GENERAL VIRTUAL TESTING METHODOLOGY FOR TYPE IV CNG TANKS

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ABSTRACT

The project MATISSE funded by European Commission's 7^{th} Framework Programme (FP7) aims to make a significant step forward in the capability of the automotive industry to model, predict and optimise the crash behaviour of mass produced fibre reinforced polymers (FRP) with the focus set on components for alternatively powered vehicles (APV). One of the project's main research goals is the development of a general virtual testing methodology (VTM) for the development of APV driven by compressed natural gas (CNG) equipped with composite FRP tanks of Type IV.
Due to the increasing legislative demands on the emission of future vehicles, the development of APVs that are in this regard superior to conventional internal-combustion engines (ICE) driven by petrol or diesel fuel is currently in the centre of attention of the automotive industry. Here, the usage of ICE with CNG supply offers advantages in comparison to other concepts, since it requires only moderate modifications of the conventional drive train. Because of the high mechanical demands on the required high-pressure storage tanks and the need for lightweight structures, which also contributes to the emission reduction, the usage of material of high specific material properties is required. Especially the full composite tanks of the Type IV show a high potential in this regard. Since these high-pressure storage components form a significant safety hazard, the accurate analysis of the mechanical demands during relevant crash load cases is of great importance. For the proper and optimal integration of the tanks into the vehicle during the APV design and development process at industrial level, moreover the predictability of the material and component behaviour using the finite element method (FEM) is indispensable.
Within the MATISSE project a new overall approach for the crash analysis of CNG tanks is proposed. This paper describes the main aspects of this VTM:
First, a FRP material modelling approach for wet wound CNG tanks, that makes use of the so-called "reverse FEM" as well as of novel physically based material models that are fed with calculative as well as literature based material values and are validated on three point bending tests of wound tubes was defined.
Then, the derived material models for glass and carbon fibre were subsequently used for the modelling of FEM tank models, whereby different steps of optimisation of on the one hand the accuracy and on the other hand the simulation time were conducted.
In a next step, different relevant load cases on a full vehicle model of a compact car equipped with a CNG tank where simulated and analysed. The detected highest mechanical demands were thereupon transferred to a component test programme on a tank-subsystem that depicts the loads obtained by the tanks. Here again, the FEM model of the tank is used to find the appropriate boundary conditions.
The developed test programme was subsequently conducted on a series of physical tanks and the simulation approach and thus the VTM was validated on the results.

INTRODUCTION

Increasing energy costs, limitation of crude oil resources as well as constantly intensifying emission targets (especially w.r.t. CO_2) are a pivotal driver for current automotive research and development [1]. In this regard alternatively powered vehicles (APV) with drive-trains that differ from conventional internal-combustion engines (ICE) supplied with petrol or diesel fuel show high potential for energy economical and environmentally friendly propulsion [2]. On the other hand lightweight structures are a fundamental requirement in order to achieve a low demand of energy and to compensate possible higher structural masses of alternatively powered drive-trains [3].
An alternatively powered drive-train that is on the one hand cost efficient since it requires comparatively minor design changes to conventional vehicles (primarily ignition and valve-train system) and on the other hand has a perspective to evoke low CO_2 emissions, is an ICE operated with compressed natural gas (CNG) [4], [5]. This energy source requires high-pressure storage tanks that have to withstand the high mechanical

demands of internal pressures of 200 bars to 250 bars. In order to achieve energy storage that is simultaneously light and safe, pressure vessels of the Type IV that are entirely made of fibre reinforced polymers (FRP) are currently state of the art [6].
For the proper and optimal integration of the tanks into the vehicle during the APV design and development process at industrial level, moreover the predictability of the material and component behaviour using the finite element method (FEM) is indispensable [7]. Besides analyses of the passenger and partner safety of the vehicle, the simulation of the component loading behaviour and subsequent analysis of the material stresses and damage allows an optimisation of components concerning weight. Especially FRP laminates offer a potential for optimisation as well as numerous influence parameters [8].
One of the major advantages of FEM simulations is that, once a model validated on test results is established, analyses for different scenarios or design changes can be carried out virtually. This can reduce the development expenses as well as development cycles drastically. However, approval tests are obligatory for the final vehicle or respectively component [9].

