

Predictive Crashworthiness Simulation in a Virtual Design Process without Hardware Testing

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In 2006 BMW made a decision to use Abaqus/Explicit for all issues concerning passive safety in the virtual design process. Code quality and reliability of simulation results were identified as the primary reasons to change, and from that decision point forward, all product development teams began migration activities to switch to Abaqus/Explicit.

Meanwhile, the entire vehicle design and development process within BMW began to undergo fundamental changes, from one which previously incorporated key milestones involving physical prototypes, to one which seeks to largely eliminate physical prototypes and associated physical tests. Nowadays, BMW design engineers will get the first feedback from physical tests only after the series production tools have been manufactured. Therefore, design changes at that point will be extremely expensive. Furthermore, no physical test results will be available to calibrate and improve finite element models of virtual crash cars in the earlier phases of the development process. So predictiveness is now the most important criterion for BMW's passive safety simulation.

Because of these fundamental changes to BMW's development process, BMW established a new benchmark for crash solvers in 2009 in order to evaluate in detail the quality of simulation results. This paper intends to demonstrate some of the capabilities of Abaqus/Explicit for crashworthiness and occupant safety, with a strong focus on predictiveness and reliability. These factors are prerequisites for an efficient, cost-effective vehicle development process that relies less and less on physical prototypes and testing. And it explains why BMW has now reconfirmed the earlier decision to use Abaqus/Explicit for its crashworthiness and occupant safety simulation.

1. Introduction

Since 1998, BMW began seeking alternative simulation tools for passive safety design issues. The criteria for selecting a new simulation tool were:

- Algorithms of high quality and overall software robustness
- Competent development team
- Strong commitment to the methods development needs of BMW

After several years of searching and evaluation, BMW made a decision to move to Abaqus/Explicit as its new tool for crashworthiness and occupant safety simulation. Beginning in late 2004, BMW carried out the first car development project using Abaqus/Explicit for passive safety simulation. Successive car projects were also migrated, until all migration was completed by the end of 2006.

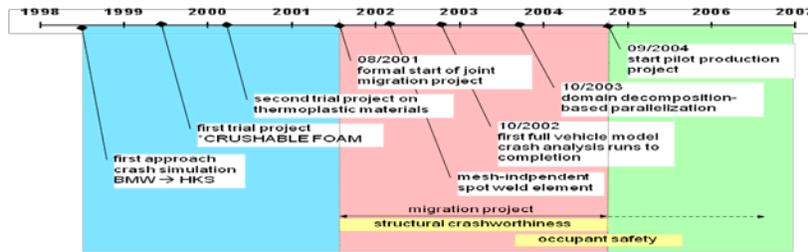


Figure 1: Time frame for software migration

Automotive companies are under constant pressure to develop and produce better cars that meet increasingly stringent legal requirements for crashworthiness and occupant safety, as well as growing consumer demands, and to bring them to market more quickly. To address such pressures, BMW's internal development process is continuously being changed and optimized.

Previously in car development projects, functionalities have been repeatedly refined and confirmed by hardware tests. Nonetheless, the number of hardware tests corresponding to a particular load case is very low, and the predictiveness of a physical test is somewhat limited by the build quality of the prototype, as well as the re-use of vehicle prototypes for multiple load cases.

Time is another unfavorable factor in a development process which relies largely on hardware proofing, because every single part has to be made using prototyping tools, and the vehicle itself is practically assembled by hand. With this conventional approach, the demand for a shortened and more efficient development process cannot be fulfilled, while at the same time being able to optimize functionality, product, and costs.

Therefore, the development process at BMW is in a state of change, from a hardware supported development to a purely virtual development, where the first cars assembled are directly used for homologation. But this requires a change also to the primary aim of virtual development or simulation. Previously, the main focus of virtual development was the global vehicle behavior. Detailed topics, such as the potential failure of connections or material rupture in components, were largely covered by the hardware tests. Because of the goal at BMW to completely eliminate prototype hardware and testing, such issues can only be subsequently evaluated through simulation. This necessarily leads to a complete realignment of virtual design, from "macrocosm" to "microcosm". The earlier simulation focus primarily on global behavior loses its importance, while the detailed behaviors of components and connections, within the context of a complex full vehicle model simulation, become a central part of virtual design for passive safety.

This change in the design and development process means that, besides the original requirements for BMW's crash simulation software to be of high quality and reliable, a new key requirement emerges: predictiveness. Can the crash simulation software accurately predict these detailed behaviors which are known to have important influence on passive safety criteria?

This was the reason for BMW to conduct a new software benchmark in 2009 with the goal of assessing which crash simulation tool can best meet this newer predictiveness requirement. A very detailed list of criteria were compiled and subsequently used to assess the crash simulation tools. In order to ensure a broad range of coverage, a large number of different models and load cases were established:

- Component models for problems typical in car body technology.
- Component models for restraint systems.
- Full vehicle models.

In the following sections, some exemplary results of the benchmark are presented.

2. Predictiveness on Component Models

Before using new methods in very complex full vehicle crash models, it is much easier to evaluate the predictiveness on component level tests. With simplified principal tests, simulation results can be assessed more readily and the level of predictiveness can be evaluated.

2.1 Comparison of Spot Weld Failure between Simulation and Test

According to EN ISO 14329 fracture modes of resistance spot welds can be categorized in three large groups: peel, shear, and mixed-mode as illustrated in this order in [Figure 2](#).



Figure 2: Fracture modes for resistance spot welds

In the peel fracture mode, failure occurs in the base material or within the heat affected zone, whereas shear fracture behavior occurs through the weld nugget mostly parallel to the joined surfaces. Often the two modes coexist in the mixed-mode failure behavior. The joint strength and the fracture type of a spot weld are primarily determined by the nugget size, the base material properties and the load case of the weld spot. A shear load case between the spot welded plates results in mostly shear stresses in the nugget, which in turn, leads to shear fracture, whereas peel fracture is more likely to occur with an increasing load angle towards a pulling loading mode. For conventional steels a correlation between fracture mode and energy absorption has been observed for spot welded joints. The energy absorption level is much higher for ductile peel fracture than it is for spot welds with (brittle) shear failure behavior.

