Crash Simulation of an F1 Racing Car Front Impact Structure

S. Heimbs, F. Strobl, P. Middendorf, S. Gardner, B. Eddington, J. Key

* EADS Innovation Works, 81663 Munich, Germany
** Force India Formula One Limited, Northamptonshire, UK

Summary:

Formula 1 motorsport is a platform for maximum race car driving performance resulting from high-tech developments in the area of lightweight materials and aerodynamic design. In order to ensure the driver's safety in case of high-speed crashes, special impact structures are designed to absorb the race car's kinetic energy and limit the decelerations acting on the human body. These energy absorbing structures are made of laminated composite sandwich materials - like the whole monocoque chassis - and have to meet defined crash test requirements specified by the FIA. This study covers the crash behaviour of the nose cone as the F1 racing car front impact structure. Finite element models for dynamic simulations with the explicit solver LS-DYNA are developed with the emphasis on the composite material modelling. Numerical results are compared to crash test data in terms of deceleration levels, absorbed energy and crushing mechanisms. The validation led to satisfying results and the overall conclusion that dynamic simulations with LS-DYNA can be a helpful tool in the design phase of an F1 racing car front impact structure.

Keywords:

Formula 1; crash simulation; energy absorption; composite sandwich material

1 Introduction

Formula 1 is the top class of motorsports, demonstrating maximum race car driving performance resulting from high-tech developments in the area of lightweight materials and aerodynamic design (Fig. 1). Since extreme racing speeds may lead to severe accidents with high amounts of energy involved, special measures are taken in order to ensure the driver's safety in case of high-speed crashes. Besides the driver's protective equipment (like helmet, harness or head and neck support device) and the circuit's safety features (like run-off areas or barriers), the F1 car itself is designed for crashworthiness and possesses special sacrificial impact structures, which absorb the race car's kinetic energy and limit the decelerations acting on the human body. The FIA as the governing body of motorsports imposes strict regulations for the performance of these energy absorbing structures, which are updated each racing season [1]. The main philosophy behind those crashworthiness regulations is to assure that the driver is enclosed within a strong survival cell, surrounded by energy-absorbing structures in the front, back and sides. Besides static tests (nose push-off test, side intrusion test etc.), the vehicle structure has to withstand dynamic impact tests (frontal impact test, rear impact test, side impact test and steering column test) [2]. Such tests are documented in [3-5].

Today almost the whole F1 racing car is made of lightweight composite materials, including the energy absorbing structures [6-10]. While metals absorb energy by plastic deformation, composites do so by braking and crushing into small fragments. The basic energy absorption capabilities of a composite laminate for the design of a crash box are typically evaluated in drop tower tests on cylindrical, rectangular or conical specimens. The design process of the final F1 racing car crash absorbers is also primarily based on experimental crash test series.

One efficient tool in the design of composite structures are numerical simulations based on the finite element (FE) method. The commercial explicit FE code LS-DYNA has been used in many past investigations for crushing simulations of composite cylinders or crash boxes [11-19] and even for crashworthiness studies of racing cars [20-22].

The aim of the following study is to apply the FE code LS-DYNA for the crushing simulation of an F1 racing car front impact structure in a frontal crash against a rigid wall. This composite structure consists mainly of the nose box, which is mounted to the chassis. Attached are the nose tip and a representative front wing with certain wing pillars (Fig. 2). The focus of this investigation is on the modelling of the composite material crushing. Simulation results are compared to experimental crash test data in a qualitative and quantitative way with respect to crush front propagation and deceleration curves.

