires a significant amount of manual work.

Isogeometric Analysis (IGA) [1] avoids this change in geometry description as it uses NURBS geometries also as the basis for analysis. IGA therefore has great potential to significantly cut down analysis model generation efforts and to speed up virtual structural design processes. LS-DYNA is, to the best of our knowledge, the only commercial FEA solver that provides IGA features. On the forefront of IGA research, LS-DYNA supports various isogeometric NURBS-based shell and solid element formulations as well as many crash relevant features such as contact, plasticity and explicit time integration with stable time step estimation and mass scaling for IGA. Another favorable aspect of LS-DYNA is the possibility to combine standard finite element with NURBS-based element components in the same analysis model, facilitating the introduction of IGA in industry. However, industrial CAD models usually consist of numerous trimmed NURBS surfaces (patches) and performing analysis on such models is far from trivial. Isogeometric B-Rep Analysis (IBRA) [2] is able to handle such complex models as it couples trimmed NURBS patches via so-called B-Rep elements in a weak sense. The recently developed extension of IBRA to explicit dynamics (Explicit IBRA) [3] combines the IBRA patch coupling capabilities with the explicit isogeometric features of LS-DYNA. This enables crash-type isogeometric analysis on complex NURBS shell structures.

In the following sections we provide (i) an overview on the challenges accompanied with isogeometric analysis on complex CAD models, (ii) the main ideas behind IBRA and Explicit IBRA, (iii) a description of the prototypically implemented design-analysis workflow based on the IBRA exchange format and (iv) two crash-related numerical examples solved with Explicit IBRA in LS-DYNA. We finally give a brief conclusion and insights into ongoing/future developments for industrial IGA applications.

2 Industrial CAD models consisting of multiple trimmed NURBS patches

Industrial CAD models mainly rely on NURBS-based boundary representations (B-Reps), i.e. the three-dimensional geometry model is represented only by its skin (bounding surfaces) rather than as a solid. Such NURBS surfaces are built as a tensor product of two one-dimensional NURBS curves and are therefore topologically restricted to quadrangular-like shapes. To overcome this restriction to simple shapes and topologies, NURBS surfaces usually get trimmed. That is, depending on the trimming curves, only portions of the NURBS surfaces are considered as material, the remaining is considered as void. Complex industrial CAD models usually consist of various such trimmed NURBS surfaces (denoted as patches in IGA), see for instance the BMW engine bonnet CAD model in Fig. 1. Two of the around 100 trimmed patches of this bonnet model are exemplarily highlighted and visualized in three different representations. The left of the three subfigures depicts only the material domain of the two trimmed patches – this is what one usually sees in the CAD program. The subfigure in the middle shows the trimmed patches together with their underlying untrimmed NURBS surface and elements, while the right subfigure also depicts the corresponding control points. The red curves indicate the common shared edge of these two patches, i.e. a topological connection in CAD. As a matter of fact, performing analysis on trimmed multi-patch NURBS models requires analysis capabilities not present in current FEA solvers. As explained in the next section, the Isogeometric B-Rep Analysis framework [2] covers these capabilities and enables structural analysis on complex CAD models.

