Application of Trimmed Solid in Isogeometric Analysis to Aluminum Diecast Part

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1 Introduction

With the changes in the global environment such as global warming, automobile OEMs and their affiliates have an urgent need to address carbon neutrality and resource circulation to reduce the environmental impact of their products and their corporate activities. Under such circumstances, as part of the effective use of materials, companies are considering the adoption of large aluminum diecast (ALDC) parts aimed at weight reduction through part integration, and enhancement of material recycling rates. Some OEMs have already introduced such parts to the market. Since prototyping and testing of large ALDC parts require enormous costs and time, it is important to be able to predict and evaluate the part performance through simulations. Crash calculations are no exception.

ALDC parts are generally thicker and more complex in shape than pressed steel parts. Therefore, tetrahedral solid elements are often used instead of shell elements for finite element analysis (FEA). While creating models with tetrahedral solid elements is relatively easy, finer elements and/or higher-order elements are required to achieve sufficient calculation accuracy. Particularly in bending deformation, it is necessary to have sufficient number of element layers in the thickness direction. As a result, the number of elements increases, and the time step size in explicit mechanics becomes smaller which significantly increases computation time compared to shell models. This increase in computation time is one of a major obstacle in crash performance development for vehicles that include large ALDC parts.

Isogeometric analysis (IGA) [1] is one method that can address this issue. Proposed by Hughes et al., this method uses higher-order spline basis functions, which are also used for shape representation in computer-aided design (CAD). Unlike FE model, it can achieve a continuity of C^{p-1} or higher within the model including element boundaries. Here, p is a polynomial degree. This allows to achieve better accuracy even with coarser elements and enables calculations with larger time step size. In bending deformation problems, sufficient accuracy can be obtained with one element in the thickness direction, significantly reducing computation time, especially in solid models. However, creating IGA models for complex and large ALDC parts with solid is still a very challenging task.

Against this backdrop, the development of IGA with trimmed solid [2] has been progressing in recent years. IGA with trimmed solid is a type of embedded method that does not require a boundary-fitted mesh that strictly defines the boundaries of the object, making model creation significantly easier. Considering both model creation time and computation time, IGA with trimmed solid is expected to have a significant effect in crash analysis, including large ALDC parts. However, there are still few application examples in the industrial field, and as far as the author knows, there are no examples of trimmed solid applied in the vehicle crash analysis.

The purpose of this study is to investigate the capability of the trimmed isogeometric solid to analyze ALDC parts, through comparisons of accuracy, calculation time, and modeling time with FEA and/or tests. We first briefly describe the IGA with trimmed solid and then introduce examples of its application to the analysis of ALDC parts. First, in a three-point bending analysis of a small flat plate, we compared the obtained load characteristics with FEA and tests to verify calculation accuracy. Next, we conducted several analyses of larger ALDC parts to confirm the applicability of trimmed isogeometric solid to larger-scale model and compared the results with FE models in terms of computation time.

2 Isogeometric analysis

2.1 Boundary-fitted isogeometric solid

Unlike general FEA, IGA [1] applies spline functions with high-order continuity, such as B-spline, as the basis function for coordinates and displacements. The most basic spline, the B-Spline basis function $N_{i,p}(\xi)$, is defined in the parameter space ξ, which corresponds to the physical space, as shown in equation (1).

$$\begin{aligned} &\text{if } p = 0: \; N_{i,0}(\xi) = \begin{cases} 1\text{ , only } \xi_i \le \xi < \xi_{i+1} \\ 0, \text{otherwise} \end{cases}; \\ &\text{if } p \ge 1: \; N_{i,p}(\xi) = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_{i,p-1}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+1,p-1}(\xi) \end{aligned} \tag{1}$$

Here, p in Eq.(1) refers to the polynomial degree of the spline function. By setting the degree to two or higher, the tangent continuity in the analytical model is achieved including element boundaries. The values with subscript such as ξ_i refer to the component values of the knot vector and it specifies the position of the element division in each direction. Three-dimensional B-spline solid is obtained by tensor-product of basis function Eq.(1) in each direction (ξ, η, ζ). Physical point $\boldsymbol{S}(\xi, \eta, \zeta)$ in three dimensional solid is depicted as

$$\boldsymbol{S}(\xi, \eta, \zeta) = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{l} N_{i,p}(\xi) N_{j,q}(\eta) N_{k,r}(\zeta) \boldsymbol{P}_{i,j,k} \tag{2}$$