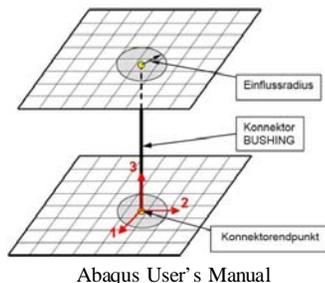


Figure 3: Spot weld model

For BMW crash calculations, spot welded joints are modeled as fasteners, each consisting of a connector element with six relative degrees of freedom for which a coupled elastic-plastic with damage and failure constitutive behavior is modeled. The connector end nodes are coupled with the shells of the joined plates via distributed couplings with a specified radius of influence..

The spot weld model was validated through component tests, i.e. T-Joints, where different local stress states were achieved in the spot welds through a variation of the global load case.

Validation results show good correlation between simulation and experiment, illustrated in [Figure 4](#). All experimental curves lie within the scatter band characterized by the standard deviation of the weld spots in series production.

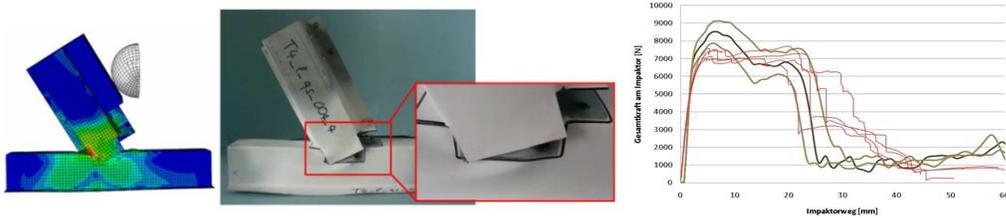


Figure 4: Validation of spot weld model through “T-Joint” component test

2.2 Material Failure Predictions Using the IDS Failure Criteria

Sheets and thin-walled extrusions made from metals generally fail due to one or a combination of the following mechanisms ([Figure 5](#)):

- Ductile fracture (based on initiation, growth and coalescence of voids).
- Shear fracture (based on shear band localization).
- Instability with localized necking (followed by ductile or shear fracture inside the neck area).

The failure strains of the different mechanisms depend primarily on strain rate, temperature, anisotropy, state of stress and strain path (deformation history).

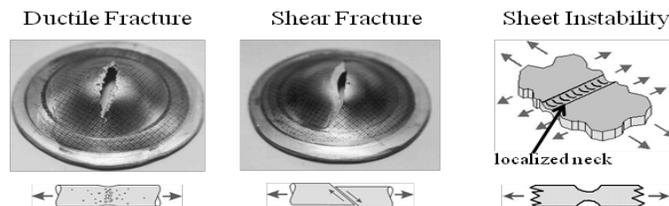


Figure 5: Visualization of ductile fracture, shear fracture and sheet instability

A comprehensive approach for predicting failure of structural components caused by any combination of these mechanisms was proposed in [2] in terms of three phenomenological failure criteria for Instability, Ductile, and Shear fracture (IDS failure criteria). The failure criteria are based on macroscopic stresses and strains and include the effect of anisotropy, state of stress, and strain path. One set of parameters is valid for one temperature and one strain rate regime (quasi-static or dynamic).

The IDS failure criteria have been integrated into Abaqus’ general capability (framework) for modeling progressive damage and failure of ductile metals. The capability supports the specification of multiple damage initiation criteria and the corresponding damage evolution laws, including element removal options.

For the characterization of the loading path for all three types of limit curves, the ratio of major to minor principal strain rates, $\alpha = \dot{\varepsilon}_2 / \dot{\varepsilon}_1$ is used as a common measure [2]. For the purpose of comparison, all failure limits are combined into a “failure map” in [Figure 6](#) for quasi-static and dynamic cases. The limit curves are plotted for the special case of linear strain paths and membrane deformation. A linear strain path is defined by a constant value of α .

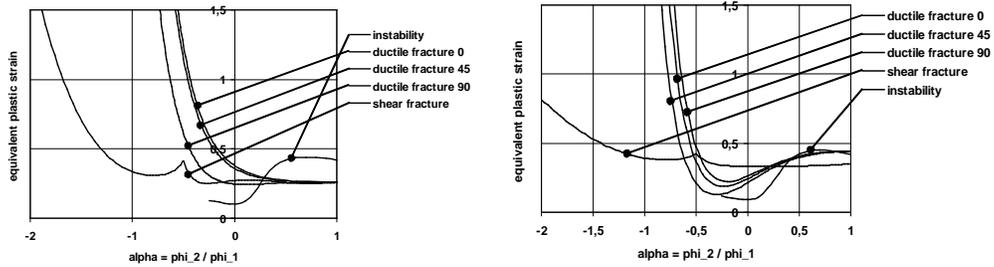


Figure 6: Quasi-static (left) and dynamic (right) failure diagram for extrusion EN AW-7108 T6

In the area of low stress triaxiality (left side of the failure map), shear failure is the dominating failure mechanism for quasi-static as well as for dynamic loading. For higher stress triaxiality, instability, ductile failure as well as shear failure can be the dominating mechanism (dependent on the quasi-static or dynamic loading).

The final validation of the failure model is performed by carrying out a controlled B-pillar intrusion test with a rigid impactor and comparing these test results against a corresponding simulation ([Figure 7](#)). In the simulation model, the effects of pre-deformation from the prior forming process for the sheet metal components are taken into consideration in the evaluation of the IDS failure criteria. Moreover, the failure behaviors of the various joining techniques used in the car structure, are also taken into consideration.

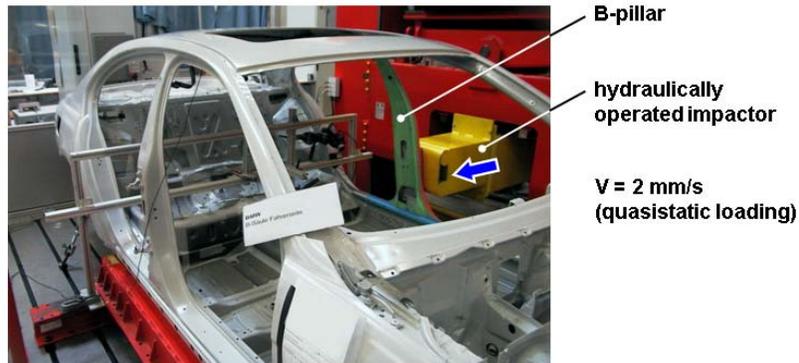


Figure 7: Set-up of the B-pillar intrusion test

The comparison of the fracture pattern between simulation and experiment is shown in [Figure 8](#). The simulations using the IDS failure criteria accurately predict the real fracture pattern which is initiated by instability (localized necking) in the flange area.

