Chapter 2
The Numerical Simulation of Foam – An Example of Inter-Industrial Synergy

Paul A. Du Bois

Abstract Low density foams made by some expansion process of polymeric materials are widely used in industry. Their main mechanical characteristic is the high compressibility expressed by the near zero value of the Poisson's ratio. The numerical simulation of these materials remained secondary and enigmatic throughout the 1980's. It was the automotive safety related CAE work that prompted systematic research into a methodology for the reliable and predictive simulation of foam materials in the 1990's. This research program was carried out by an FAT working group and would last 12 years. Complementary work preliminary with respect to high velocity impact, sever shear deformation and tensile fracture was performed by NASA during the Columbia accident investigation and the results of this development work have in turn benefited the automotive industry. The article reviews the history of the foam simulation related R& D work during the last 2 decades.

2.1 Introduction

Throughout history the defence industry has acted as an engine for technological innovation. It suffices to realize that most of Archimedes' inventions were motivated by the defence needs of Syracuse and that Newton and his contemporaries unravelled the mystery of gravity while working on very down to earth problems of ballistics [1]. Similarly, the ultimate discontinuity in humanity's technological evolution : world war 2, has given us radar technology, electrical computing, nuclear energy, jet engines and space flight amongst many other innovations. Industry as a whole has profited traditionally from the investments made in defence research through a continuous technological transfer.

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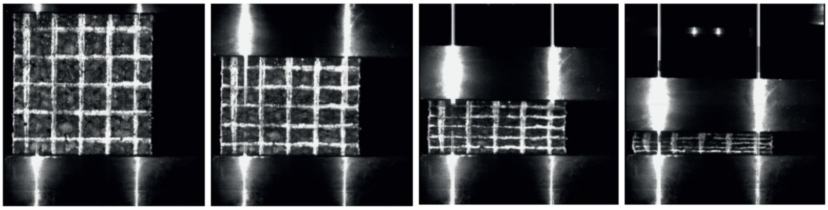

Fig. 2.1 Compression test on a low density foam.

Numerical simulation has not been an exception to this general rule, the roots of modern simulation techniques go back to the war years at Los Alamos where John von Neumann and Robert Richtmeyer supported the design of the implosion device that would render the plutonium bomb possible. Up to the 1960's publications on simulation work [2] show mainly applications originating in the defence community. The simulation of foam materials on the other hand originated, at least to the best of knowledge of this author, entirely in the automotive world but its evolution was not less diverse nor inter-disciplinary and somewhat remarkable. The purpose of this article is to review this interesting story.

2.2 Foams – Physical Nature and Numerical Modeling

From the viewpoint of a material scientist, any material that is manufactured by an expansion process is considered a foam. The base material is thereby irrelevant and can be polymeric, metallic or other. Foams are of course used in every industry ranging from furniture to building isolation products but the need for simulation originally arose in the automotive world. In automobiles foams are needed for comfort (seats), safety (bumpers and paddings) and stiffness (so called structural foams).

To a numericist the intuitive notion of a foam has little to do with the art of manufacturing and a material is said to be foam-like if it exhibits no lateral deformation under a uniaxial compressive load (see Figure 2.1). Most foam materials are also elastic in the sense that they recover to their undeformed configuration after some period of time. The numerical simulation of foams is based on the observation of Storakers [3] that Hill's energy functional of hyperelasticity can be used to describe the simple special case of foams where principal engineering stresses are uncoupled , i.e. depend only upon the stretch ratio in the corresponding principal direction. To see this we start from the expression for Hill's energy functional

$$W = \sum_{m=1}^{k} \frac{\mu_m}{\alpha_m} \left(\lambda_1^{\alpha_m} + \lambda_2^{\alpha_m} + \lambda_3^{\alpha_m} - 3 + \frac{1}{n} \left(J^{-\alpha_m n} - 1 \right) \right) \tag{2.1}$$