MOTIVATION

Although virtual methods like FEM analyses have become an integral part of the automotive industry, they still lack in broad acceptance concerning their reliability. Especially, when it comes to unconventional materials like FRP, the development is characterised by conventional component tests. With regard to CNG tanks, the InGAS project identified the following open issues:

- No crash simulation models are available for such complex composite structures
- No standardised test procedures are available
- No validated methods are available to transfer the test results to the crash situation in a vehicle [10]

In order to overcome these issues and to make a step forward in the capability of the automotive industry to model, predict and optimise the crash behaviour of vehicles equipped with Type IV tanks, a virtual testing methodology (VTM) was developed within the project MATISSE funded by European Commission's 7th Framework Programme. As a demonstrator a belly mounted CNG tank consisting of a combined carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) wet wound structure with a polyamide (PA) liner and aluminium bosses was used. However, the feasibility of the approach was also verified for a neck mounted design.

The physical tanks used as reference within the VTM are produced and provided by the MATISSE partner Xperion Energy & Environment GmbH and are approved for vehicle application.

All simulations within the VTM are carried out using the explicit FEM solver LS-DYNA which is provided by the MATISSE partner DYNAmore Nordic AB.

VTM APPROACH

The here presented VTM approach aims to achieve an adequate level of prediction of the failure behaviour of composite high-pressure storage tanks (HST) under crash loading conditions, both at component and vehicle level. This general VTM involves four main steps:

- Identification of relevant (full vehicle) crash scenarios.
- Their numerical simulation through FEM codes.
- Analysis of results obtained from these simulations and extraction of the envelope of crash loading conditions of interest insisting on HST.
- Definition of simplified/reduced test set-ups capable of generating, on the isolated HST, loading conditions that are equivalent and/or representative of the ones that are seen by the composite tank within the vehicle during full car crashes of interest (the above mentioned envelope), so that corresponding physical test-rigs

can be designed in detail and subsequently built for experimental testing campaigns on the composite tanks.

The general VTM is illustrated in Figure 1.

