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Development of a numerical tool for Step & Gap prediction on Space Rider Windward

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Abstract

The objective of the work is to predict the value of the Steps and Gaps among the windward shingles that could be a critical issue for re-entry vehicle. To achieve this goal efficiently, a computational cost-saving approach was adopted through the use of a homogenized model. The windward TPS (Thermal Protection System) consists of flat and curved shingles, as well as complex Hinge TPS elements, connected to the structure with an attachment system designed for rigidity, flexibility, and thermal insulation. The presence of discontinuities like protuberances, cavities, gaps, or steps on the vehicle's surface can impact the aerodynamic characteristics and heat transfer rates during high-speed flight, potentially leading to catastrophic consequences. The optimization of the Standoff's placement is crucial to mitigate in-flight deformations, which influence thermal flow behaviour and windward deformations.

The homogenization process involves accurately defining the mechanical and thermal properties of the structural components, specifically the Standoff, through iterative tuning. The analyses focus on monitoring results along the shingle edges and deformations along the contour. The homogenized model simplifies the complex Standoff structure while maintaining accuracy, leading to reliable results in reduced timeframes.

The obtained results were validated through cross-validation with three-dimensional models, reducing the maximum average error to a few tenths of a millimetre. Conventions for step and gap definitions were established, and an algorithm was developed to obtain outcomes within the local reference system of each curved shingle edge element. Despite the introduction of some approximation in the results, particularly for Steps, they are considered reliable when calculated as average values and are consistent with 3D models and reference literature.

Keywords: TPS, Step, Gap, Windward, Spacerider

Nomenclature

CAD - Computer-Aided Design
CS - Cold Structure
ESA - European Space Agency
I/Fs - Interface(s)
RBE3 - Rigid Body Element 3
TPS - Thermal Protection System
TSI - Thermal Structural Integration

1. Step & Gap

This abstract outlines the workflow employed to determine Step & Gaps on the Windward, of the space plane Space Rider (Space Reusable Integrated Demonstrator for Europe Return), which is a planned uncrewed orbital lifting body spaceplane aiming to provide the ESA with affordable and routine access to space, emphasizing the overarching objectives of the work.

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1.1. Work Overview

The core concept of this paper revolves around optimizing the computational efficiency of structural analyses for assemblies featuring redundant elements. The aim is to develop a method that generates a single element capable of homogenizing physical properties relevant to a specified output. Depending on the desired outcome, varying degrees of complexity may be required in defining the mathematical properties of this element.

One potential advancement of this concept involves the creation of software capable of autonomously constructing such elements. This software would need to define a range of input parameters and iteratively determine the mathematical properties necessary to achieve a desired output. For instance, it could establish the relationship between pressure loads and resulting deformations, ensure accurate temperature distribution and thermal deformations under thermal loads, and account for the element's ability to deform in response to shear forces.

In the specific context of this project, the focus lies on analyzing the deformation along the edges of Space Rider panels under different flight conditions. The outputs sought are deformations measured within the local reference system of the panel edges. These deformations are influenced by various inputs, including pressure loads, thermal loads, and inertial forces.

To accurately model these deformations, the mathematical properties assigned to the element must correspond to its behavior under each type of load. This includes defining how the element responds to pressure loads to achieve the correct deformation, determining its thermal properties to ensure accurate temperature distribution and subsequent thermal deformation, and establishing its ability to deform in-plane under shear loads.

The combined study of Steps and Gaps, along with an analysis of dimensional deviations measured downstream of manufacturing processes, offers the potential to fine-tune the Standoff's integration phase.
This fine-tuning aims to mitigate in-flight deformations, which, in turn, influence the thermal flow behaviour and the resulting Windward deformations.
The image below presents a summary of the workflow used to determine the result.