Fig. 2.2 Member Companies of the FAT AK27 Working Group Foam.

and set n=0 :

$$W = \sum_{m=1}^{k} \frac{\mu_m}{\alpha_m} \left(\lambda_1^{\alpha_m} + \lambda_2^{\alpha_m} + \lambda_3^{\alpha_m} - 3 \right) \tag{2.2}$$

We then obtain the expression for engineering and true principal stresses in the usual way of hyperelasticity :

$$\lambda_l \lambda_k \sigma_i = \tau_i = \frac{\partial W}{\partial \lambda_i} \tag{2.3}$$

$$\tau_i = \frac{1}{\lambda_i} \sum_{m=1}^{k} \mu_m \left(\lambda_i^{\alpha_m} - 1 \right) \tag{2.4}$$

The decisive step for practical applications is then made by observing that a tabulated generalisation is trivial due to the uncoupled nature of the equations. Consequently the results of uniaxial tensile and compressive tests in terms of engineering stress and engineering strain can be used directly as input to the material model for use in an engineering software such as LS-DYNA.([6] and [7]).

However, the way from a theoretical model to industrial application usually proves to be a long and tedious path. The number of practical problems to be solved is important to say the least. We are confronted with the physics of foams that show viscosity causing such phenomena as damping, rate dependency, hysteresis, stress relaxation and creep. All these phenomena cannot be described by simple hyperelasticity and imply that the solution of the problem in terms of computing stresses from strains and strain rates no longer has a unique solution. Then there is the problem of numerical stability, accuracy and efficiency. The efficiency aspect when dealing

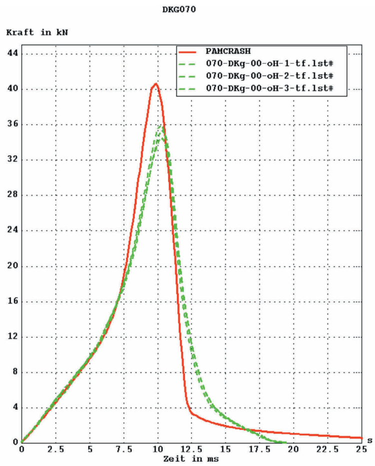

Fig. 2.3 Comparison test/Simulation results for a sphere impact on Bayfill RG70.

with explicit integration codes that are used in crash simulations and dynamic simulations of all kinds is strongly depending on the stable timestep of the simulation. Foams are highly compressible and small dimensions of the compressed finite elements will inevitably lead to small timesteps and correspondingly high computing times.

2.3 Numerical Modeling of Foams in Automotive Crash

Due to the necessity of simulating foam response during an automotive crash event and the lack of fast, reliable solution algorithms as well as material data a working group foams (’Arbeitsgruppe Schaum’) was founded by the German FAT (Forschungsgemeinschaftautomobiltechnik) in the autumn of 1996. Participating members of the working group were most of the German automotive companies (Volkswagen, AUDI, Mercedes-Benz, Opel, Ford and Porsche) and a number of supplier companies (JCI, Keiper, Karmann, BAYER, BASF and Autoliv). (See Figure 2.2) Speaker of the working group was dr. Christian Stender from Volkswagen during the entire research effort. The project would consist of a large combined numerical/experimental program where the author would perform numerical simulations with 3 widely use softwares (LS-DYNA, Pamcrash and Radioss) and the experimental data would be produced by a team around Dr. Hartwig Nahme at EMI (Ernst Mach Institute) in Freiburg. The total effort would extend over a period of roughly 12 years and was completed recently towards the end of 2008. The project was divided into two phases. The first phase or methodology phase ran from 1996 till 2002. Four classes of low density foams were selected : seatfoam, PU-bumper foam, padding foam and EPP-bumper foam. For each of these materials a suitable simulation technology able to accommodate the dynamic response under impact loading was developed. This was done based on the example of a single material for each class of foams with a selected density of around 50 g/l. In the second phase of the project databases were created for all 4 classes of foams at different densities, varying between 30 g/l and 200 g/l.

