NAFEMS World Congress 2025 – Innovative front-end structure concepts for improved crash compatibility

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Abstract

Road safety has increased steadily in recent decades. This is particularly evident from the number of serious accidents involving fatalities and injuries with long-term consequences. Nevertheless, further efforts must be made to achieve the ambitious goals of the EU's "Vision Zero" road safety initiative.

The EU project SALIENT is intended to make an important contribution to the implementation of this initiative, particularly by considering the aspect of front-dominated crash load cases of vehicles of different classes (compatibility). In SALIENT various concepts for the redesign of front-end structures using innovative materials and manufacturing technologies are developed to increase crash safety while simultaneously reducing the weight of the components.

In addition to a passive basic concept, innovative approaches based on active components are also being investigated. By means of ADAS sensors, the opposing vehicle can be identified according to certain vehicle classes such as small cars, trucks or SUVs. Furthermore, information is available about the opposing vehicle and the anticipated crash situation, such as velocity, impact angle and crash overlap. Based on these data, the stiffness of the load paths can then be specifically adapted to reduce the severity of the accident. One of these concepts is based on a fibre-reinforced crash box with embedded shape memory alloy (SMA) layer, which allows a stiffening of the crash box when activated.

In this paper, this approach as well as the passive basic concept (BCFES) are presented, virtually analysed and evaluated for their effectiveness in several scenarios. In the first step the concepts are extensively validated at component level, supported by experimental data and finite element (FE) models. The understanding and verification of this behaviour at component level provides the basis for the development of assessment methodologies at full vehicle level, which can only be investigated virtually due to their high costs.

Alongside standard Euro NCAP crash load cases (FWRB, MPDB) additional scenarios are considered that will become relevant in a future mixed traffic with autonomous and non-autonomous vehicles. The findings highlight the potential benefits of integrating advanced active systems into future front-end structure designs.

1. Introduction

Road traffic accidents remain a significant concern in the EU, resulting in numerous fatalities and injuries each year. While there was a notable decrease in fatalities in 2020, this improvement was largely due to reduced traffic volumes during the COVID-19 pandemic. Despite efforts to improve road safety, the EU's goal of significantly reducing fatalities within the last decade was not fully achieved.

Advancements in active safety technologies, such as Advanced Driver Assistance Systems (ADAS), have significantly contributed to reducing road fatalities. However, the decline remains insufficient to meet EU targets [1]. Regulation (EU) 2019/2144 mandates the inclusion of ADAS in all new vehicles, reflecting its critical role in enhancing road safety. Despite this progress, passive safety systems such as airbags, seatbelts, and crumple zones remain indispensable for mitigating injuries during collisions. Integrating active and passive safety systems offers a promising approach to address these challenges comprehensively.

The compatibility of vehicles in crashes has long been a recognized issue. For instance, the disparity in injury risk between colliding vehicles of different masses is more significant for lighter vehicles. Efforts to improve compatibility, such as redesigning bumpers to align better between SUVs and sedans, have demonstrated potential benefits. Euro NCAP has developed frontal tests to assess crash compatibility performance, penalizing poorly performing vehicles.

The SALIENT project aims to revolutionize vehicle safety by developing a next-generation front-end structure (FES) that integrates advanced materials and technologies. A core focus of this paper within SALIENT project is the implementation of an adaptive concept based on a smart material adaptation system designed to enhance crashworthiness and compatibility. This concept is referred to as AC1 in the rest of the paper. The system utilizes multi-material structures and innovative manufacturing processes to optimize the energy absorption and structural performance of vehicles during collisions. By focusing on smart passive safety systems, SALIENT addresses the limitations of existing crash systems, which often perform optimally only in specific scenarios, such as direct frontal impacts.

This paper summarizes the progress of the SALIENT project, focusing on the design and manufacturing of a CFRP-crash box with AC1 integration, preliminary test results, and simulation techniques. It also evaluates the crashworthiness of the front-end structure at the full vehicle level simulations. These findings offer early insights and highlight future development opportunities for advancing vehicle safety systems.

2. Active Component Crashbox

In general, a crash box is a sacrificial energy absorber positioned between the bumper beam and the vehicle's main frame. It reduces peak loads on the passenger compartment, minimizes damage to other structural components, and enhances reparability by localizing deformation. While metallic crash boxes absorb energy through plastic deformation, CFRP structures dissipate impact energy through progressive fibre breakage and fragmentation. Due to CFRP's brittle nature, adaptive reinforcement, such as Shape Memory Alloys (SMAs), can improve impact performance through electrical stimulation. The activation of the active components is intended to be controlled by the vehicle's Advanced Driver Assistance System (ADAS), enabling a predictive response to potential collisions. However, in terms of crash performance prediction, the active components have only two relevant states: activated or non-activated.

In this study, SMA wires are embedded within the thermoplastic tapes of the crash box, following the modeling principle illustrated in the following Figure 1.

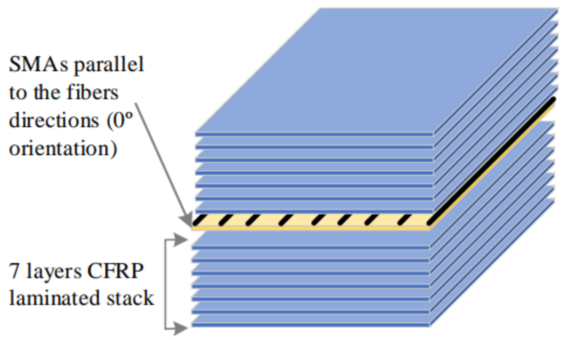


Figure 1: Principle of CFPR crash box layer setup

Manufacturing process

One Shape Memory Alloy (SMAs) have been integrated into the crash boxes of the Front-End Structure (FES), which were designed by Fraunhofer IWU and manufactured from Carbon Fiber Reinforced Polymer (CFRP).

To determine the appropriate design for the crash boxes, the extrapolation method from [2] was applied for dimensioning. This is an analytics-based sizing tool for CFRP crash tubes, which has been experimentally and numerically verified.

The crash boxes required for the component tests were produced using laser assisted tape winding (LATW). The thermoplastic tapes (CF-PA6) from thermoPre ENGINEERING GmbH were heated by laser, wound and pressed onto a winding core (diameter 63.5 mm). A section of the production process is shown in Figure 2. Two tubes with a length of approx. 1 m were produced. The tube sections required for the crash boxes (length 90 mm) were cut out after removing the core. The layer structure of a total of 18 layers of UD-Tape (PA6-CF) was as follows: $[[+30°/-30°]_2/[0°]_{10}/[+30°/-30°]_2]$.