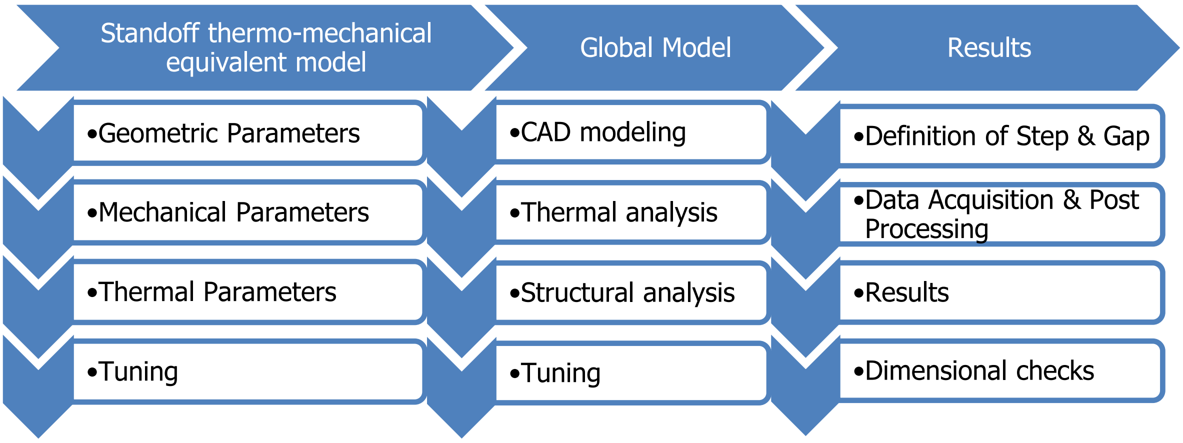

Fig. 1 Workflow

This imperative arises from the paramount significance of gaining a profound insight into the windward's response across a spectrum of conditions. The notable feature of this endeavour is the emphasis on computational cost savings, prompting the adoption of a homogenized model.
The windward ISiComp® TPS is composed by 5 flat shingles, 16 curved shingles and the two complex and large Hinge TPS elements.
Each shingle is a monolithic piece of ISiComp® and is connected to the CS by means of an attachment system designed to provide rigidity, flexibility and thermal barrier as it is for the Nose I/Fs.

Each shingle is composed by a skin, reinforced by Omega shaped ribs and 'T' shaped ribs. The Omega shaped ribs also provide the interface to the attachments. The 'T' shaped ribs lay on geodesic curves that connect the attachment points. [1]

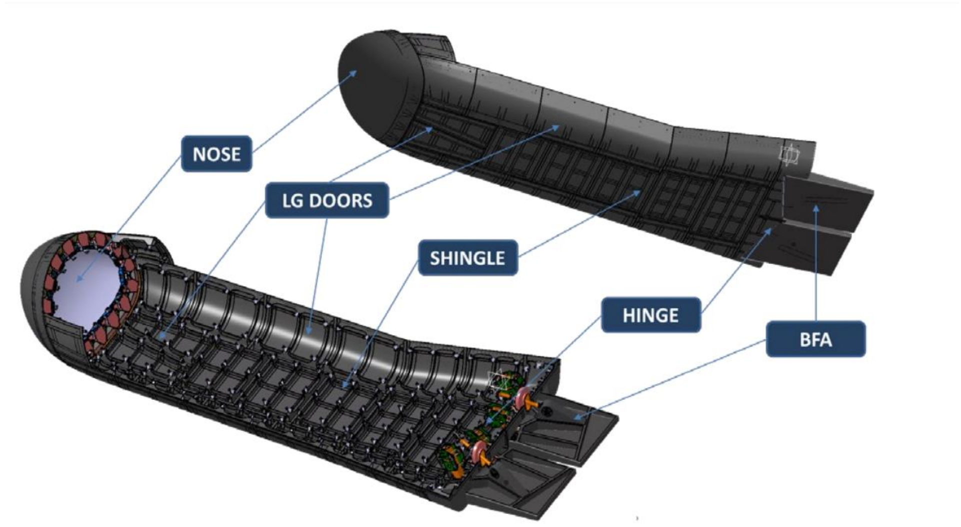

Fig. 2 Space rider TPS

1.2. Physics of the phenomenon

These discontinuities, due to the interaction with external flows, may contribute to physical phenomena related to the problem of flow separation. When separation occurs in high Mach number flows, changes on the pressure distribution acting on the surface and on the heat transfer rate to the surface can have catastrophic effects on the vehicle. The presence of hot spots at separation and reattachment points changes the characteristics of the flow over the vehicle and can cause failure in the thermal protection system of the vehicle, for instance. Gaps, even by themselves, promote transition. However, a gap of a given width is not as effective as a step of equal height. Tiles which are depressed (a negative misalignment height) are not quite as effective in promoting transition as tiles which protrude above the adjacent tiles in the configuration.
Hypersonic vehicles are thermally protected during the re-entry in the Earth atmosphere by a thermal protection system made by a large number of tiles on their structures. [2]

1.3. Homogenized model

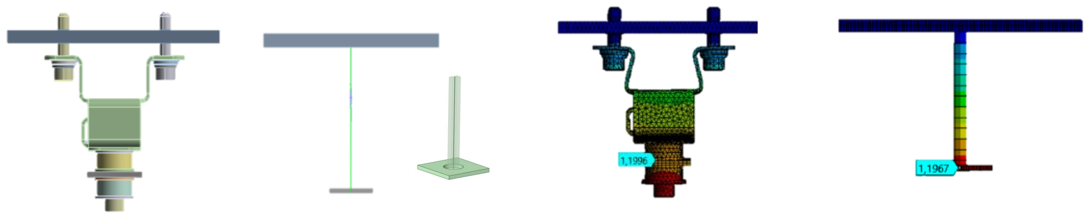

Fig. 3 Homogenized model

The image above presents a graphical display of the homogenized model compared to the standoff.
The analyses primarily benchmark total deformations along the edges of the shingles. Therefore, all assessments, tuning, and comparisons primarily focus on monitoring results along the shingle edges and, of course, the full contour of total deformations.
The mechanical properties of the element were defined. To gradually study how to obtain good results, the material was assigned as isotropic. This choice proved to be in agreement with the results and therefore was not changed retrospectively.