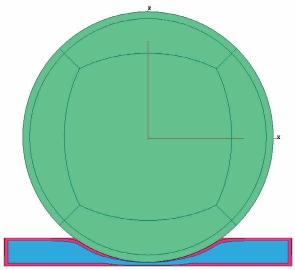

Fig. 2.4 Simulation model for a large sphere impact on a Foam Block, deformed shape.

Realizing that only a massive approach can lead to a reliable simulation tool, the FAT project involved many thousands of experiments and corresponding numerical simulations. Indeed maybe the most challenging aspect of numerical simulation is to define what can be reasonably expected from a simulation result. In other words : how close to the test result can we get, how predictive can we possibly be. The answer to this question lyes in a good understanding of experimental spread and model limitations. In the case of foams the problem seems somewhat freightening at first sight. Indeed a foam is not a continuum but a structure consisting of open and/or closed cells. The mechanical properties are a function of the intrinsic material properties of the cell wall material but also of the geometry of the structure : the size and shape of the cells. The numerical model is based on solid finite elements and uses continuum theory. It consequently cannot account for microstructural effects and can only be valid as long as the element size exceeds the cell size by some factor (preferably at least 10). Due to the small cell size in automotive foams this is usually uncritical (with the exception of certain thin structures such as roof covers) but other problems arise at the macroscopic level.

Density variations are the main problem in foam parts. Global density variations can occur in individual batches due to the manufacturing process. Local density variations showing a density gradient from the surface to the inner of the part are an inevitable consequence of skin formation that occurs in the cold forming process of PU foams and during the pressure bonding of EPF (Expanded particle foams). These local density variations depend (amongst other factors) upon the part geometry and

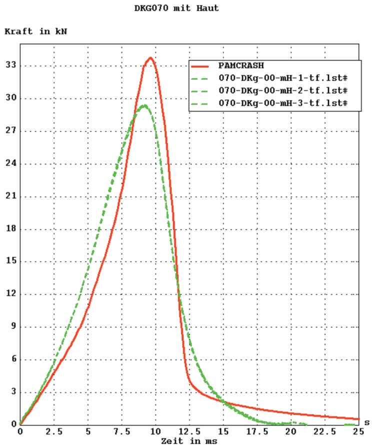

Fig. 2.5 Comparison test/Simulation results for a sphere impact on Bayfill RG70 Kernel density assumed 70g/l.

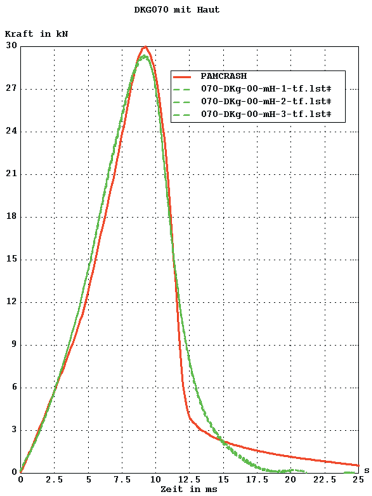

Fig. 2.6 Comparison test/Simulation results for a sphere impact on Bayfill RG70 Kernel density assumed 76g/l.

