A NOVEL VIRTUAL DEVELOPMENT PROCESS FOR SIDE IMPACT AT MAGNA STEYR BASED ON NUMERICAL SIMULATIONS VERIFIED BY COMPONENT TESTING

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Abstract

Increasing demands for reduced development costs and timeframes have resulted in a growing need for numerical simulations to facilitate the vehicle development process. The use of simulations is shifting towards the early design phases, a practice also known as “frontloading.” This reduces the need for expensive, complete-car prototypes.
Previous complete-vehicle development projects at MAGNA STEYR included one or more generations of prototype vehicles. In terms of side impact requirements, each prototype generation was developed using numerical simulations and knowledge gained from crash tests performed on previous prototype generations.
For a recent project the company decided to cancel prototypes, especially for side impact, and to develop the car using virtual design tools. The challenge was to release parts and serial tools based on results from numerical simulations. Since the accuracy of the numerical simulations would no longer be verified by crash tests, there was a serious risk that serial parts and tooling would require subsequent, high-cost modifications if crash tests with pre-production cars did not show the same results as the simulations.
For this reason, a new development approach based on previous R&D projects was introduced. It consists of a single, numerical Finite-Element-Method (FEM) model, used for both the design of the Body-in-White (intrusion characteristics of the side structure) and the optimisation of the restraint (occupant simulation); relevant experiments on prototype parts and parts from other car models with similar designs and materials; and simulation models of these component tests, which are validated against the test results.

Keywords: Side Impact, Crash Simulation, Virtual Development Process, Sled Test, Impactor Test

Presenting Author’s biography

Arno Eichberger is assistant at the Institute of Automotive Engineering, where he is preparing his habilitation thesis. Prior to this appointment he was employed at MAGNA STEYR, where his duties included involvement in several car development projects, especially in the design of side impact protection restraints using CAE methods.

1 Introduction

Since their inception, vehicle manufacturers have been seeking faster times-to-market. Depending on the OEM, the time for serial development currently stands at about 24 months, and further reduction is anticipated. This trend has been made possible by increasing the use of numerical methods in all phases of the development process [1]. Of course the problem of "virtual development" is the prognosis quality of the simulation models.
Consumers in Germany cite vehicle safety as the most important factor when purchasing a new car [2]. For this reason, one of the most important aspects of a car is its crashworthiness, as is evident in the several different crash-test configurations that have been defined by legislation and customer organizations.
The lateral impact of a vehicle or a fixed object into a passenger car is responsible for approximately half of the deaths and severe injuries in Germany [4]. Similar accident statistics from other studies confirm this number worldwide.
Today, a car model intended to be sold on a worldwide market has to meet requirements of about 10 to 20 different load cases for side impact [3]. Most of these side-impact crash tests are performed on a non-moving target vehicle struck by a moving trolley with a deformable honeycomb barrier mounted on its front to simulate the stiffness of a typical passenger car (Fig. 1).

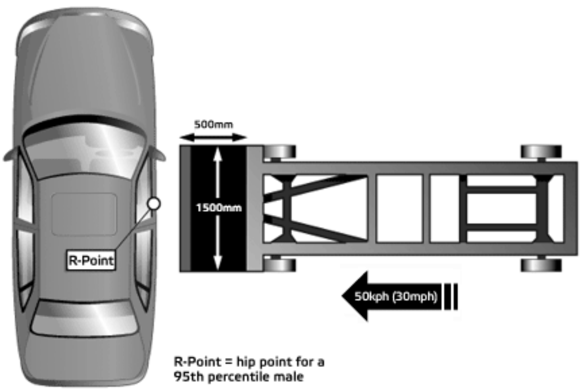

Fig. 1: Example of a side-impact test (source: Euro Ncap [11])

Since a development process based on hardware tests would be a significant deviation from the aforementioned practice of frontloading, MAGNA STEYR has developed a design process for side impact based on numerical simulation.

