CONNECTING DESIGN AND ANALYSIS: EXPLICIT ISOGEOMETRIC ANALYSIS USING ANSA AND LS-DYNA

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ABSTRACT
Despite significant advances of pre-processing tools such as ANSA in the past years, generating high-quality FEA models from CAD geometries is still a time- and cost-intensive part of the virtual vehicle development process. One reason why these model generation steps (geometry cleanup, de-featuring, meshing, etc.) are still not fully automated is the fact that FEA and CAD models rely on different geometry descriptions, i.e. (linear) polynomials and Non-Uniform Rational B-Splines (NURBS), respectively.
Isogeometric Analysis (IGA) (1) has the potential to drastically cut-down these model generation efforts by performing the analysis on NURBS-based CAD geometries directly. In order to perform IGA on complex industrial models which usually consist of numerous trimmed surface patches, novel analysis capabilities such as numerical integration of trimmed elements or coupling of trimmed surfaces are required. The Isogeometric B-Rep Analysis (IBRA) framework (2) and its recently developed extension to explicit dynamics (Explicit IBRA) (3) cover these capabilities. The corresponding IBRA exchange format (4) furthermore allows transferring topology, geometry and analysis-related data bi-directionally between CAD system and solver, leading to a closed design-analysis loop. For our prototypical workflow we connected the CAD program Rhinoceros with the leading commercial IGA solver LS-DYNA by means of user interfaces.
In a perfect world, CAD engineers would design models according to specific modeling guidelines to enable isogeometric analysis on CAD models without any further modifications. However, 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. ANSA recently enhanced its preprocessing capabilities with several IGA model preparation features.
In this contribution we (i) provide a brief overview on Explicit Isogeometric B-Rep Analysis in LS-DYNA and (ii) demonstrate how we use the ANSA IGA features to prepare a historical, not guideline-conforming CAD model for isogeometric analysis.

TECHNICAL PAPER

1. INTRODUCTION

A highly competitive and volatile market forces automotive OEMs (Original Equipment Manufacturers) to speed up vehicle development processes. Virtual structural vehicle design via Finite Element Analysis (FEA) is a significant part of the whole development process. Despite significant advances of pre-processing tools such as ANSA in the past years, generating high-quality FEA models from CAD geometries is still time- and cost-intensive. One reason why these model generation steps (geometry cleanup, de-featuring, meshing, etc.) are still not fully automated is the fact that FEA and CAD models rely on different geometry descriptions, i.e. (linear) polynomials and Non-Uniform Rational B-Splines (NURBS), respectively. Isogeometric Analysis (IGA) (1) has the potential to drastically cut-down these model generation efforts by performing the analysis on NURBS-based CAD geometries directly.

2. INDUSTRIAL CAD MODELS CONSISTING OF MULTIPLE TRIMMED NURBS PATCHES

Industrial CAD models are mainly based on the so-called *B-Rep* modeling approach, where the term *B-Rep* stands for *boundary representation*. In B-Rep modeling, a 3D component is not represented by an actual volume but rather by its boundary representation, i.e. only by its outer surface. That is, a 3D volume part is described by a 2D surface boundary representation. Similarly a 2D surface is circumscribed by a 1D curve boundary, and a 1D curve is limited by (0D) vertices. In order to allow more complex shapes and topologies, NURBS surfaces are usually trimmed. This means that directed trimming loops consisting of multiple trimming curves separate the surface into visible and invisible domains, see the two highlighted trimmed patches in Figure 1. As also visible from Figure 1, industrial CAD models usually consist of numerous such trimmed surfaces, denoted as *patches* in IGA. To form an actual component, the individual trimmed surfaces of a B-Rep model are topologically connected along common (trimmed) edges as indicated by the red edge in Figure 1.
During analysis, forces and moments need to be transferred between trimmed patches. Because of non-matching discretizations and control points not directly located on trimmed edges, a direct node-by-node coupling is generally not possible. One way to couple trimmed patches mechanically is to enforce these coupling conditions in a weak integral sense, as described in the following section on Isogeometric B-Rep Analysis (IBRA).