are impossible to account for in an exact way in a numerical model. An approximate way is to lump the skin effect or the higher density part of the foam component in a single layer of solid elements at the surface of the part. Only practical and massive experience can determine the confidence level that may be attributed to such an approach. In [4] an example is shown of the influence of a density variation in the kernel of a PU bumperfoam upon the maximum force measured during the impact of a 30kg aluminium sphere on a foam block with and without skin layer. Figure 2.4 shows the test setup. In Figure 2.3 the comparison between test an simulation results is shown for the foam block without skin (a so-called cut sample) and a density of 70 g/l. The correspondence is good in particular where the initial slope of the force-time curve is concerned. The high intrusions later on lead to rupture in the foam block which was not simulated and thus leads to a divergence between test and numerical results. However these differences are explainable. next a cold formed part was examined. The intention was to manufacture a cold formed part with a kernel density of 70 g/l. The resulting global and thus measurable density was 85 g/l due to the higher density in the skin layer. In Figures 5 and 6 we again compare test and simulation results. In Figure 5 the numerical model assumed a kernel density of 70g/l (resulting in a rather bad comparison to test) and in Figure 6 the kernel density was assumed to be 76 g/l. The variation of less then 10% in kernel density could very well occur in real manufacturing circumstances. The conclusions from studies like these are very important for the industrial analyst:

- Repeated tests are essential to get an idea of the scatter in test results
- Different kinds of tests are essential to deal with unknown parameters such as the density distribution in the part
- There are always outlayers
- Much time could otherwise be waisted fitting models to single test results
- Kernel density is decisive rather than the nominal density
- Damage (and failure) modeling is desirable (but was not assessed by the working group at this point in time)

The first phase of the FAT project resulted in numerous improvements of the foam material laws in all 3 participating softwares. A user friendly setup based on input of directly measurable engineering stress-strain curves under uniaxial compression and uniaxial tension was at the base of the methodology. Further improvements with regard to numerical stability included optimized estimates of the stable timestep as well as stiffness proportional damping and strain rate filtering. Underintegrated solid elements were usually employed in order to accommodate the huge aspect ratios that can occur due to the high compression (up to 98%) that is sometimes locally observed in foams.

Engineering stress-strain curves can be defined for loading and unloading regimes at different strain rates. Suitable experimental techniques were developed by EMI, in particular the need for dynamic testing at constant velocity (constant engineering strain rate) was clearly established. An example of static and dynamic input curves for a PU62IF70 foam with a density of 70 g/l is shown in Figure 2.8. Maybe the most important aspect of the data preparation for foam material laws is the need to extrapolate the experimental data at high compressions. Foam plateau stresses are very low (less then 1. MegaPascal) compared to the yield strength of the surrounding metallic structures. Experimental data are at best available to 20 times the level of the plateau stress and thus still an order of magnitude below the stresses that can

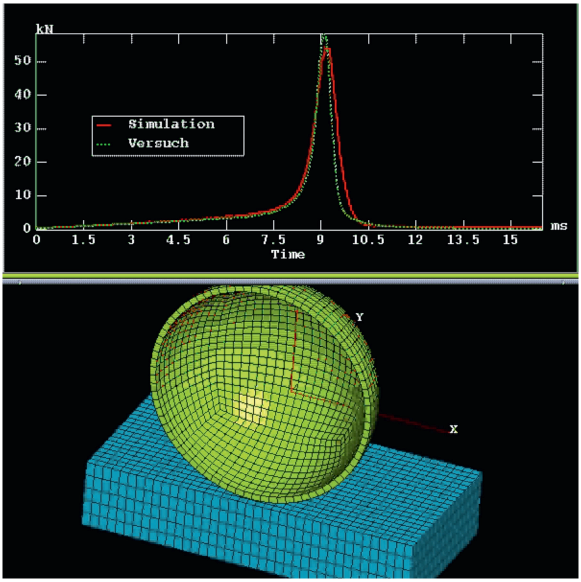

Fig. 2.7 Simulation model and results comparison for a Foam validation test.