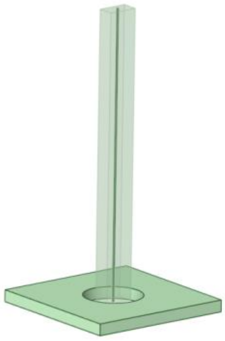

Fig. 4 Homogenized one-dimensional element

The geometric properties of the one-dimensional object shown in the figure were initially defined. To ensure precise positioning within the CAD model, ensuring an unequivocal alignment, shingle by shingle, the midpoint between the two Standoff bolts was selected as the first vertex, and the midpoint of the Shingle hole was chosen as the second vertex.
A rectangular section was then defined for the line, ensuring it could adequately respond to loads in-plane. Next, the transverse stiffnesses of the standoff were evaluated, and a rectangular section was assigned that best reproduced the transverse stiffness of the three-dimensional element. Once the geometric characteristics were defined, mechanical properties were assigned to best meet deformation requirements at various temperatures. Subsequently, thermal parameters necessary to accurately propagate heat waves within the one-dimensional element were identified. Finally, the thermal expansion coefficient that best reproduced the deformations of the standoff at various temperatures was determined. The image below shows the iterative process that was conducted to determine all the properties of the one-dimensional element.

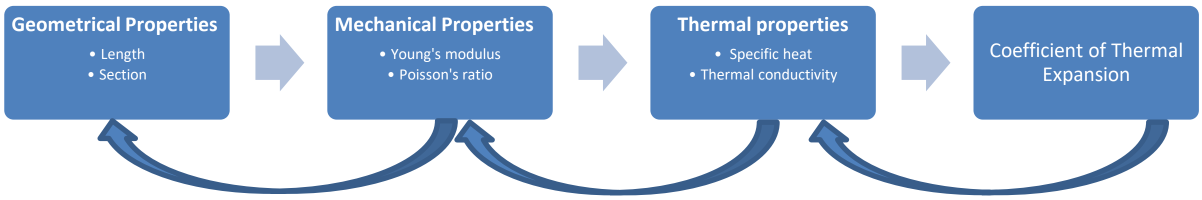

Fig. 5 Block diagram describing the process used to derive the parameters

Subsequently, structural analysis of the standoff was conducted, where was verified the expected deformation and adjusted the Young's modulus progressively to meet the desired results.

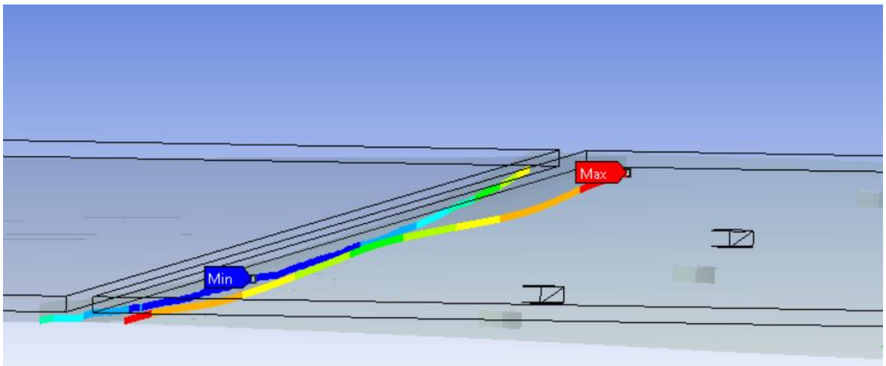

Fig. 6 Total deformations of two adjacent sides for step & gap evaluation

This iterative process was carried out across various temperatures, particularly those anticipated within the standoff, allowing for a margin of safety. The initial tuning was executed, referencing a portion of Omega, followed by a section of Shingle, and ultimately encompassing the entire Shingle structure. The contact relationship between the one-dimensional element and the surface of the hole followed a Master-Slave type, akin to an RBE3 formulation. To optimize computational cost savings, a mixed 3D analysis with 1D elements was adopted, focusing on the Standoff structure.