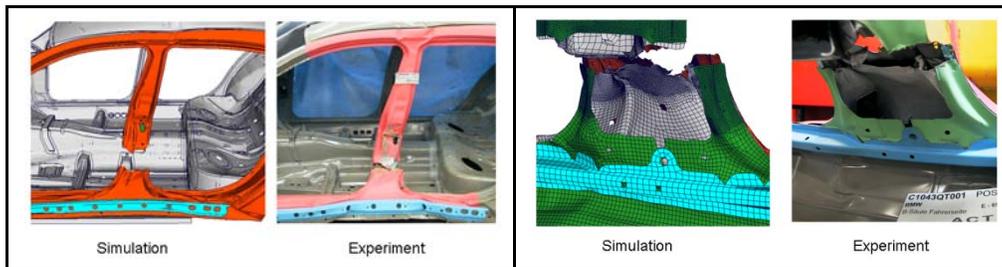


Figure 8: Fracture pattern initiated by instability from test and simulation

Figure 9 shows the force-deflection curve from the contact between the B-pillar and rigid impactor. The drop in force resulting from the crack initiation (instability) and the subsequent elimination of failed elements that initiates in the flange area of the B-pillar correlates extremely well with the experimental test results.

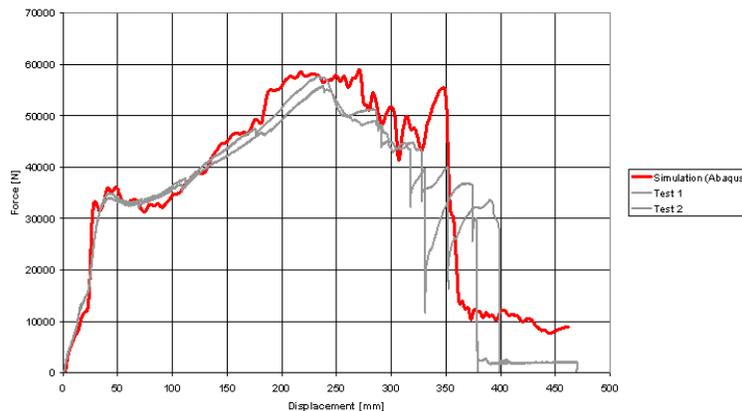


Figure 9: Force-deflection curve from test and simulation

2.3 Airbags

The simulation of airbag restraint systems generally focuses on two working points:

- Airbag in a fully deployed state: In the case of frontal crash, the occupant is protected by fully deployed airbags at the moment of initial contact. It can be assumed that in this state, the gases in the airbag chambers are distributed homogeneously and this simplifies the simulation significantly, since gas flow effects can be neglected and the simplified modeling technique known as the “uniform pressure method” (UPM) can be used.
- Airbag in a partially deployed state: Sometimes, due to trim parts or out-of-position occupants, initial contact between surroundings and airbag can occur before the airbag is fully deployed. During this “airbag unfolding” phase, localized high pressure gradients and high flow velocities have a strong influence on the shape and behavior of the airbag. For this time period, the uniform pressure assumption is not valid and cannot be adopted in studies where the deployment has to be investigated to show the interaction with trim

parts and/or out-of-position occupants. Alternative methods, based on spatial discretization of the airbag volume and consideration of the flow dynamics, are required. Abaqus/Explicit provides the coupled Eulerian-Lagrangian (CEL) capability for this purpose.

In addition to other functionality needed for occupant restraint simulations, the second working point above – description of the flow dynamics in airbags – was considered in detail in the benchmark evaluation. It should be noted that different modeling techniques are available to consider the flow of gas into the deploying airbag. In the following, the software requirements and the results of the current development status of the CEL capability in Abaqus/Explicit are shown, using the example of a curtain deployment in a static test. The intention is the modeling and optimization of the curtain unfolding process as the airbag interacts with trim parts.

In order to be able to consider the flow dynamics in the airbag using the CEL capability, a hexahedron mesh is built over the airbag's volume and the region where the deployment will occur. In each of those elements, the Eulerian equations are solved to describe the gas dynamics. The elements that model the airbag itself follow the Lagrangian equations of motion and intercommunicate with the flow field in the Eulerian elements via momentum exchange.

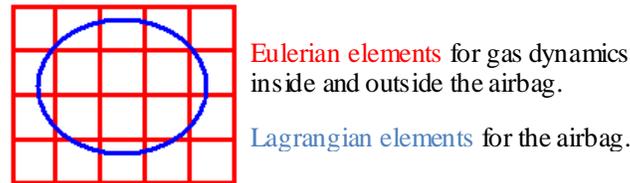


Figure 10: 2D schematic diagram of the mesh formation: Eulerian cells and Lagrangian elements for CEL simulations

The curtain airbag poses a difficult challenge because of the combination of closely folded fabric layers and long flow channels from the inflator to the far ends of the airbag. While the development of CEL in Abaqus/Explicit is ongoing, the characteristic deployment of the curtain airbag can be modeled in good accordance to the test behavior. [Figure 11](#) shows characteristic airbag shapes in test and simulation, which are investigated in detail. Simulation results shown include both CEL and UPM results in order to contrast the important differences that exist between the two during the deployment.