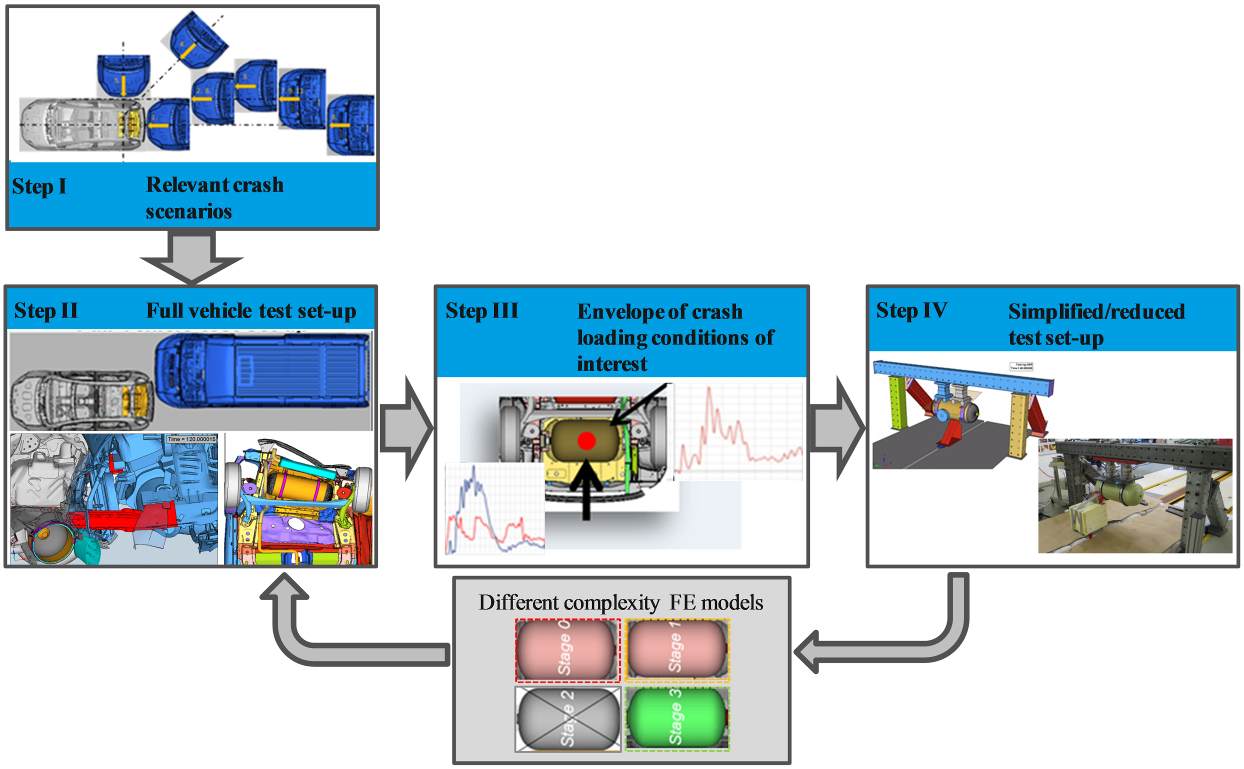


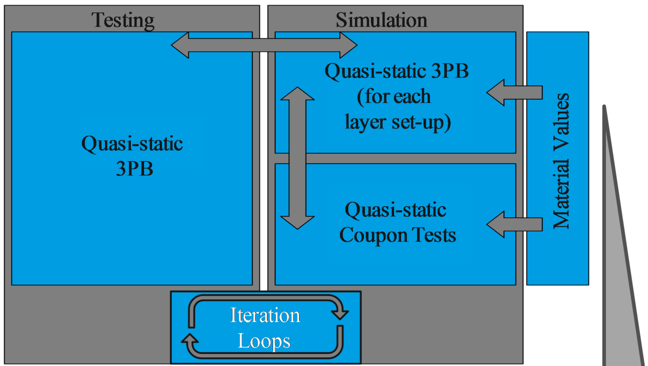
Figure1. Schematic diagram of the VTM

SIMULATION TOOLS

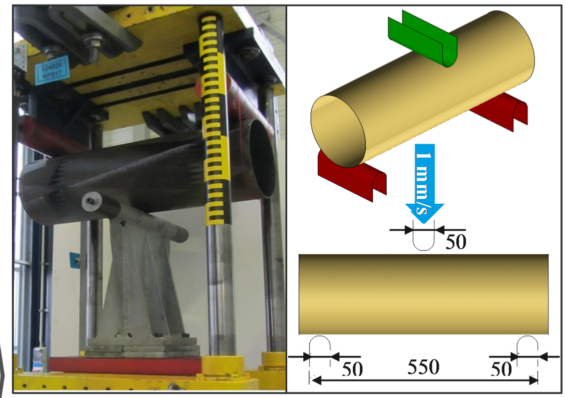
In order to successfully pass through these steps, a special focus has to be set on the CNG tank model, which is considered to be the key element of the methodology. The model is based on geometry and material information for the components liner and bosses as well as the winding and material information for the CFRP and GFRP winding layers. In order to achieve the highest precision of results but on the other hand to allow an efficient course of the project, here four different stages of modelling complexity are applied in the steps of the VTM. For the validation of the material model a so-called reverse FEM approach is applied.

Reverse FEM Approach

Based on the applied wet winding production process used to manufacture Type IV CNG tanks, a rather unconventional simulation approach has to be carried out, since the process does not allow the production of flat or ring shaped specimens for standardised quasi-static tests (for general data acquisition as it is usually done for FRP materials). In order to use a material structure that is windable and comparable to the investigated tanks, several tubes with different layer set-ups are tested in a quasi-static three point bending (3PB) test, with two circular lateral constraints and a cylindrical central indenter with a constant velocity of 1 mm/s. The material model for the simulation is defined using calculated literature or assumed values and then calibrated on the test results of the 3PB and checked for plausibility on virtual quasi-static coupon tests (that consider tensile, compression and shear loading). Furthermore, the delamination failure criteria are virtually validated by the simulation of an end notch flexure (ENF) test and a double cantilever beam (DCB) test. In order to achieve robust modelling different laminate set-ups are tested in the 3PB. The MATISSE modelling approach is presented in Figure 2.



Set-up Type	Layer	Angle	Layer Thickness	Laminate Thickness
[-]	[-]	[°]	[mm]	[mm]
1	1	+/-10	1.04	2.1
	2	+/-10	1.04	
2	1	+/-10	1.04	2.1
	2	90	0.53	
	3	90	0.53	
3	1	+/-30	1.05	1.6
	2	90	0.53	



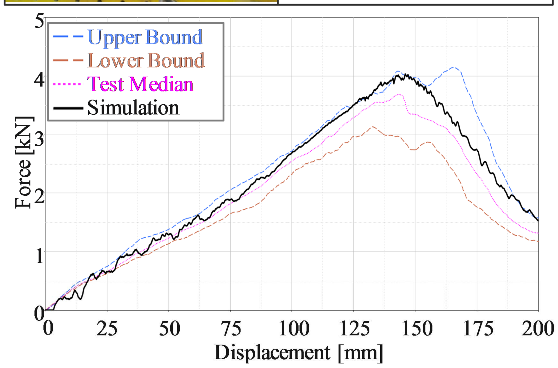


Figure2. Reverse FEM approach

Stage 0 tank model

Stage 0 defines a rough CNG tank model that has the geometry of the tank to be analysed but is meshed rather coarse with shell elements (average size of 10 mm) and assumes only elastic and isotropic material behaviour, without any failure criteria for the composite layers. The bosses are modelled as solid elements with elastic and isotropic material properties, too. However, the mechanical properties of the composite part of the vessel are correspondent to the in-fibre properties of the materials applied (average Young's modulus and density). The stage 0 derives from the past FP7 project InGAS and is applied in order to evaluate the crash conditions in a very early stage of the project since it does not require in-depth information of the materials and the winding set-up (see Figure 3).