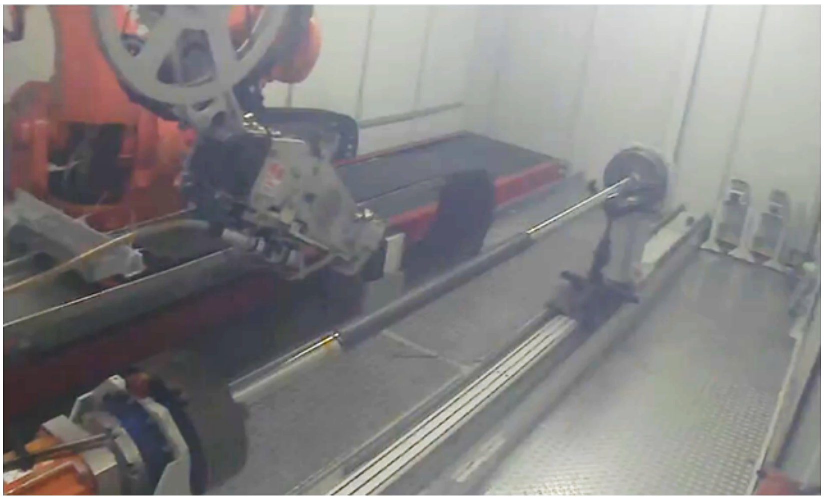


Figure 2: Production Process of the crash boxes

For the desired crash behaviour, it is important that a chamfer is created at one end of the crash box. This cross-section reduction ensures that failure is triggered and begins at exactly this position. The geometric dimensions of the crash box without actuator (BCFES) and a prototype manufactured accordingly for component testing are shown in Figure 3.

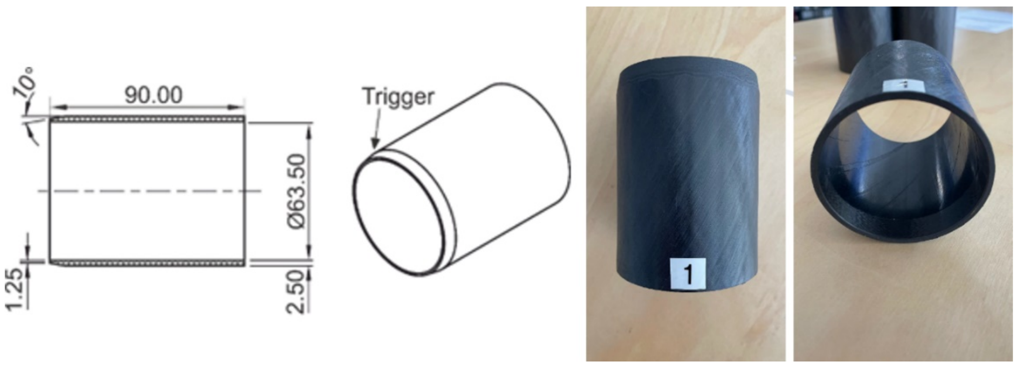


Figure 3: Crash box properties (left) and realized component (right)

The AC1 crash boxes were manufactured in the same way. The actuators (SMA wires) were integrated in the middle of the layer structure. Figure 4 shows the orientation of the wire in the composite tube.

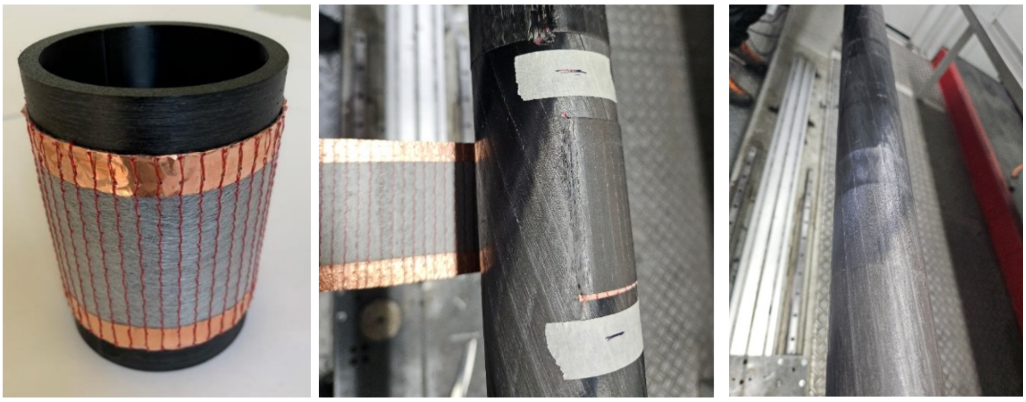


Figure 4: Schematic representation of the actuator arrangement (left); Integration of laminated SMA semi-finished product in tape winding process(middle); Covering SMA semi-finished product by CF-PA6 tape using tape winding process (right)

Figure 5 shows the contact between the copper foils and the wires so that an electrical voltage can be applied afterwards.

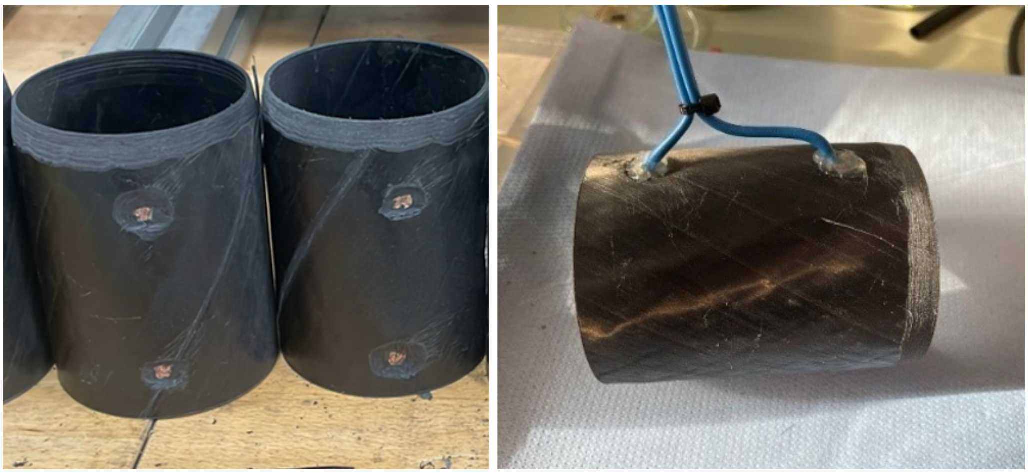


Figure 5: Exposed contact areas at crash boxes (left); AC1 crash box with connected contacts (right)

Component testing

Component tests are essential for validating and improving crash simulations. They provide real data on material behavior, deformation, and energy absorption, ensuring accurate numerical models. By comparing force-displacement curves, failure patterns, and deformation modes, simulations can be calibrated and uncertainties reduced. Additionally, they allow the effectiveness of the activation of AC1 to be assessed under realistic conditions.