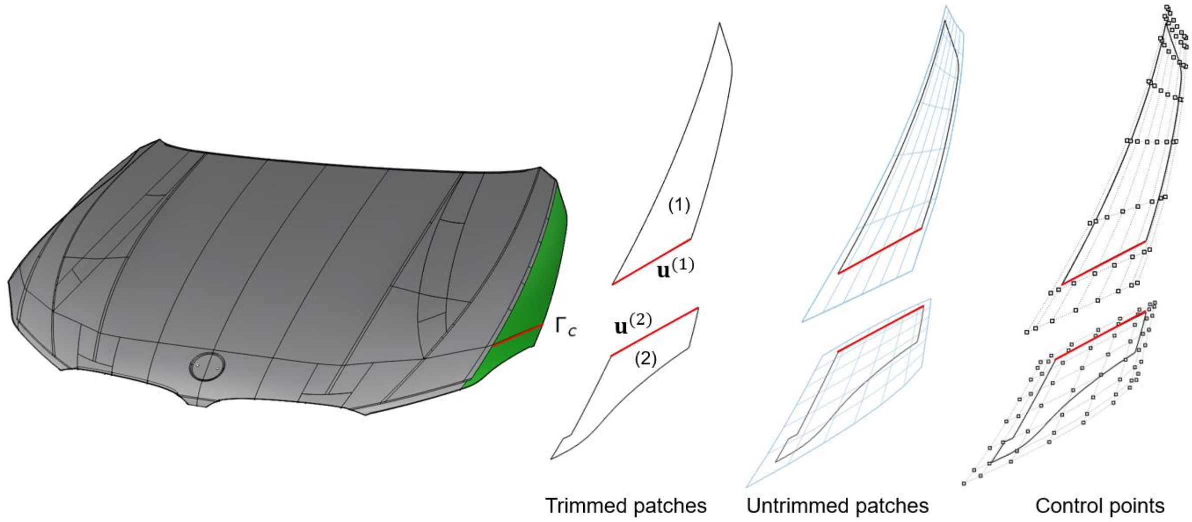

Fig.1: Trimmed multi-patch CAD model of a BMW engine bonnet.

3 Explicit Isogeometric B-Rep Analysis (Explicit IBRA)

3.1 Isogeometric B-Rep Analysis (IBRA)

In order to perform structural analysis on trimmed multi-patch B-Rep CAD models, IBRA has to deal with the following novel analysis aspects:

1. Trimmed elements with material and void domains. Such trimmed elements require a special numerical integration rule. IBRA therefore uses the so-called Adaptive Gaussian Integration Procedure (AGIP) [4], which maps the trimmed element Gaussian space to an untrimmed Gaussian space and generates standard Gauss points in there. However, also the numerical integration methods for trimmed isogeometric elements in LS-DYNA are applicable, see for instance [5].

2. Coupling of trimmed patches during analysis, i.e. transfer of forces and moments across common edges of adjacent patches. This cannot be done by a simple node-by-node coupling due to different, non-matching discretization and the fact that control points are generally not located on trimmed boundaries (see the right subfigure in Fig. 1.). For this reason, IBRA uses so-called B-Rep coupling elements to weakly enforce the coupling conditions based on a simple and efficient penalty approach. That is, a coupling term forcing the displacement difference *($\boldsymbol{u}^{(1)}$-$\boldsymbol{u}^{(2)}$)* between two patch boundaries to be zero in a weak integral sense is added to the virtual work:

$$\delta W_p = -\alpha \int_{\Gamma_c} \left(\boldsymbol{u}^{(1)} - \boldsymbol{u}^{(2)}\right)\left(\delta\boldsymbol{u}^{(1)} - \delta\boldsymbol{u}^{(2)}\right) d\Gamma_c,$$

where α denotes the penalty factor and Γ_c the coupling edge. Similar expressions are used for the enforcement of coupling conditions on rotational displacements. Please note that IBRA is not restricted to penalty-based coupling; also other approaches such as the Lagrange Multiplier or Nitsche's method can be deployed for the B-Rep element formulation. In addition to coupling, these B-Rep elements can also be applied to enforce Dirichlet and Neumann boundary conditions.

IBRA is furthermore designed to enable a consistent data flow between CAD systems and the solver, since both geometry and topology information are directly inherited from the CAD system without further user interaction. Geometry information is used to define model shapes and trimmed domains, while topology information is crucial in order to automatically couple adjacent patches along common edges.

3.2 Explicit IBRA – The extension to explicit dynamics

Explicit IBRA [3] is the recently developed extension of IBRA to explicit dynamic problems and basically a combination of the patch coupling capabilities of IBRA with the explicit (crash) features such as explicit time integration, plasticity and contact in LS-DYNA. In its original form, Explicit IBRA and the corresponding B-Rep elements were developed for the Reissner-Mindlin shells with rotational degrees of freedom (DOFs) implemented in LS-DYNA [6]. As demonstrated on various penalty-coupled trimmed multi-patch problems in [3], Explicit IBRA allows for accurate results with reasonable time step sizes. An open issue for highly dynamic explicit problems was the stability of control points with extremely small mass and stiffness caused by small trimmed elements. Stabilization techniques currently under development show promising results and will open the door for explicit isogeometric crash-type simulations of industrial CAD models.