Stage 1 tank model

For a more sophisticated evaluation of the crash behaviour the stage 1 model is applied. The model is provided with the geometry and winding information of the tank to be analysed and uses a much finer shell mesh of 3 mm with layer definition applied to different integration points. The shell mesh is used in order to allow time efficient modelling and calculation. However, the section of the wound areas of the tank show thicknesses up to 22.5 mm and thus exceeding the limitations of the shell theory. Furthermore, it is modelled with a special composite material model (*MAT_58) that considers material moduli and strength values for the fibre and transversal direction as well as for shear. The liner is considered to be elastic and the bosses are modelled as rigid. All material values are based on either literature research or calculations (see Figure 3).

Stage 2 tank model

The stage 2 represents the most complex tank model of the VTM and is used for the second loop of step IV. It uses the same component geometry and winding information as stage 1 but is meshed with several layers of thick shell elements with layer definition applied to different integration points. It uses a novel continuum damage model (*MAT_262). The model considers material moduli and strength values for the fibre and transversal direction as well as for shear and material damage mechanisms that are physically based and consider fracture toughness values.

Furthermore, the structural failure due to delamination is adressed using cohesive elements between the thick shell elements that consider different failure modes (see Figure 3).

Stage 3 tank model

Stage 3 is a predictive composite model suitable for the use within full car crash FE simulations and applied in a third loop of step 1 and respectively step IV of the VTM . It is based on the Stage 2 but comprises a set of simplifications such as coarsening, layer clustering and numerically more efficient elements. It derives from a number of simplification and subsequent simulation loops within step IV that are evaluated in comparison to the Stage 2 simulation results. After each measure of simplification the simulation results are compared and the accuracy and efficiency of the measure is evaluated. If the related gain in efficiency is considered to be worth the loss in accuracy a simplification measure is kept. If not, the measure is withdrawn and another measure is applied (see Figure 3).

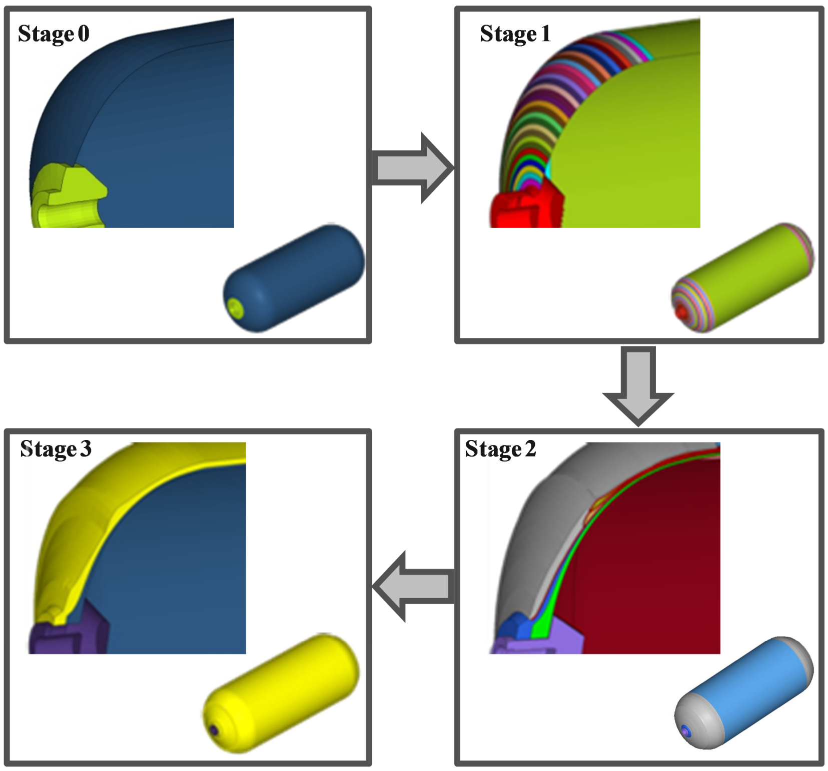


Figure3. Stages of CNG tank model

STEPS OF THE VTM

In the following the different steps of the VTM are described in detail and their application within the MATISSE project is presented.