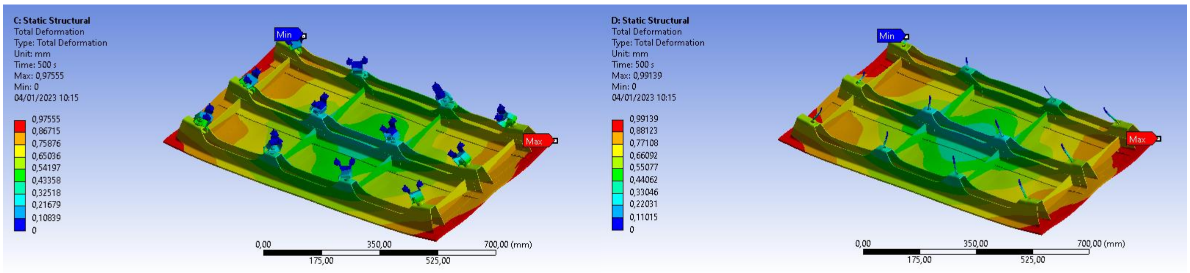

Fig. 7 Comparison of total deformations in the two models

1.4. Global model

The next step involved replacing all the standoffs with the one-dimensional element. Furthermore, the original CAD was modified to facilitate the meshing operation and to obtain better results in the desired areas. In the image below the CAD model with the one-dimensional elements followed by the detail of the mesh:

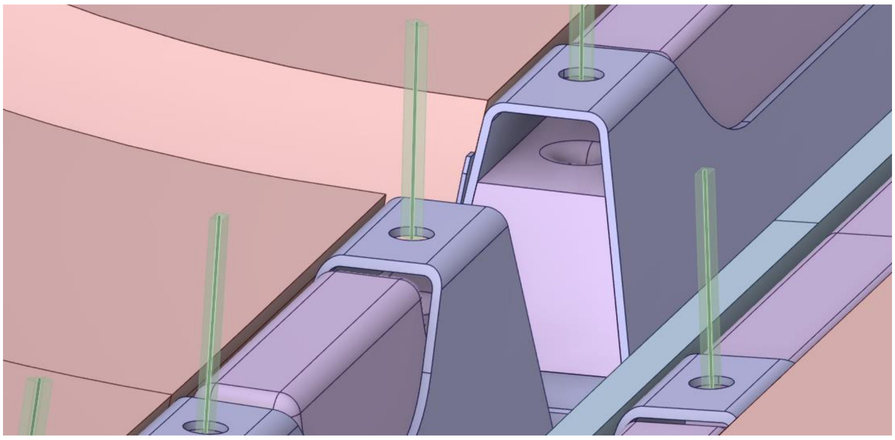

Fig. 8 Detail of the homogenized element applied to the assembly

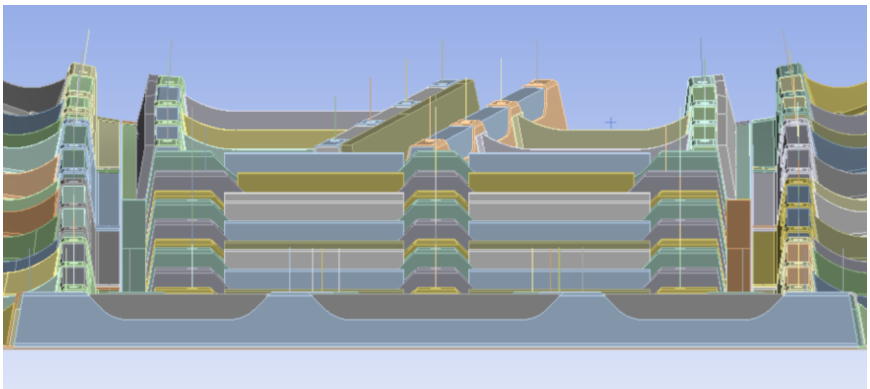

Fig. 9 CAD-Global model

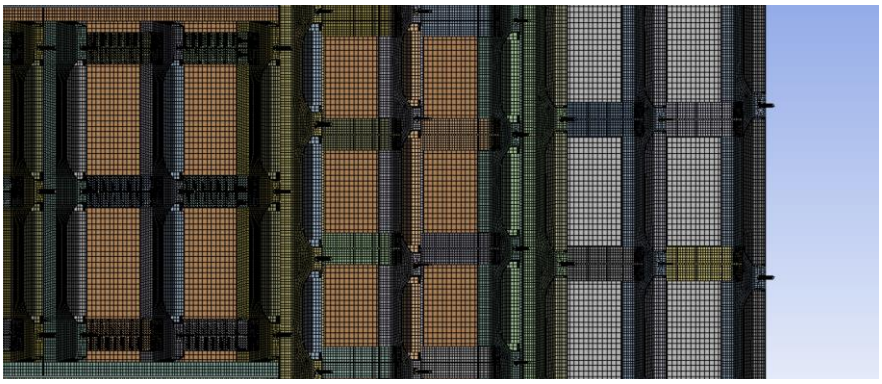

Fig. 10 Mesh-Global model

Special attention was directed towards the skin and omega components, as they play a pivotal role in shaping the structural outcomes of the analysis. The analysis transitioned to a transient study along the Max Heat Flux trajectory. Specifically, the maximum temperatures did not exceed the Isicomp limits, and the minimum temperatures remained within the permissible range for the CS. Subsequently, the temperatures obtained from the thermal analysis were integrated into a structural analysis. Insulation components that did not contribute to structural rigidity were excluded from the analysis, and the pressures calculated along the trajectory were incorporated.
To verify whether the results were in conformity with the 3D model, analyzes were carried out on various Shingle samples and a numerical comparison was made to understand the deviation between the two models.