$$\delta W_p = -\alpha \int_{\Gamma_c} \left(\boldsymbol{u}^{(1)} - \boldsymbol{u}^{(2)}\right)\left(\delta \boldsymbol{u}^{(1)} - \delta \boldsymbol{u}^{(2)}\right) d\Gamma_c = 0$$

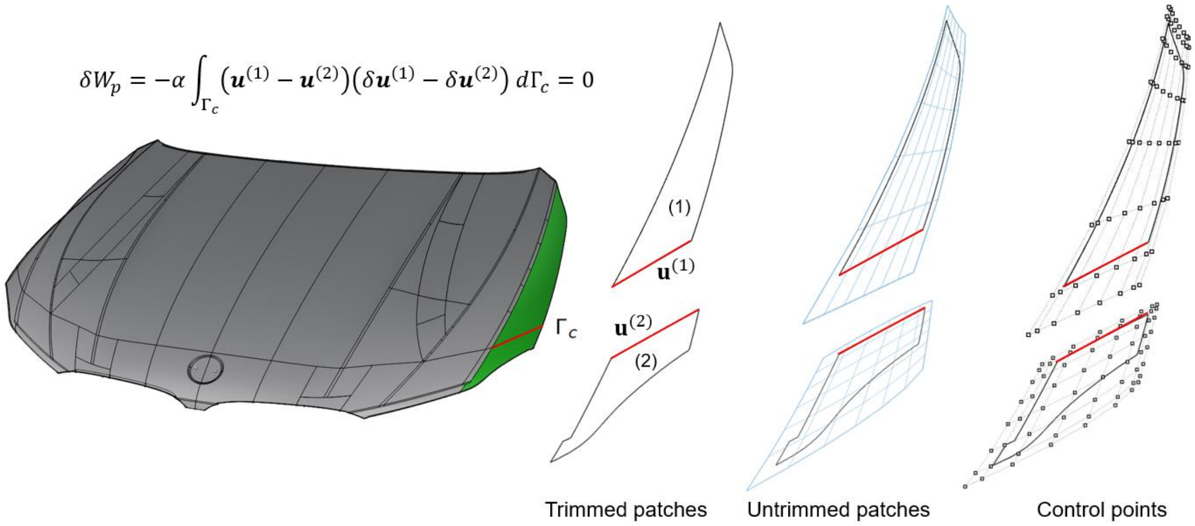

Figure 1 – Trimmed multi-patch CAD model of a BMW engine bonnet.

3. EXPLICIT ISOGEOMETRIC B-REP ANALYSIS (EXPLICIT IBRA)

Isogeometric B-Rep Analysis (IBRA)

IBRA (2) aims at performing structural analysis directly on trimmed multi-patch NURBS CAD models without or with a minimum number of model modifications. This requires particular analysis capabilities like the numerical integration of trimmed elements and coupling of trimmed NURBS patches. To the best of our knowledge, IBRA was the first approach that covered all these necessary functionalities. For the application of coupling and boundary conditions along trimmed edges, IBRA uses so-called *B-Rep edge elements*. These special elements enforce coupling and boundary conditions in a weak integral sense based on a simple and efficient penalty approach. That is, an additional virtual work term δW_p forces the displacement difference ($u^{(1)} - u^{(2)}$) along a common edge Γ_c of two patches to be zero in a weak sense, see Figure 1. The penalty factor α allows adjusting a suitable coupling stiffness. Rotational continuity is handled in a similar manner, see (2,3).