Step 1: Identification of Relevant Crash Scenarios

The identification of the crash scenarios is not primarily based on statistical relevance since the focus of the VTM is not set on the most likely load cases but on crash scenarios that are relevant w.r.t. the potential to induce damages on the composite CNG tanks. For this concern numerous crash situations are proposed and evaluated by crash experts concerning their severity but also w.r.t. to probability.
More precisely, for the here described reference case eleven full car-to-car collisions involving a B-class vehicle equipped with an unpressurised CNG tank system and two different types of opponents (bullet vehicles) were chosen. As relevant bullet vehicles a B-class car and a van were considered. The target car is always assumed to be

stationary with released brakes. For the target car three different types of muffler locations/lay-outs were considered. The eleven load cases are as follows:

Target car without muffler between the tank and the rear crossbeam; bullet: B-class car impacting at 55 km/h

1. Rear impact, "full overlap"
2. Rear impact, "50% overlap"
3. Rear impact, "25% overlap"
4. Side impact, from the right side, "oblique"
5. Side impact, from the right side, "perpendicular"

Target car with muffler between the tank and the rear crossbeam; bullet: B-class car and van impacting at 55 km/h

6. Rear impact by car , "50% overlap"
7. Rear impact by van, "50% overlap"
8. Rear impact by van, "full overlap"

Target car with muffler between the tank and the rear crossbeam but with reduced distance w.r.t. tank; bullet: van impacting at 55 km/h

9. Rear impact by van, "50% overlap"
10. Rear impact by van, "full overlap"

Target car with muffler with reduced distance to tank; bullet: van impacting at 80 km/h

11. Rear impact by van, "50% overlap"

In this step of the VTM neither simulations nor physical tests are applied. However, the choice of relevant load cases forms the basis for the fully virtual step 2.

Step 2: Numerical Simulation of Relevant Crash Scenarios

Subsequently in the second step of the VTM all the considered collision scenarios are simulated and the results are evaluated concerning their severity. This includes the stresses and strains of the tank structure but also general endangerments of these components due to impacts on sharp or rigid components as well as the loading in the valve area.

In the reference case the simulation was carried out in LS-DYNA using existing models for the B-class car and the van. The model of the impacted vehicle is equipped with a tank model as well as the corresponding environment structure. In a first loop of the step 2, the stage 0 model was used due to the fact that the complex modelling and reverse FEM activities made a very early availability of stage 1 model within the project not possible. As the stage 1 model was released, the general conclusions of the simulations could be verified and refined in a second loop using this more significant model.

The results obtained from the numerical simulation campaign confirmed that the most severe loading conditions for the CNG composite tank are achieved when the reference vehicle is impacted by the van. In particular, impact configuration no. 9 resulted to be the worst one. Due to the offset and to the "aggressivity" of the van (stiffer and higher main rails, almost double vehicle mass) w.r.t. the reference car, the latter is subjected to very high rear intrusions with the van front structure arriving to interact directly with the tank. Configuration no. 11 (in practice the no. 9 repeated with the speed increased at 80 km/h), despite being more severe in terms of overall target vehicle deformations, was almost similar to configuration no. 9 in terms of loading conditions on the composite tank. This is the case mainly due to the fact that the extra energy introduced by the speed increase was absorbed essentially through more deformation of the vehicle structure in front of the tank area. The deformations for the target vehicle in this crash configuration are presented in Figure 4.

Again no physical tests are foreseen in this step of the VTM.

