Calibration and Experimental Validation of LS-DYNA Composite Material Models by Multi Objective Optimization Techniques

Stefano Magistrali*, Marco Perillo**
** Omega Srl, Research and Innovation Centre, Tortona fraz. Rivalta Scrivia (AL), Italy*
*** EnginSoft SpA, Firenze, Italy*

Abstract

Experimental quasi-static tensile and impact tests were conducted over two different types of composite laminates and four different types of sandwich laminates, in order to evaluate their basic mechanical characteristics and energy adsorption capability. The second phase of this research work approaches and resolves the calibration of the mechanical parameters included into the LS-DYNA composite material models. This calibration starts and is based on the material physical properties derived from the test results.

LS-DYNA model parameters, model constrains and objectives defining the problem have been studied and analysed by using modeFRONTIER. modeFRONTIER is a multi-objective and multi-disciplinary integrated platform. Input parameters were varied into a controlled range. This allows to find quickly and to define accurate model configuration as well as model sensitivity to those parameters, leading to reliable numerical models for impact simulations.

Accurate comparison of simulation results with experimental material results is crucial to achieve optimum and precise material models.

The present research study offers also an understanding of the effect of numerical input parameters and variables on sandwich laminates structural response in terms of absorbed energy, maximum energy, maximum force and curve morphology.

Calibration of material models, able to reproduce the effective impact behaviour of real composite materials, is fundamental in order to simulate general crashworthiness problems. This kind of approach allows either to understand variable influences on composite dynamic structural response or to get improved solution for industrial case studies.

Introduction

Composite or sandwich structure impact behaviour can be investigated according to two different approaches: impact damage tolerance – capacity of a structure to survive to an impact without prejudicing its residual structural performances and impact resistance – capacity of a structure to absorb as much energy as possible during an impact phenomenon, without any need of residual mechanical characteristics. The first approach is generally used by the aeronautic industry and many efforts have been carried out to develop strong design procedures. On the contrary the impact resistance approach is mainly employed for safety applications i.e. protective equipments or helmets, and, in particular, the objective of this type of methodology is to design a complex structure able to minimizing the force transmitted to the protected object, maximizing the energy adsorbed by the structure.

Some authors have documented efforts over the past two decades to understand the behaviour of laminated composite structures under transient loading conditions. These efforts were to identify and characterize the relevant failure mechanisms, to understand their interactions, and to be able to predict the extent of damage within a given composite system under a set of specified loading conditions. These studies identify some parameters as basic design parameters, i.e. material

parameter (matrix, reinforcement and interfaces between layers), stacking sequence, laminate thickness, striker geometry.
The aim of this work is to provide specific guidelines to support and to facilitate the development and innovation of complex composite structures submitted to low velocity impact events in term of impact resistance performance. A design methodology has been developed to validate the numerical prediction of energy absorption capability of a composite or sandwich laminate, through the combined use of experimental, numerical and optimisation tools: experimental tests were conducted over different types of composite laminates and different types of sandwich laminates, in order to calibrate LS-DYNA composite material model input parameters.
LS-DYNA model parameters, model constrains and objectives defining the problem have been studied and analysed by using the multi-objective and multi-disciplinary integrated platform modeFRONTIER.
The modeFRONTIER approach allows to handle a huge number of information deriving from different sources, and to obtain quickly the best model configuration comparison experimental ones. Moreover modeFRONTIER tools permit to understand the effect of the numerical input parameters on the laminates structural response as well as model sensitivity to those parameters, leading to reliable numerical models for impact simulations.

Materials and Methods

Two different types of autoclave-moulded composite laminates and four types of autoclave-moulded sandwich laminates were fabricated, details of which are given in Table 1. Note that the all the sandwich laminates were made of an upper Kevlar skin and a lower carbon fiber skin.