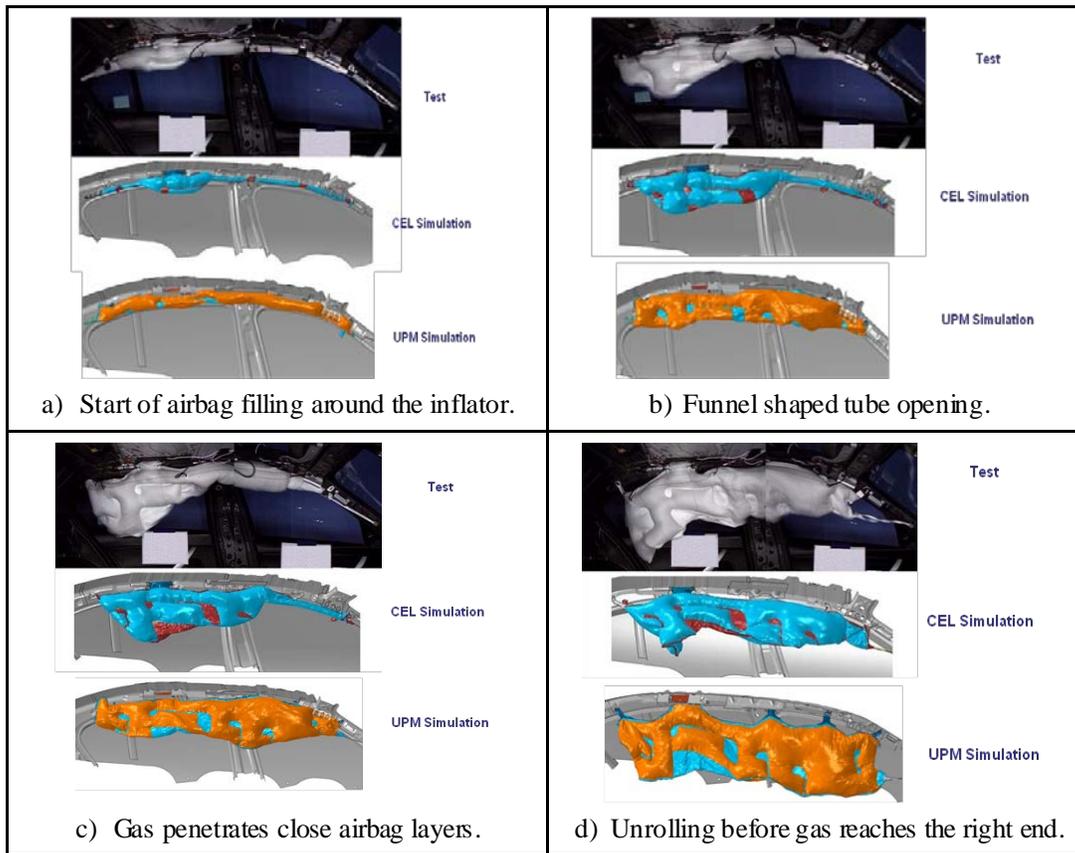


Figure 11: Characteristic airbag shapes in test (above) and simulation (below)

The airbag filling starts around the inflator (a) and propagates first in the horizontal channel. During these first few milliseconds, the inflowing gas inflates the region of the airbag near the inflator, and begins to produce a funnel-like shape of the airbag in regions further removed from the inflator (b). The unrolling and unfolding of the airbag layers is caused by the combination of two factors:

1. Pressurized inflator gas incrementally penetrates between folded layers, causing them to incrementally separate.
2. Forces that develop in the airbag fabric due to rapid introduction of inflator gas cause overall motions of the airbag that induce further unrolling and unfolding.

As the second factor above begins to become active, it has a loosening effect on the airbag that further facilitates the penetration of inflator gas between fabric layers that are now not so closely folded together as they were in the original configuration.

In a subsequent stage of inflation (c), the region of the airbag nearest the inflator continues to deploy more strongly than regions further removed from the inflator, though inflator gas is

beginning to penetrate these regions. In the last stage shown (d), the airbag has unrolled nearly completely at the right end, even though little inflator gas has reached there at this point in time.

In comparing the simulations against these experimental test results, some very distinct differences between UPM and CEL become apparent.

- The simplifying assumptions in the UPM simulation are clearly unable to capture the deployment characteristics, as pressure in the UPM simulation is applied to the entire interior surface of the airbag, regardless of whether inflator gas can physically reach closely folded layers of fabric. In the UPM simulation, the airbag is predicted to open in a generally uniform manner from one end to the other, which clearly is not what happens in the physical test.
- The CEL simulation captures the real deployment characteristics in a much more accurate manner, with early strong inflation and deployment in regions close to the inflator. Reproducing the funnel-like shape of the airbag in the very early stages of deployment is somewhat dependent on the level of mesh refinement for the Eulerian cells. In the latter stages of deployment, the CEL simulation shows a similar unrolling of the right end of airbag with only minimal penetration of inflator gas, as is also indicated in the physical test.

SIMULIA development of the CEL capability continues, and is expected to result in a very powerful tool for the design of airbags and the interaction with their environment during the deployment phase.

3. Predictiveness of Full Car Crash Models

Predictiveness for crash simulation models is best achieved by using proper physical formulations for all phenomena which affect the pertinent functional behavior. For body-in-white structures, the exact formulations of the material behavior, including the failure mechanisms, as well as the failure mechanisms of all joining techniques, are important for the performance of the model. Therefore, following the completion of the migration project in 2006, SIMULIA and BMW continued their strong cooperation in these areas, and as a result, BMW is now able to set up physical crash models with Abaqus/Explicit to meet the BMW internal vision for a design process without physical hardware tests.

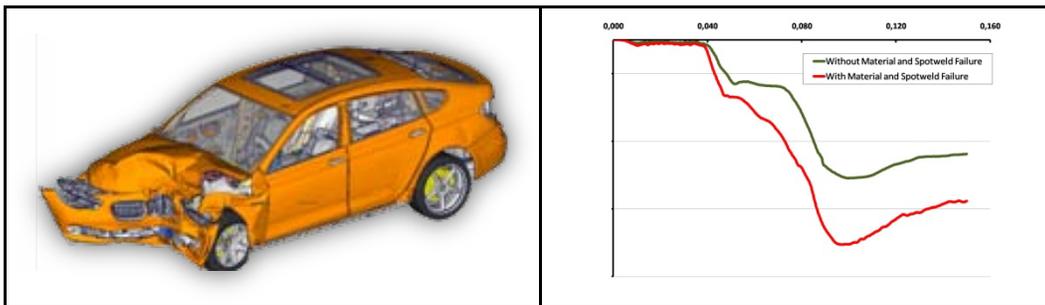


Figure 12: Firewall intrusion result of crash models with old and new modeling

As an example, [Figure 12](#) shows the difference in the firewall intrusion into the passenger compartment for simulation of a frontal offset crash test against a deformable barrier, comparing the old modeling technique (without failure mechanisms) and the new modeling technique (with failure mechanisms). Without any failure mechanisms, the predicted intrusion of the firewall in this full vehicle model shows a response that is 30% stiffer than when compared to a model with all necessary failure mechanisms. In this particular case, as well as in various others, the simulation results obtained when not accounting for potential failure mechanisms to develop are not conservative – they predict less intrusion into the passenger compartment than actually will occur. With fewer and fewer hardware tests to be carried out in the future, there will be little to no experimental information available for validation and tuning of a crash simulation model, and therefore a 30% uncertainty in deformation modes compared to reality is not acceptable. That is the reason why BMW use the new approach for material and spot weld failure now as a standard practice in all crash simulations.