Here, q and r are polynomial degrees in direction η, ζ respectively and $\boldsymbol{P}_{i,j,k}$ is a coordinates of control points. A solid defined in Eq.2 basically targets only cuboid geometries. Therefore, when reproducing complex CAD geometries including the geometrical boundary, it is necessary to divide the geometry into multiple hexahedral blocks, then create B-Spline solid patches for each block, and finally join them together. We call this type of B-Spline mesh as “boundary-fitted isogeometric solid”.

In practice, it is very challenging for many of the cast parts to be geometrically divided into only hexahedral blocks, making the application of the B-spline model impractical. In addition, the boundary between the B-spline patches becomes a C^0continuous boundary that can be tangency-discontinuous. In IGA, a high-order continuity is achieved including the element boundary, but as the continuity decreases at the B-spline patch boundary, separating the part into several patches not only impairs the IGA’s advantage, but also may cause unnatural stress concentration or failure at the boundary which is not seen in the FEA.

2.2 Trimmed isogeometric solid in LS-Dyna

To overcome the drawback of boundary-fitted isogeometric solid as stated in the section 2.1, trimmed isogeometric solid is proposed in [2]. The trimmed isogeometric solid is an immersed/embedded method. As shown in Fig.1, the analytical mesh and the geometry boundary are defined independently, eliminating the need to generate a B-spline mesh with strictly defined boundaries. In this case, a calculation can be run as long as the B-spline solid is large enough to fully cover the geometrical boundary, e.g., a cuboid shape defined by a uniform knot vector can be used which makes model creation significantly easy. In fact, a cuboid shape mesh defined by such a uniform knot vector can be generated if the coordinates of the eight cuboid vertices, the B-spline order p, and the knot span size are determined. In addition, as there is no need to separate the splines in patches, there is no issue about the continuity on the patch boundary.

In a B-spline model defined by uniform open knot vector, if a geometrical boundary Γ_{Geom} lies within an outer-most B-spline element on Γ_{Patch}, control point spacing narrows as shown in Fig.2(a). In such a case, the time step size in the explicit calculation will become smaller. By applying a uniform periodic knot vector, the control points can be kept equally spaced so that the time step can be kept larger, as shown in Fig.2(b).