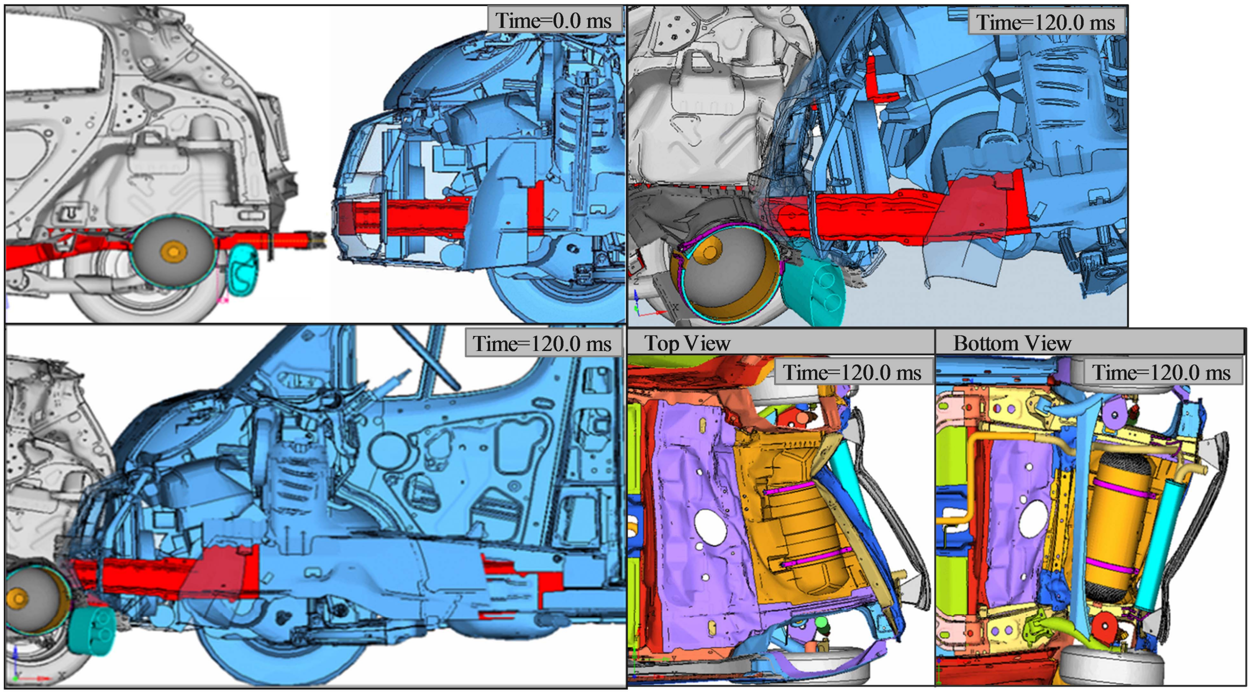


Figure4. Configuration 9: Deformations on target vehicle equipped with Stage 1 tank model

Step 3: Envelop of Crash Loading Conditions

In the third step of the VTM there is a more in depth analysis of the loading to the tank, especially on areas that have potential of hazard to the environment due to damage or even leakage and burst. This includes for example:

- accelerations in different points
- global contact force and maximum interface resultant force
- interface normal pressure
- section forces on the tank
- section forces on tank fixations

Furthermore, this analysis gives information about which boundary conditions and subsystems of the full vehicle impact have to be transferred to the subsequent definition of an adequate simplified test that is significant for the loading of the tank.

Then, the third step of the VTM led to the identification of some important indications towards the definition of an equivalent simplified/reduced subsystem test set-up.

Such indications are recalled in the following:

- An equivalent simplified test-rig should have the possibility to impact the tank on different locations and from different directions.
- This possibility should be realised by an impactor capable to reproduce similar normal pressures on the tank and global contact forces (i.e. having the proper shape and energy level).
- The simplified test-rig should have the possibility to allow some deformation of the tank anchorage points, by acting on their stiffness/strength within a proper range, in order to reproduce the boundary condition seen by the tank when mounted on the specific reference vehicle.

Step 4: Simplified Test Set-up

The step 4 of the VTM is a pivotal step for the application of this methodology since it is not only carried out in the virtual environment but is also performed on physical tanks, thus providing the input for a comparison between the simulation and the tests and allowing a subsequent validation of the approach. In step 4 the task is to accurately reflect the boundary conditions of loading conditions considered to be relevant and significant (i.e. like the already mentioned full vehicle configuration 9) with a test rig that can be set up on the one hand simple and easy and on the other hand reproducible, in order to avoid expensive and complex full vehicle tests. The validation by the experimental test results obtained with such a test-rig shall provide a tank model that can be applied in a validated full vehicle model in order to obtain information about the crash saftey of the CNG tank system. For these in-vehicle applications, the validation process should comprise a final simplification of the tank model in order not to affect the simulation costs too significantly (i.e. the already described stage 3 model).

Starting from the reference case (i.e. the full vehicle configuration 9) a suitable test rig for a crash test facility, considering the above mentioned indications, was developped in several loops of iteration leading to a flexible set-up that allows the application of different tank sizes and mounting systems (e.g. belly and neck mounting) as well as different impact orientations, positions, masses, surfaces and velocities. As a result of such test-rig flexibility, other impact configurations than the one corresponding to the reference case (named test-rig configuration 6) were explored at numerical simulation level, so that a possible test-matrix for the experimental campaign with the reduced set-up was proposed. Among these test-rig configurations, four (including the reference case) were identified as the most relevant ones and subsequently for complexity reasons only this subset of configurations was tested (see test-rig configurations 2, 5, 6 and 7 in Figure 5). The specimen is mounted as it is applied in the vehicle but upside down, since this allows the highest flexibility and accuracy of the test rig set-up on a crash test facility. Here, the tests are documented using load-cells at the mounting plate and high-speed video cameras from different positions.