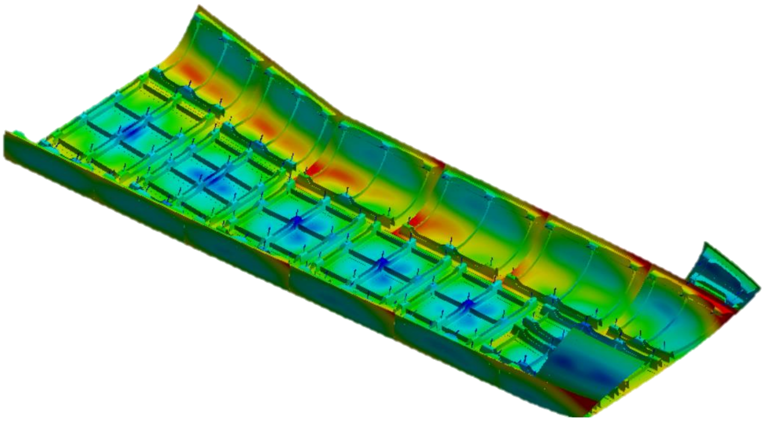

Fig. 11 Total Deformations-Global model

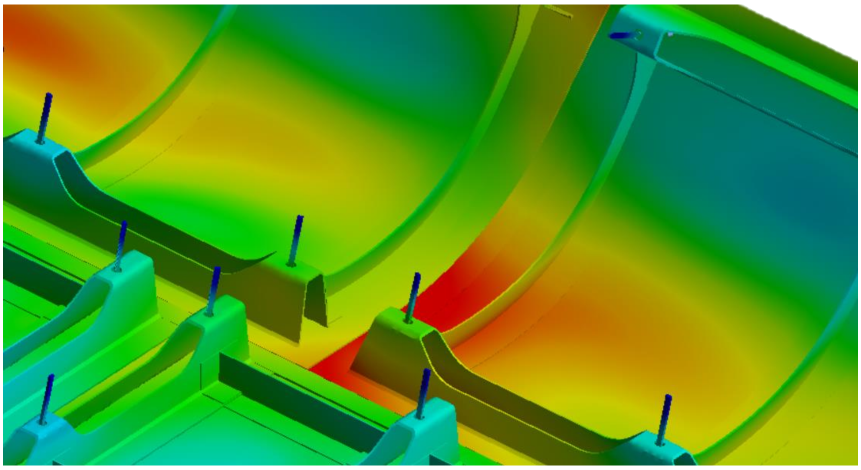

Fig. 12 Total deformations-Detail of the global model

The numerical deviations both in terms of total deformations and in terms of deformations along the reference axes comply with the tolerances expected by the project.
Furthermore, an evaluation was conducted regarding computational cost and calculation times to determine the extent of the net saving in an analysis with all three-dimensional elements compared to that with the 1D element. It is estimated that, on average, the saving exceeds 85 percent.
This is because the standoff, being composed of many small elements, requires a detailed mesh with a small pitch.
By homogenising the standoff, all the local results linked to the standoff are certainly lost, but the analysis is streamlined both in terms of nodes and elements, both in terms of contacts to be implemented in the analysis, and in terms of materials to be defined.
In this specific case, however, the local results of the Standoff are not particularly interesting, since the output of this study is only the deformation along the edges of the Shingle, therefore the useful effects of the Standoff are those related to its deformation due to the thermal load and pressure load.

1.5. Results

The selected results are presented at specific time that best encapsulates the evolution of Windward deformation. These instants encompass the initial times to study the progression as the average temperature increases, the moment of maximum temperature, the point at which the most severe condition occurs due to the simultaneous presence of high pressure and elevated temperatures, and, finally, the later time instants to facilitate a more comprehensive examination of the results during the turbulent phase.