For the benchmark, four different cars have been analyzed and compared to results from real tests. As already mentioned, not only the global deformation has to be calculated exactly but also local effects due to material and joining failure have to be predicted. For that reason a model for an entire car is now built up to include about 3.5 million elements. For a more detailed prediction of the failure, between 100 and 150 parts are mapped with data from deep drawing simulations of these parts. [Figure 13](#) shows the setup of a typical crash model that incorporates effects from deep drawing simulations, material definitions with failure, and spot weld and adhesive definitions with failure mechanisms. In constructing such models, care is taken to ensure that BMW meshing guidelines are followed, and that BMW-released models (including damage and failure) for materials, spot welds, and adhesives are incorporated. These methods have been in standard production usage at BMW for more than a year.

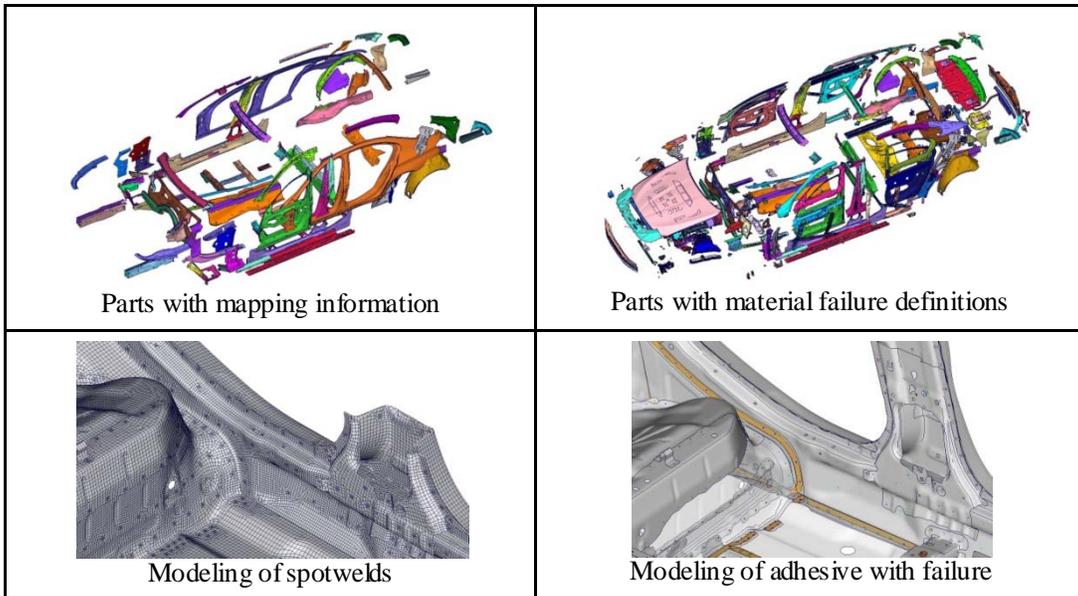


Figure 13: Standard features for BMW crash simulation models

3.1 Global Deformation Behavior

The global deformation can be characterized as the global condition of the BIW after the car has been relaxed after the crash. The main issues are global deformations such as dashboard intrusion, pulse, or other geometrical or kinematic results.

In a hardware test, only a few test parameters are recorded; videos from several viewpoints are also recorded to aid in analyzing the hardware test. Only these limited recorded data are then available to help explain and understand the complex deformations that develop throughout the car during the test, as well as the measured injury criteria for the crash dummies. A key advantage of a virtual crash is the wealth of data available throughout the entire model and history of the simulation in order to assist in understanding the detailed deformations, kinematic results, and injury criteria to evolve. To do so requires constructing the full vehicle model with sufficient detail, building it up from the hundreds of different components that are typical in a modern car. Only if the model is constructed with this level of attention to detail will the simulation then be able to accurately predict the hardware test results. For that reason there was done an intensive comparison between simulation and real test for different time steps during the crash.