Within IBRA, the analysis model directly inherits the CAD data structure including topology and trimming information. This enables a completely new feature-based analysis paradigm, since CAD features like cut-outs or beadings are also identified as such in the analysis model. That is, analysis-related information like material properties or boundary and loading conditions can be directly assigned to features instead of individual elements/nodes as in FEA. Through this consistent data structure, design modifications made in CAD (e.g. change of position or size of a hole) are automatically updated in the analysis model. A particularly developed plug-in for the CAD program Rhinoceros furthermore allows performing all design, pre- and postprocessing steps within the CAD environment. The corresponding *IBRA exchange format* (4) allows transferring all necessary data between the CAD program and the solver.

Explicit IBRA – The extension to explicit dynamics

In order to perform crash-type simulations on trimmed multi-patch NURBS models used in industry, we extended IBRA to explicit dynamics (3) and implemented the B-Rep elements for coupling via a user interface in LS-DYNA (5). Together with the IBRA exchange format (4) and CAD plug-ins we developed a closed design workflow between the CAD program Rhinoceros and LS-DYNA, see (3). The accuracy and effectiveness of Explicit IBRA were demonstrated by means of benchmark problems including large deformations, plasticity and contact (see Figure 2) and an actual BMW component model (3). Comparisons between IGA and FEA results yielded good agreement (3).

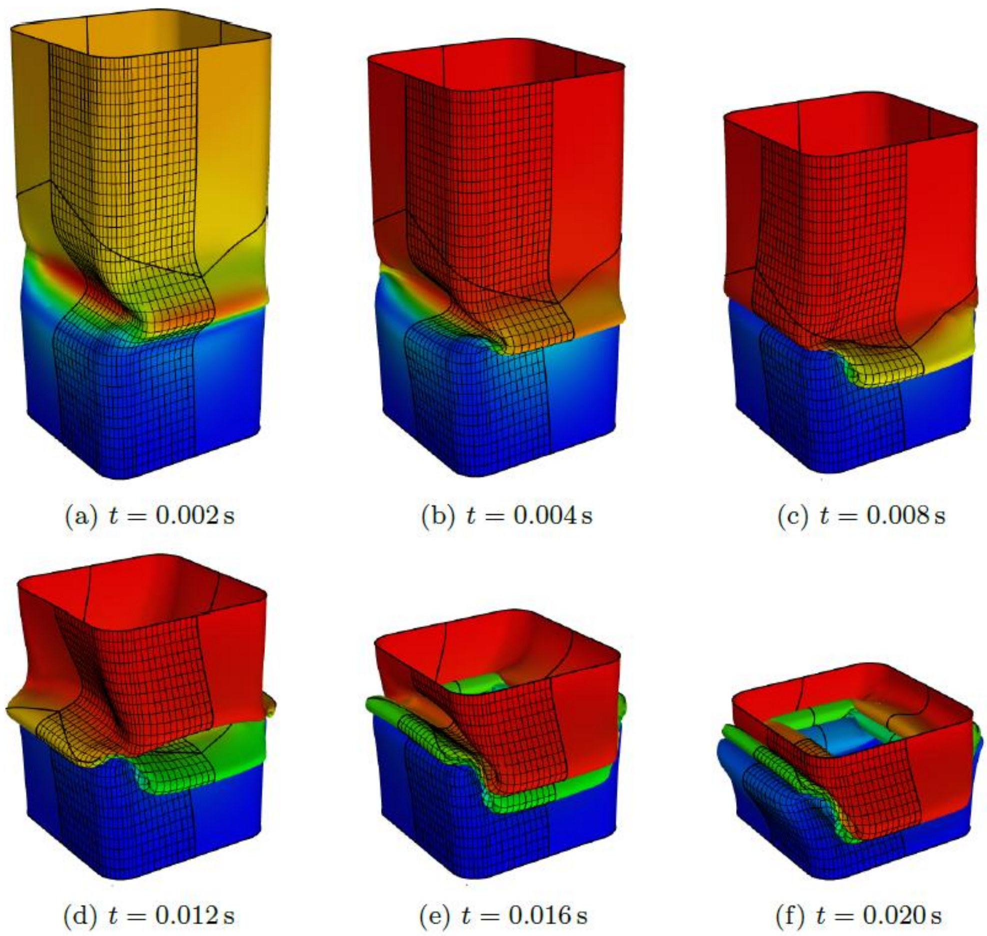

Figure 2 – Dynamic buckling of an energy absorbing tube consisting of multiple coupled trimmed NURBS patches in LS-DYNA, taken from (3).