The crash boxes were tested in a horizontal impactor device consisting of a steel beam of determined mass, which is launched at 40 km/h towards the tested object (crash box), causing its collapse. The beam, which weighs 60kg, has a rectangular cross-section, and a flat impacting surface to ensure that the force transfer occurs in the axial direction of the crash box (Figure 6, left). In this setup, the crash boxes are fixed to a rigid steel wall by means of a tooling manufactured to this end. The tooling consists of a plate counting with a cavity in which the crash box is inserted, centering its position thanks to four screws located around the cavity (Figure 6, right). For the activation of the AC1 crash box, two pre-inserted electric cables that stem from the part are connected to a portable power source feeding 2A DC current.

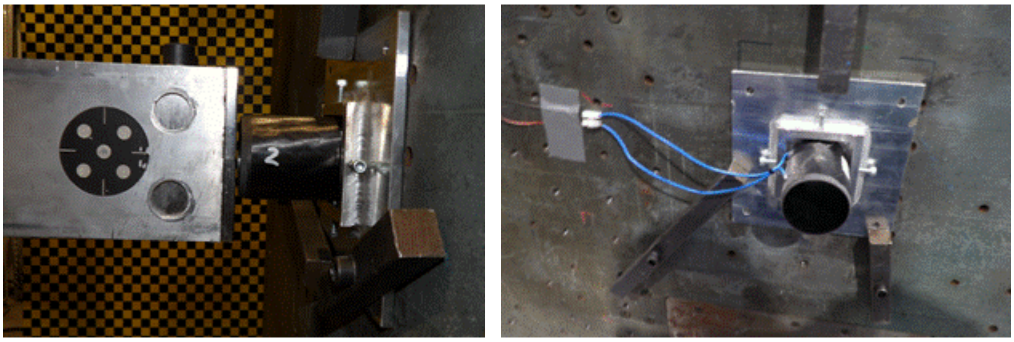


Figure 6: General view of the horizontal impactor device and the AC1 crash box. Left: lateral view. Right: front view.

The main variables recorded during the tests were acceleration and displacement. Accelerations were measured by means of two accelerometers (ENDEVCO 7264B-2000T) located symmetrically onto the beam. Displacement was measured with a magnetic displacement sensor (ASM PMIS3-50-125-50-TTL-S). The acceleration signals, after averaging and filtering, were integrated to obtain force and energy absorption values. The tests were also recorded with a high-speed video camera (VISION RESEARCH VEO-440S) at 2000 fps. The recording allowed tracking the collapse of the crash boxes (Figure 7).

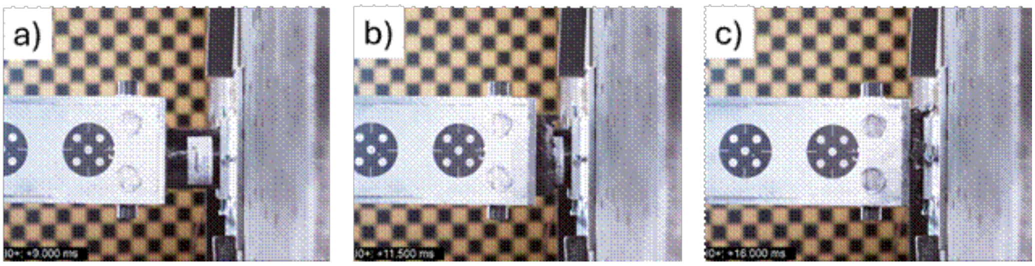


Figure 7: Collapse evolution of the AC1 crash box

During the collapse, the inversion mechanism implemented by design proves to work effectively, in the sense that the crash box is split in two halves, one collapsing towards the inner part, and other towards the outer part. If compared with the BCFES version, the AC1, either active or non-active, presents some degree of interlaminar delamination at the SMA+non-woven GF/PA6 interface, as can be seen in Figure 8.

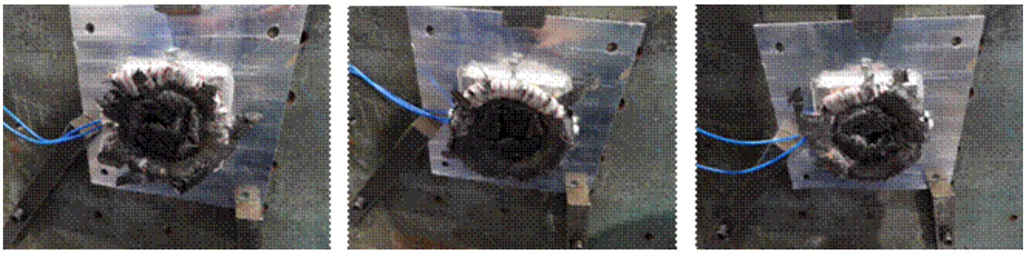


Figure 8: Post-testing state of the AC1 crash boxes.

The acceleration-displacement curves are presented in Figure 9. The variables measured are quite repetitive and fit well with the dispersion inherent to this kind of test. In some of the AC1 tests an acceleration peak is observed at the end of the test, indicating that the component has not been able to absorb all the energy transferred by the impactor, which is a limitation of the current iteration of the design.