2 Methodology

Previous complete-vehicle development projects at MAGNA STEYR included one or more generations of prototype vehicles. In terms of side impact requirements, each prototype generation was developed using numerical simulations and knowledge gained from crash tests performed on previous prototype generations.
The performance of the Body-in-White (intrusion characteristics) and the restraint system (energy absorbing interior trim parts and side airbags) were developed by separate simulations, i.e. complete-car FEM simulation and FEM occupant simulation.
For a recent project the company decided to cancel prototypes completely and to develop the car on a virtual basis.
The challenge was to release parts and serial tools based on results from numerical simulations. Since the accuracy of the numerical simulations would no longer be verified by crash tests, there was a serious risk that serial parts and tooling would require subsequent, high-cost modifications if crash tests with pre-production cars did not show the same results as the simulations.
Therefore a new development approach based on earlier R&D projects was introduced. It consists of:
• A single numerical FEM model, used for both the design of the Body-in-White (intrusion characteristics of the side structure) and the optimisation of the restraint (occupant simulation).
• Relevant component tests of prototype parts and parts from other car models with similar designs and materials.
• Simulation models of these component tests, which are validated against the test results.

2.1 Description of the process

The fundamental idea of the process can be explained with the V model structure [12].
The complete vehicle is divided into its subsystems (Body-in-White, engine and drive train, seats, cockpit, airbag, belt etc.) and components (sheet metal parts, airbag fabric and gas generator, etc).
The number of subsystems is determined by the vehicle requirements (e.g. side impact according to legal specification ECE-R95). For each subsystem a simulation model is created that consists of components, which are created in the next break down step (Fig. 2, descending side of the V).

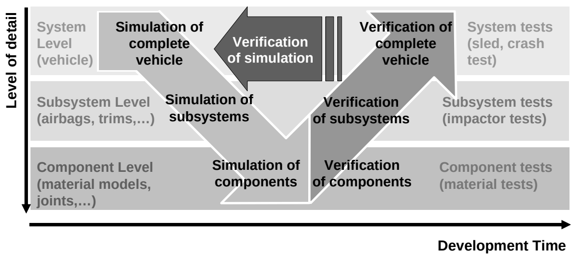

Fig. 2: Breakdown process of the simulation models

The verification process (ascending side of the V-model) proceeds from component to subsystem and finally to system level.

The proposed process is based upon the assumption that specifically tailored experiments can provide data for verification of the component, subsystem and system. Thus a simulation based development process is made possible, shifting the efforts to the left side of the V model (depicted by left pointing arrow in Fig. 2).

Therefore the main objective of the experiments conducted is not assessing vehicle performance directly (e.g. crash tests), but rather verifying the numerical models. Consequently, this idea can be translated into a multi-stage approach to numerical models, as depicted in Fig. 3.

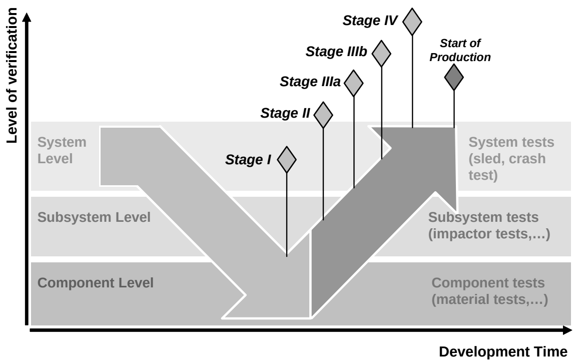

Fig. 3: Multi-stage approach

The process can be roughly divided into four stages, which are described in more detail below.

Before stage I, design tools are applied for the concept phase, which very often includes simulations that combine components from previous projects. The level of verification at this point is usually low.

Step by step, the level of verification gradually ascends as the results from component, subsystem and system tests are applied, thereby eliminating errors from the numerical model of the complete vehicle FEM simulation.

Examples of these experiments are:

Component level:

- Material models of the sheet metals and plastics out of which the parts used in the vehicle, barrier and dummy model are made
- Tensile and shear tests of joining types, such as spot welds or bolts

Subsystem level:

- Impactor tests for the airbag system
- Impactor tests on the door trim module
- Impactor tests on the crash test dummy

System level:

- Sled test
- Complete vehicle tests

2.2 Stage I – component verification

The process starts with the calculation of the vehicle's requirements (e.g. dummy injury values such as rib deflections) by using a Finite-Element-Method model on complete-vehicle level that includes the following subsystems:

- Body-in-White with doors and closures
- Engine, power train and related components (e.g. exhaust system)
- Chassis
- Seats in all seating positions where the placement of a crash test dummy is required, including belt and (if applicable) belt pretensioners.
- All trim parts that interact with the dummies (door and B-pillar trims, roof liner)
- Lateral restraint systems (pelvis/thorax/head airbags or energy absorbing elements in pelvis, thorax or head contact areas)
- Impacting trolley and honeycomb crash barrier
- Crash test dummy

It must be pointed out that, especially in all contact areas of the dummy on the vehicle side, the level of detail of the FEM model must be adequate (e.g. window lifts in the door or ribs in the pillar trims must be included).