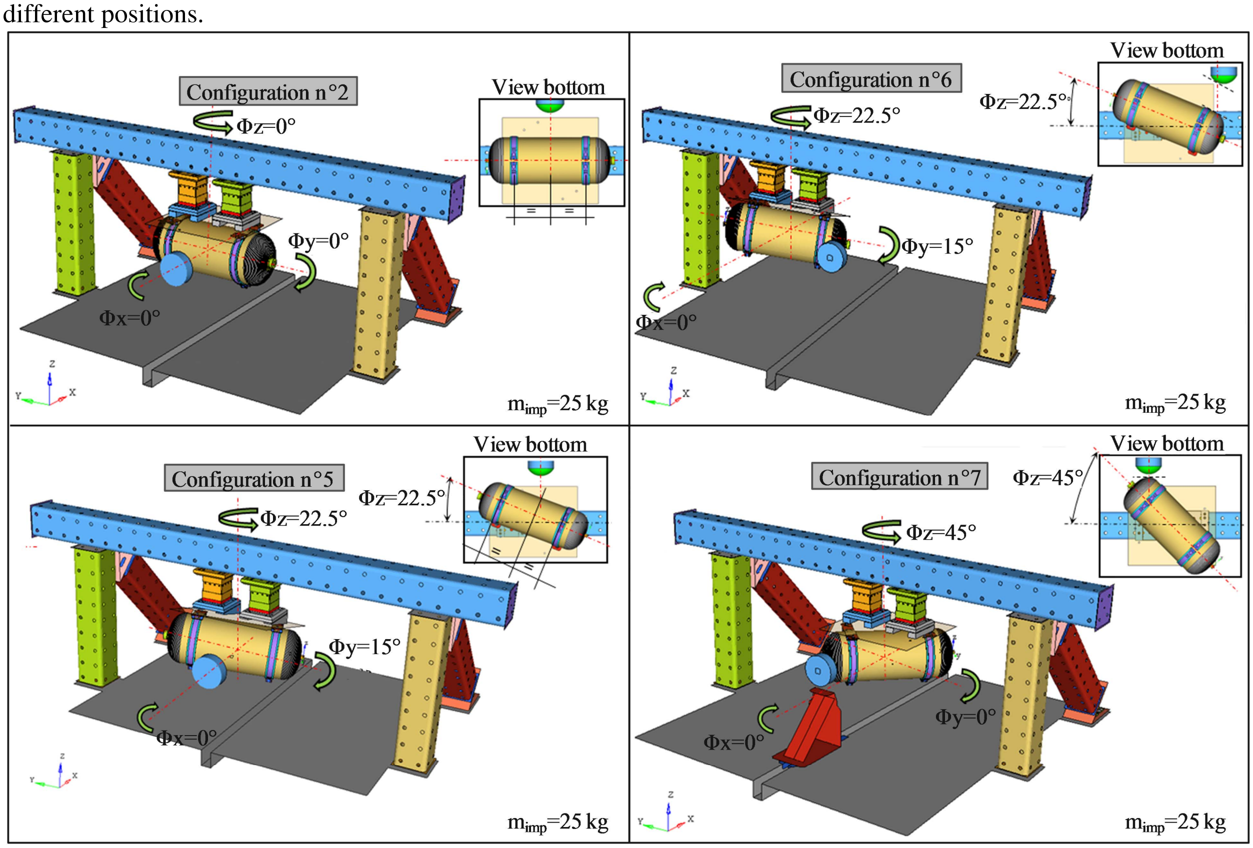


Figure5. Simplified test set-up and analysed impact configurations

After the conduction of the tests several evaluations were carried out. These were analysis of force and acceleration curves measured on the test rig, optical check of tank surface as well as of the mounting straps and interior, microscopy and CT of cut-out specimens as well as burst pressure and cycling pressure tests in order to understand the failure criteria and to see potential areas of hazard (see Figure 6). Furthermore, the experimental results were applied in order to validate the stage 2 model and to subsequently derive the simplified stage 3 model, i.e. the final one that is suitable for the application in all the VTM steps, then closing the methodology loop for potential future structural optimisation or evaluation of different vehicle and tank structures.