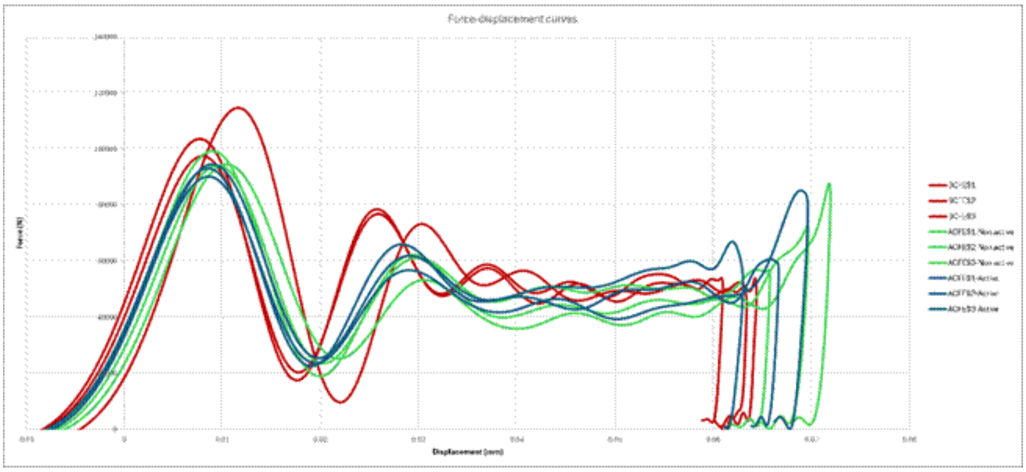


Figure 9: Force-displacement curves for all the crash box configurations analyzed.

From the acceleration values, the average force for all crash box variants was calculated (Table 1). If compared to the BCFES reference (Figure 9, red line), both AC1 variants presented worse performance, which is attributed to the non-homogeneity in the composite lay-up introduced when inserting the extra SMA+non-woven GF layer. Nevertheless, the electrical activation of the SMA wires enhanced the performance of the component in around 8%, almost matching the baseline despite the manufacturing complexities. Therefore, it is considered that once the manufacturing process is optimized, the contribution from the active SMA wires will enable outperforming the BCFES, thus increasing the energy absorption capabilities of the component.

Table 1: Performance summary of the different crash box configurations

	Average force (kN)	Comparative performance (%)
BCFES	52.8	-
AC1 non-active	47.2	-10.6%
AC1 active	50.9	-3.6%

3. Model Setup and single component simulation

In vehicle development, virtual methods are essential for reducing development costs by minimizing the need for physical prototypes. The process typically begins at the component level, where simulations and virtual tests help optimize individual parts. Once validated, these components are integrated and analysed at the full vehicle level to ensure overall performance, safety, and compliance. This stepwise approach, which is also applied in this paper, enables early detection of issues, reduces testing costs, and accelerates the development cycle.

Modelling technique for AC1

Figure 10 (left) illustrates the layered structure of the CFRP crash box within the *PART_COMPOSITE framework in LS-DYNA. This framework enables the assignment of individual orthotropic material layers to their respective material cards, allowing the SMA wire layer to be accurately represented within the shell material's layer structure. Figure 10 (right) shows the schematic of the test setup within the simulation model. The chamfer (trigger representation) is also represented in the simulation model according to the suggestion in the following study [3].

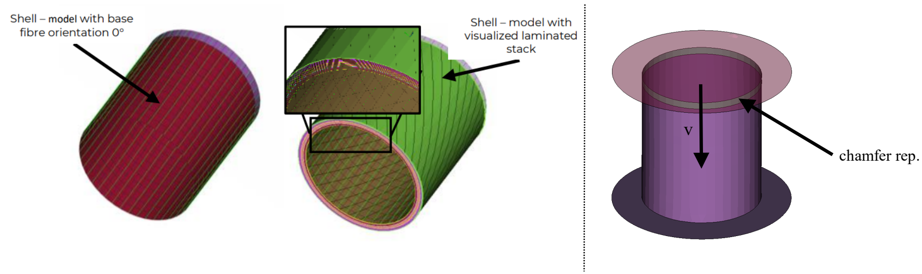


Figure 10: Modelling principle for the CFRP crash box containing one layer of SMA wires

This approach facilitates the straightforward implementation of the active crash box in both its activated and non-activated states within the full vehicle model.

The shape memory alloys (SMA) are integrated into the crash box using a 17-layer configuration, comprising seven layers of CFRP on either side of a central SMA wire layer, with the wires aligned at 0 degrees. To simulate the behavior of the shape memory alloys, the MAT_30_SHAPE_MEMORY material model in LS-DYNA is employed.

The SMA selected for this application is Nitinol (NiTi), which exhibits two distinct phases: the austenite phase (active state) and the martensite phase (inactive state). These phases have different mechanical properties and are incorporated into the simulation depending on the desired state of the SMA during each iteration of the simulation runs. The SMA wires, with a diameter of 200 µm, are integrated within the central layer, and the surrounding CFRP layers are adjusted to account for their thickness. This ensures that the original thickness of the crash box is maintained.

Simulation results of crash box component test

In the baseline configuration (Figure 11), the force-displacement curve exhibits multiple load peaks, characteristic of CFRP structures undergoing controlled fragmentation. The energy absorption curve shows a steady increase, with a significant initial peak, indicating a moderate but effective energy dissipation. The simulation data aligns well with experimental results, confirming the expected behavior of the CFRP crash box.

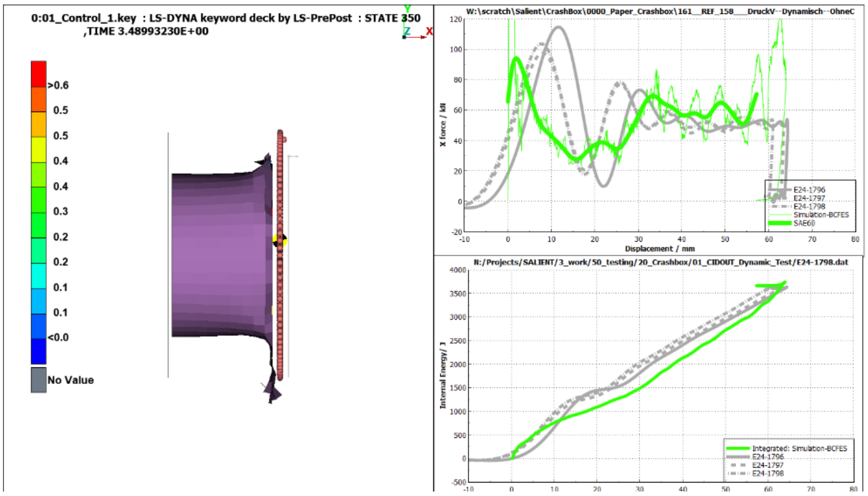


Figure 11: BCFES crash box configuration

When the SMA layer is integrated and actively engaged (see Figure 12), the force-displacement response exhibits a more stable progression with reduced peak forces. This suggests that the activation of SMA influences load distribution and mitigates sudden force spikes. However, the total energy absorption remains largely unchanged compared to the baseline crash box. This indicates that while the active component contributes to a smoother crash behaviour, it does not significantly alter the overall crash performance in terms of absorbed energy.