Figure 1: Force India F1 racing car of 2008 season (photo: Sutton Motorsport Images)

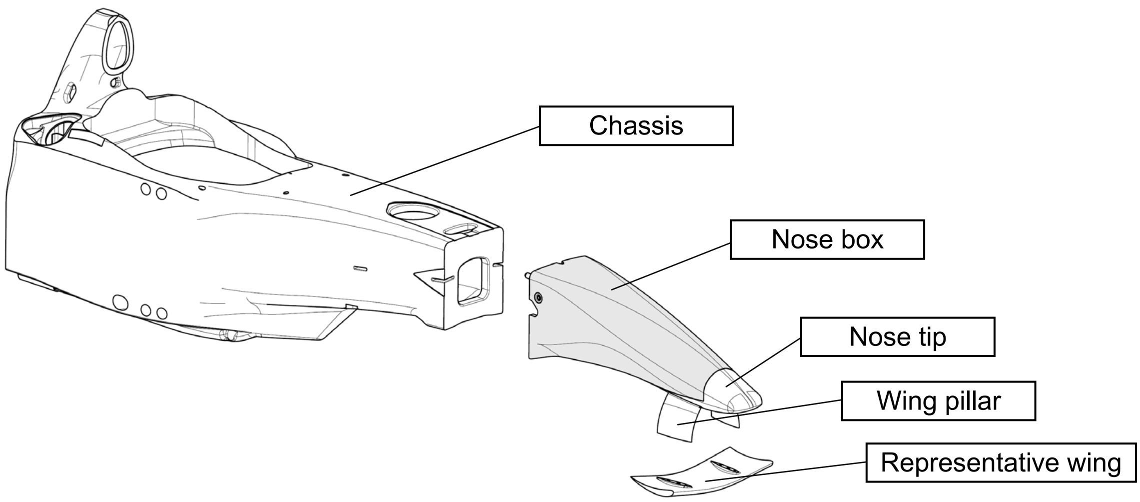

Figure 2: Illustration of F1 racing car front structure components

2 Frontal impact crash testing

The frontal impact crash test specified by the FIA aims at assuring that the nose box is able to dissipate the kinetic energy involved in the crash and the driver is protected from injurious deceleration forces. The crash tests were performed at the Cranfield Impact Centre according to FIA regulations (Fig. 3). Those demand a total weight of 780 kg and an impact velocity of 15 m/s [1]. This velocity obviously is much lower than typical race track speeds, but before a racing car frontally strikes a rigid wall its speed is usually reduced by gravel run-off areas and the deformable tire barriers.

The chassis with a 75 kg dummy was mounted on a test sled, which was accelerated to the specified velocity. When the test sled strikes an immovable steel plate, mounted on a huge concrete block, the peak deceleration over the first 150 mm of deformation may not exceed 10 g, the peak deceleration over the first 60 kJ of energy absorption may not exceed 20 g and the average deceleration of the chassis may not exceed 40 g. These values are measured by accelerometers mounted on the sled.