Name	**Weave type**	**Lay-up**	**Matrix**	**Core Name**
KL	Twill	$[0/45/0]_S$	Epoxy	/
CL	Twill	$[0/45/0]_S$	Epoxy	/
S1	Twill	$[0/45]_S$	Epoxy	PVC foam
S2	Twill	$[0/45]_S$	Epoxy	PMI foam
S3	Twill	$[0/45]_S$	Epoxy	PU foam
S4	Twill	$[0/45]_S$	Epoxy	Honeycomb

Table1: Laminates details for impact testing

All the impact tests were conducted in house according to the ASTM 3763 on 110 x 110 mm square samples, using a Fractovis CEAST drop tower. The striker mass was 3.84 kg and the energy levels (6,8,10 J) were changed modifying the falling height of the impactor, obtaining variable impact speeds. A pneumatic clamping fixture with two hollow cylindrical elements with 110 mm outside diameter and 76 mm internal diameter clamps the laminates. The samples were impacted with 12.7 mm diameter striker with hemispherical tip, constructed out of high strength steel. Impulse software was used to display and store the impact data: up to 4000 read were recorded. Compressive and tensile quasi-static tests were conducted over composites laminates and foams at the laboratories of the University of Padova, using a MTS810 testing machine with a 10-100 kN load cell

Transient response of each laminates was recorded in terms of load, energy, velocity and deflection. Load and energy versus time response were plotted in Fig.1. Key impact parameters commonly used to describe an impact event are delamination threshold load (DTL), energy to DTL, peak load, energy to peak load, absorbed energy. Impact energy is initially absorbed through elastic deformation till a threshold energy or load value (DTL). Basically the birth of a damage is due to matrix cracking, which will propagate to the interface of two laminates and will progress as delamination. The crack will initiate transverse to the fibers within a ply and it will propagate through the thickness when it comes across stiffer fibers in the ply leading to development of delamination. At and beyond the threshold energy or load value, impact energy is absorbed through both elastic deformation and creation of damage through various failure modes. The extent of delamination will depend on the portion of impact energy available to fracture the interface.

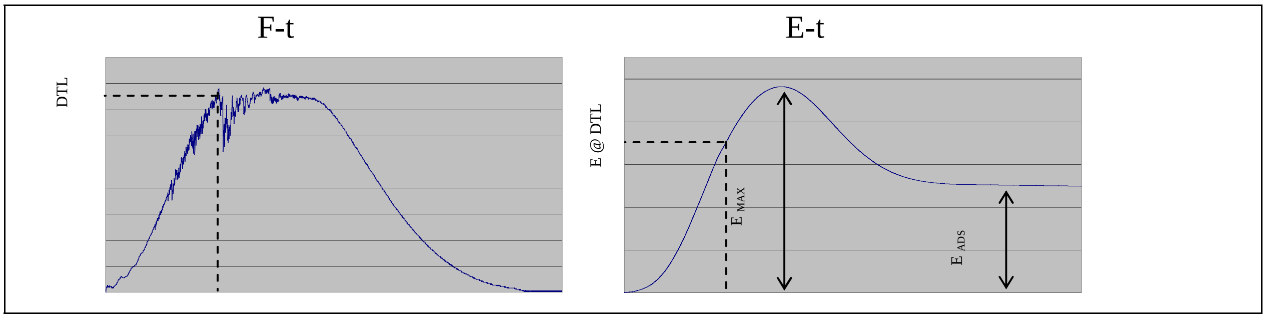

Fig. 1: Key impact parameters

Finite element analysis of the composite laminates

All the finite element analyses of the investigation reported in this paper are performed using the commercial explicit code LS-DYNA, that has been developed especially for impact and non-linear dynamic simulations, in combination with the multi-objective and multi-disciplinary integrated platform modeFRONTIER employed for the optimisation procedure.
The laminates are modelled by shell elements with Belytschko–Tsai formulation. A multi-layered shell is used with one integration point per layer. The different composite materials are modelled using material type 58, which implements a smooth failure surface. The smooth failure criterion defines the following failure limits, for tension and compression:

$$f_p = \left[\frac{\sigma_{aa}}{(1-\omega_{11,c,t})X_{c,t}}\right]^2 + \left[\frac{\tau}{(1-\omega_{12})S_c}\right]^2 - r_{p,c,t} = 0$$

$$f_n = \left[\frac{\sigma_{bb}}{(1-\omega_{22,c,t})Y_{c,t}}\right]^2 + \left[\frac{\tau}{(1-\omega_{12})S_c}\right]^2 - r_{n,c,t} = 0$$

where Xt is the longitudinal tensile strength, Xc is the longitudinal compressive strength, Yt is the transverse tensile strength, Yc is the transverse compressive strength, Sc is the shear strength, ω is a damage parameter described by an exponential law.