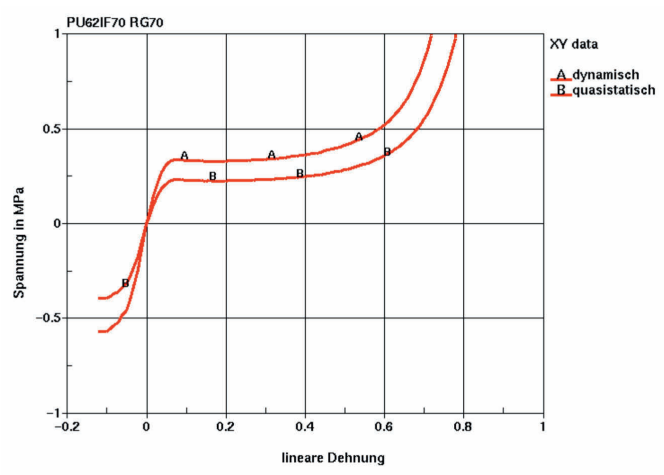

Fig. 2.8 Static and dynamic stress-strain curves for Bayfill RG70.

occur during a crash event when the metallic parts are plastified. The extrapolation of experimental data is always to some degree arbitrary. We have consistently used a higher order hyperbolic function with good practical results and an example of our extrapollation procedure is shown in Figures 2.9 till 2.11.

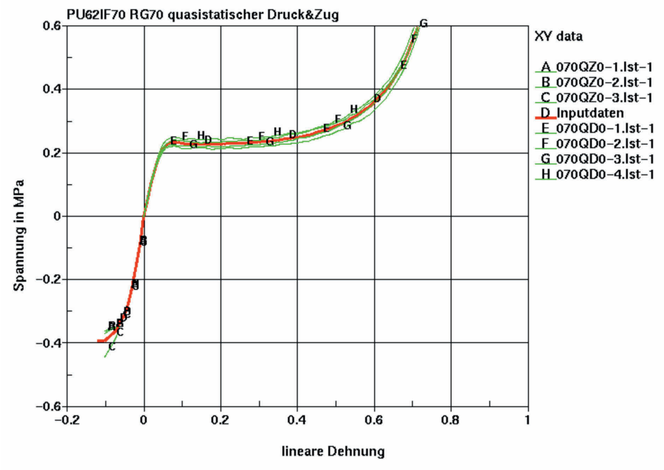

Fig. 2.9 Quasistatic stress-strain curves for Bayfill RG70 test results versus material model input-data up to 0.6MPa.

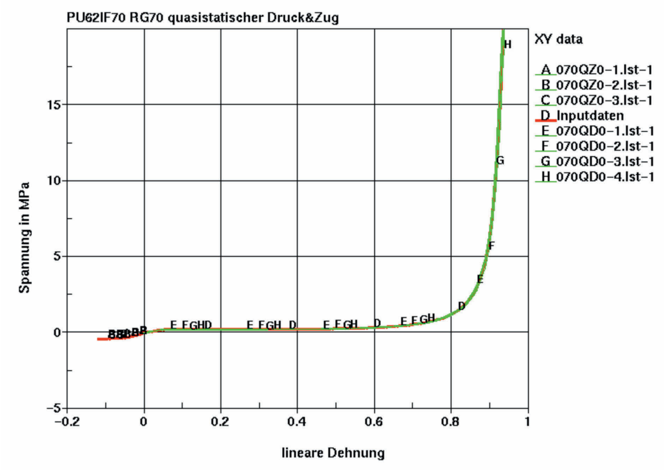

Fig. 2.10 quasistatic stress-strain curves for Bayfill RG70 test results versus material model input-data up to 20.0MPa.

2.4 Impacted Foam – The Columbia Accident

Such was the situation when on January 16 2003, Columbia's leading edge was impacted by a chunk of foam suspected to have separated from the external tank bipod ramp at 81 seconds into its launch. Columbia was traveling at Mach 2.46, at an altitude of 65,860 feet. The foam was calculated to have hit the orbiter at 700 – 800 feet