4 Data flow between CAD and analysis

The main motivation for the development of IGA is to speed up virtual vehicle development processes by bringing design and analysis closer together. To achieve this, a consistent data flow between CAD systems and solvers is crucial. This section describes how we set up a prototypical design-analysis workflow between the CAD system Rhinoceros and LS-DYNA based on the IBRA exchange format.

4.1 CAD environment for design, pre- and postprocessing

Starting point for the closed design-analysis workflow depicted in Fig.2 is the CAD program Rhinoceros with a specifically developed IBRA plug-in called TeDA (Tool to enhance Design by Analysis) [7]. With TeDA, analysis-related information like shell thickness, material, boundary conditions and loads can be defined in the CAD program directly on the NURBS geometry. TeDA furthermore allows exporting all necessary information directly as a solver input file or via the IBRA exchange format described in the following section. After analysis, solution data in the form of displacements, velocities and accelerations on control points as well as stresses or strains on integration points can be processed by TeDA and visualized on the deformed NURBS geometry in the CAD program, see for instance Fig.4 and Fig.7 in Section 5.

TeDA is the proof of concept for a CAD-integrated pre- and postprocessing tool allowing for a tight connection of CAD and isogeometric analysis on research level. For large scale industrial applications and real benefits in the development process, more powerful tools directly provided by CAD or CAE software vendors are desired and inevitable.

4.2 IBRA exchange format

The IBRA exchange format [8] allows transferring all necessary analysis data from the CAD system to the solver. Because the IBRA exchange format is based on the popular JavaScript Object Notation (JSON) format, in- and output interfaces can be easily implemented in most software APIs (Application Programming Interfaces). Through its several different data extraction levels, see Fig.3, the IBRA exchange format enables almost any kind of downstream solver, be it a highly sophisticated IGA solver or a standard FE solver. For IGA solvers information on the geometry level (a) may be sufficient, while standard FE solvers may even extract shape function values evaluated at integration points (d). The crucial information for structural shell analysis can be briefly summarized as:

- Geometry information (shape, faces, edges, vertices, degrees, trimming information)
- Topology information (edges connecting adjacent faces)
- Element information (2D elements, B-Rep elements, integration points, control points)
- Problem-specific information (boundary conditions, material information, solver-specific parameters)
- Solution information (displacements, velocities or accelerations on control points, or stresses and strains on integration points)

4.3 LS-DYNA with IBRA interface

LS-DYNA already has many IGA features for implicit and explicit such as NURBS-based solid and shell elements, trimmed isogeometric shells and numerical integration of trimmed elements. LS-DYNA furthermore also supports mass scaling, stable time step estimation, plasticity and contact for IGA. For

Explicit IBRA of trimmed multi-patch shell structures we implemented the penalty-based B-Rep elements via a user-defined FORTRAN interface. Because LS-DYNA already supported 2D patch definitions for shells, data from the geometry level (a) of the IBRA exchange format could be used. For the B-Rep elements not existent in LS-DYNA, on the contrary, we needed to extract data on level (d) with pre-evaluated shape functions at integration points.

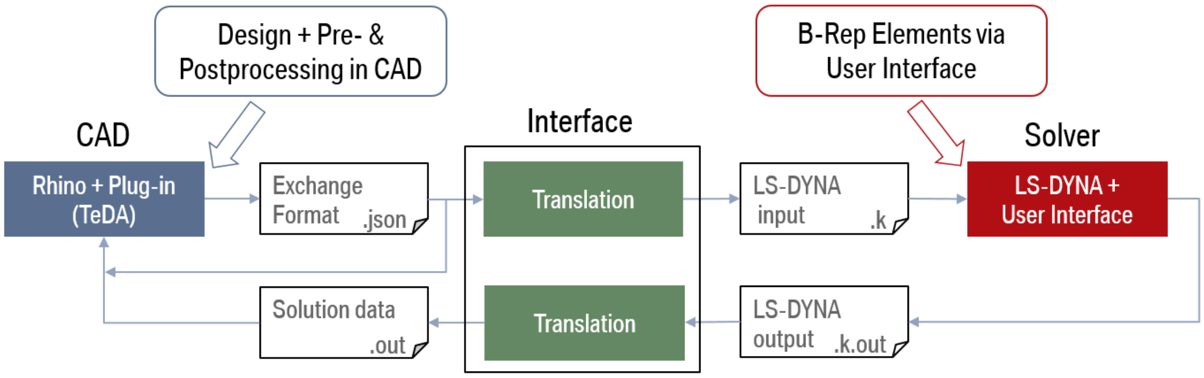

Fig.2: Prototypical workflow enabling a closed design cycle between design and analysis.