The limits of material formulation 58 are related to the lack of any parameter controlling the delamination failure and to the need for a calibration of the reduction factors for tensile and compressive fiber strength, after matrix compressive or tensile failure.
After a preliminary mesh sensitivity analysis, two different but parallel approaches were carried out in order to evaluate the best way for calibrating the reduction factors:

- Tensile test simulation approach
- Impact test simulation approach

Both the simulations were performed with a self-contact algorithm based on the penalty formulation: different sets of contact segments were defined on the mesh surface to prevent the elements to penetrate.

modeFRONTIER multi-objective approach

The effect of the mechanical characteristics of the materials involved and of the reduction factors over both composite and sandwich laminates structural response was managed and investigated by means of multi-objective and multidisciplinary integrated platform modeFRONTIER. Data coming out from the mechanical characterization with statistical variability ranges were used as input parameters. On the other hand the reduction factors were set as variables in a defined range. Objectives of the optimisation were the matching of all the reference parameters between points on experimental and numerical F-t and E-t curves. In particular it was imposed 3 control points to be reached: maximum transmitted force, maximum energy and adsorbed energy. Multi Objective Genetic Algorithm (MOGA) was used for all the optimisation sessions.

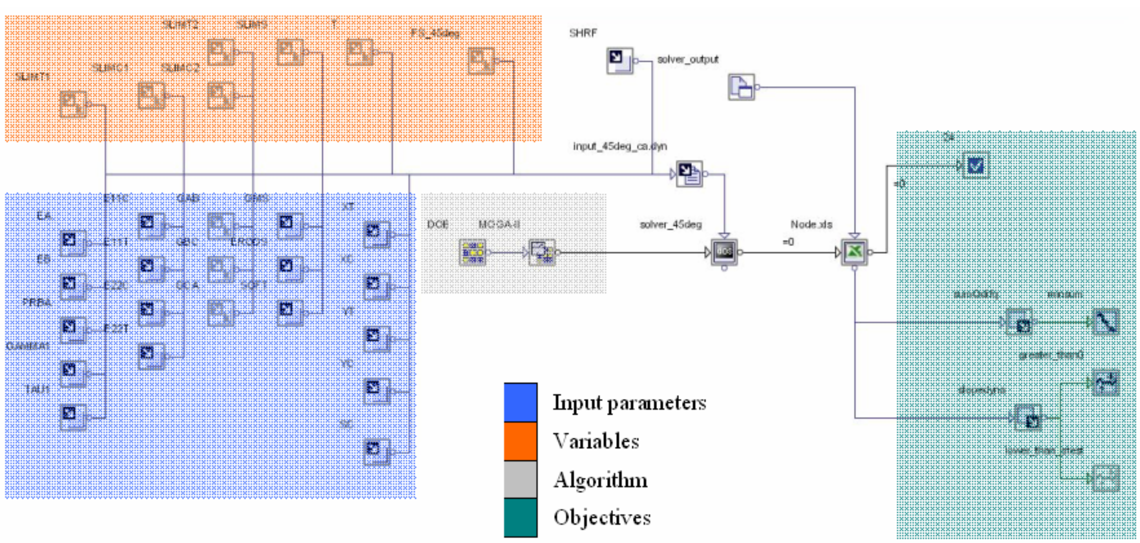

Fig. 2: modeFRONTIER flow chart

Two main tools were used for the multi-objective analysis: Pareto’s frontier and Student’s chart. Basically, Pareto’s frontier is the curve where you can find all the optimum designs coming out from the optimisation. As example, Maximum Energy Delta was plotted versus Adsorbed Energy Delta for a sandwich laminate (see Fig. 3). Delta is the difference between numerical and experimental results at a defined energy level and its minimization is one of the optimisation

objectives. Design 16 was selected because it represented the best solution as compromise between the two tendencies, i.e. decreasing Delta for both the parameters. It's important to underline that the Pareto's frontier is not so close to results distribution: this could be seen as a wrong understanding but this effect is linked with the use of discrete variables.
On the other hand Student's Chart allowed estimating the weighting of the input parameters and of the variables on a specific objective. As example, Student's chart for Maximum Energy Delta is presented in Fig. 4 for the sandwich laminate made with a PVC core. It is clear from the picture that the most weighting factors were Poisson's ratio of the foam and laminates thickness.