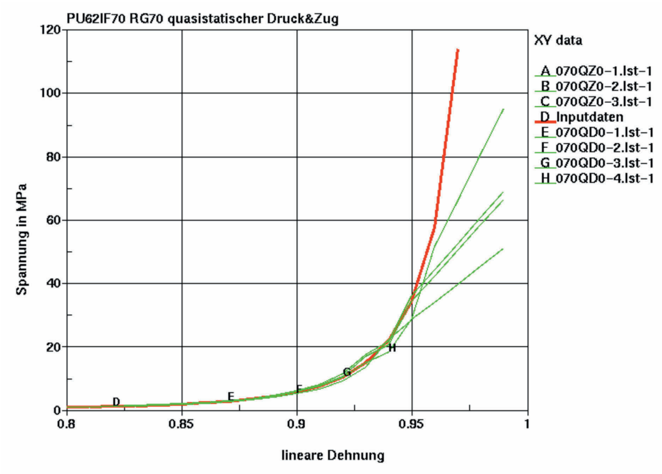

Fig. 2.11 quasistatic stress-strain curves for Bayfill RG70 test results versus material model inputdata up to 120.MPa.

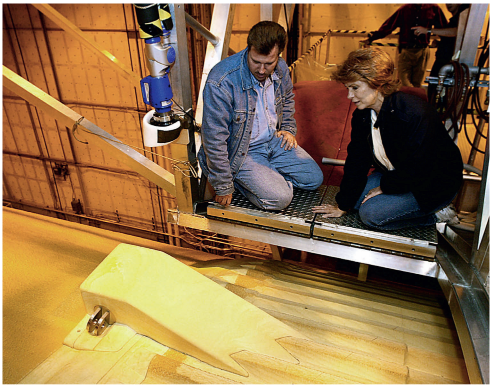

Fig. 2.12 BX250 foam block like the one that separated from the bipod ramp.

per second. A similar chunk of foam is shown in Figure 2.12. The object was suspected to have hit the Reinforced Carbon-Carbon (RCC) Panels Protect the Leading Edges of the Orbiter (Figure 2.13 and 2.14). The GRC (Glenn research Center) Impact Lab was Requested to Assist in the Columbia Accident Investigation based on its extensive expertise in impact testing and analysis. Most of GRC's previous work had been in jet engine debris containment. Now they were asked to provide simulation and testing work in support of the full scale impact test that would be performed in San Antonia Texas by SWRI. The first part of the job was to do Impact Testing to

Characterize ET Foam and RCC and constitute adequate material models for both materials.

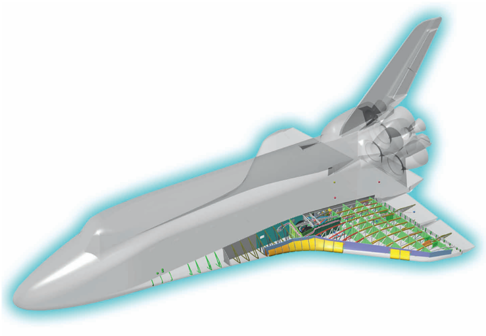

Fig. 2.13 Reinforced Carbon-Carbon Panels Protect the Leading Edges of the Orbiter.

Fig. 2.14 RCC Leading Edge with T-Seal.

The analysis work was performed with the LS-DYNA code by a team around dr. Kelly Carney from GRC. Through literature and personal contacts with the author the results of the FAT investigations were available to this group but they soon realized that the circumstances of the Columbia accident called for extensive additional research. In particular it became necessary to investigate the response of the foam at very high strain rates and assess the response in vacuum. It was also proven important to simulate the tensile failure of the material upon impact.