Industrial example – BMW engine bonnet structure

We are permanently working on improving the robustness of this rather young technology and try to solve ever more complex problems. As in conventional FEA, also the result of an isogeometric analysis depends on the quality of the underlying geometry discretization. This means that IGA models also need to fulfill certain quality criteria and that analyses on existing CAD models originally not generated for IGA, would not lead to high-quality results. IGA model quality criteria as for FE mesh generation are subject of current research and will be successively developed.

A typical BMW CAD model of an engine bonnet structure is depicted in Figure 3. This midsurface model consists of 2630 trimmed surfaces, some of which are extremely small and of high polynomial degree. As in FEA, small elements lead to a small time step size and higher polynomial degree requires a higher number of integration points. To enable more efficient simulations with accurate results, we slightly modified the CAD model according to certain guidelines such as maximum polynomial degree, minimum element size and minimum patch size, see Figure 4. This guideline-conforming CAD model consists of 130 trimmed NURBS patches with a maximum polynomial degree of four. First results of an explicit isogeometric B-Rep analysis of this model in LS-DYNA are depicted in Figure 5. The model with linear elastic material, clamped outer edges and symmetry boundary conditions (applied via B-Rep elements) is subjected to a uniform pressure load. The refinement step was automatically performed by an algorithm. As visible from the smooth deformed shapes in Figure 5, the weak penalty-based coupling within the 130 trimmed works as desired.

4. ISOGEOMETRIC ANALYSIS OF TRIMMED MULTI-PATCH NURBS MODELS WITH ANSA AND LS-DYNA

The numerical examples presented above were generated with our research workflow (3) and solved in LS-DYNA with prototypically implemented B-Rep elements. However, for a productive, efficient and robust industrial design process, professional implementations and tools are required. Inspired by the promising concepts and results of IBRA, the commercial CAE tools ANSA and LS-DYNA are about to implement an efficient industrial workflow for trimmed multi-patch NURBS models.