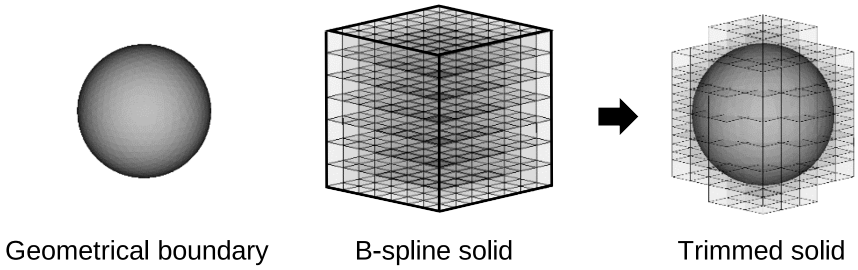


Fig.1: Schematic Image of Trimmed Solid

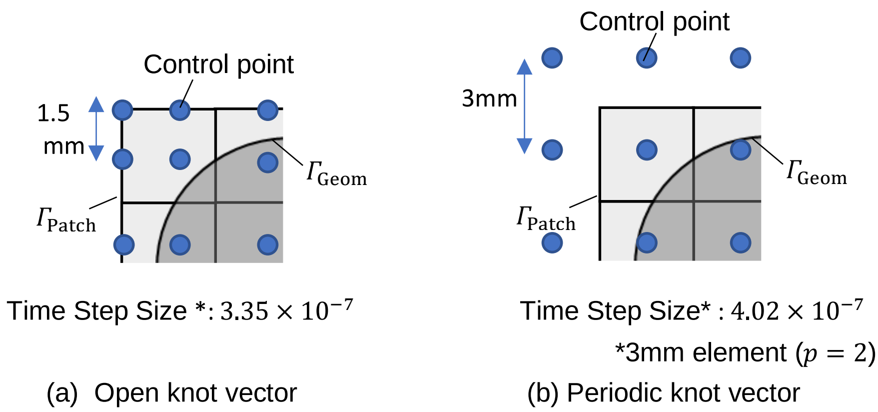


Fig.2: Position of Control Points and Corresponding Time Step Size

3 Numerical Examples

In this chapter, examples of numerical analyses using trimmed solid are presented to demonstrate its advantage over tetrahedral elements and its applicability for crash analysis of ALDC parts. First, a relatively simple three-point bending analysis was performed to evaluate the accuracy of the analysis in the bending deformation. Next, a simulation of a static loading test on a cast aluminum wheel was performed to compare the calculated load characteristics and computational time with FEA and a test result. Finally, the trimmed solid was applied to large ALDC parts in a frontal crash analysis of a vehicle's front structure. It's applicability to a large-scale part was studied and remaining issues were summarized. All cases were computed with an under-development module based on R16, in a dynamic explicit method assuming crash calculations. Polynomial degrees in all directions (Eq.2) were set as the same value ($p = q = r$).

3.1 Three Point Bending Test

The analysis and the test conditions were based on the bending test standardized in the Verband der Automobilindustrie (VDA). The detailed conditions are summarized in Table 1. ELFORM13 was used for the 4-node tetrahedral element, and ELFORM16 for the 8-node tetrahedral element of the FEA for comparison. Quadratic (p=2) and cubic (p=3) B-spline solid were used for the trimmed solid, and the tetrahedral mesh for geometrical boundary was created with an element size of 3mm. The created models are shown in Fig.3. When the B-spline element size was set to 2mm or 3mm, all the elements were trimmed because the element size is larger than or equal to the plate thickness, while the element size can be defined equally regardless of the plate thickness. This verification was performed using an SMP calculation.

Size of specimen	Width: 20, Length: 55mm, Thickness: 2mm
Diameter of supports	30mm
Radius of pusher	0.4mm
Distance between supports	4mm

Table 1: Conditions of the Bending Test

Figure 4 shows the calculated force-stroke curves. For the FE model with the 4-node tetrahedral elements (ELFORM13), there is a large deviation with the test result when applying 2- or 3-mm mesh size. They show a large enhancement by modifying them to the 8-node elements. For the trimmed solid, both quadratic and cubic elements showed good correlation with the test results regardless of the element size.

Figure 5 shows the relationship between the analysis time and the error of load between the analysis and the test at 4mm stroke. The 4-node tetrahedral model, which is shown in gray, was fast, but the error was large. The 8-node tetrahedral model, shown in yellow, showed smaller error compared to the 4-node tetrahedral model, but the analysis time was longer. On the other hand, both trimmed solids showed an error within ±5% with respect to the test result and ran faster than the 8-node tetrahedral models. One of the reasons for the shorter analysis time is the time step size. Because the B-spline elements can be made larger than the thickness of the plate in the trimmed solid model, the time step size becomes larger than the FE mesh. Furthermore, according to Hartmann et.al. [3], a stable time step size of the spline element becomes larger with increasing B-spline order p and interelement continuity. This fact may have also contributed to the faster analysis with the trimmed solid. These results demonstrate the reproducibility of bending deformation due to the high-order continuity of B-Spline solid, and validity of the geometry (or thickness) reproduction of the trimmed solid.