This initial model is used to determine the vehicle's behaviour in all load cases. Naturally, since no verification tests on subsystem and system level are available, only verification on component level is applicable. Material models of sheet metal and plastic components, which have been verified by material testing, are usually available. These material models provide a significant portion of the crash model's knowledge base. The numerous related component tests (e.g. tensile tests, drop weight and pendulum tests) will not be discussed in more detail here.

A plausibility check of the results with regard to previous vehicle projects and the engineer's experience provides important guidance in this development phase. In a top-down approach, the results from the dummy injury responses are analysed down to the vehicle components (e.g. the time-history of a specific thorax rib deflection curve and the intrusion velocity of the passenger compartment in the same area).

After this analysis and correction of errors, a multidisciplinary optimisation process is carried out in order to meet the vehicle's specification in all side-impact load cases while maintaining vehicle functions in other disciplines (e.g. vehicle stiffness, weight and cost targets, producibility). This optimisation process, coordinated within the so-called "CAE team" in the simultaneous engineering process, concludes this phase of the development project and usually marks the attainment of the development milestone "confirmation of concept."

The complete vehicle is modelled, including all components relevant to the side impact. This is a departure from previous projects, which were based on the following sub-model approach:

The side-impact model was divided into a model that simulated the intrusion characteristics of the vehicle structure ("crash structural simulation") and a sub model that contained only the components and subsystems that affected the dummy's biomechanical responses ("occupant simulation"). In the sub model the intrusion characteristics were defined by boundary constraints and only the structural parts in the area of the dummy were modelled (Fig. 4).

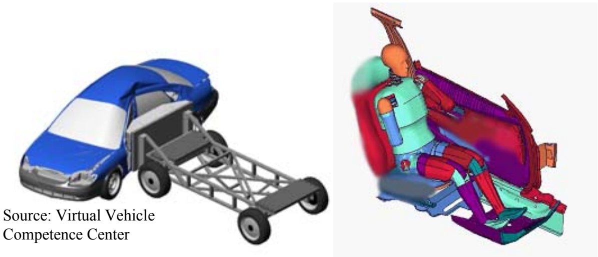

Fig. 4: Crash structural simulation vs. occupant simulation

In the project described here, these two separate models were combined to form a single model that serves both purposes.
This combination reduces the required setup time of the input decks. Although the computation time of the single model is slightly higher, the end result is a reduction in the overall process time.

2.3 Stage II – subsystem verification

In stage II the verification level of the complete-vehicle model moves up from component level (material models) to subsystem level.
Subsystems of interest for side impact include crash test dummy, honeycomb crash barrier, seats, airbags, paddings and trim parts.
While the dummy and barrier models are usually provided by software suppliers (who validate their subsystems through specific testing), the other subsystems are project-specific and must be developed and verified for each new project. The most important subsystems for side impact – airbags and trims – are discussed in more detail below.

2.3.1 Airbag verification

Verification of the Airbag FEM models was performed by the supplier of the lateral airbag system. This lateral airbag system consisted of a seat-integrated, single-chamber side airbag that covers the dummy from the shoulder to the pelvic area (Fig. 5) and a roof-mounted head airbag.

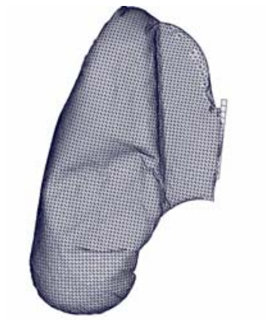

Fig. 5: thorax airbag

For side impact it is essential to verify two main properties – the positioning of the airbag and the damping characteristics.
Especially in side impact, the positioning of the lateral airbag system is influenced by the vehicle's intruding side structure. The space remaining at the specific moment when the airbag electronic control unit's control algorithms trigger the airbag deployment, determines the success of the final airbag positioning.
Secondly, the damping characteristics of the airbags are influenced by the volume of the fully inflated airbag (determined by the geometry of the fabric and additional features, such as tethers), the amount of gas in the airbag (produced by the gas generator), and the leakage of gas out of the airbag (determined by vent orifices, leakage of the airbag fabric and seams, and gas flow in multi-chamber airbags).
These two main properties of the airbag are verified by state-of-the-art component testing:

- Deployment tests of the folded airbag

Deployment tests were filmed with high-speed video. The resulting images from each millisecond could then be compared with the unfolding and positioning behaviour predicted by the simulation (A prerequisite is that a folded airbag model must be available).
New techniques for the calculation of the non-stationary gas flow of the deploying airbag were recently developed [16], which have proven to be suitable for serial development [14]. In the future, these techniques will predict the positioning behaviour more accurately.

- Impactor tests on the fully inflated airbag.

These tests provide force-deflection curves that can easily be reproduced with the airbag FEM model. It must be pointed out that the verification of the damping characteristics is a prerequisite for successful engineering, while the positioning characteristics can also be checked at a later point.

2.3.2 Trim part verification

The lateral trim parts of the doors and the B-pillar are essential elements of the lateral protection system. Since prototype parts were not available, a different approach was chosen: the geometry, materials and assembly of the new parts were compared to parts from similar cars of the same brand based on CAD data.

Fig. 6 shows cross sections of the door trim in the area of the dummy's thorax. The cross sections are drawn in planes normal to the vehicle's longitudinal X direction. The red line corresponds to the actual car (A), while the blue and green lines represent other cars (B and C) of the same brand. It is evident that the red and blue lines (car B) exhibit sufficient similarity, especially in the areas of interest (thorax and armrest area).

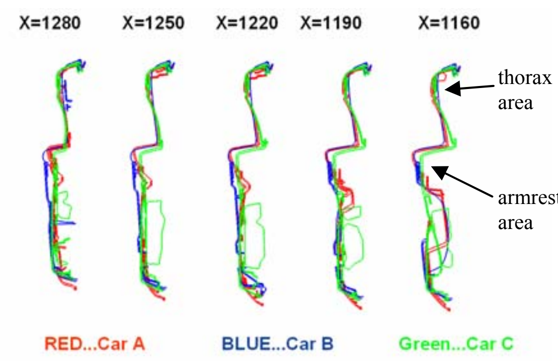

Fig. 6: cross section of door trims in longitudinal plane in dummy's thorax area

Therefore, relevant tests on module level were conducted using trim parts from car B. These experiments consisted of impactor tests performed on the trims to obtain data for the energy absorption capabilities.
Fig. 7 shows an example of the set-up of this impactor test. Different impactors representing the relevant body regions of the dummy (rib, abdomen, and pelvis) were prepared, and the trims were loaded with adequate impact energy. Mass and velocity of the impactors were derived from the numerical model.

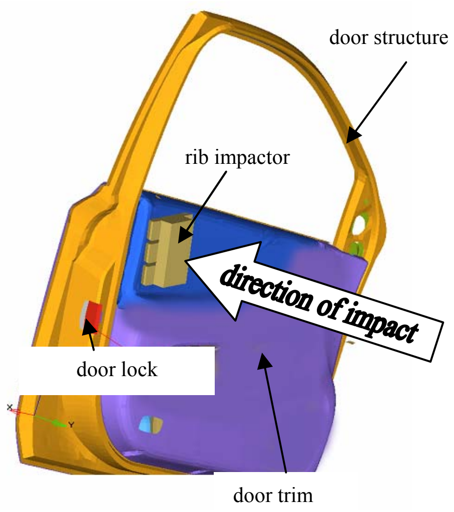

Fig. 7: Example of an impactor test

Additional verification techniques for the door-trim simulation models can be found in [13].

2.4 Stage III – System verification

Standard industry practice in side impact development involves the usage of test rigs to simulate the complex side-impact crash test on a simplified test rig, which allows for a fine-tuning of the lateral protection system.
Such test rigs can be found in many locations at OEMs and airbag suppliers [17], [5], [6] and have been successfully used for many years.
A novel test rig for the development of lateral protection system was developed at MAGNA STEYR ([7], [8], [10]). This rig is intended to simulate a side crash test as "realistically" as possible, while still minimizing testing costs (Fig. 8).