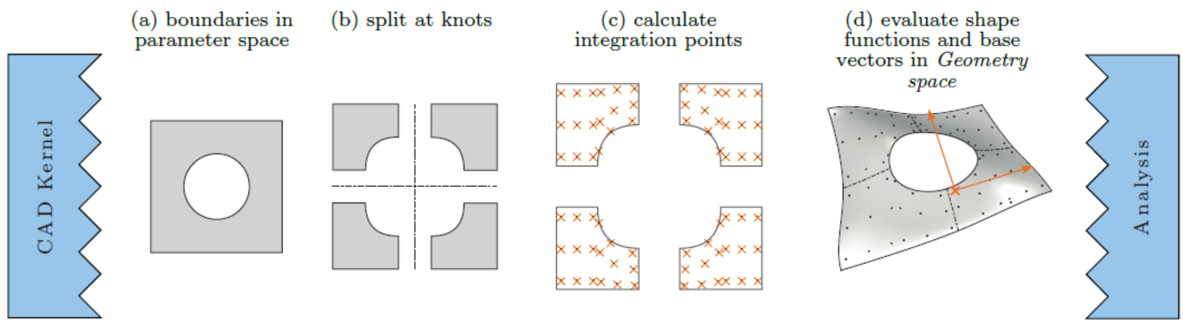

Fig.3: IBRA exchange format with different data extraction levels [8] for a flexible data transfer between CAD system and solver.

5 Numerical examples

The accuracy and effectiveness of Explicit IBRA is shown in [3] by means of various benchmark problems reaching from quasi-static linear elastic to highly dynamic elasto-plastic with large deformations. In this section we present explicit isogeometric simulations related to automotive crash, namely dynamic buckling of an energy absorbing tube and the dynamic loading of a BMW engine bonnet structure.

5.1 Dynamic buckling of an energy absorbing tube

This example is intended to demonstrate the possibility of performing Explicit IBRA in crash-type problems including large deformations, plasticity and contact. Due to symmetry reasons, only a quarter of the problem is modeled with corresponding symmetry boundary conditions. As shown in Fig.4, the geometry consists of two artificially trimmed patches with non-matching discretization. Penalty-based B-Rep elements are used to couple these patches during analysis. Figure 4 depicts the initial configuration (left) along with three deformation states. The periodic folding behavior leading to self-contact is clearly visible. Please note that the contact is handled via a fine background finite element mesh in LS-DYNA. A more detailed study on the accuracy and efficiency of such a buckling tube can be found in [3].