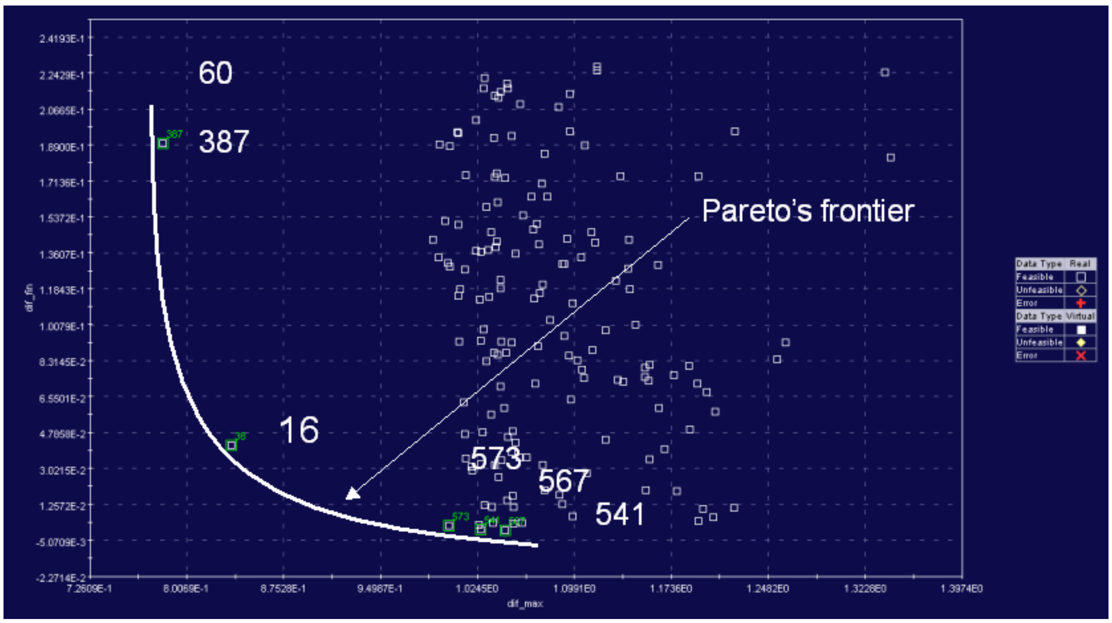

Fig. 3: Pareto's frontier for sandwich panel with PVC foam

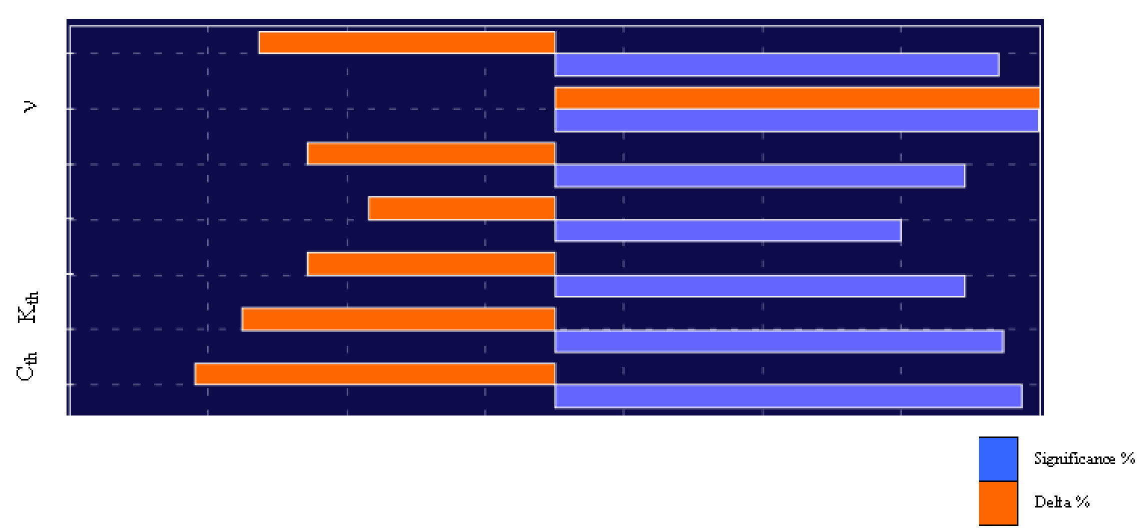

Fig. 4: Student's chart for sandwich panel with PVC foam

Experimental numerical simulations comparisons

LS-DYNA is an explicit solver useful for transient analyses, however it is possible to simulate quasi-static tensile tests changing the integration time step. Simulations of quasi-static tensile test on composite laminates were performed on simple model based on a $[0]_8$ carbon and kevlar specimens with two values for the orientation angle (0° and 45°), in order to evaluate how the material model could manage coupling of stresses. Even if numerical results show a good compliance with the experimental ones (Fig. 5), the limits of this approach were linked to the use of two different sets of reduction factors for the two test cases. This means that the material model couldn't correctly manage stress coupling, in the reproduction of a quasi-static phenomenon.