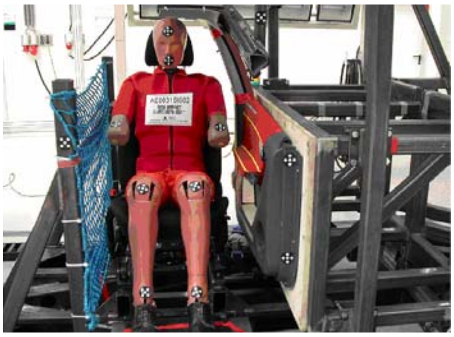

Fig. 8: MAGNA STEYR side impact test rig

What sets this test rig apart is its well-controlled acceleration-deceleration device ("Hyper-G", [7]). This device eliminates the need for expensive pretests by enabling an "online controlled" simulation of the vehicle side structure's intrusion characteristics that has a guaranteed high-accuracy with regards to repeatability.
The test rig (Fig. 9) consists firstly of a main "seat sled" that simulates the motion of the whole car being pushed away by the impacting trolley. The seat sled is powered by a so-called "mini Hyper-G," which reproduces the motion of the complete vehicle. The seat, dummy and lateral car structure ("side panel") can be mounted on this sled. The seat can also move on the seat sled, which allows for the simulation of a lateral seat motion caused by the intruding vehicle structure.

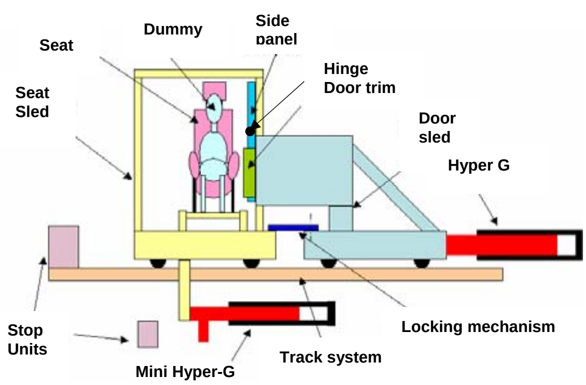

Fig. 9: scheme of the side-impact test rig

The second important element of the test rig is the so-called "door sled," which carries the door and the door trim. Its function is to simulate the intrusion of the lateral vehicle structure caused by the impact of the striking car. The door sled also impacts the vehicle side panel. Hinges installed in the side structure enable buckling at well-defined locations without destroying the parts of the side structure.

In order to simulate the complex interaction between the striking object, the vehicle lateral Body-in-White structure, the trim parts, airbag system and the crash-test-dummy, several pretests have traditionally been necessary: Tests for adjusting the intrusion behaviour of the door sled are followed by tests to adjust the sled set-up to match the dummy injury responses as predicted by a side-crash test or numerical simulation.

In order to avoid these pretests and to enable a virtual development process, a detailed FEM model for the complete test rig has been developed and verified in initial test series [9], Fig. 10.

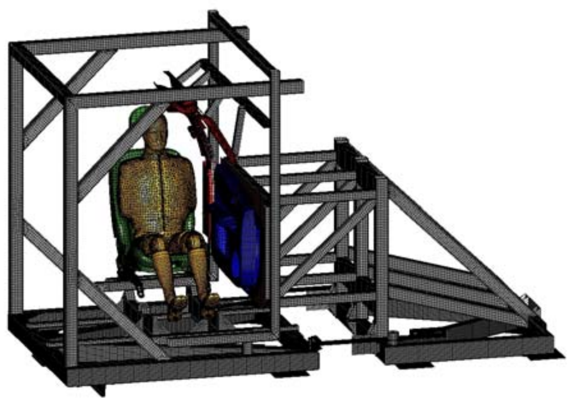

Fig. 10: FEM model of the test rig

The FEM model is used to define all relevant parameters for the test.

The function of the FEM model has now been enhanced in order to verify the prognosis quality of the complete vehicle performance (described below).

The system verification is accomplished in two different steps (Stage IIIa and IIIb) based on the availability of parts.

2.4.1 Stage IIIa – system verification using prototype parts

In this early test series on the sled test rig, serial parts were not available and had to be replaced by either prototype parts of the subsystems (seats, airbags, trims, side structure) or by using similar parts from other cars that have demonstrated similar behaviour in testing (see section 2.3.2).