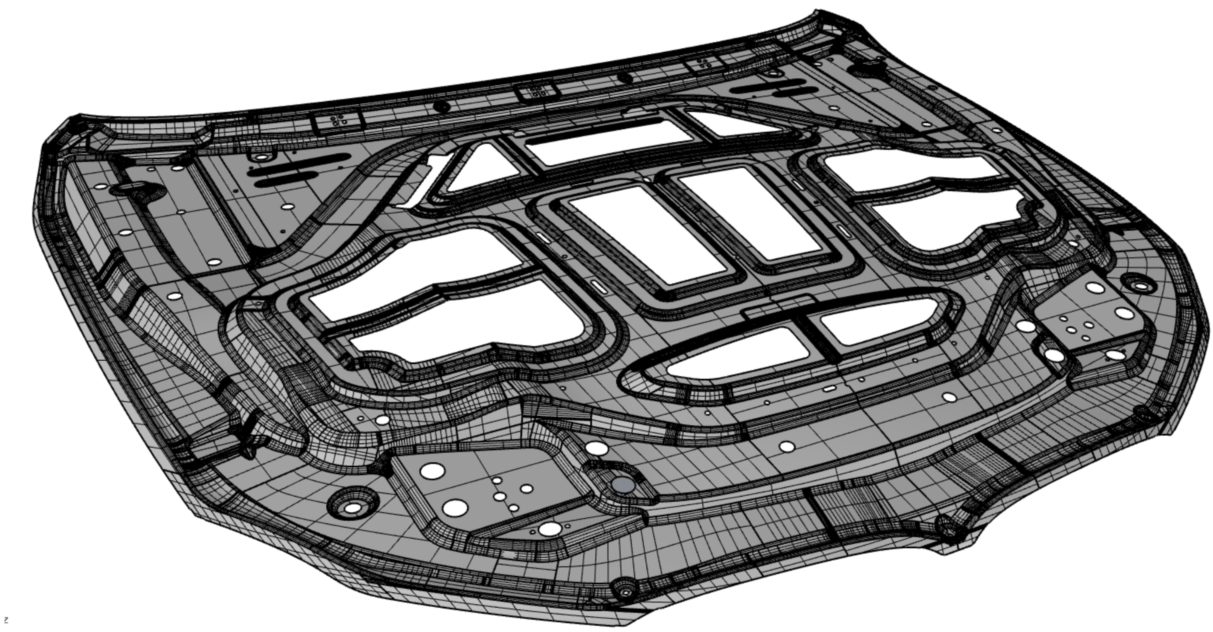

Figure 3 – BMW engine bonnet structure: Midsurface of the original CAD model with 2630 trimmed NURBS patches (automatically generated in CATIA).

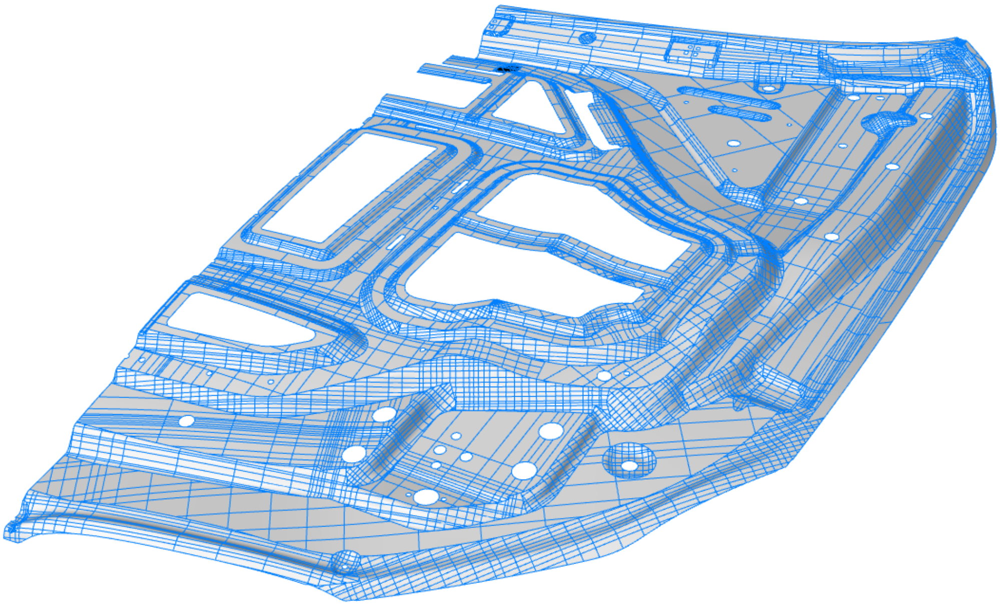

Figure 4 – BMW engine bonnet structure: Guideline-conforming multi-patch model consisting of 130 trimmed NURBS patches.