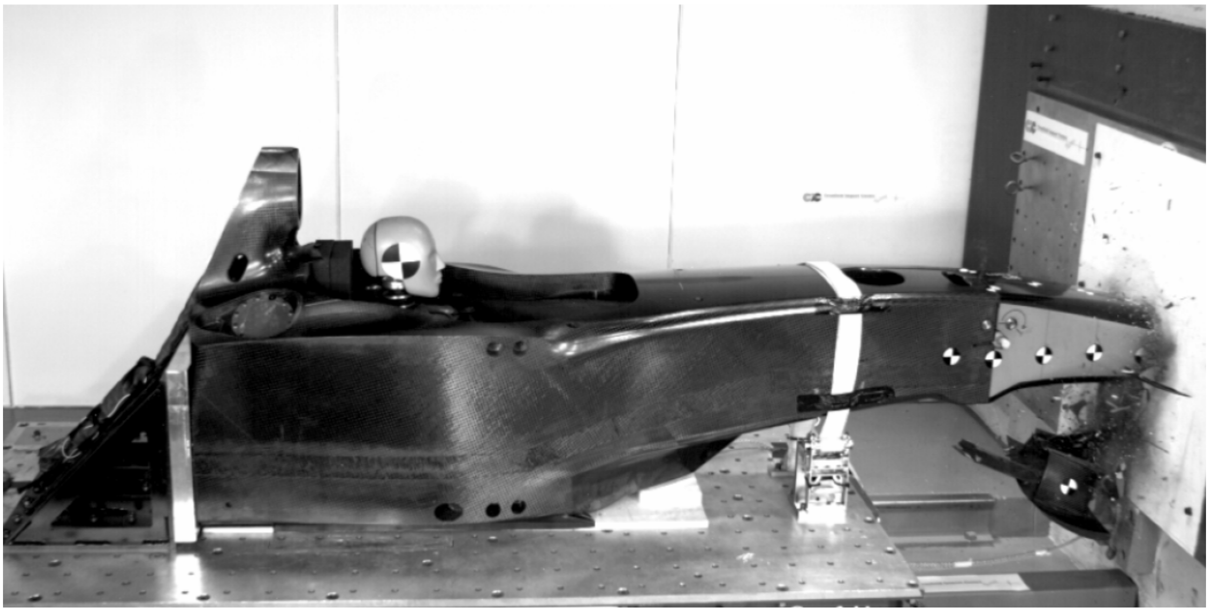

Figure 3: Frontal impact crash test setup

3 Model development

3.1 Mesh generation and boundary conditions

The FE model for crash simulations of the F1 racing car front impact structure consists of the nose box, nose tip, wing pillar and wing. The mesh was generated in Hypermesh based on CAD data. In a preliminary study a full model was compared to a half model using symmetrical boundary conditions. Since the influence on the simulation results was negligible, the half model was prioritised due to the significantly lower computational cost. The model in Fig. 4 has been mirrored for visualisation purposes. It consists of 58 different part definitions, resulting from numerous assembly parts and different composite laminate lay-ups. The influence of different mesh sizes was investigated in a further preliminary study. Finally, an element size of 3 mm was used, which leads to approx. 78000 elements in the half model. The chassis with its respective mass was modelled as a rigid body dummy plate of solid elements connected to the nose box. Displacements of this part are only possible in x-direction, representing the requested fixture to the test sled.

The connection of different parts like wing and wing pillar or wing pillar and nose tip is achieved by the utilisation of contact algorithms, partly with and without failure option, allowing for realistic energy absorption due to debonding. An additional global single-surface contact is used to avoid penetrations between different parts. An initial velocity of 15 m/s is ascribed to the whole model to impact a fixed rigid wall.

