

A Study on Fracture Analysis Using Isogeometric Analysis with Trimmed Solids

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The adoption of integrated components such as aluminum die-cast and additively manufactured parts in automotive body structures has increased in recent years to reduce weight and part count. These structures often possess complex three-dimensional geometries, making shell-based modeling insufficient for accurately representing thick-walled regions and intricate local features. As a result, solid elements are commonly employed in crash simulations. However, achieving reliable fracture predictions with conventional finite element analysis (FEA) typically requires significant mesh refinement and higher-order elements, which reduce the stable time step size in explicit dynamic analyses and increase computational costs.

Trimmed Solid Isogeometric Analysis (Trimmed Solid IGA) has been proposed as an alternative framework that combines accurate geometric representation with high-order continuous basis functions. Unlike conventional boundary-fitted IGA formulations, which require structured control meshes to accurately represent complex geometries, Trimmed Solid IGA directly utilizes CAD boundary representations (B-Rep), enabling efficient analysis of complex geometries while maintaining the advantages of higher-order spline approximations. Previous studies have demonstrated significant reductions in computational costs for automotive crash simulations; however, applications to fracture-dominated problems remain limited.

In this study, Trimmed Solid IGA was applied to fracture analyses of aluminum die-cast components subjected to crash-related loading conditions. Its performance was evaluated by comparison with conventional tetrahedral finite element models. Two benchmark problems were investigated: a three-point bending test of an aluminum plate and an axial compression test of a die-cast frame component representative of automotive structures. Fracture behavior was modeled using an element erosion approach based on plastic strain criteria, with failure thresholds defined as a function of stress triaxiality.

For the three-point bending problem, first-order tetrahedral elements (Tet4) exhibited significant overprediction of structural stiffness and load response, even with refined meshes. Although second-order tetrahedral elements (Tet10) enhanced the accuracy, the predictions required relatively fine discretization and large computational costs. In contrast, Trimmed Solid IGA produced force-displacement responses that agreed closely with experimental measurements over a wide range of element sizes. The method also reproduced the sudden load drop associated with fracture initiation and crack propagation more accurately than conventional tetrahedral models. These enhancements are attributed to the high-order continuity of spline basis functions, which alleviates shear and volumetric locking effects.

The axial compression analysis of the die-cast frame component yielded similar trends. Trimmed Solid IGA accurately predicted the peak load and energy absorption characteristics observed in physical tests (Figure 1), while both Tet4 and Tet10 models tended to overestimate post-peak load levels and absorbed energy. Furthermore, the IGA models maintained comparable accuracy with substantially fewer computational resources. The larger stable time step size achievable with Trimmed Solid IGA reduced the total number of explicit solution cycles, resulting in a computational time reduction of up to 94% compared with conventional tetrahedral FEA models (Table 1).

The results demonstrate that Trimmed Solid IGA provides an effective framework for fracture analysis of aluminum die-cast automotive components, achieving both enhanced prediction accuracy and computational efficiency. Nevertheless, due to the high continuity of spline basis functions, extensive element deletion was observed around fracture regions. Future work will focus on introducing local continuity reduction techniques to enhance the prediction of crack initiation and propagation.

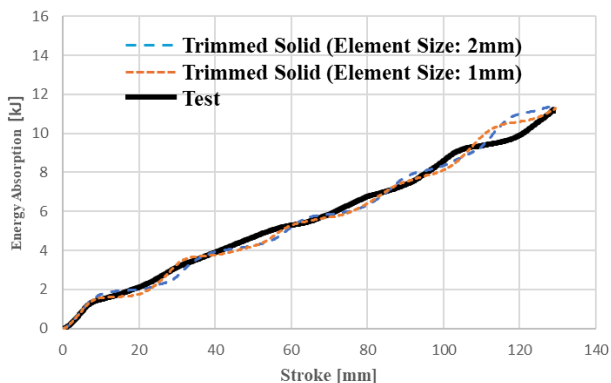


Fig.1 Comparison of Force-Displacement responses for the Die-Cast Frame Model

Table 1. Computational Time Comparison

Model	Computational Time	Reduction Rate over Tet4
Tet4 (Element Size: 1mm)	23.4 Hours	-
Tet10 (Element Size: 2mm)	21.8 Hours	-7%
Trimmed Solid (Element Size: 1mm)	14.3 Hours	-39%
Trimmed Solid (Element Size: 2mm)	1.4 Hours	-94%