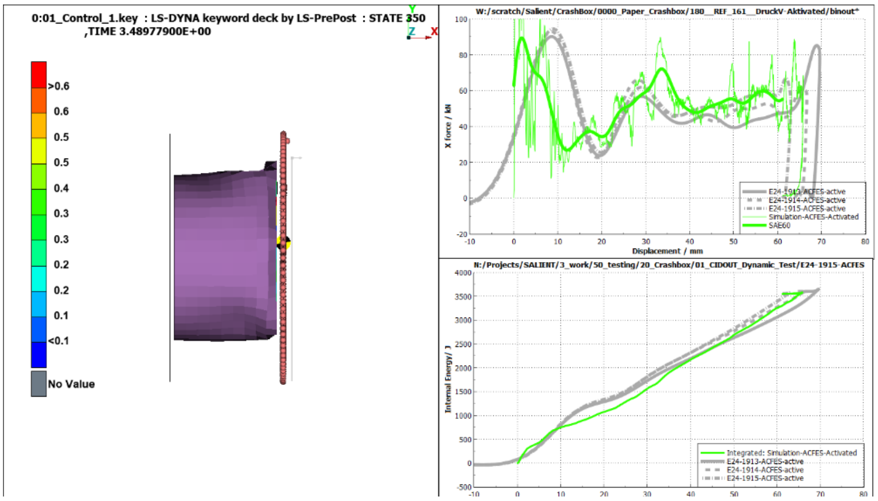


Figure 12: AC1 crash box configuration in activated state

In contrast, the crash box with an inactive SMA layer in Figure 13 shows a clear reduction in energy absorption and an increase of intrusion depth. The force-displacement curve indicates irregularities and a less efficient load-bearing response, suggesting that the integration of SMA without activation negatively affects the structural behaviour. This can be attributed to the challenges in embedding SMA wires into the CFRP matrix, where improper bonding or material incompatibilities might hinder the energy dissipation process.

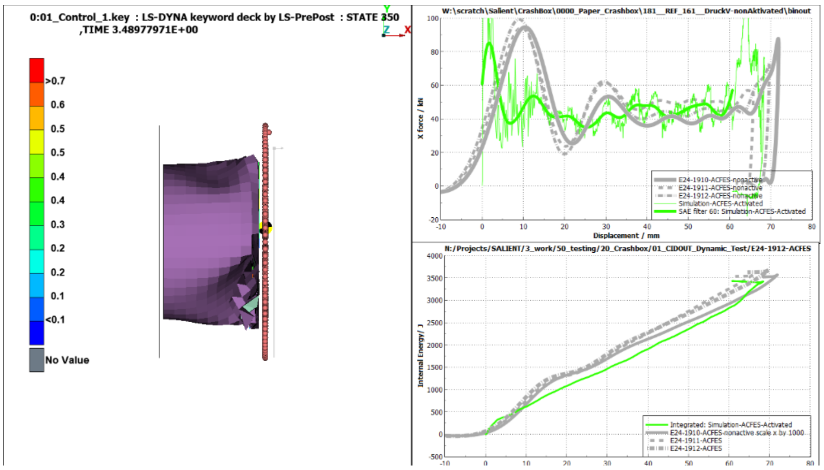


Figure 13: AC1 crash box configuration in non-activated state

4. Crash Assessment at Full Vehicle Level

The SALIENT project introduces active components to enhance front-end structures by adapting energy absorption based on impact angle and speed, integrating active and passive safety. A consortium of 12 partners contributed to design, material development, feasibility, crash analysis, and testing to create a lighter, safer, and more sustainable structure. These adaptive concepts especially the active CFRP - crash box are still under validation, with room for improvement and alternative solutions. This paper outlines the development based on the AC1 concept (Figure 14).

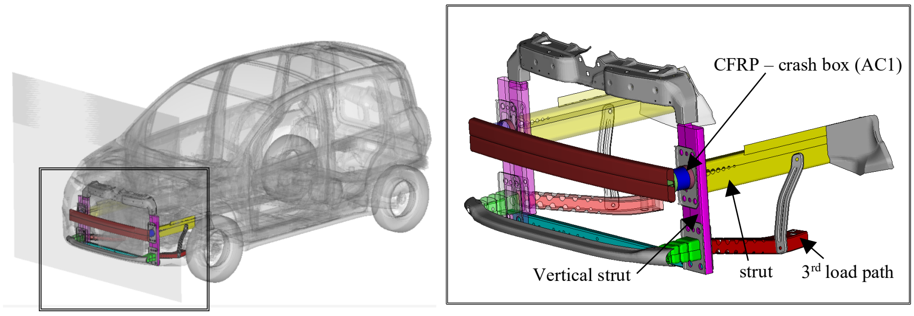


Figure 14: Front-End Structure (FES) and active CFRP crash box highlighted on vehicle model

MPDB - Chosen load case

To get a reasonable basis to compare new FES features and developments, the load case setup Mobile-Progressive-Deformable-Barrier [4] (MPDB) is considered and therefore was used to evaluate the active component behaviour. Unlike a classic rigid wall test (which is also part of SALIENT), MPDB provides a more complex operating crash scenario by incorporating a deformable barrier and a moving trolley, allowing for a better assessment of structural interactions. MPDB was chosen to investigate the impact on the new active crashbox, as the variation of the trolley setup enables to analyse how different impact conditions influence its performance.

The full vehicle simulation model (FVM) is built from 1995514 nodes and 2105555 elements. The duration time of this simulation showcase (MPDB, see Figure 15) was 20 hours and 30 minutes on 64 CPU cores by generating data in scale of ~20GB (depending on the predefined output timestep scale).