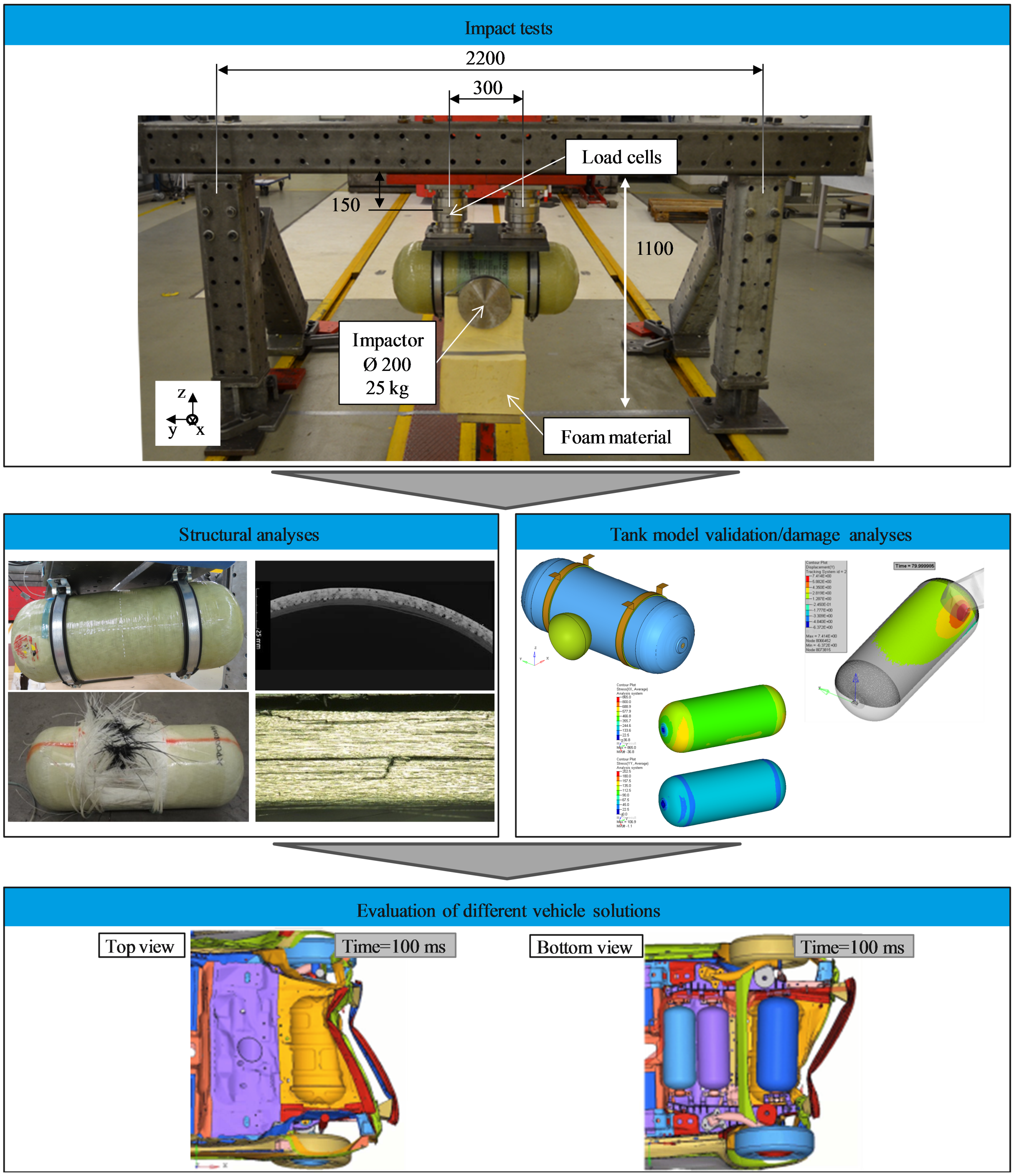


Figure6. Evaluation of CNG tanks after testing

CONCLUSIONS

A stepwise virtual testing methodology for the evaluation and optimisation of vehicles equipped with CNG tanks was developed in the MATISSE project. This methodology allows a reduction of the development effort related to the crash safety design of such a type of APV, on the basis of a validated vehicle simulation model and a simplified experimental test rig set-up that is suitable for the evaluation of the tank crash behaviour as well as for the validation of an appropriate tank model for the crash simulation.

In the course of the methodology a set of relevant crash load cases (at full vehicle level) was defined and subsequently modelled in the FEM environment by using the vehicle model of interest that includes the adopted tank model(s) according to the specific lay-out solution to be examined. Based on the simulation results from this scenario, the most relevant loading conditions acting on the tank(s) can be isolated and further analysed. The results of such an analysis can be used for the definition of a suitable simplified and equivalent test-rig configuration as well as for an adequate experimental test programme. With the conduction of physical tests according to that test programme and together with their corresponding FEM simulations, a tank model can be improved/refined to cover adequately the composite behaviour under impact conditions. Furthermore, it can be validated against the obtained experimental results and subsequently reduced/simplified in order to be more efficiently applied in full vehicle simulations, by maintaining at the same time an appropriate level of failure prediction/detection during the industrial development process of CNG tanks and vehicles equipped with such systems.

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