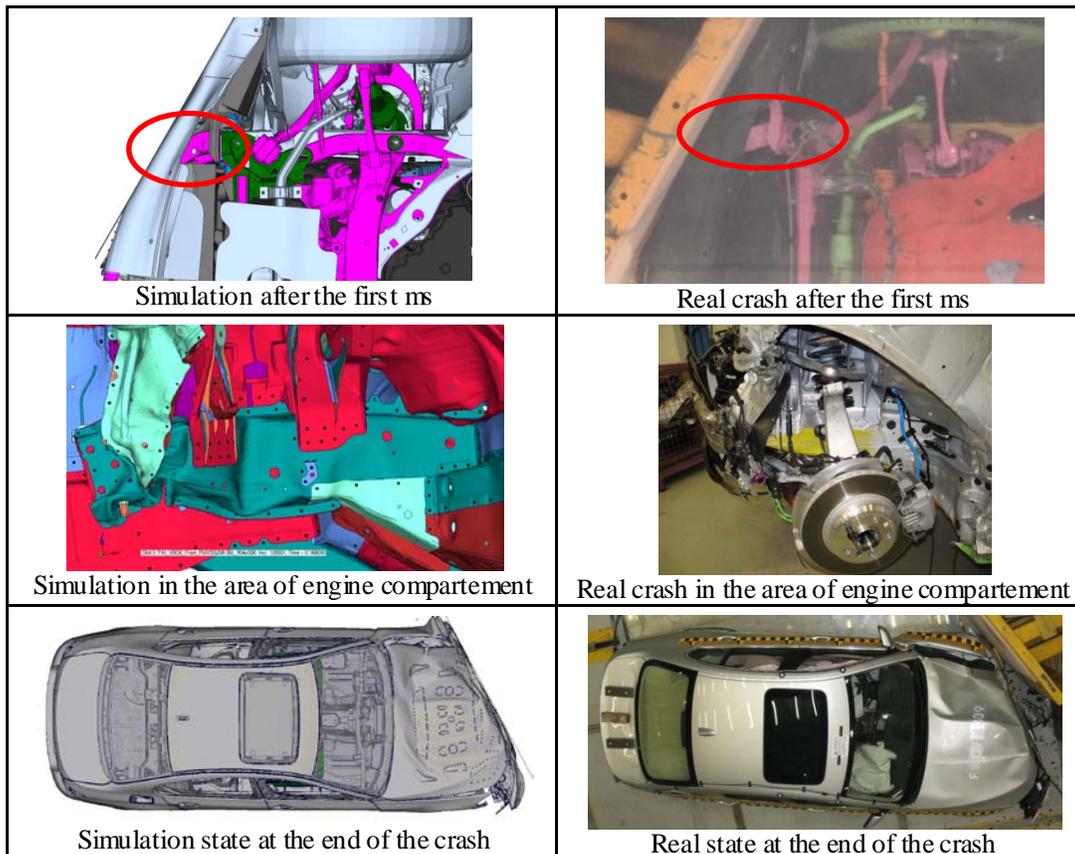


Figure 14: Deformation chain for 30° frontal impact test

Figure 14 shows the comparison of the deformation between simulation and real test at a few locations and points in time. In order to calculate the final state of the global deformation as precisely as possible, the response and deformation that develop within the first few milliseconds are very important, as that influences subsequent load transfer into the entire car. The top two pairs of images in Figure 14 demonstrate that Abaqus/Explicit correctly predicts the critical sequence or chain of deformations early in the crash event. The last pair of images shows the comparison between test and simulation at the end of the test.

The same level of scrutiny was carried out for all vehicle models included in the benchmark, and in all cases, results from Abaqus/Explicit exhibited the best correlation against physical test.

3.2 Local Deformation Behavior

Because of the significantly reduced hardware testing during a car development program, not only the global deformation characteristics of the car are important, but also very localized behaviors are important to capture, including that of individual spot welds and local sections of components. For that reason, the calculation of such local effects received considerable attention during the benchmark and was also an important factor in BMW's final decision regarding crash simulation software.

Spot weld failure is dependent on the material grades and thickness of the panels being joined. In each car there are typically several hundred different combinations of material grades and panel thickness that are joined by spot welding, and each combination generally requires its own set of failure parameters. It is not feasible to identify the failure parameters for each combination of material grade and thickness by experiment. Therefore, a formula has been developed to calculate the required failure parameters for each combination, based on a limited number of experiments as well as the diameter of the spot weld [3]. The comparison between prediction of spot weld failure from simulation and physical test is shown in Figure 15.

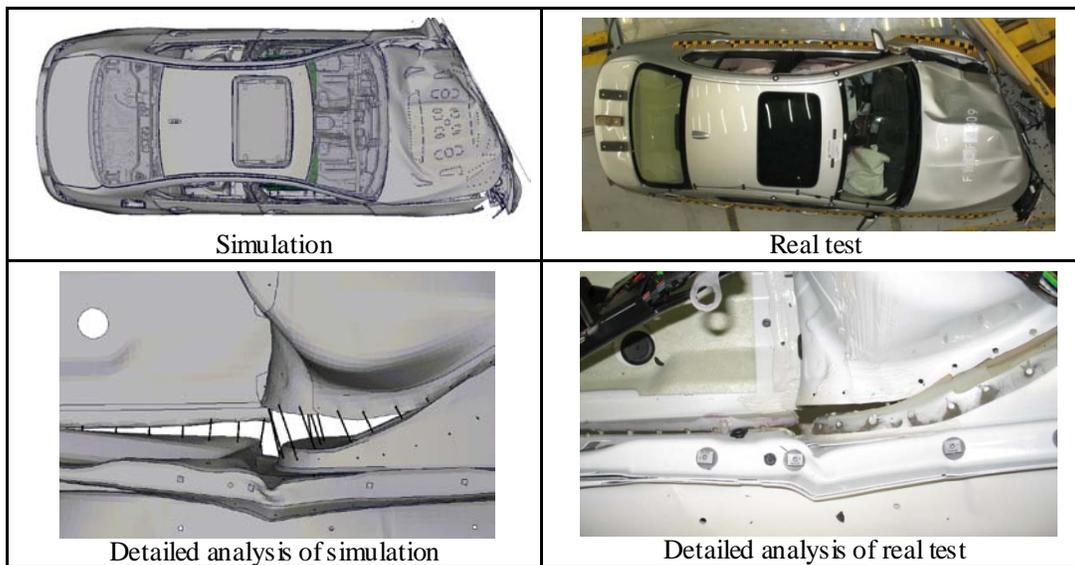


Figure 15: Spot weld failure during crash

It is evident that the simulation with Abaqus/Explicit and the spot weld model from BMW predicts the failure of a spot weld very accurately. An important consideration is that, to obtain such predictions of localized spot weld failure behavior with Abaqus/Explicit, no additional or follow-on simulations are necessary – such results are directly available from the crash simulation involving the entire car. Achieving this level of prediction within the context of the full vehicle simulation is an important factor in being able to most efficiently and effectively carry out the virtual design process.

In the early stages of a car development program, it is important to know and understand not only the global deformations that will develop due to various crash load cases, but also the potential for key structural components to rupture or develop cracks. If these can be predicted early in the program, then there is the best opportunity to make design changes that will preclude such behavior. With the previously described method for the calculation of material failure, along with the prescribed meshing guidelines, crack initiation in a part can be predicted very accurately with Abaqus/Explicit. To obtain such predictions, it is not necessary to know a priori where a crack might initiate and subsequently generate a fine mesh in that section. The global element size prescribed in the meshing guidelines is adequate for accurate predictions of where cracks will initiate. Figure 16 shows the comparison of the simulation and hardware test for a side impact load case. As the pictures show, the crack initiation in the B-pillar is predicted very closely to what develops in the hardware test. Differences between simulation and test that do occur are often regarding the length of a crack. However, as cracks are mostly not wanted and sometimes even not allowed, prediction of crack initiation is more important than that of crack length. Nevertheless, the prediction of the exact length of a crack is a subject of pre-development projects within BMW.