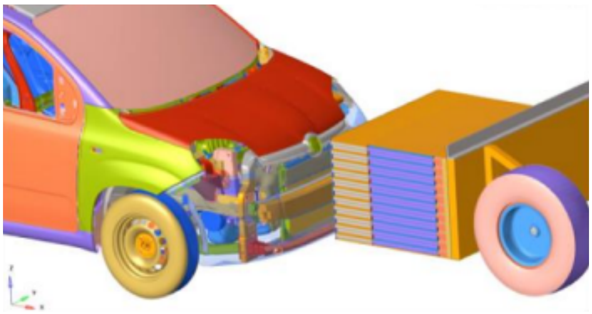
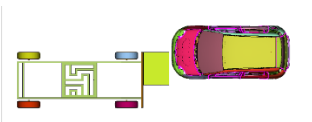
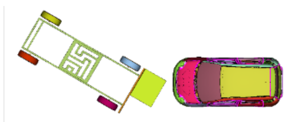
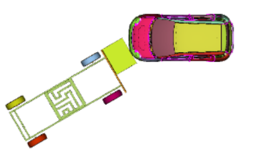


Figure 15: Mobile-Progressive-Deformable-Barrier (MPDB)

Compatibility assessment

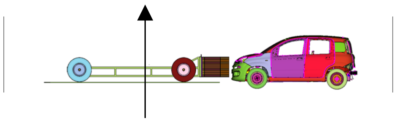
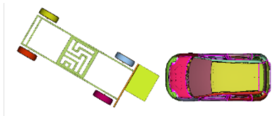
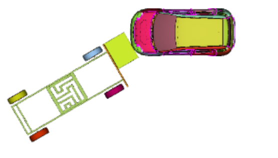
The variation of impact angles in the MPDB test provides a broader basis for assessing AC1. By considering both the standard configuration and ±30° impact angles, the evaluation captures a wider range of potential crash scenarios, ensuring a more comprehensive analysis of AC1's effectiveness. Table 2 shows the chosen test compatibility scenarios as they are most promising candidates for representing the primary crash encounter configurations appearing in turning manoeuvres.

Table 2: MPDB - Variation of impact angle

MPDB-regular	MPDB-30°	MPDB-neg30°
		

In addition, a change in the mass (+500kg) and (at the same time) height (+150mm) of the opposing vehicle is intended to further broaden the assessment basis and shall represent a larger crash opponent (see Table 3). This allows for the evaluation of whether active components can compensate for potential disadvantages arising from the smaller vehicle geometry.

Table 3: MPDB - Variation of height/mass and impact angle

MPDB-regular	MPDB-30°	MPDB-neg30°
		

Measures for crash performance

Figure 16 illustrates an insight into all the of the main components of the FES which are in the focus of SALIENT. The shown analysis uses color coding to correlate specific components with their respective energy absorption characteristics, as seen in both the graph (left) and the deformation plot (top-right). The graph on the bottom right shows the total internal energy absorbed by the entire FES over time.

The primary objective in the first place is to determine whether there is a noticeable effect on the overall crashworthiness performance of the vehicle by comparing the AC1´s activated state configuration to the nonactivated respectively standard BCFES configuration. The analysis revealed that the most significant impact besides the crash box occurs in the energy absorption of the strut (yellow dashed line, e.g. ~4000J), primarily due to the activation of the crash box and its associated change in stiffness. This information now can be used to compare different load case variants.

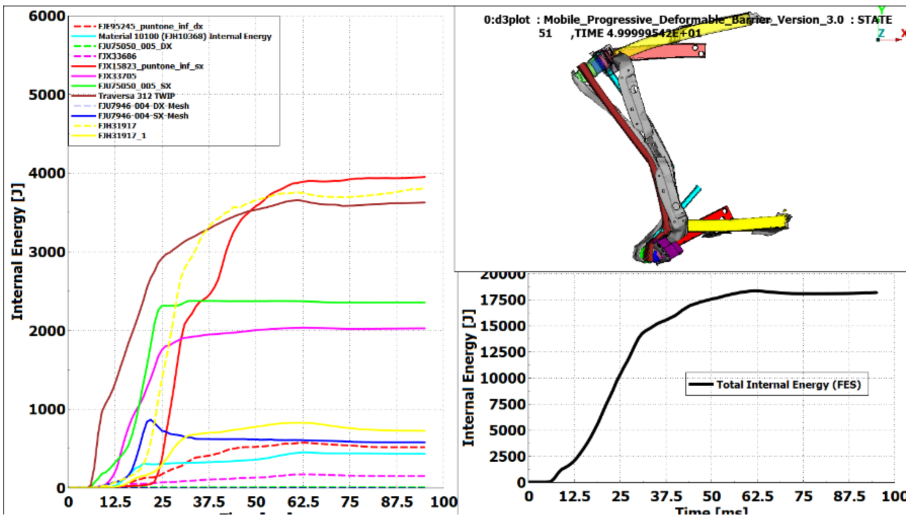


Figure 16: Exemplary illustration of the evaluation method for assessing crash performance

In vehicle crash tests and simulations, analysing firewall intrusion is crucial to assess the deformation of the partition between the engine compartment and the passenger cabin. Excessive deformation can compromise occupant safety by reducing footwell space or exposing sharp edges. Additionally, examining the crash pulse—which describes the vehicle's deceleration over time during an impact—is essential, as its shape significantly influences seat and occupant responses, thereby affecting injury risks. By evaluating both firewall intrusion and crash pulse characteristics, engineers can ensure the vehicle's structural integrity and minimize injury risks to occupants.

Therefore, the firewall intrusion and the crash pulse (measured in the area of the B-pillar) are also taken into account in selective simulation runs in order to be able to substantiate the argumentation more broadly with additional parameters.

Comparison of BCFES/AC1

As previously described besides the effects on the crash box it turns out that one of the most influenced components has been the strut (see Figure 14). The following Table 4 presents the energy absorption of the strut across all conducted simulation variants at this stage of the project. It can be observed that the activated AC1 state generally results in higher energy absorption compared to the non-activated state, with percentage increase ranging from approximately 3.4% to 10.1%, depending on the configuration. This also correlates with the observation in section 3 where it is indicated that the activated crash box achieves additional stiffness in comparison to the non-activated state. At this point AC1 has the most impact on the standard configuration, due to its origin intention to primarily deal with axial loads resisting and passing onto the subsequent components (Strut). Nevertheless, also a slight increase in energy absorption can be spotted as well for the other load cases.