The fundamental idea is to use the same parts for the FEM model of the sled and the physical tests, even if this requires the preparation of FEM models for parts from a different car. In this way, the simulation can be verified.

2.4.2 Stage IIIb – system verification using serial parts

The next step in the development process is the verification of the numerical models using parts from the actual car (A), including Body-in-White, seats, belts, airbags and trims with (pre-) production quality.

This step verifies the performance of the car in side impact at the next level of detail. At this stage of development only minor changes are feasible at reasonable costs (e.g. fine tuning of the airbag vent orifices, defining the "stiffness" and energy capabilities of the airbag…), since serial tooling and production processes are already established.

2.5 Stage IV – final system verification (certification tests)

The final verification of the side impact development process is of course achieved at the complete-vehicle level. Failure to meet the vehicle requirements could result in high-cost changes of serial tooling and eventually in even higher-cost delays in the start of production. This again highlights the importance of a virtual development process that is verified by component, subsystem and system testing and becomes more detailed throughout the various steps of development.

Even at this stage a final verification of the model is advisable for two reasons. First, this final verification offers an opportunity to review the development process and identify further measures for the improvement of the simulation's prognosis quality (see also section 3.4). Second, the final, verified model can be used for further projects – its subsystems and components can be disassembled and stored in databases. Verified simulation models are also helpful during model upgrading of the car.

3 Results and Discussion

3.1 Stage I – component verification

The initial model was built up as soon as all product data for all relevant components were available.

After an initial optimisation focussed principally on the body structure (intrusion characteristics), it was demonstrated that the vehicle requirements had been achieved to a large extent.

Nevertheless further improvements were necessary to meet all vehicle targets, and the prognosis quality of the models had to be proven in order to avoid expensive changes before the start of production.

It is important to note that at this level only verification on component level (material models) was available.

3.2 Stage II – subsystem verification

3.2.1 Airbag verification

Verification of the airbag deployment and damping characteristics is standard industry practice (e.g. [15]).

The procedure was explained in section 2.3.1. Since the results were within common requirements, they will not be presented in this paper.

3.2.2 Trim part verification

As explained in section 2.3.2, numerical models of the trim parts were verified by impactor tests. The impactors and the trim parts of car B were modelled in detail based on the CAD data and material specifications.
One example of the verification results is depicted in Fig. 11 (several impact points with sometimes different impactor blocks and impact energy have been investigated). The level of verification for this impactor test is not sufficient.

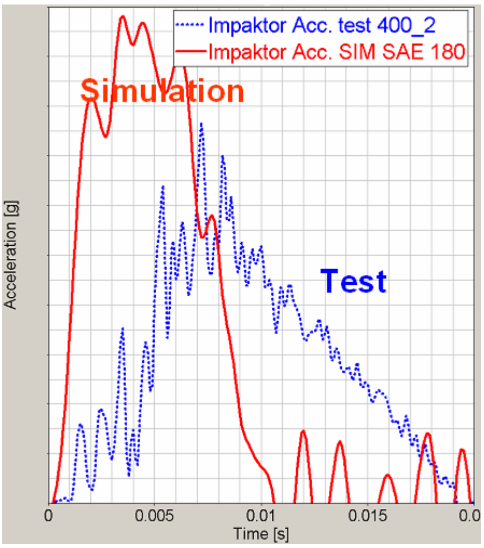

Fig. 11: Results of simulation and experiment for the trim impactor tests (example for a specific point on the door trim)

At this point of the work, an important issue with the chosen test setup was identified. For the door trim tests, the trims were mounted on the complete door and the original fixation elements (i.e. the strike plates and the door lock). The problem was that the door lock consists of a bracket and the lock itself, which provides a certain degree of freedom. Taking this into account in the FEM model is complicated and does not comply with the objective of the test, namely to provide verification data on a "clear" level of accuracy. Furthermore, the use of the metal structure of the door as a carrier for the trim part introduced additional uncertainty (elastic-plastic deformation of the sheet metal parts).
Fig. 11 shows the low level of verification between the impactor test of the door trim and the corresponding FEM model (this does not consider the motion in the door lock).
For future projects, it will be important to use a rigid surface on which the trim parts can be mounted, despite the more complicated test preparation.
Since the results of the FEM model were at least plausible, the same model was prepared for the "new" trim parts of car A, and the impactor tests were calculated again. A sufficient correspondence between the trim parts of car A and B were observed. The project team concluded that there was sufficient correspondence with the geometry and energy absorption of car B's trim parts to confirm the verification of car A's trim parts and to continue with the subsystem test using parts from car B (similar behaviour in energy absorption).