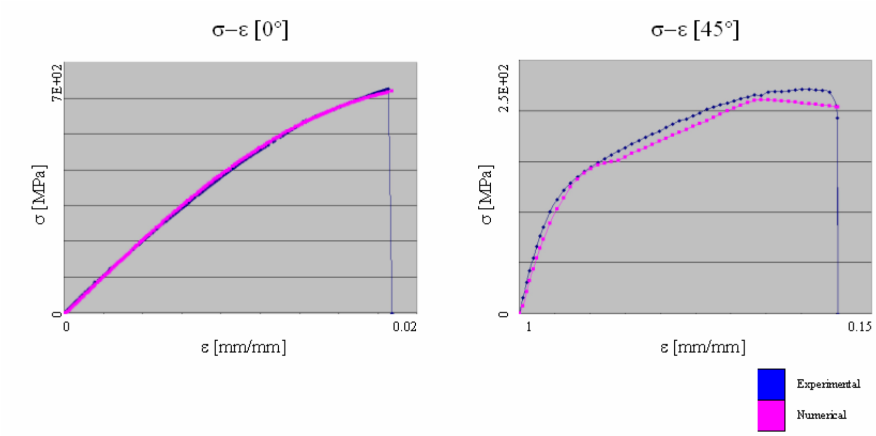

Fig. 5: Numerical vs. experimental results for quasi-static tensile tests - carbon fiber specimens

Simulations of drop tests on composite laminates were performed on simple model based on a [0/45/0]s carbon and kevlar laminates. Multi-objective analysis demonstrates a good compliance, with a delta less than 5% between numerical and experimental results both for all the reference parameters and the curve morphology, see Fig. 6. This approach allows defining only one set of reduction factors for each material: this means that the correct way to approach the definition of material input parameter for composite in LS-DYNA is to calibrate the reduction factors via numerical drop test simulation.

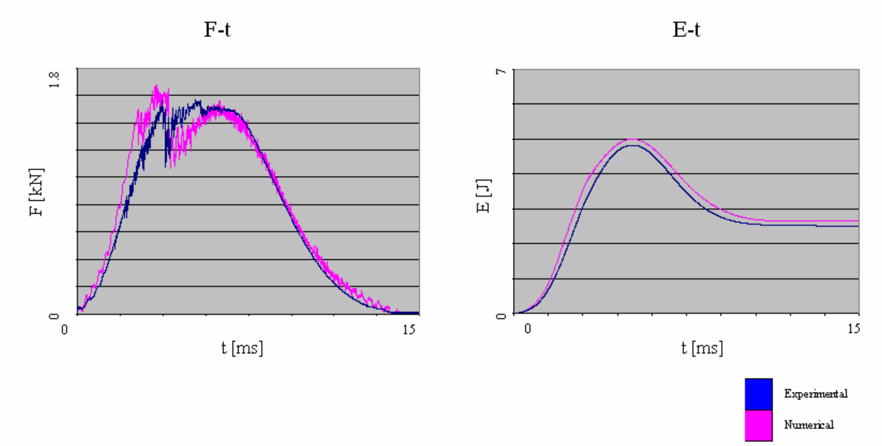

Fig. 6: Numerical vs. experimental results for impact test over carbon fiber laminates

Sandwich laminates simulations

Starting from results coming out from the impact test simulation over composites laminates, the next step was to perform an impact simulation over sandwich panels. Sandwich laminates were made of an upper kevlar skin and a lower carbon skin combined with 4 different 3 mm thick cores:

- PMI foam
- PVC foam
- PU foam
- Aramidic honeycomb

Both kevlar and carbon skins had a $[0/45]_S$ lay-up. Note the composite skins lay-up was changed to test the robustness of the numerical model for composite materials. A shell-brick-shell model was used for the simulation: shell elements were used for modelling the sandwich skins as for composite laminates, while eight-node hexa solid elements were selected for the core, with two elements along the thickness (Fig. 7). The different core materials are both modelled using material type 63. This material model is formulated for isotropic crushable foams that crush one-dimensionally, without coupling between principal stresses, with a Poisson's ratio that is essentially zero. Shear stresses are not taken into account and this represents a problem for the honeycomb modelling: this issue will be examined in a future phase of this research work.