Table 4: Simulation results based on several impact angles scenarios

Energy absorption [J] of strut		BCFES	AC1		Change activated / non-activated in %
			activated	non-activated	
MPDB	standard	2774	3654	3286	10.1
	30deg	3065	3151	3044	3.4
	neg30deg	3576	3642	3490	4.2

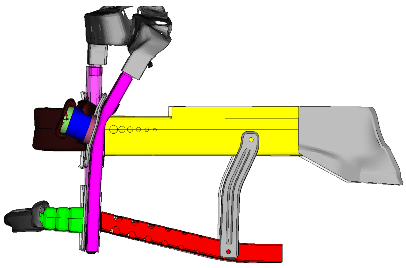
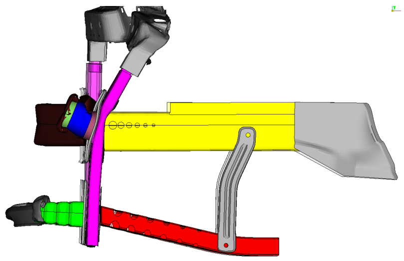
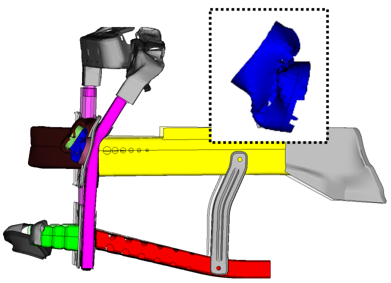
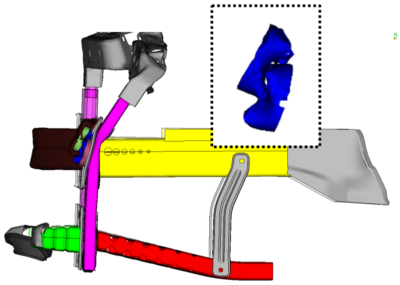
In the following impact angle in combination with an increase in height and (at the same time) mass have also been investigated and the results in terms of energy absorption of the strut can be seen in Table 5. In analogy to the previous setup, it can be spotted that the influence of activating the active component even raises (for the standard configuration) which can be explained by the fact that the 3rd load path of the FES (see Figure 14) is out of reach due to the higher impact height and therefore with limited function in terms of energy dissipation. So, the strut has to compensate the loss in collaboration.

Table 5: Simulation results based on several impact angles scenarios including adaptation in height/mass

strut Energy absorption [J] of			BCFES	AC1		Change activated / non-activated in %
				activated	non-activated	
MPDB	height/ mass increased	standard	3091	3605	3052	15.3
		neg30deg	2508	2741	2751	-0.4

An interesting delaying effect has also been spotted (MPDB height/mass increased standard) and is highlighted in the following Table 6. The crash box is going to be more stable according to its higher stiffness during crash in activated state and results in a delayed overall collapse of its integrity over time.

Table 6: Deformation pattern of AC1 crash box over time in activated / non-activated state

Activated AC1	Non-activated AC1
T=17ms; start of crash box deformation	
	
T=19ms; end of crash box deformation	
	

Based on these results, the effect was further enhanced by introducing additional SMA layers in the crash box model and examined in the following study.

Additional SMA layer setup

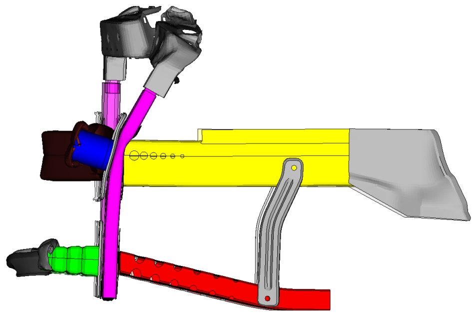
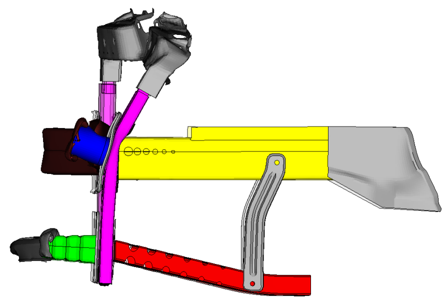
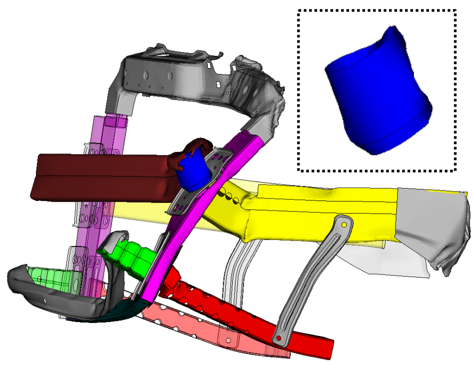
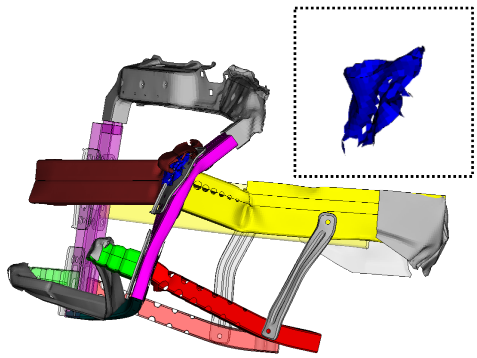
Within the PART_COMPOSITE layer configuration, two additional active layers are added (see Figure 10) which leads to a higher stiffness of the crash box in the activated state, which can be seen in the results of the component test in 7 Appendix. By replacing the original single SMA layer setup in the selected MPDB load case (standard), shown in Table 5, with this three-layer setup an increase in total effectiveness from 15.3% to 22.2% can be seen (see Table 7).

Table 7: Simulation results based on 2 additional SMA layer crash box setup

Energy absorption [J] of strut			AC1		Change activated / non-activated in %
			activated	non-activated	
MPDB	height/ mass increased	standard	4289	3337	22.2

In the following Table 8 two main investigations are depicted: At first the crash box remains stable through all the deformation process till the end of the impact in comparison to the AC1 non-activated stage. Second, the vertical strut (see Figure 14) experiences a different load distribution due to the remaining integrity of the crash box in activated state. Overall, the whole FES rotates counterclockwise.

Table 8: Deformation pattern of AC1 crash box over time in activated / non-activated state with additional 2 SMA layer setup

Activated AC1	Non-activated AC1
T=17ms; start of crash box deformation	
	
T=42ms; end of crash box deformation	
	

The following Table 9 gives an estimation of the firewall intrusion comparing the non-activated to the activated crash box simulation runs at the end of the calculation time. It can be observed that the activation has substantially lowered the intrusion of the firewall (less red highlighted area compared to non-activated state) which also confirms the previously described phenomenon.