3.3 System verification

3.3.1 Stage IIIa – system verification using prototype parts

The next step was to prepare the FEM model of the sled. All parts that were designated for the subsequent sled testing were included in the model, including trim parts and seats from the similar car model B and airbags from car A (early prototype parts). In addition, the set-up of the sled FEM model was tuned until the dummy injury responses and the intrusion characteristics matched the results from the stage II numerical model.
The parameters that can be tuned are described in more detail in [9]. They mainly include the intrusion velocity profile of the door, main and seat sled. The component and subsystem models were verified earlier, as described above.
As an example, Fig. 12 depicts the dummy, seat, airbag and door trim kinematics. The left side shows the situation 20ms after the initial contact of the barrier face with the door, and the right side is 60ms after initial contact.

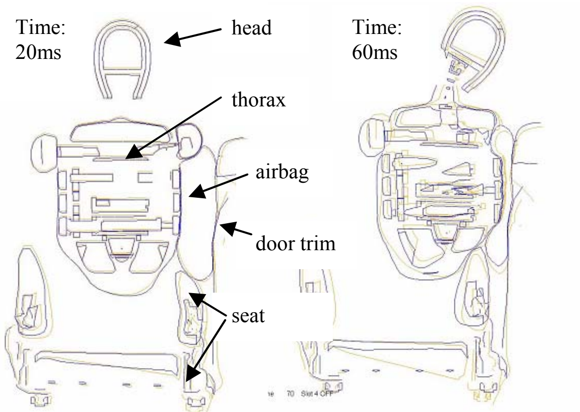

Fig. 12: Comparison of kinematics between complete vehicle simulation and sled model

The light lines represent an X section at thorax level of the dummy from the complete-vehicle FEM model. The head, thorax, seat, airbag and trim are depicted.
The dark lines show the same components as calculated by the FEM sled model. A very high level of accuracy is visible, which indicates that the

substitution of the complete vehicle for the simplified sled model is appropriate.

The next step was to perform tests in the predicted configuration. Fig. 13 shows a representative example of the correspondence between the simulation and the physical tests (deflection of the lower rib of the crash test dummy).

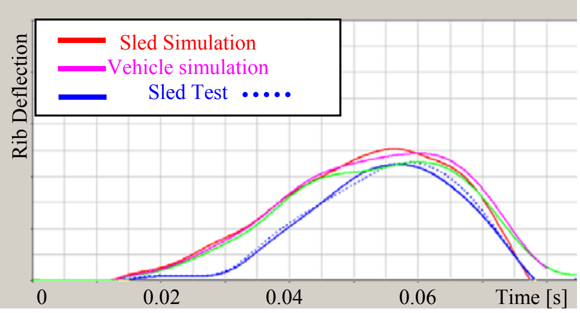

Fig. 13: Comparison of lower rib deflection between sled test (blue), sled simulation (red) and complete vehicle simulation (magenta)

The blue lines show the lower rib deflection as measured in two consecutive sled test with the same set-up. Their close correlation demonstrates the sled test rig's high level of repeatability.
The red and the magenta lines depict results from the FEM simulations (red line = the sled simulation; magenta line = the complete vehicle simulation). A close similarity can also be observed here, which confirms the close correspondence described in Fig. 12 at the level of dummy injury responses.
Although the deviation between the simulation and the experiments was higher, the maximum rib deflections could still be predicted sufficiently. Within the first 50ms of the impact, the injury responses in the experiments (blue lines) were delayed. An investigation revealed that this was mainly due to the fact that the sensor that determines "Time zero" (T0) is not working sufficiently. New methods for determining T0 would solve this problem to a large extent. Another issue identified was that the door acceleration measured in the experiment was slightly delayed compared to the required acceleration pulse. In the future, correction factors in the control unit of the Hyper G will solve this problem.
A significant deviation between the sled test and the sled model would invalidate the results of the complete model. If such a deviation is detected, the predictions from the numerical model must be analysed and corrected, and these corrections must then be transferred to the complete vehicle model. In this way, the complete vehicle model is verified.