In addition to the traditional quasistatic testing of the BX250 ET foam dynamic testing was performed to evaluate the projectile performance of the material model. The test originally employed to verify the MAT83 model was performed at

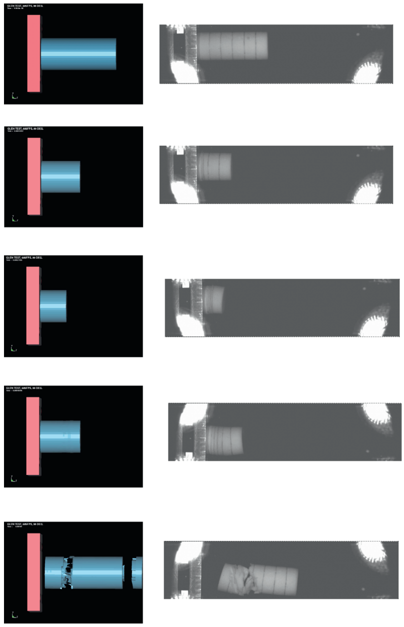

Fig. 2.15 90 degree impact simulation and test.

NASA/GRC, consisting of a foam projectile impacting a comparatively rigid plate. Load cells were mounted at the corners of the plate and high speed video was also employed. The test set-up was modeled employing LS-DYNA and results were processed based on the output of the analytical load cells and visual data available via LSPREPOST. A freeze frame video clip for both analysis and test may be seen compared in Figures 2.19 and 2.20, for 90 and 23 degree impacts respectively. The dynamic impact tests required a specially built 2 inch vacuum gun. BX250 ET foam specimens were shot at angles of 10, 15, 23, and 90 degrees on load cells at 700 and 800 ft/sec to evaluate foam projectile response at 1 psi and atmospheric pressures.

The strain rate testing was limited to less than 500 sec^{-1} due to equipment operation limits. The actual strain rate experienced at a point mid way in the specimen has been solved for analytically and were seen to be far in excess of anything tested before. However, the effect of strain rates within the limited testing performed indicated that the strain rate dependence of the stress strain relationship becomes constant above the existing 429/s curve.

The simulation boundary forces were summed in the plate normal direction and compared to the summed plate normal load cell responses as shown in Figures 2.21 and 2.15 for 90 and 23 degree impacts respectively. As can be seen in these figures, the model conservatively replicates the loading events from the projectile as

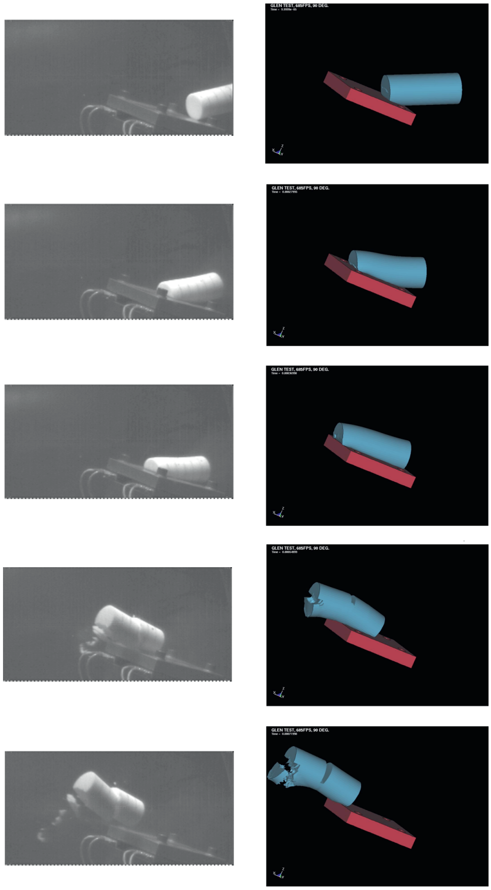

Fig. 2.16 23 degree impact simulation and test.

predicted from test. These experimental data were at the base of the analysis foam model. The high strain rate and failure response of the material was reverse engineered by comparison of numerical and test results.