Table 9: Firewall intrusion comparison (additional SMA layer setup)

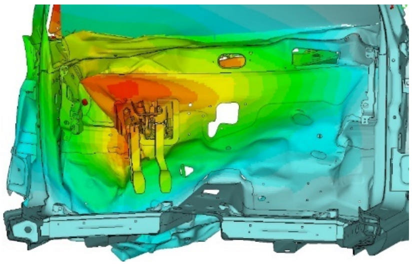
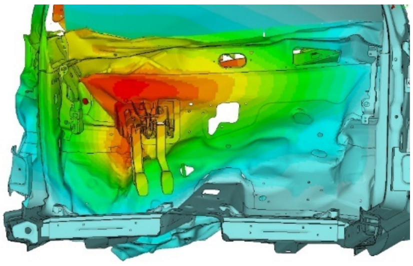
Activated AC1	Non-activated AC1
	

Figure 17 shows differences in the pulse measured in the lower area of the B-pillar by comparing the activated with the non-activated state. The acceleration peaks are being flattened out in the activated state (red line) indicating lower accelerations affecting the B-pillar and therefore contributing to the general argumentation. Nevertheless, no major change in the overall characteristics can be identified.

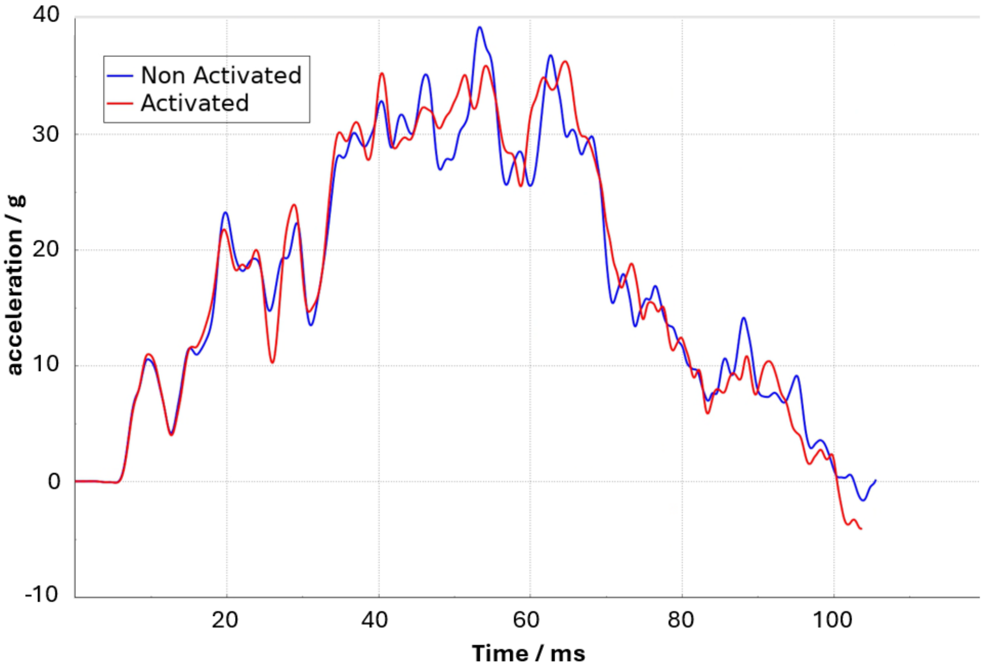


Figure 17: Pulse analysis of the acceleration measured in the lower area of the B-pillar.

5. Discussion

The adaptive crash box AC1 concept has shown promising results in balancing energy absorption particularly in the context of the MPDB (Mobile Progressive Deformable Barrier) test. Different impact angles were investigated to assess the adaptability of the concept under various crash scenarios.

While AC1 theoretically allows for improved performance in oblique and offset crashes through selective activation of crash boxes, the current findings indicate that its most significant benefits are achieved in the primary impact direction. In this configuration, controlled energy absorption and optimized deformation behaviour may contribute to an efficient distribution of crash forces, reducing both structural intrusion and overall damage severity.

A notable effect observed in the investigations is the delayed collapse of the crash box influencing the interaction with the MPDB. By means of a virtual study based on an increased number of SMA-layers in the crash box, it could be shown, that this effect could become relevant in scenarios where the MPDB characteristics—such as height or mass—increases. Such scenarios could raise from collisions with bigger opposing cars and might also get relevant in future evolving regulatory test conditions. The delayed energy absorption might reduce the impact severity for a smaller vehicle equipped with the AC1 concept by improving energy dissipation patterns.

6. Conclusions and Outlook

In this paper, innovative approaches to improving vehicle crash compatibility are explored within the framework of the EU project SALIENT. Both passive and active front-end concepts are investigated, including a fiber-reinforced crash box with an embedded shape memory alloy (SMA) layer that adapts stiffness based on real-time crash data (AC1). Using virtual simulations and experimental validation, the effectiveness of these concepts is assessed across various scenarios, including standard Euro NCAP tests and future mixed-traffic conditions.

All contributory results indicate that the AC1 concept is a strong candidate for improving crash compatibility, particularly in frontal impact configurations. While its adaptability to oblique and offset crashes shows potential, the primary benefits were observed in standard MPDB conditions. The identified delaying effect suggests that a controlled, staged collapse of the crash box could further enhance safety, especially for smaller vehicles, but requires further validation.

Future research should focus on refining the activation strategy of AC1 to optimize its performance across a broader range of crash scenarios. In particular, a more detailed investigation is needed to quantify the conditions under which the delaying effect provides measurable safety benefits. Additionally, the influence of AC1 on secondary safety aspects, such as occupant protection and post-crash vehicle behavior, should be examined to fully assess its potential for real-world applications.

7. References

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8. Appendix

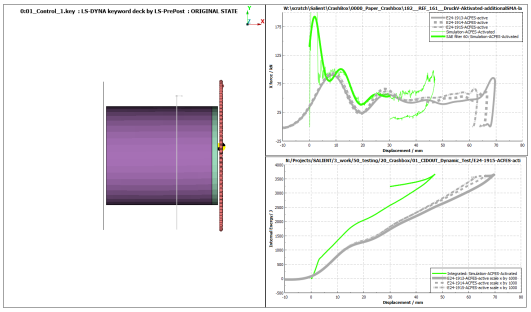

Figure 18: Component test —2 additional SMA layers – AC1-activated

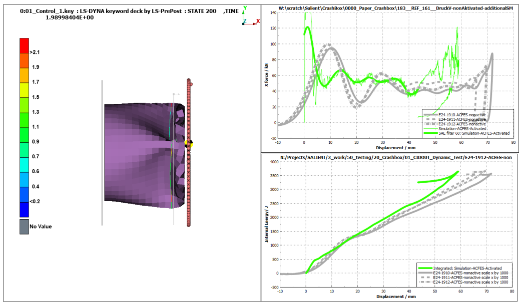

Figure 19: Component test - —2 additional SMA layers – AC1-nonactivated

9. Acknowledgement

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