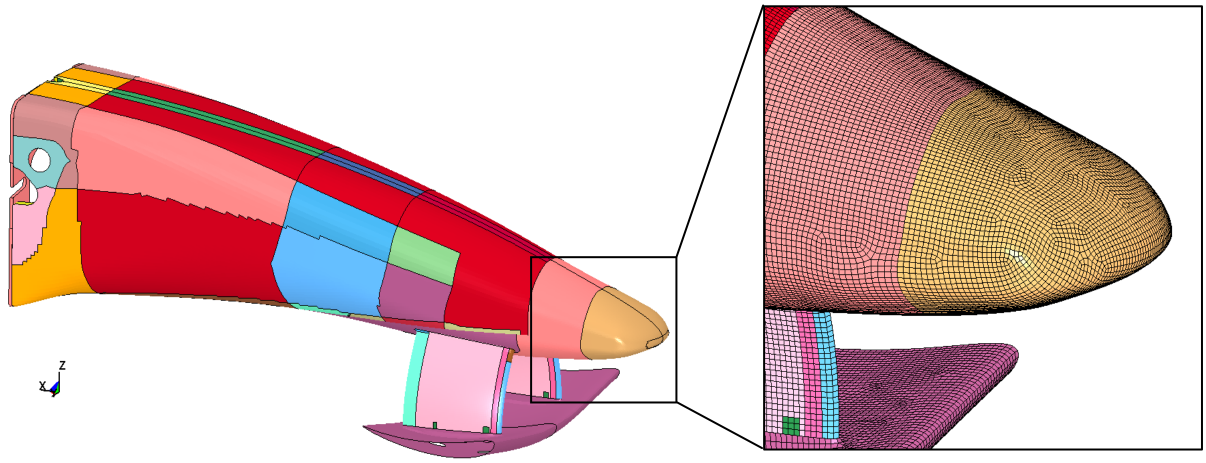

Figure 4: LS-DYNA model of F1 front impact structure

3.2 Material modelling

Nose box and nose tip are made of a lightweight sandwich structure consisting of carbon fibre/epoxy skin laminates and an aluminium and Nomex® honeycomb core. During the crash test the nose box is literally converted into a cloud of dust and fragments within one tenth of a second with matrix cracking, fibre breakage and delaminations in the crush front mainly contributing to the energy absorption. Two modelling approaches come into consideration for such sandwich composites:

The first option is to model the honeycomb core with homogenised solid elements and the skins with shell elements, connected by a contact formulation (‘shell-solid-shell’ approach) [24]. Lamb [25] has adopted this approach for his crash simulations of an F1 racing car front impact structure with PAM-CRASH. In general, this rather expensive technique enables to cover skin/core debonding, a better representation of core shear deformations and core indentation in thickness direction. However, since those effects play a less important role in axial crushing of the sandwich structure and the reduction of computational cost was of higher importance to establish crash simulations as an efficient tool in the fast moving F1 development process, this approach was not adopted here.

The second option, which was used in this study, is to model the whole sandwich structure within a multi-layered shell element ('layered shell' approach). A certain number of integration points are defined through the thickness of the shell element in a user-defined integration rule, representing the core and skin laminate layers (Fig. 5). For the sandwich materials in this study, this led to a maximum of 23 integration points across the thickness. For this purpose, underintegrated Belytschko-Tsay elements based on the first order shear deformation theory were used. Different material models may be ascribed to the individual integration points.

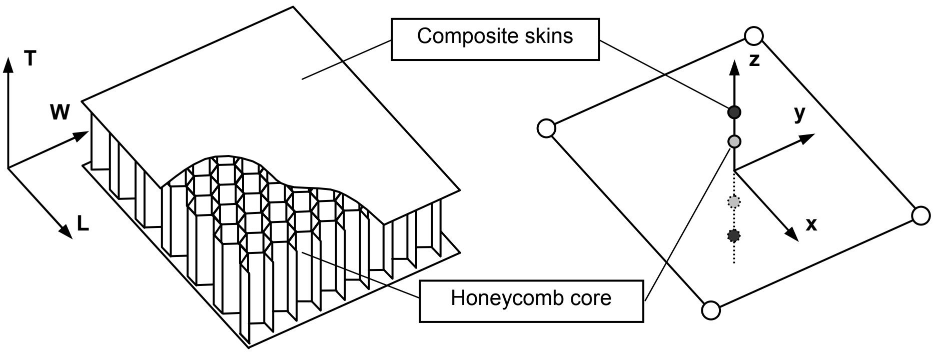

Figure 5: Illustration of honeycomb sandwich structure and layered shell modelling

For the carbon fibre/epoxy skins the composite material model MAT54 was used. This orthotropic, linear elastic material law is based on the Chang/Chang failure criteria, which control failure in longitudinal and transverse direction under compressive, tensile and shear loads [26]. In addition, failure strain parameters DFAILx were used to control the erosion of individual layers and the total absorbed energy. Since delaminations, occurring ahead of the crushing zone under crash loads, cannot be represented physically in the model, the so-called crash-front algorithm of MAT54 was adopted: The crash-front parameter SOFT of the material model reduces the strength of those elements neighbouring failed elements to capture this pre-damage effect and allow for a continuous crushing. It turned out that SOFT=0.8 is sufficient for the generation of a stable crush front.

The inner honeycomb layers were also modelled with MAT54 since it allows for orthotropic linear elastic-perfect plastic stress-strain behaviour, which is characteristic for the in-plane compression of honeycomb structures [27].