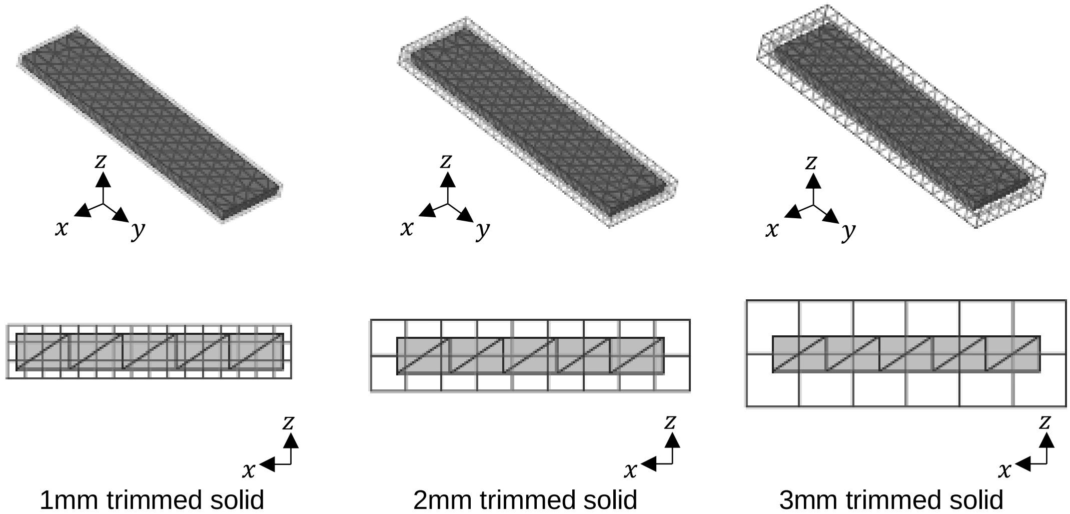


Fig.3: Trimmed Solid Model for Bending Test

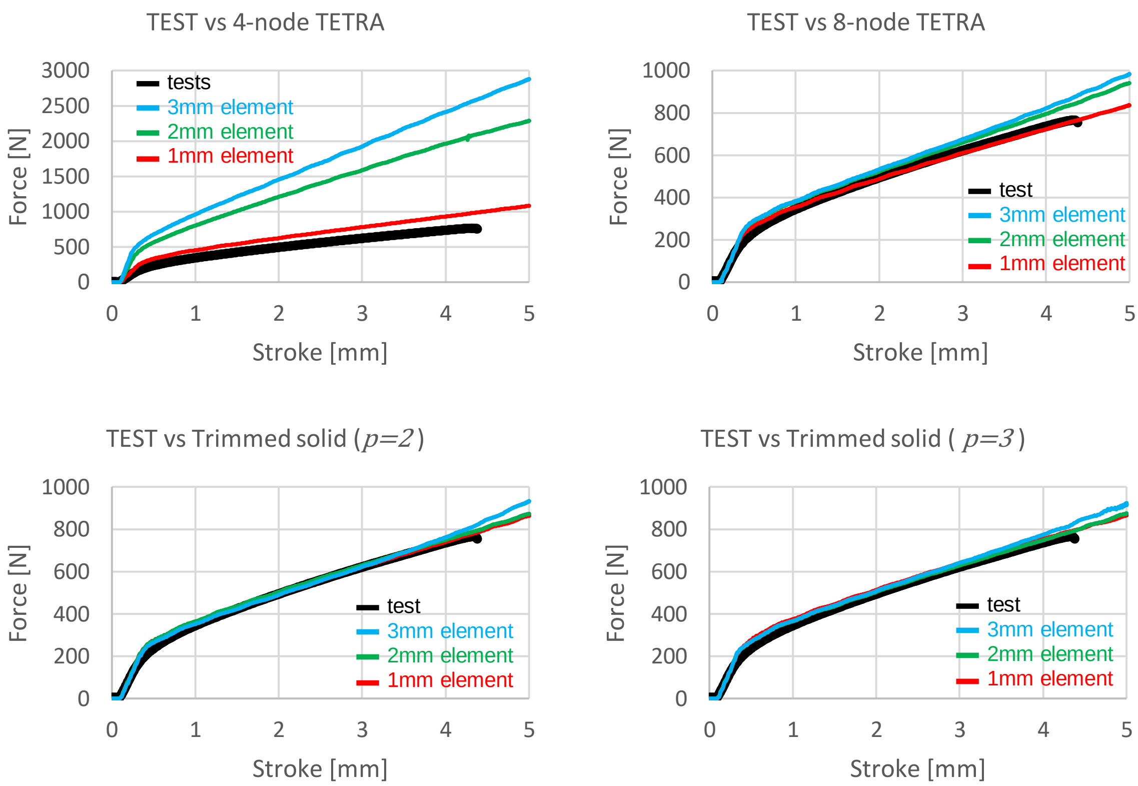


Fig.4: Force-Stroke Curves of VDA Bending Analysis

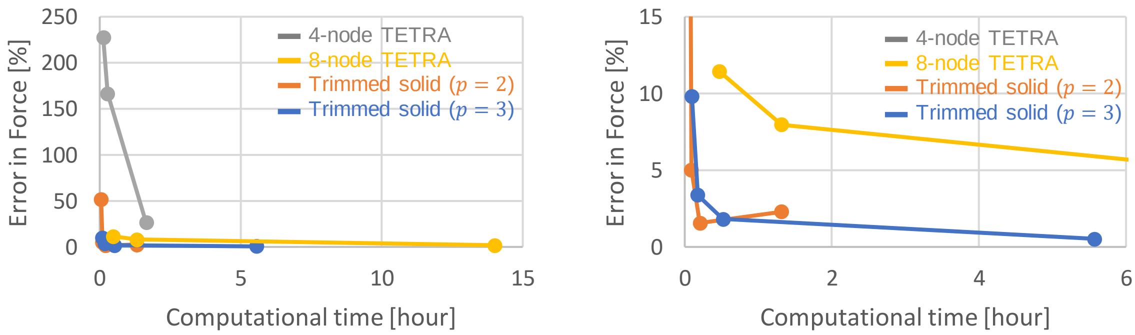


Fig.5: Error vs Computational Time in VDA Bending Analysis

3.2 Aluminum Diecast Wheel

Next sample case is the static loading test of an ALDC wheel. The boundary conditions are shown in Fig.6. 3mm and 5mm B-spline elements ($p = 2$) were applied for the trimmed solid model, and 3mm 8-node tetrahedral elements for the FE model. In Fig.7 the deformation and plastic strain distribution of the trimmed solid model is shown, and it can be observed that the plastic strains are concentrated at the location where the crack initiated in the actual test.

Figure 8 shows the force-stroke curve. Both trimmed solids with different mesh size were able to reproduce the load characteristic up to the load peak, and they were similar to the load behavior obtained from 3mm 8-node tetrahedral mesh. It showed that coarser B-spline mesh can still reproduce the load characteristic in the similar accuracy as compared to finer 8-node tetrahedral mesh in this analysis case. Table 2 shows the list of analysis time for each model. The 8-node tetrahedral model which had a good accuracy in terms of force, took more than 14 hours for the calculation. On the other hand, 5mm trimmed solid only required 1.5 hours to achieve the similar accuracy. One of the main reasons for this is that the time required for element processing was significantly reduced due to the larger time step size.