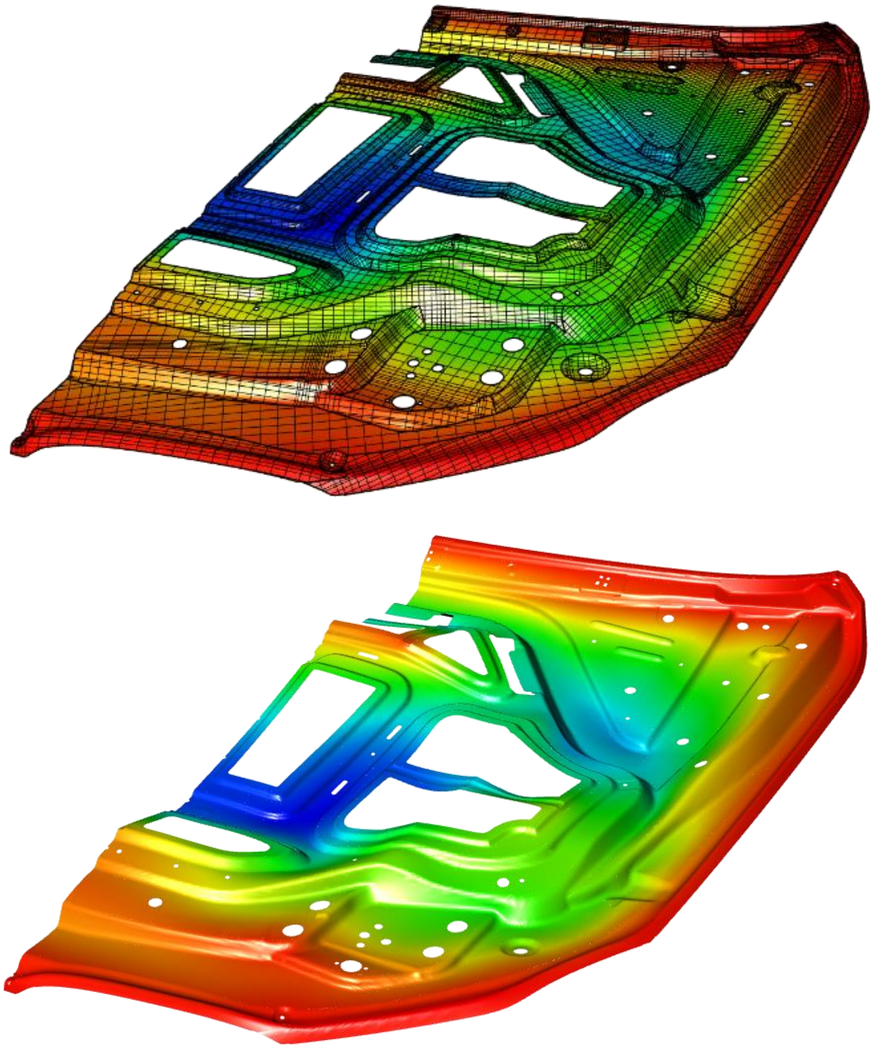

Figure 5 – BMW engine bonnet structure: Scaled deformed shapes of an explicit isogeometric B-Rep analysis in LS-DYNA with (top) and without (bottom) indicated elements.

Isogeometric Analysis in LS-DYNA

Since the early days of IGA, LS-DYNA successively developed IGA features and now covers a wide range of functionalities like NURBS-based shell and solid elements, trimming, contact, various material models as well as explicit features like time step estimation and mass scaling (5). LS-DYNA is furthermore able to combine conventional finite element with isogeometric NURBS-based element components, strongly facilitating the introduction of IGA in industry. Recently, the IBRA patch coupling capabilities were extended to thin shell problems and firmly implemented into LS-DYNA (6), allowing for efficient isogeometric analysis without user-defined interfaces.

Isogeometric Analysis with ANSA

In a perfect world, CAD engineers would design models according to specific modeling guidelines to enable isogeometric analysis on CAD models without any further modifications. However, CAD and analysis models might have different requirements on level of detail, quality or parametrization. Moreover, current CAD models are not designed in accordance to IGA modeling guidelines. In such cases, some amount of model preparation as shown above for the bonnet structure will remain. For the bonnet CAD model in Figure 4, the preparation steps (basically merging of patches and reduction of polynomial degree), were performed in the CAD program CATIA, which is not designed for preprocessing. Therefore more efficient IGA model preparation tools are desired. For this purpose ANSA recently enhanced its existing preprocessing capabilities with several IGA features. Since the ANSA tools for conventional FEA model generation were designed such as to perform geometry clean-up already on the CAD model prior to meshing, many of these tools can be directly used for IGA as well. Together with the specifically designed IGA tools, we expect the CAD model preparation in ANSA to be much more efficient than in current CAD programs.