Mass scaling was used to speed up the simulation: 1% increase of mass increased the time step from 0.17E-6 to 2.25E-4 ms and led to a total CPU time of 8 hours on twelve parallel processors for a simulation time of 110 ms.

4 Simulation results and validation

The front impact crash simulation begins with the nose tip hitting the wall, being compressed and partly being fractured. Then the lower structure of the nose tip and the wing pillar are detached through a debonding failure under shear loads covered by the chosen contact definition. Afterwards, the nose box strikes the wall and is crushed continuously until all kinetic energy is absorbed. An image sequence of the crash simulation results is shown in Fig. 6. For comparison reasons, a sequence of images taken from the high speed film in the crash test at corresponding time steps is also shown.

The qualitative correlation appears to be very good. The only difference is in the detachment of the front wing, which is highly affected by the erosion of specific elements. However, this was proven to have no influence on the global results. Almost all elements of the nose box are eroded in a continuous crushing process, which is illustrated in Fig. 7, where all eroded elements are dark shaded. A comparison of the deceleration curves vs. crushing displacement in Fig. 8 – both being recorded with a sampling frequency of 20 kHz and filtered with an SAE 60 filter – also shows a good quantitative correlation with noticeable discrepancies only occurring between 200 mm and 400 mm crushing displacement, which might make an enhanced modelling of the stiff wing pillar attachment section necessary.

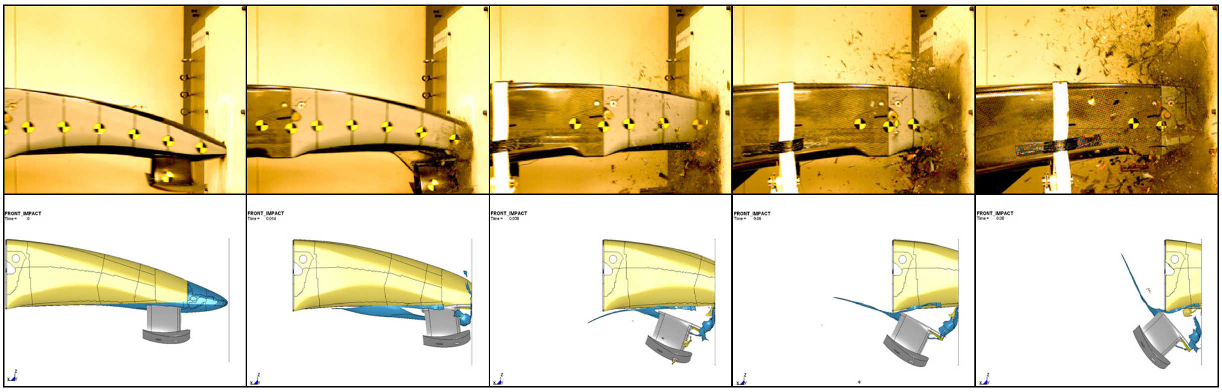

Figure 6: High speed image sequence of front impact crash test vs. simulation results

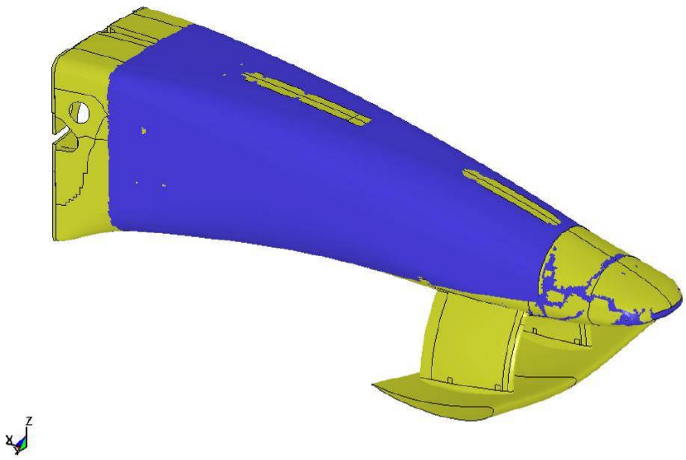

Figure 7: Illustration of eroded elements due to fracture (dark colour)

