Calibration of Material Models for the Numerical Simulation of Aluminium Foams – MAT 154 for M-PORE Foams @ 3 Loads

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Abstract

Metallic foams are very promising for engineeristic applications due to their peculiar characteristics, like the high energy-absorbing property coupled with a reduced weight. Even if applications can be widespread in several fields, such as automotive, civil, aerospace, etc., industrial requirements are still far to be fully accomplished, especially in terms of technological processes and a whole mechanical characterization.
Material modeling of metallic foams, like the aluminium ones, is a crucial point for performing accurate numerical simulations along with the design phase. Material models available in the explicit, non-linear finite element code LS-DYNA® represent a very efficient way to handle and to investigate foam behavior.
An extended experimental/numerical activity has been set out at the aim to calibrate and validate suitable material models with respect to different aluminium foams and several loading conditions.
While a previous phase of the activity [1] has been focused on the assessment of a procedure addressed to point out, starting from the available experimental data, the key points of material model calibration, the current activity has been focused on the procedure application, i.e. the exploitation of the built-up methodology in respect of calibration of M-PORE open cells aluminium foam at three different loading conditions.
A good number of foams material models are available in the LS-DYNA database, and further in the last years different enhancements have been performed at the goal to include the physical phenomenons able to increase the accuracy of the models. Amongst the available ones, MAT 154 (MAT_DESHPANDE_FLECK_FOAM) has been here chosen because it provides satisfactory results compared with the experimental ones, but at the same time it still requires to be studied for more loading conditions.
Since the calibration process requires to optimize the material model free parameters according to different objectives, LS-DYNA has been coupled with modeFRONTIER®, Process Integration and Design Optimization software platform. Once all the FE (Finite Element) models related to the corresponding experimental tests have been integrated into modeFRONTIER, a first sensitivity analysis has been performed at the purpose to get confidence with MAT 154 behavior and then an efficient optimization phase in order to pursue the numerical configurations satisfying the different targets provided by experimental tests.
Efficient and intuitive post-processing tools have been applied firstly to get a deep knowledge of the investigated phenomenons and eventually to look for the best solutions.

1. Introduction

The current activity is focused on calibration of the MAT 154 material model with respect to M-PORE aluminium foams specimens submitted to three different loading condition: uniaxial compression test, 3 points bending test and Charpy pendulum test. The final goal is looking for MAT 154 parameters values able to satisfy contemporaneously the experimental behavior of quasi static and dynamic tests. The calibration is performed both according to literature practices and according to an approach designed to highlight the relationships between the investigated phenomena without a priori constraints.
The calibration procedure exploits a methodology based on modeFRONTIER, integration platform for multi-objective optimization and advanced data mining.

2. Calibration Procedure Assessment

The assessment of the calibration procedure has been established according to the below key points:

- exploitation of a set of experimental tests able to characterize the static and dynamic behavior of aluminium foam samples. A step-by-step approach has been preferred by selecting a reduced number of experimental results with the intention to get confidence with material model calibration
- set up of accurate and robust FE models for the selected experimental tests
- building up of the tool dedicated to manage the numerical analyses (modeFRONTIER workflow)
- definition of the calibration strategy coupled with a multi-objective optimization

2.1 Experimental Tests

At the purpose to characterize the static and dynamic behavior of aluminium foam samples, in a previous activity [1] a suitable set of experimental tests have been chosen and executed. Such database collects a wide set of experimental tests, that are different in terms of foam typology (closed and open cells that is ALPORAS and M-PORE respectively), loading type (uniaxial compression, 3 points bending, Charpy pendulum, shear), loading direction (parallel or perpendicular to foaming direction), foams density (30 and 45 ppi), and geometry size [8,9]. Accordingly to the procedure assessment, at the aim to get confidence with the chosen material model calibration, avoiding to manage a too much big amount of data, the behavior of M-PORE aluminium foam samples with a 45 ppi density loaded along the foaming direction has been studied. The experimental tests are the following:

- uniaxial compression test vs. 40x40x10 mm specimen
- 3 points bending test vs. 10x10x100 mm specimen
- Charpy pendulum vs. 10x10x100 mm specimen

The **Error! Reference source not found.** sketches the experimental tests with their basic informations and typical experimental curves (the selected ones will be shown along with the numerical analyses).

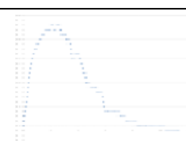
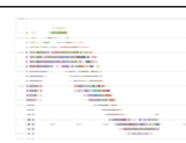
Experimental Tests				Aluminium Foams: M-PORE	
Test ID	**Test Name**	**Test Set-Up**	**Test Equipment**	**Specimens**	**Experimental Curve**
1a	uni-axial compression - **parallel** to foaming direction	test rate = 0.60 mm/min = 0.01 mm/sec		**40x40x10 mm base @ density 45 ppi (x4 tests)**	
3a	3 points bending - **parallel** to foaming direction	striker_vel = 10 mm/min = 0.166 mm/sec span = 60 mm		**10x10x100 mm @ density 45 ppi (x3 tests)**	
4a	Charpy pendulum - **parallel** to foaming direction	impact energy = 8.33 J impact velocity = 2.2 m/s span = 60 mm		**10x10x100 mm @ density 45 ppi (x10 tests)**	

Table 1: experimental tests

2.2 Numerical Set Up

The building up of the finite element (FE) models has been addressed to get accurate results within reasonable computation times, especially in the perspective that a calibration process has to be carried out. Accordingly an initial FEM robustness investigation has been performed with respect to three numerical models at the purpose to evaluate their behavior in terms of mesh element size, element formulation, loading rate, and further to realize how contacts policy affects the numerical performances. The development of the three FE models focused on aluminium samples modeling after a first evaluation of the equipment numerical modeling, as explained below. The R5.1.1 LS-DYNA release (SMP featured) has been used for all the numerical analyses. The workstation is equipped with a quad core (Intel Core i5-2500 CPU 3.30 GHz) with 16 GB of RAM. All the models have been built up with [N, mm, tons, sec] unit system.