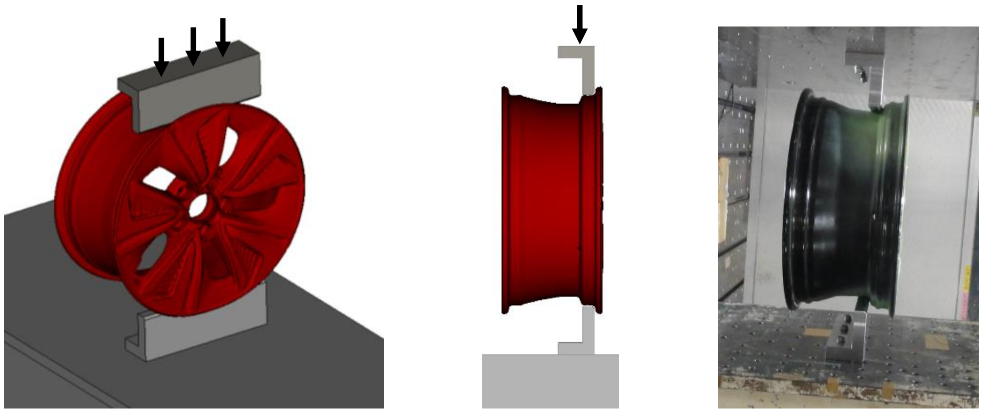


Fig.6: Boundary Condition of the Static Wheel Compression Test

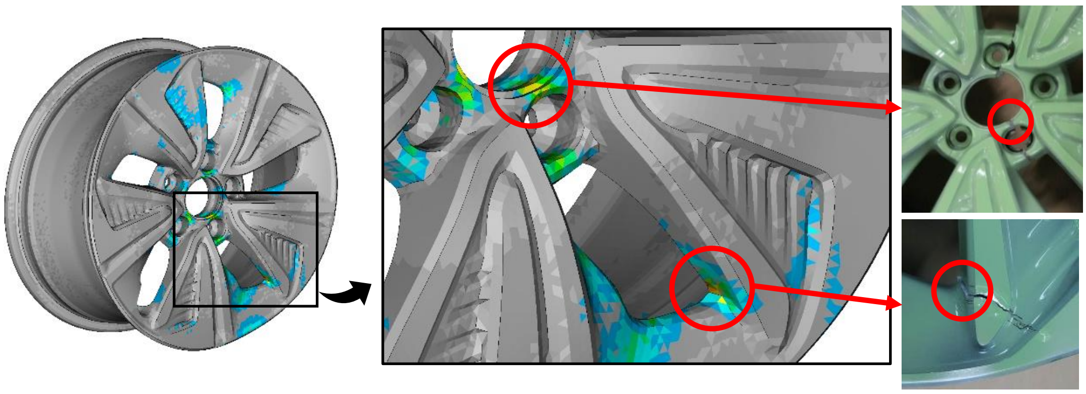


Fig.7: Deformation and Plastic Strain Distribution of Trimmed Solid Compared with Actual Test

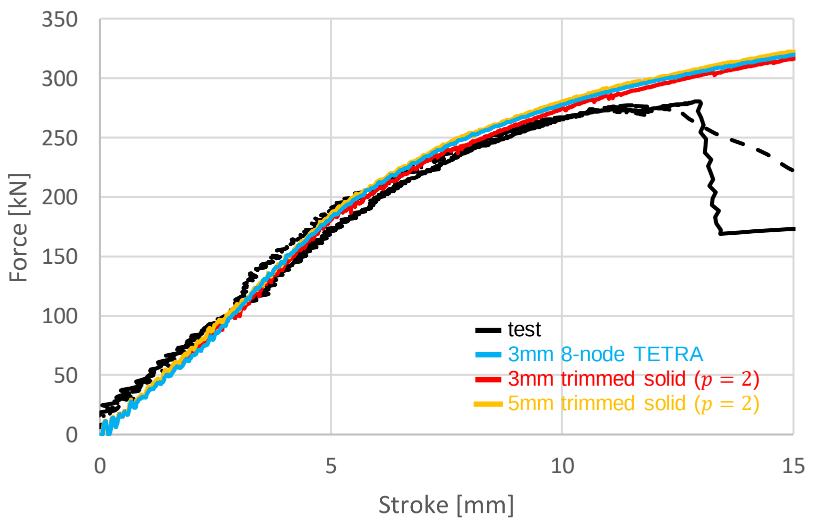


Fig.8: Force-Stroke Curve of the Static Wheel Compression Test

	8-node TETRA 3mm	Trimmed solid 3mm ($p = 2$)	Trimmed solid 5mm ($p = 2$)
Time step size	0.9×10^{-7} s	4.0×10^{-7} s	4.4×10^{-7} s
Total CPU time	14 hr 54 min	3 hr 10 min	1 hr 31 min
Element process	10 hr 22 min	1 hr 29 min	23 min