Figure 6 gives an impression of the IGA preprocessing capabilities in ANSA. It shows the BMW engine bonnet structure reparametrized as a single trimmed NURBS surface with 610 x 740 cubic elements in ANSA. This reparametrization was applied to a CAD midsurface geometry (see Figure 3) prepared with the automatic model clean-up functions in ANSA. For the reparametrization, model parameters such as maximum distortion distance to the original model, minimum and maximum span (~element length), and uniformity of the discretization can be chosen. Based on the concept of trimming, holes, cut-outs and outer edges are still identified as features instead of a set of individual nodes as in FEA. This strongly facilitates the application of boundary, coupling and loading conditions, and a consistent treatment throughout the CAD/CAE process.

In order to obtain a single-surface NURBS model with such a high quality and small deviations from the original model consisting of 2630 surfaces, a relatively fine discretization is required, see Figure 7. As in FEA, also small elements in IGA lead to a small time step in explicit analysis. Modeling the bonnet structure with multiple surfaces – single surfaces for geometrically similar areas – would allow larger elements with a comparable overall accuracy. Thus, although generally possible in ANSA, single surface models will in many cases not be the best choice for the analysis. For components with closed cross-sections, a single surface approach would not be feasible anyway. In the future, the reparametrization might be applied to geometrically similar surfaces, which are then coupled along natural geometrical edges during analysis.

To summarize, the analysis-suitable trimmed single surface model of the BMW bonnet structure in Figure 6 was prepared without manual user modifications and maintains a feature-based analysis model, making the IGA approach well-suited for a highly-automated and consistent CAD/CAE development process.

Remark: At the time of submission of this contribution, work on BMW CAD models prepared for IGA in ANSA and simulated in LS-DYNA is ongoing; results will be presented at the conference.