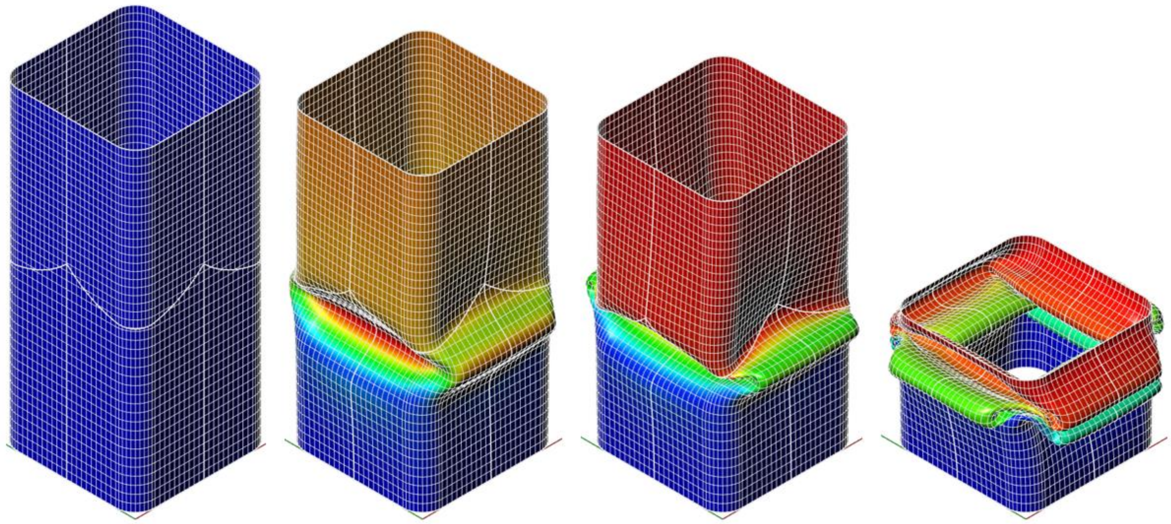

Fig.4: Dynamic buckling of an energy absorbing tube: Initial configuration (left) and deformed shapes of the trimmed NURBS-based multi-patch model.

5.2 Industrial example: BMW engine bonnet structure

In order to demonstrate the applicability of Explicit IBRA to complex industrial problems, we consider the CAD model of a BMW engine bonnet structure. The midsurface of the original CAD model consisting of 2630 trimmed NURBS patches is shown in Fig.5. This is a typical BMW CAD model designed without having isogeometric analysis in mind. As in standard FEA, also in IGA, accurate results require a proper geometry discretization following certain quality criteria. This makes clear that the original CAD model will not be appropriate for accurate, efficient and robust simulations. However, since IGA is a relatively new technology, model quality criteria as for mesh generation in FEA are successively developed. The multi-patch model depicted in Fig.6 is an adjusted version of the original CAD model and follows modeling guidelines such as maximum polynomial degree, minimum element size and minimum patch size. This guideline-conforming CAD model consists of 130 trimmed NURBS patches with a maximum polynomial degree of four. Explicit IBRA results of this penalty-coupled multi-patch model subjected to a uniform pressure load with clamped outer edges and symmetry boundary conditions (applied via B-Rep elements), and linear elastic material are depicted in Fig.7. Please note that the refinement step was automatically performed by an algorithm and that the results are visualized in the CAD program Rhinoceros via TeDA. For a productive application of IGA in the future, CAD models directly generated in accordance to these design guidelines, will allow isogeometric simulations without or with a minimum number of modification steps and a tight integration of CAD and CAE.