Table 2: Comparison of Time Step Size and CPU Time

3.3 Large Aluminum Diecast Component

Lastly, a frontal full-lap crash analysis was performed on a vehicle's front structure with large ALDC component which the trimmed solid was applied. Fig. 9 shows the part composition and the boundary conditions. This model consists of both ALDC parts and aluminum extrusion parts. Linear shell elements were applied for the extrusion parts and 5mm trimmed solid elements for the ALDC parts. The structure was fixed at the rear ends, and was crashed by a flat rigid barrier travelling at the constant velocity of 56.4 km/h. For the bolt connections, the bolts themselves were modelled as rigid tetrahedral elements, and the connection was reproduced by contact between the parts and the bolts.
Point connection models, as shown in Fig.10, were applied to represent rivet connections between the two ALDC parts. As a means of point-connection, several nodes which lies within the connection area were bonded rigidly by *CONSTRAINED_ NODAL_RIGID_BODY for the FE model. On the other hand, similar method cannot be applied for the trimmed isogeometric solid, as a location of control points does not match with a physical point. Therefore, free nodes were created on the surface of the trimmed solid which are to be connected, and these nodes were rigidly connected by *CONSTRAINED_NODAL_ RIGID_BODY. The penalty connection between the trimmed solids and the free nodes were established by *IGA_POINT_UVW which is implemented in LS-Dyna. Furthermore, element erosion was triggered based on an integral ductile fracture condition [4,5], as typified by Cockcroft and Latham.
Figure 11 shows the calculation results of two models, (a) without an element erosion and (b) with the erosion. Both calculations reached normal termination. The one without the erosion showed deformation concentrated in the front and rear portion of the motor room, while the one with the erosion showed different deformation mode, with more progressive deformation from front to middle portion of the motor room. The rivet connections with *IGA_POINT_UVW and *CONSTRAINED_NODAL_RIGID_BODY functioned properly as the bonded parts did not slide or separate with respect to each other.
Figure 12 shows the close-up of the eroded region. As seen in the figure, majority of the B-spline was eroded within the dotted area, which is unrealistic. As the higher-order B-spline elements have high continuity of displacement, an influence on the neighboring element upon element erosion is larger than FEA, resulting in excess progressive erosion of elements. Representation of extensive failure mode with IGA is one of remaining future works.
A calculation time was about 1.5 hours for both cases with 140 cores, which was about 41% of the FE model which applied 5mm 8-node tetrahedral solid for the ALDC parts. This result shows significant advantage of calculation time over FE model.