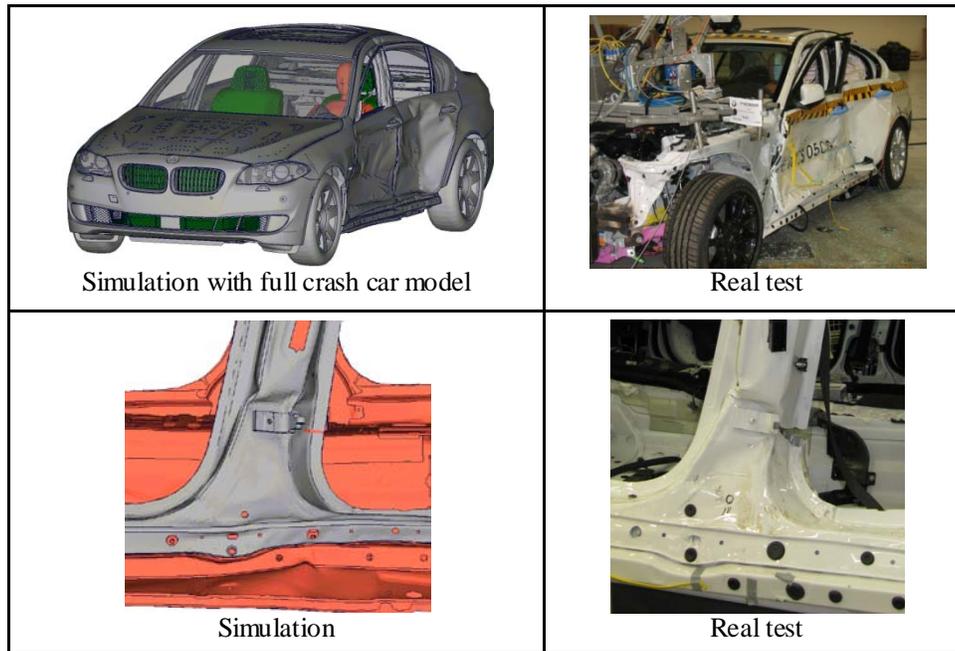


Figure 16: Prediction of crack initiation

Both above mentioned examples show that it is possible to predict the failure of material as well as of spot welds by Abaqus/Explicit and failure models developed at BMW.

4. Special Investigations

In addition to the topic of predictiveness at the component level as well as for full crash car models, the quality and robustness of the results are essential criteria in the evaluation of crash simulation software. Therefore, additional tests were done during the BMW internal crash software benchmark.

Small perturbations introduced during a crash simulation, such as round-off errors, should not lead to large differences in results. If the crash simulation software uses the proper stable time increment, and the model is adequately discretized and corresponds to a stable and robust vehicle design, results should not change much from one run to another. In the worst case, an unstable model will result in divergence; in other cases it can result in a moderate to severe violation of the energy balance. In addition, since the introduction of stochastic analysis into the study of design robustness, nondeterministic behavior of the crash solver is clearly undesirable because it is unpredictable. Determinism of the solver is a requirement, even if it comes at an additional computational expense. Therefore, BMW investigated numerical sensitivity for one of the benchmark models.

Two basic investigations were performed, and some results are shown in [Figure 17](#). First, a single front impact crash car model was submitted five times on the same hardware with the same number of processors, and all of the results were compared. On the left side of this figure, the firewall intrusions for all five runs are shown. All simulation results are absolutely identical. This is not a standard which can be expected from other crash simulation software.

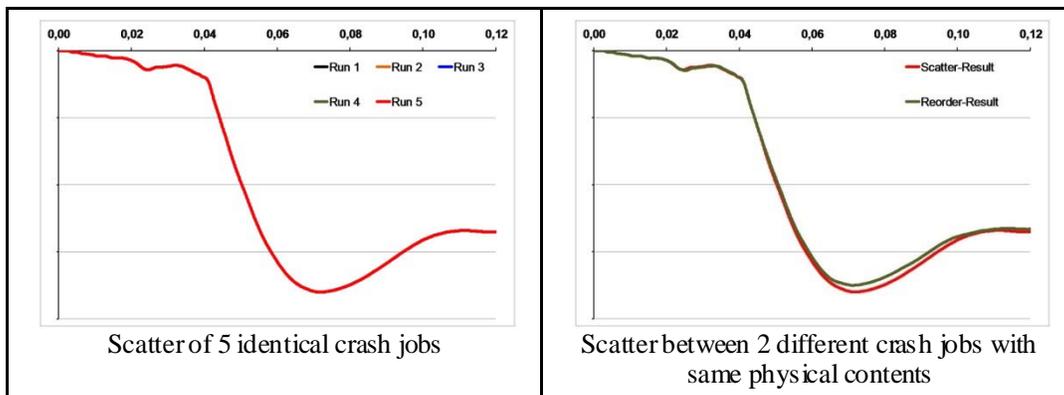


Figure 17: Scatter analysis

Next, stability was examined by increasing the complexity of the investigation. The input file from the same front impact model was assembled in a different way, without changing the physical content. Such a reordered input file is a completely different problem for an explicit solver even if the physical content of the model is exactly the same. The results matched very closely between the original and reordered model. The graph on the right in [Figure 17](#) compares the firewall

intrusion between the two simulations, showing a small difference of 3 % in the peak values. This is sufficiently small to allow design engineers to quantify the effects of design changes without having to consider numerical scatter caused by the crash simulation software.

An additional investigation concerning software quality deals with scatter in results caused by changes of the software version. Within our internal benchmark, a comparison between the current general release, Abaqus/Explicit 6.9-EF, and a snapshot of the Abaqus/Explicit 6.10 was performed (this snapshot version 6.10 had not yet been put through the SIMULIA internal release qualification process). The comparison of the driver dummy rib intrusion during a side impact simulation is shown on the left side of [Figure 18](#). The results from both versions are more or less identical.

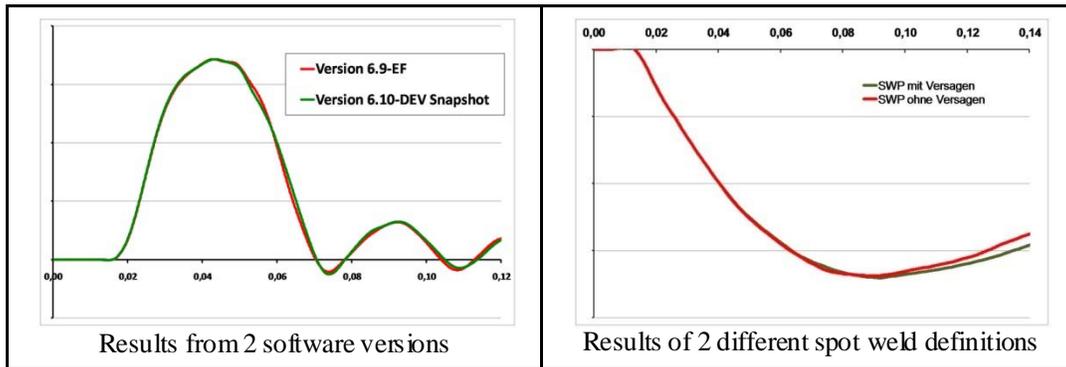


Figure 18: Quality of physical formulations with Abaqus/Explicit

One of the primary reasons BMW migrated to Abaqus/Explicit several years ago was due to its strong implementation of physically-motivated models and algorithms. One aspect of the most recent benchmark carried out by BMW sought to confirm this through a particular example – modeling of a spot weld, which can be accomplished in different ways in Abaqus/Explicit if potential damage and failure of the spot weld are not considered:

- Spot weld formulation with rigid connectors (BMW method) without switching damage and failure behavior on.
- Spot weld with the default fastener formulation, where no failure behavior is implemented.