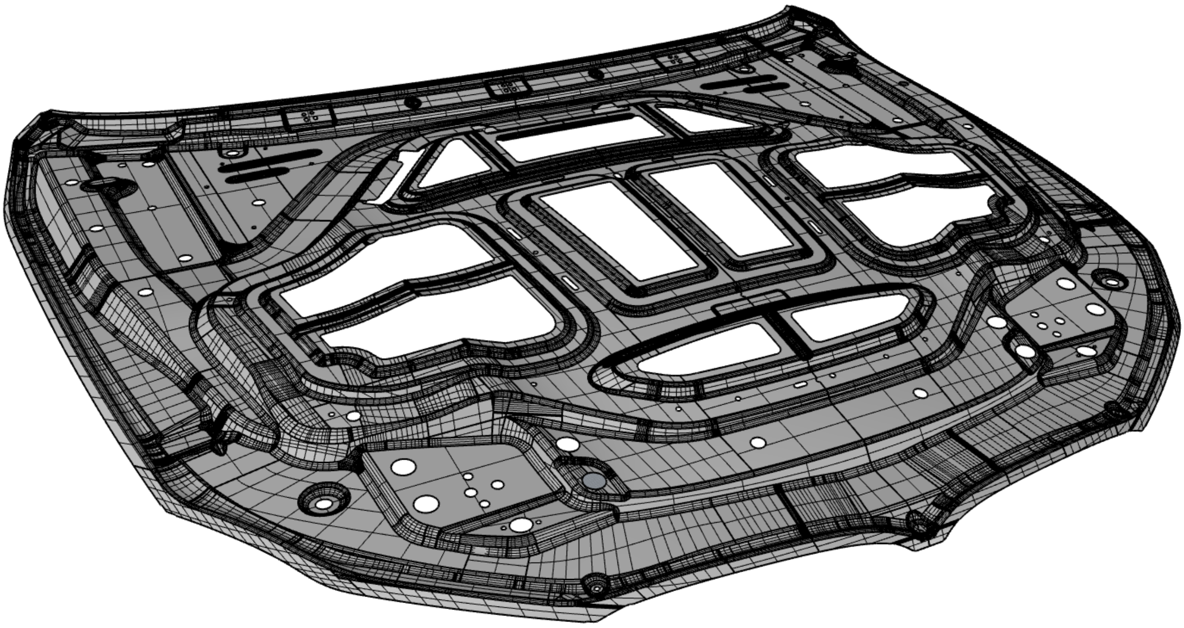

Fig.5: BMW engine bonnet structure: Midsurface of the original CAD model with 2630 trimmed NURBS patches (automatically generated in CATIA).

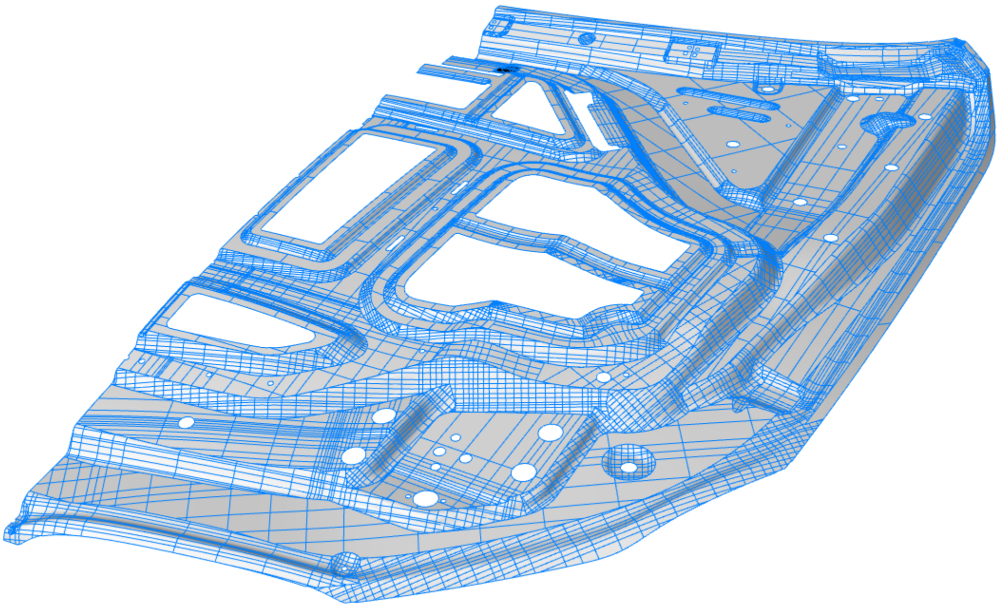

Fig.6: BMW engine bonnet structure: Guideline-conforming multi-patch model consisting of 130 trimmed NURBS patches.