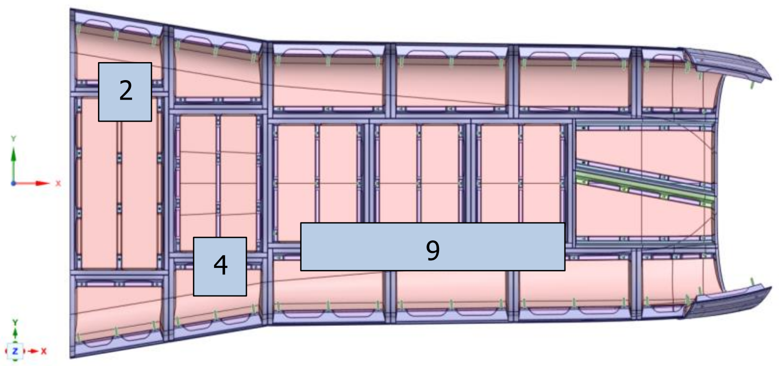

Fig. 13 Legend of the edges whose results are reported

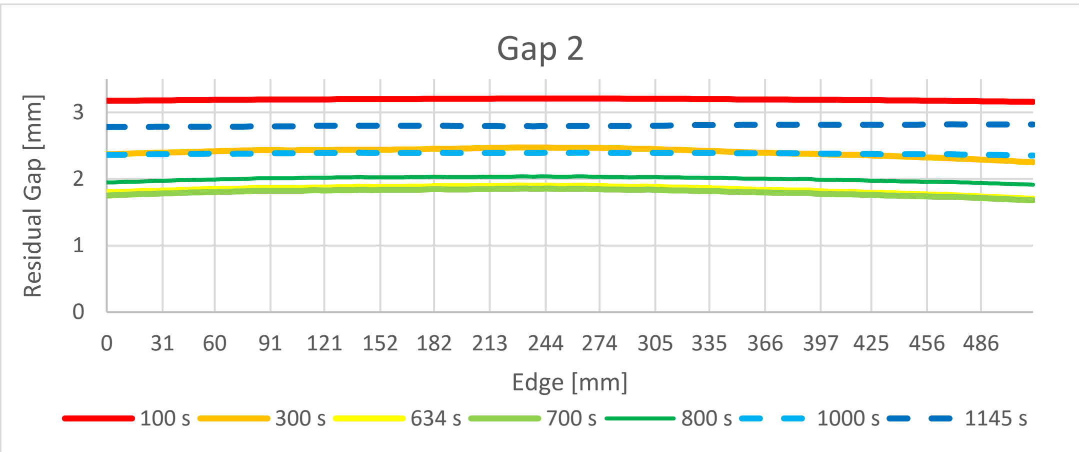

Fig. 14 Gap calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 2

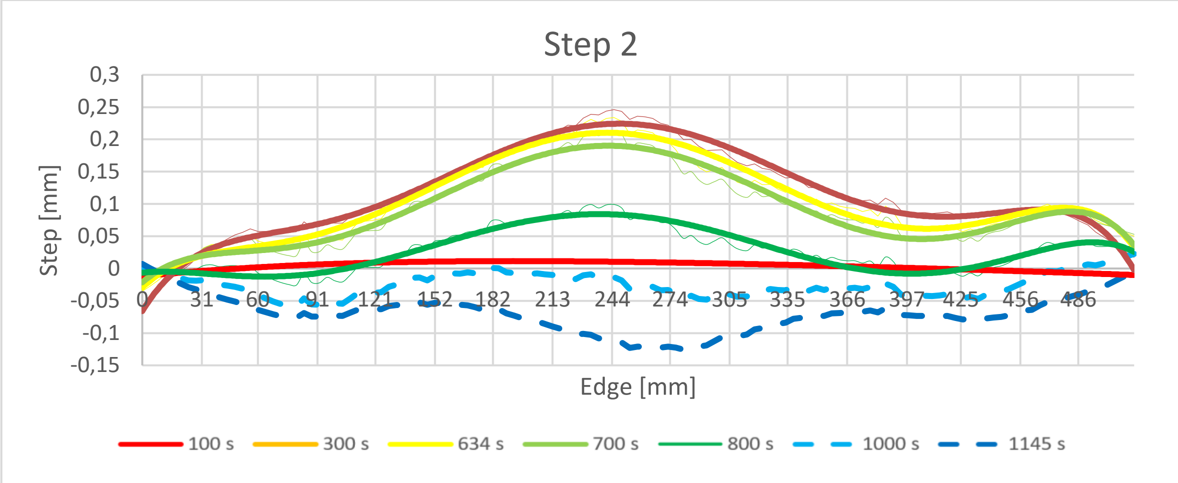

Fig. 15 Step calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 2

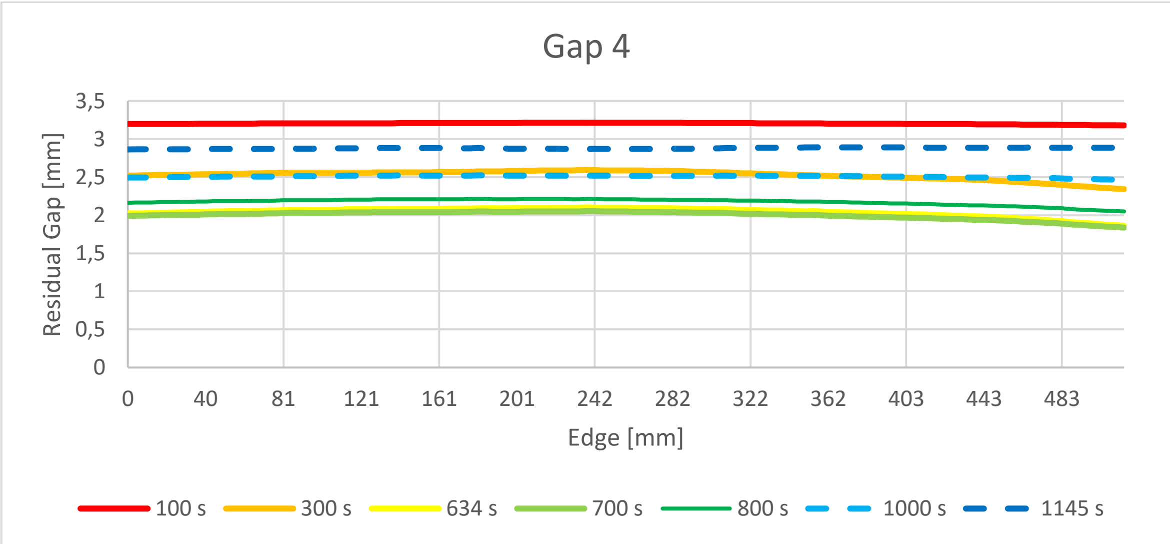

Fig. 16 Gap calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 4

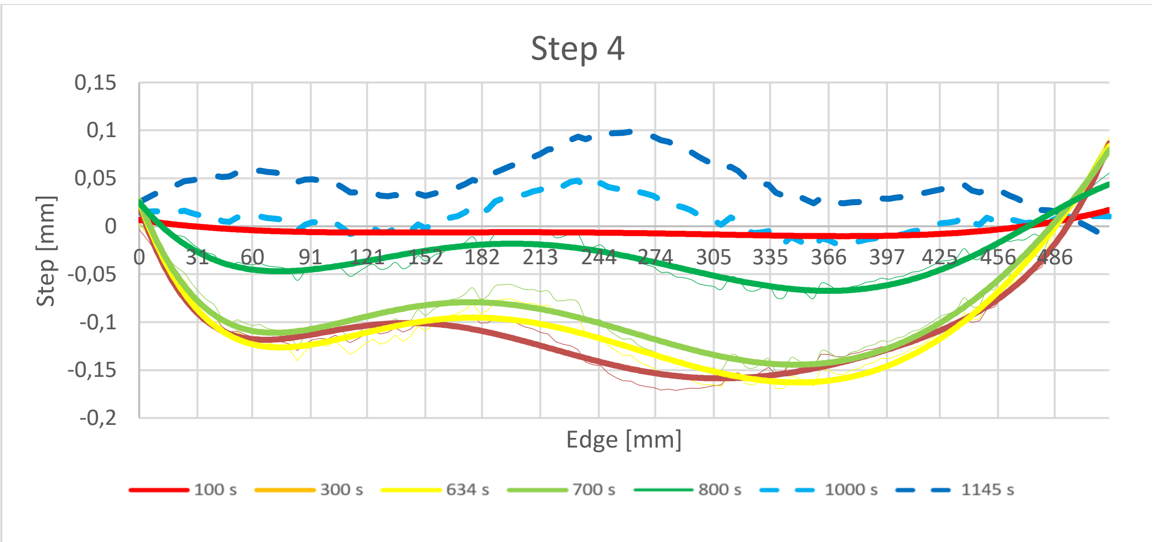

Fig. 17 Step calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 4

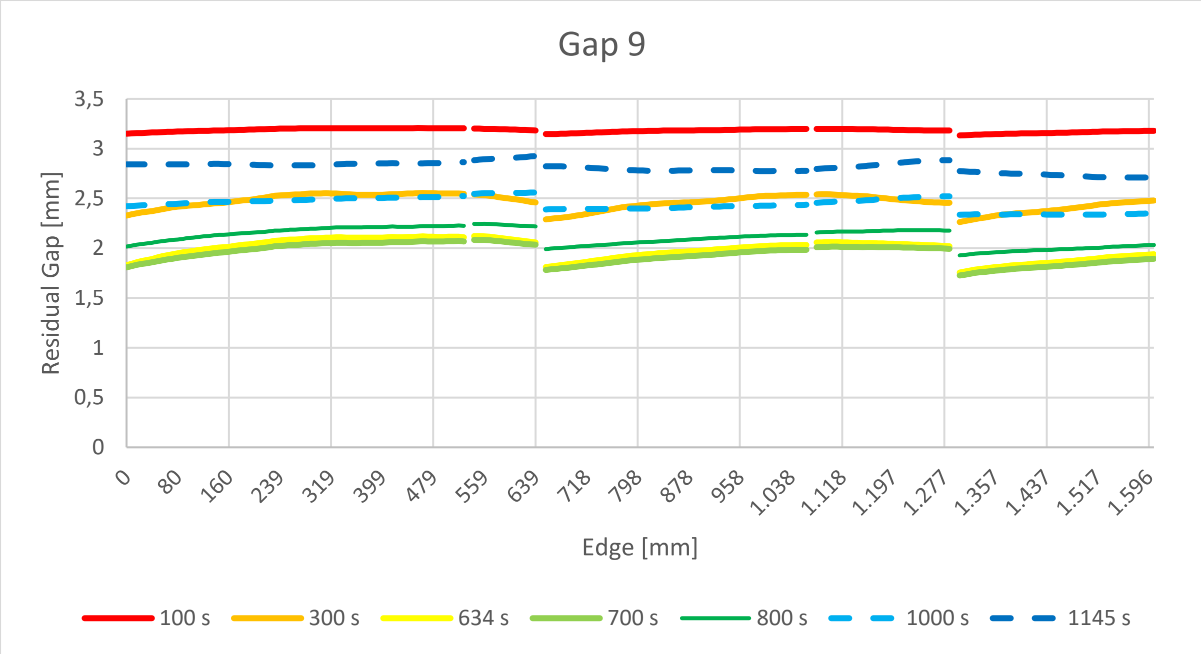

Fig. 18 Gap calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 9