In a second phase of the investigation foam samples were shot at RCC coupons and the response was used to evaluate the RCC numerical model. Finally different impact scenarios were investigated with foam blocks impacting RCC leading edge panels at different angles and velocities. For this purpose a numerical model of the RCC panel was built with 43000 shell elements and the foam block was modeled with 147000 solid elements. Figure 2.16 shows the numerical model used in the simulation of the critical panel 8 impact event. The LS-DYNA predictions corre-

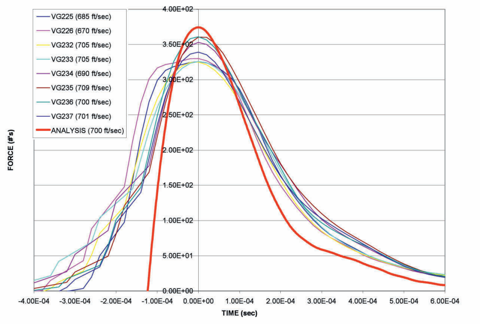

Fig. 2.17 Simulation vs Test Plate Normal Boundary Forces (90 deg.).

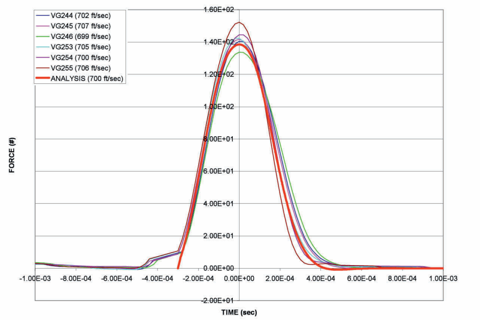

Fig. 2.18 Simulation vs Test Plate Normal Boundary Forces (23 deg.).

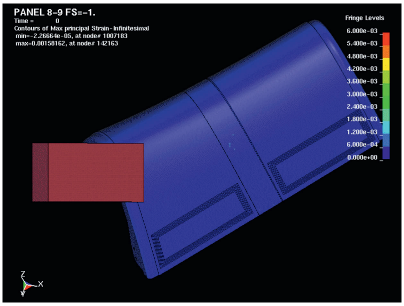

Fig. 2.19 Simulation model for impact of Foam Block on Orbiter Leading Edge Mock-Up.

lated well with the full scale test that was ultimately performed in San Antonio. (See Figures 2.17 and 2.18).

The external tank foam test and simulation program had thereby been completed. It was demonstrated full scale tests at SWRI at atmosphere would be representative

Fig. 2.20 Ballistic impact test results.

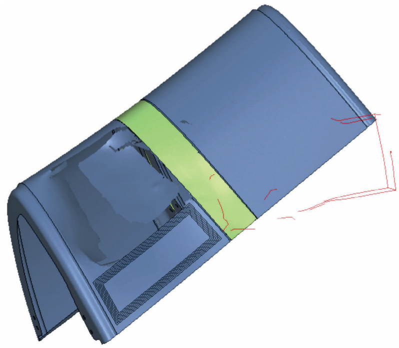

Fig. 2.21 LS-DYNA Simulation result.

of actual impact event in vacuum and a validated foam model for computer analysis predictions had been developed. In particular the numerical model for the foam included a tensile rupture criterion allowing the foam block to separate into multiply connected parts after impact.

2.5 Summary and Conclusion

In the Columbia accident investigation NASA had added a capability to simulate extreme conditions to the foam material models. This became relevant to the automotive industry in the 21*st* century with the implementation of pedestrian protection legislation and the subsequent use of very low density (30 g/l) foams in bumpers leading to extreme deformations and occasional rupture during lower leg impact test events. The next step in the simulaton of these high deformation phenomena could be the introduction of meshless or particle methods such as EFG (element free Galerkin) which allow to push the simulation beyond the point where classical Lagrangean elements can go. In conclusion, it can be said that the industrial application pushes the simulation techniques forward as more challenging problems are assessed. Specific problems and the subsequent research and progress in simulation technology occurs in many different fields but most of the resulting methods turn out to be amazingly general and useful in a broad range of industries. The value of a continued exchange of information can therefore not be overstated.

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