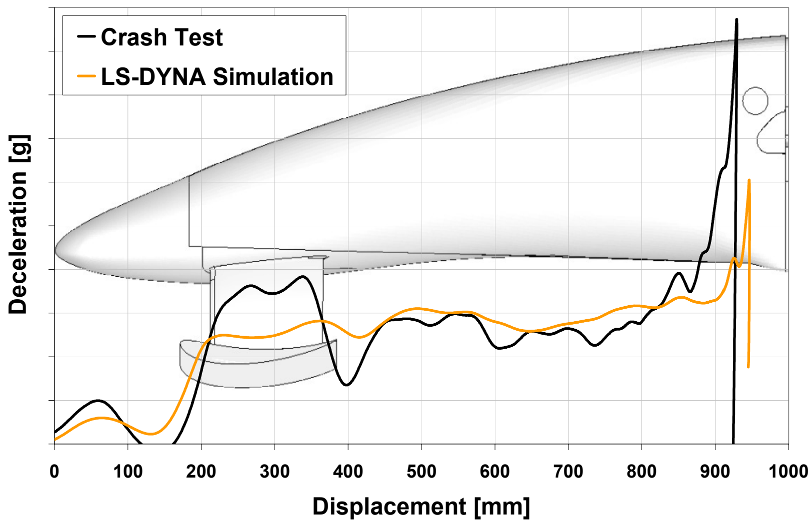

Figure 8: Deceleration-displacement diagram for frontal impact: test vs. simulation

The initial kinetic energy of 88 kJ is mainly absorbed by material deformation and fracture (internal energy) and friction between the impact structure and the rigid wall (sliding energy). The hourglass energy, resulting from the underintegrated shell elements, is less than 5% of the total energy.

5 Summary and conclusions

Crushing simulations of an F1 racing car front impact structure striking a rigid wall have been conducted and validated against experimental crash test data. Since it is very difficult to represent the crushing and fragmentation of the composite material with relatively coarse finite elements, the crash-front algorithm was used as a substitute numerical method to cover the continuous crushing of the structure in a layered shell model. A fair correlation with respect to qualitative and quantitative results could be obtained with this model. Those results relate to only one configuration of the front impact structure. Different designs with different laminate lay-ups have been analysed in the framework of this study with comparisons of crash simulations and experimental data to evaluate the robustness of the model. The validation led to satisfying results and the overall conclusion that dynamic FE simulations with LS-DYNA can be a helpful tool for an evaluation of the crash performance of different configurations in the design phase of an F1 racing car front impact structure, although this method is not qualified for a replacement of crash tests.

6 Literature

[1] 2008 Formula One Technical Regulations, FIA, Paris, 2008.

[2] Mellor, A.: Impact testing in formula one. International Journal of Crashworthiness, 7(4), 2002, 475-486.

[3] Feaboli, P.; Norris, C.; McLarty, D.: Design and certification of a composite thin-walled structure for energy absorption. International Journal of Vehicle Design 44(3/4), 2007, 247-267.

[4] Savage, G.; Bomphray, I.; Oxley, M.: Exploiting the fracture properties of carbon fibre composites to design lightweight energy absorbing structures. Engineering Failure Analysis, 11, 2004, 677-694.

[5] Browne, A.; Fuchs, H.; Johnson, N.; Watling, P.; Melvin, J.; Pierce, J.: Side-impact testing of race car sandwich panels. Automotive Engineering, 105(3), 1997, 99-104.

[6] Wright, P.: Formula 1 technology. Society of Automotive Eng., Warrendale, 2001.

[7] Macknight, N.: Technology of the F1 car. Hazleton Publishing, Richmond, 1998.