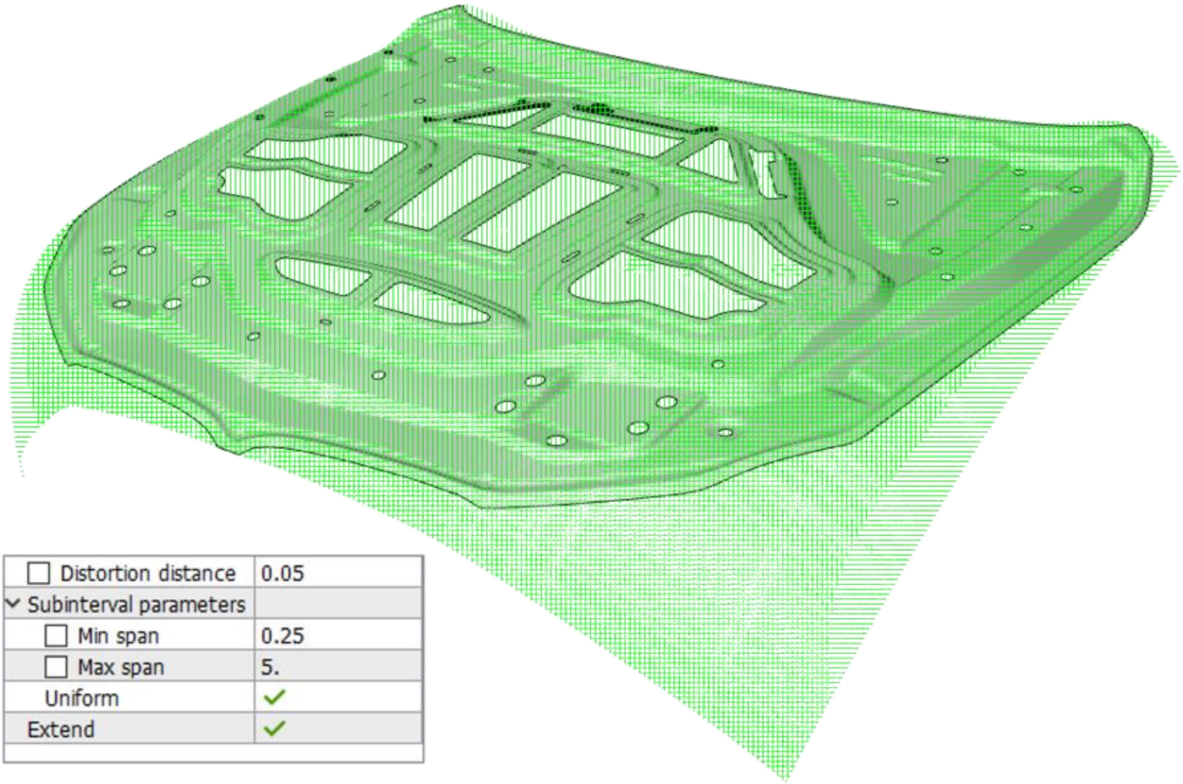

Figure 6 – BMW engine bonnet structure: Trimmed single-surface NURBS model with 610 x 740 cubic elements automatically generated with the ANSA IGA preprocessing tools. The untrimmed surface is indicated in green.

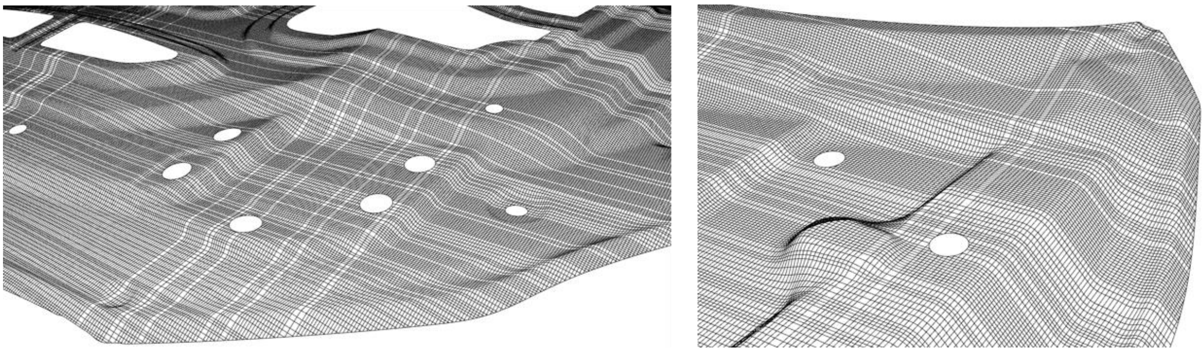

Figure 6 – BMW engine bonnet structure: High geometrical accuracy and fine discretization of the trimmed single-surface NURBS model generated in ANSA.

Industrial IGA workflow

In close collaboration with industry and research, ANSA and LS-DYNA are developing a sophisticated IGA data structure based on trimmed multi-patch NURBS models for efficient and powerful industrial applications. This yields a tight connection between CAD and analysis, and opens the door for first productive applications of IGA in the BMW development environment.

5. CONCLUSIONS

Isogeometric Analysis of trimmed multi-patch NURBS shell structures enables a tight design-analysis connection through a feature-based analysis paradigm. Motivated by promising concepts and results on Isogeometric B-Rep Analysis (2,3,4), ANSA and LS-DYNA enhance their comprehensive capabilities to enable efficient industrial applications of IGA.

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