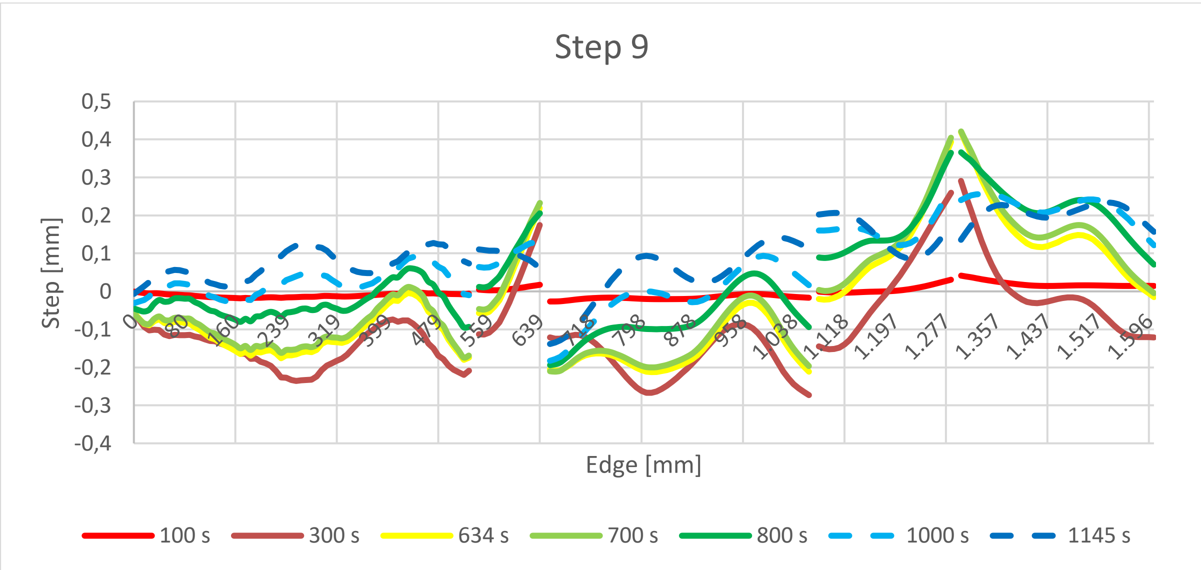

Fig. 19 Step calculated for two adjacent edges of the Space Rider with the one-dimensional model, position 9

1.6. Conclusion

In conclusion, the results presented above will be integrated with the deformations detected downstream of the manufacturing process. By combining the deformation results obtained during manufacturing with the anticipated deformations during the re-entry phase, is possible to assess the optimal assembly solution during integration to minimize steps and gaps. This approach not only ensures a more efficient assembly process but also contributes to enhance product quality and performance. A possible future development of the tool used to calculate the deformations in the reentry phase, could be to automate the process of investigating the parameters to assign to the one-dimensional element. The utilization of autonomous software for structural analysis could offer significant benefits in terms of efficiency and cost-effectiveness. This approach could represent a step towards optimizing engineering processes, enabling the creation of more sophisticated and accurate tools for structural calculation.

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