[8] O'Rourke, B.P.: The uses of composite materials in the design and manufacture of formula 1 racing cars. Proc. of the Inst. of Mechanical Engineers, 204, 1990, 41-48.

[9] Savage, G.: Composite materials in formula 1 racing. Metals and Materials, 7(10), 1991, 617-624.

[10] BMW Team: Materials in the BMW Sauber formula 1 race car. Advanced Materials & Processes, 166(11), 2008, 59-62.

[11] Hörmann, M.; Wacker, M.: Simulation of the crash performance of crash boxes based on advanced thermoplastic composite. 5th Eur. LS-DYNA Users Conference, Birmingham, UK, 2005.

[12] El-Hage, H.: Numerical modelling of quasi-static axial crush of square aluminium-composite hybrid tubes. Int. Journal of Crashworthiness, 9(6), 2004, 653-664.

[13] Schweizerhof, K.; Maier, M.; Matzenmiller, A.; Rust, W.: Energy absorption with composite crash elements in frontal crash - an analysis with LS-DYNA3D. 11th CADFEM user meeting, Bamberg, 1993.

[14] Papapostolou, D.: Finite element modelling of the static axial compression and impact testing of square CFRP tubes in LS-DYNA3D. 5th Eur. LS-DYNA Users Conf., Birmingham, UK, 2005.

[15] Mamalis, A.G. et al.: The static and dynamic axial collapse of CFRP square tubes: finite element modelling. Composite Structures, 74(2), 2006, 213-225.

[16] Agaram, V.; Bilkhu, S.S.; Fidan, S.; Botkin, M.E.; Johnson, N.L.: Simulation of controlled failure of automotive composite structures with LS-DYNA3D. Proc. 12th ESD/SAE Advanced Composites Conference, Detroit, MI, 1997, 181-190.

[17] Botkin, M.E.; et al.: Numerical simulation of post-failure dynamic crushing of composite tubes. 2nd International LS-DYNA Conference, San Francisco, 1994.

[18] Matzenmiller, A.; Schweizerhof, K.: Crashworthiness simulations of composite structures - a first step with explicit time integration. In: Nonlinear Computational Mechanics: State of the Art, Springer, Berlin, 1991, 643-670.

[19] Kerth, S.; Ostgathe, M.; Dehn, A.; Maier, M.: Experimental investigation and numerical simulation of the crush behaviour of composite structural parts. 41st SAMPE Symposium and Exhibition, 1996, Anaheim, CA, 1397-1408.
[20] Bisagni, C.; et al.: Progressive crushing of fiber-reinforced composite structural components of a formula one racing car. Composite Structures, 68(4), 2005, 491-503.
[21] Siegler, B.P.; et al.: The application of finite element analysis to composite racing car chassis design. Sports Engineering, 2(4), 1999, 245-252.
[22] Williams, T.D.; et al.: The prediction of frontal impact crashworthiness of a space-frame sportscar. International Journal of Crashworthiness, 4(2), 1999, 147-158.
[23] Borg, R.: Simulation of delamination initiation and growth in fiber composite laminates. PhD Thesis, Linköping University, Sweden, 2002.
[24] Heimbs, S.; Middendorf, P.; Maier, M.: Honeycomb sandwich material modeling for dynamic simulations of aircraft interior components, 9th International LS-DYNA Users Conference, Dearborn, MI, 2006.
[25] Lamb, A.J.: Experimental investigation and numerical modelling of composite-honeycomb materials used in formula 1 crash structures. PhD Thesis, Cranfield University, UK, 2007.
[26] Chang, F.K.; Chang, K.Y.: A progressive damage model for laminated composites containing stress concentrations. Journal of Composite Materials, 21, 1987, 834-855.
[27] Heimbs, S.; Schmeer, S.; Middendorf, P.; Maier, M.: Strain rate effects in phenolic composites and phenolic-impregnated honeycomb structures. Composites Science and Technology, 67(13), 2007, 2827-2837.