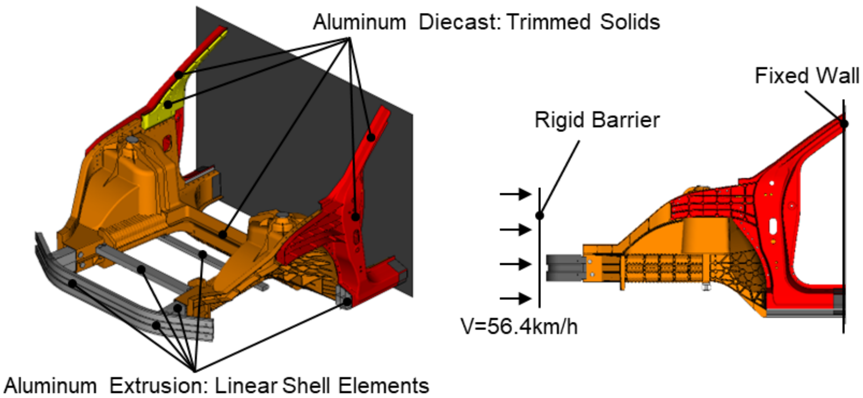


Fig.9: Part Composition and Boundary Conditions for Frontal Crash Model

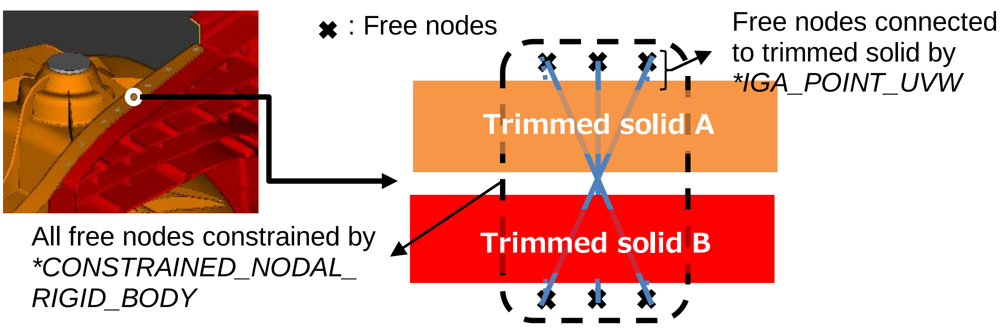
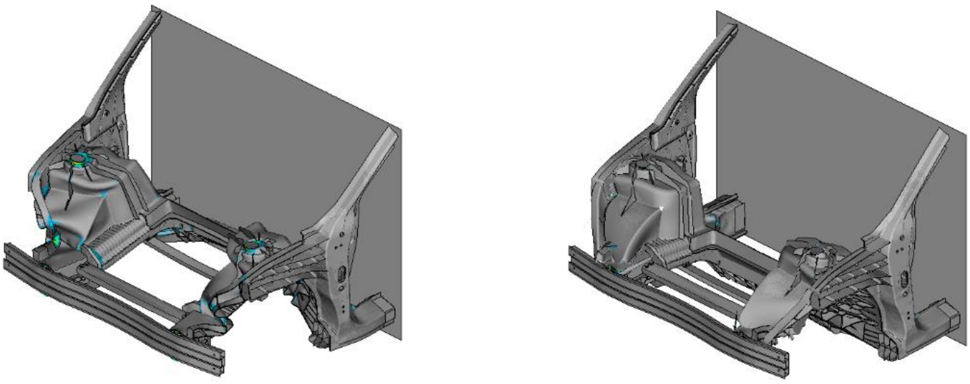


Fig.10: Point-Connection Model for Trimmed Solid



(a) Without element erosion (b) with element erosion

Fig.11: Frontal Crash Analysis Results

Before element erosion After element erosion

Fig.12: Excess Element Erosion in the Front Structure

4 Summary

In this study, a trimmed solid for IGA was applied to ALDC part analysis, aiming for increase in analysis speed compared to the conventional tetrahedral solid. At first, a three-point bending analysis was performed and was compared with tetrahedral mesh. The trimmed solid model achieved similar or better accuracy than the tetrahedral mesh with shorter calculation time. In the ALDC wheel example, the tested load-stroke behavior was well reproduced by the trimmed solid, while achieving significantly faster analysis time compared to the tetrahedral mesh, showing that the trimmed solid is applicable to parts with complex shape. Finally, it was applied to a frontal full-lap crash analysis with large ALDC part, demonstrating that it is applicable to large-scale model. On the other hand, there is still an issue in the analysis with crack generation and failure, as it showed an instability. Especially in the analysis case with pronounced failure, element erosion tends to be more extensive than expected. It is necessary to further investigate on how to better represent failure which suits to the B-spline elements with high-order continuity.

5 Literature

[1] Hughes T.J.R., Cottrell J.A., Bazilevs Y.: “Isogeometric analysis: CAD finite elements NURBS exact geometry and mesh refinement”, Computer Methods in Applied Mechanics and Engineering, Vol.194, 2005, p.4135-4195

[2] Meßmer, M., Teschemacher, T., Leidinger, L.F., Wüchner, R., Bletzinger, K. -U : "Efficient CAD-integrated isogeometric analysis of trimmed solids”, Computer Methods in Applied Mechanics Engineering, Vol. 400, 2022, 115484

[3] Hartmann S., Benson D.J.: "Mass scaling and stable time step estimates for isogeometric analysis", International Journal for Numerical Methods in Engineering, Vol.102, 2015, p.671-687.

[4] Cockcroft, M.G. and Latham, D.J.: "Ductility and the workability of metals". Journal of the Institute of Metals, Vol. 96, 1968

[5] Takuda H., Hama T., Nishida K., Yoshida T., Nitta J.: "Prediction of Forming Limit in Stretch Flanging by Finite Element Simulation Combined with Ductile Fracture Criterion", Computer Methods in Materials Science, Vol.9, 2009, No.1, p.137-142.