Both spot weld formulations were investigated in a side impact crash model, where the car impacts a rigid pole. Results from both simulations are shown in the plot on the right in [Figure 18](#), comparing the intrusion of the rigid pole into the vehicle. For both definitions of spot welds, the peak intrusion value is identical, and the general shape of the intrusion behavior is nearly the same. Only during the unloading phase do very minor differences between the two simulations become visible.

The quality and robustness of Abaqus/Explicit have been proven by numerous other separate investigations carried out at BMW, each producing consistency of results similar to these four examples. The combination of quality, robustness, and predictiveness are the reasons why Abaqus/Explicit has been confirmed as the best crash solver for BMW needs.

5. Performance

Confidence in results, predictiveness of the simulation, and quality of the software are essential components in the decision process for simulation software in the area of crashworthiness. Additionally, turnaround time for a given simulation is an important factor for effective daily application in product design. Variants should be simulated and evaluated within a very short time. The target turnaround time for a full vehicle simulation, including the new level of predictiveness now available through incorporation of local effects, is approximately 24 hours. And in urgent cases, this target needs to be still lower.

Of course, an increased level of predictiveness would be expected to increase the runtime to some degree, due to greater model refinement and more computationally intensive algorithms. Therefore the change in runtime was investigated between the previous simulation method and the current method, which incorporates the demand for accurate prediction of local effects.

In [Figure 19](#), the green curve displays the dependency of simulation turnaround time on processor count for the old, conventional simulation method. BMW was able to produce results within a very short time. The same figure also displays the increase in turnaround time by a factor of 2.3 due to the application of the new methods which increases the level of predictiveness. At the same time, the number of elements has increased from 1.8M to 3.5M (full vehicle model, including dummy and folded airbags), and significantly more intensive algorithms are activated to simulate failure of spot welds and materials, thereby putting the increase in turnaround time into perspective.

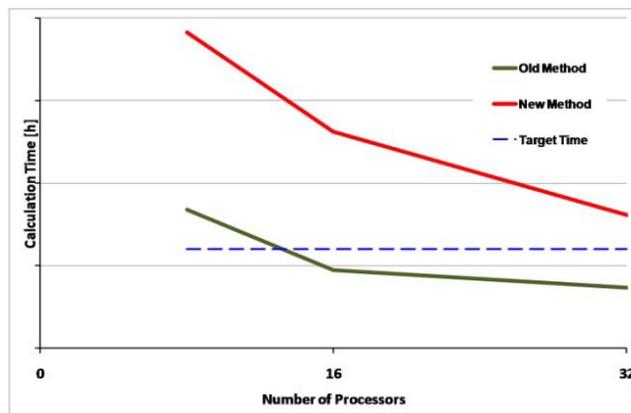


Figure 19: Computation time for a full crash car model (on 2006 hardware)

Since the results using Abaqus/Explicit were so convincing in comparison with the competitors in terms of predictiveness and software quality, additional investigations were made with SIMULIA in the course of the benchmark to get the turnaround time within the target range of 24 hours without sacrificing quality or predictiveness.

Figure 20 displays the jointly identified targets to improve simulation performance. The diagram shows the potential to make adjustments to the BMW internal IT infrastructure that can yield substantial performance gains without a significant incremental investment in hardware. Additionally, performance is a key focus area for ongoing Abaqus/Explicit development, which also positively impacts the overall aim to reduce turnaround times. It is expected that these jointly identified targets regarding hardware and software improvements can be realized within a relatively short timeframe, which should position BMW very well to address its crashworthiness simulation requirements over the coming years.

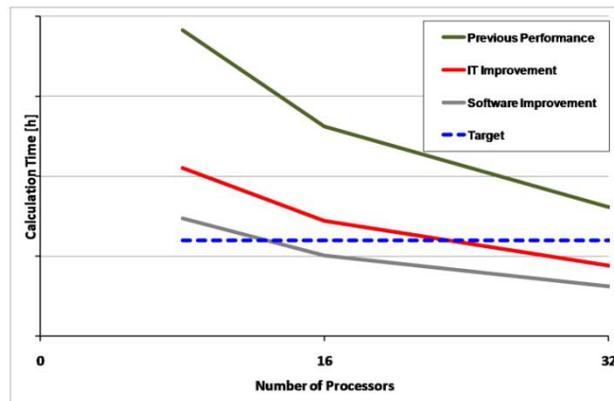


Figure 20: Opportunities for performance increase

6. Conclusion and Outlook

The requirement at BMW to reduce hardware tests by increasing the usage of virtual testing has led to new BMW internal demands for its crash simulation software. The ability to accurately predict local effects like material and connection failure now receives much more attention than has previously been the case. It can be shown that accurately accounting for such behaviors can have a substantial influence on important passive safety criteria – not doing so can lead to incorrect and often non-conservative predictions for these criteria, which are only then realized upon hardware testing.

Therefore a new benchmark of the different vendors of crash simulation software was conducted at BMW in 2009. The focal point of the benchmark was on predictiveness and credibility of simulation results. To be able to reliably evaluate these criteria, the direct comparison of simulation and test was key, both at the component level as well as the full vehicle level. The range of investigations was extensive, and only a small fraction of them have been shown in this paper. In direct comparison with the competitors' products, a significantly higher level of predictiveness can be demonstrated with Abaqus/Explicit – accurate predictions of critical local effects can be obtained for the complete range of relevant models, from components up through full vehicles.

Therefore Abaqus/Explicit continues to be the key design simulation tool for passive safety for BMW cars. Only Abaqus/Explicit enables BMW to fulfill its internal demands

for continuing enhancements to simulation functionality and performance, while also meeting the stringent requirements to further compress vehicle development cycles and reduce physical prototypes and associated testing. These benefits can be quantified by cost savings measured in millions of Euros and months of product development time.

7. References

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