3.3.2 Stage IIIb – system verification using serial parts

The final stage concludes with the conduction of sled tests with serial parts. The sled model is once again validated with the results from the experiments.
This last test series is also mainly used to fine-tune the system.

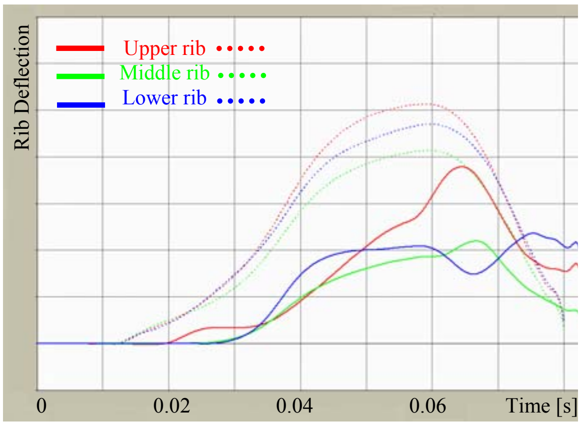

Fig. 14: Comparison of the initial model and the final model

Fig. 14 shows how the dummy injury responses were improved during the development process, as exemplified by the rib-deflection curves. The dotted lines represent the initial FEM model, while the solid lines represent the status of the car released for serial production.

3.4 Stage IV – certification

The development concluded with the conduction of certification tests (real crash tests). Though the overall vehicle requirements could still be maintained, the results of the side impact tests with pre-production cars unfortunately did not exhibit satisfactory correspondence with the results of the Stage IIIb complete-vehicle model.

A subsequent study revealed significant differences between the actual intrusion characteristics and those predicted by the crash structural analysis.
Fig. 15 shows the difference in the intrusion velocity at 3 distinct points of the Body-in-White.

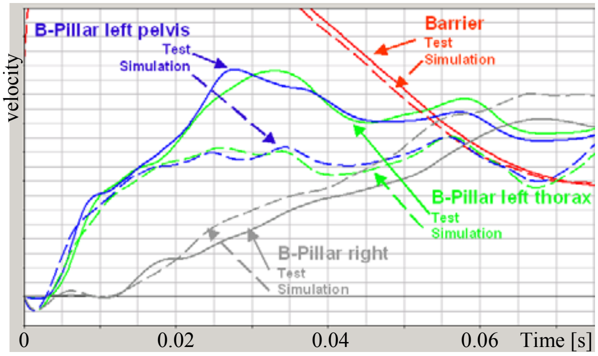

Fig. 15: Difference in intrusion velocities between FEM simulation and crash test

A detailed analysis revealed that these differences were caused by insufficient models for the honeycomb crash barrier of the impacting trolley, as well as insufficient material models of both high-strength steels and light-weight materials (aluminium alloy). In particular, when modelling high-strength steels, one must take into account the influence of the production process, such as stamping and heat effects (hot formed steels, bake hardening steels).

An additional factor that contributed to the differences in results was the fact that the level of modelling accuracy of the spot welds and other joining technologies was not high enough to predict failure realistically.

These insufficiencies have since been addressed by further advanced development activities and will be examined with new approaches in the near future.

In particular, the results presented here suggest that component and subsystem testing for the vehicle side structure should be included, e.g. by a dynamic impact test on a subset of the vehicle structure. This would require the availability of a certain amount of sheet metal parts as prototype parts.

4 Conclusions

This paper described a virtual development process for the crashworthiness of a vehicle for the side-impact load case. This process employs detailed FEM modelling of the complete car, relevant subsystems and components combined with validation tests on component, subsystem and system level.

The fundamental goal was to replace model verification through complete crash tests with experiments on component, subsystem and system level. The experiments were specially tailored for the validation needs of the models.

Since the vehicle requirements were ultimately fulfilled, the procedure proved effective.

Nevertheless, the final assessment of the development process showed inadequacies in the prognosis quality, especially in the intrusion characteristics of the vehicle structure.

The further actions required to increase prognosis quality have already been addressed in subsequent advanced development projects. In particular, the investigation of failure prediction and joining technologies is an area of significant ongoing research activities in crash simulation worldwide.

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