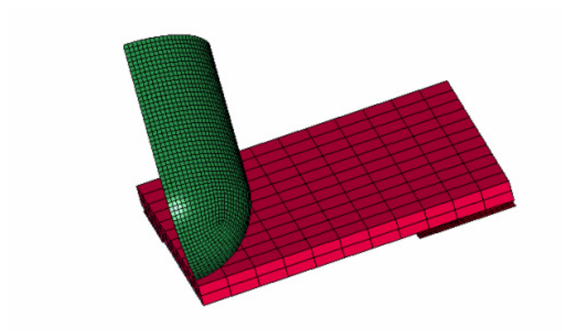

Fig. 7: FE model for impact test simulation over sandwich laminates.

Analyses performed with LS-DYNA in combination with modeFrontier demonstrate a good compliance, with a delta less than 6% between numerical and experimental results for all the reference parameters and the curve morphology (Fig. 8).

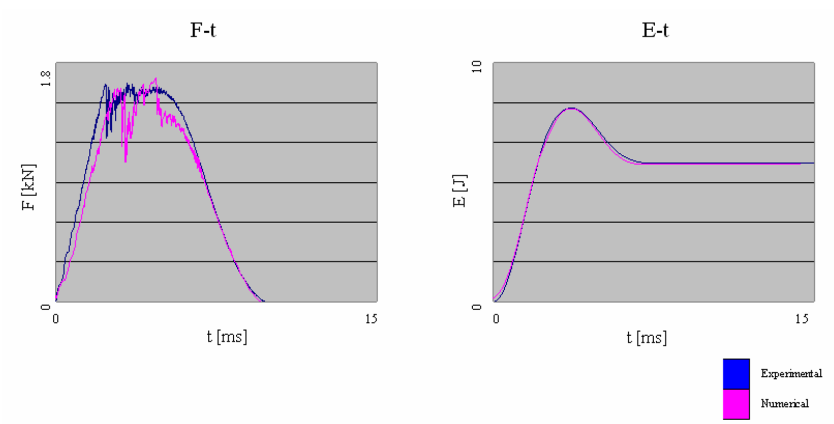

Fig. 8: Numerical vs. experimental results for impact test simulation over sandwich laminates

Conclusions

This paper describes an integrated experimental-numerical procedure for the calibration of LS-DYNA input parameters for material model 58 and 63, by means of the integrated platform modeFRONTIER. Material model 58 was used for modelling woven fabrics, while material model 63 was used for crushable foam modelling.

Tensile and impact tests were performed over composite and sandwich laminates, compressive tests were performed over structural foams. Tensile test and Impact test simulations were conducted over composite and sandwich laminate. It was demonstrated how to manage multi-objective analyses by the combined use of LS-DYNA with modeFRONTIER.

Without shown procedure, it was approached with a Trial and Test method. Its better results (Fig. 9) demonstrated it was not possible to achieve contemporarily each target (Maximum Energy and Adsorbed Energy) without a real multi-objective methodology.

Obtained results are a general indication about the procedure quality used for calibrating numerical input parameters needed for confident impact simulation of simple or complex composite or sandwich structures.

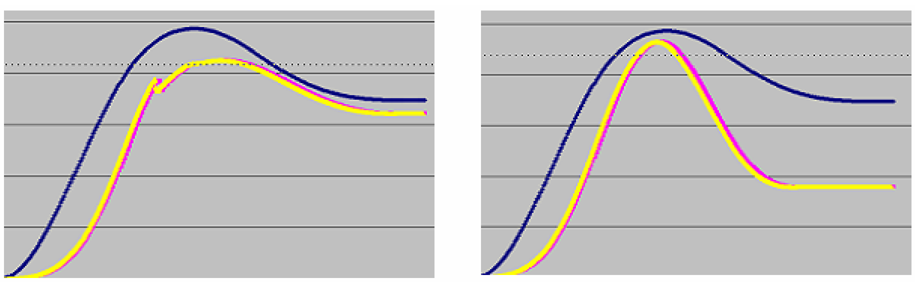

Fig. 9: Trial and Test better solutions – Impact tests – E-t curve