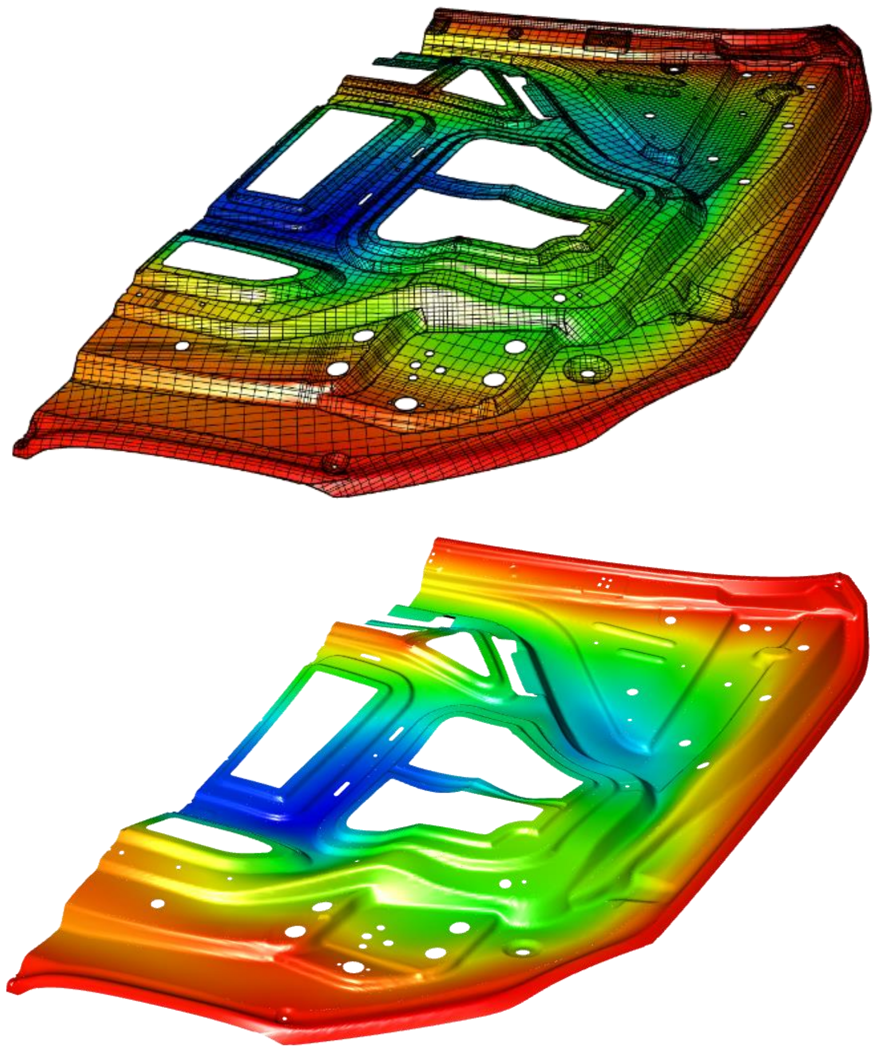

Fig.7: BMW engine bonnet structure: Results of an Explicit Isogeometric B-Rep Analysis in LS-DYNA. Scaled, deformed shapes with and without knot lines visualized in the CAD program Rhinoceros with TeDA.

6 Conclusion and Outlook

The content of this paper can be summarized as follows:

- Explicit Isogeometric B-Rep Analysis is the combination of the patch-coupling capabilities of IBRA with the explicit isogeometric (crash) features of LS-DYNA.
- Explicit IBRA in LS-DYNA enables explicit dynamic analysis on trimmed multi-patch NURBS shell structures including large deformations, plasticity and contact.
- Penalty-based isogeometric B-Rep elements allow enforcing coupling and boundary conditions along trimmed edges in a weak integral sense.
- Extensive theoretical and experimental studies show that accurate results can be obtained with penalty factors that have no or only a minor influence on the stable time step size [3].
- Isogeometric B-Rep coupling elements are implemented via a user-defined LS-DYNA interface.
- We achieved a closed prototypical design-analysis workflow between the CAD program Rhinoceros and LS-DYNA, based on the IBRA data exchange format and the CAD plug-in TeDA. This workflow allows performing all design, pre- and postprocessing steps within the CAD system, without further user interaction.

Through the analysis-related developments undertaken by LSTC/DYNAmore, the Technical University of Munich and BMW Group, IGA is now approaching a level that enables both implicit and explicit analysis on complex industrial CAD models, i.e. trimmed NURBS-based multi-patch models. These isogeometric patch coupling capabilities are now also firmly implemented in LS-DYNA, allowing efficient

analysis without the limitations of a user interface. It is fair to say that the analysis now stands on a solid foundation. Besides steadily increasing the complexity of our models, the next steps are to integrate IGA into a performant software environment. The ideal case for a closed design-analysis workflow is a performant and efficient IGA interface in the CAD system that directly writes the required isogeometric solver input file. This, together with a design guideline-conforming CAD model will allow exploiting the full speed-up potential of IGA in the development process.
As we are currently gaining knowledge on how to effectively perform simulations on large scale NURBS geometries, these guidelines are also steadily evolving. In case a CAD model does not conform to such guidelines – be it for historical or practical reasons – some amount of model preparation will remain even for IGA models. The CAE software ANSA recently enhanced its preprocessing capabilities with several IGA model preparation features and is about to establish a direct link to LS-DYNA for trimmed isogeometric multi-patch models. This yields an industrial isogeometric workflow between CAD and LS-DYNA, and opens the door for a first integration of IGA into the BMW development environment.

7 Literature

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