Assessment of Equipment Numerical Modeling

The models set up started from an assessment of the experimental equipment, that is a preliminary assessment of the test apparatus numerical modeling has been carried out by experimental tests accomplished on a simple and well-known material (i.e. homogeneous aluminium). Being aware of standard material model parameters, it is possible to check whether what will be the “casing” in the real calibration is accurate or induces an initial delta able to mislead the following results. Such preliminary assessment has been performed for the 3 points bending and Charpy pendulum tests. For the 3 points bending test a 30x5x100 mm aluminium plate has been used, while for the Charpy pendulum test a 10x10x100 mm aluminium bar. The MAT_003 material model (PLASTIC_KINEMATIC) has been introduced with the mechanical properties coming from a very common aluminium alloy, i.e. Al 6061 T6. Unfortunately, the real mechanical properties were not known thus some numerical analyses have been executed updating them around their nominal and thus realizing their influence. Figure 1 and Figure 2 depict the numerical/experimental comparison. In respect of the 3 points bending test, different FE models set up have been evaluated in terms of mesh element size, element formulation and loading rate (e.g. Figure 1 points out the initial “bump” due to an increased scale factor for the sinusoidal velocity curve) and for all the analyses the numerical curve is ahead versus the experimental one, while slope and plateau force are almost the same, as Figure 1 highlights for just a single numerical analysis. With regard to the Charpy pendulum test, numerical trends show a better fitting, where the discrepancies displayed by Figure 2 can be recovered by adjusting the mechanical properties.

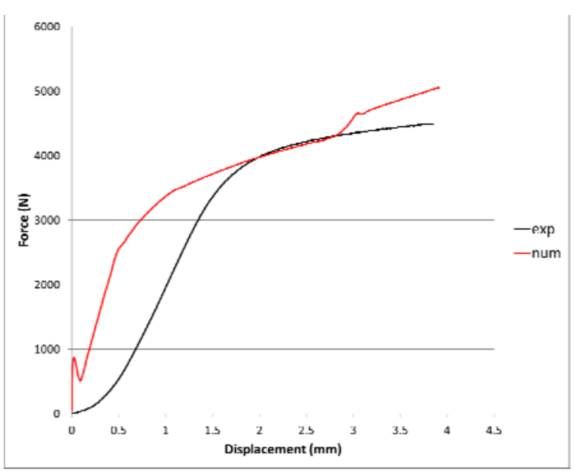


Figure 1: 3 pts num-exp comparison

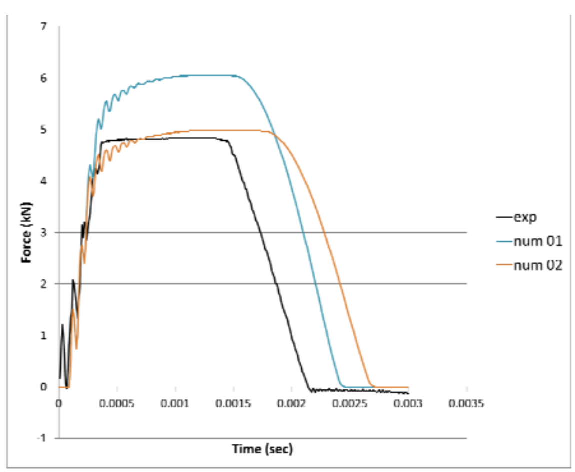


Figure 2: Charpy num-exp comparison

According to the previous results, the more significant difference rises for the 3 points bending test for which the experimental curve shows an initial phase in which the slope increases with the displacement. Such “drift” has been observed also for the compression test, therefore the numerical-experimental comparison has to be accomplished taking into account this phenomenon.

Material Model

As stated in the previous activity [1], the MAT 154 (MAT_DESHPANDE_FLECK_FOAM) has been chosen. This selection is very suitable with respect to the goal of the current activity, that is performing a goodness assessment of a material model whose performances are well suited for uniaxial compression loading but are still not well established for different loading conditions, even if some studies are available in literature [2,6,7]. Further, the above three experimental conditions can be supported by the constitutive equations embedded into the material model. Details of constitutive modeling are available in literature [2-5], where in the following only the most significant relations are provided at the aim to point out the free parameters that are going to be calibrated.

Being the plastic flow of metal foams related not only to the elastic shear energy but to the elastic volumetric energy as well, in MAT 154 the hydrostatic stress is embedded into the equivalent yield stress $\hat{\sigma}$ as given by [2]:

$$\hat{\sigma} = \hat{\sigma}(\sigma, \alpha) = \frac{\sigma_{VM}^2 + \alpha^2 \sigma_m^2}{1 + \left(\frac{\alpha}{3}\right)^2} \tag{1}$$

where:

σ_{VM} = Von Mises stress

σ_m = mean stress (hydrostatic pressure)

α = shape factor. It defines the shape of yield surface and can be expressed in terms of the plastic Poisson ratio ν_p:

$$\alpha^2 = \frac{9(1-2\nu_p)}{2(1+\nu_p)} \tag{2}$$

The values of α^2 needs to belong to the range [0,4.5], otherwise α is physical meaningless. The 0 value corresponds to the Von Mises criterion, while 4.5 means that lateral plastic deformation does not exist in uniaxial compression test. The last case ν_p =0 is esteemed to be the usual condition for aluminium foams [5].

The yield stress function σ_y takes the evolution of yield surface $\Phi = \hat{\sigma} - \sigma_y$ into account because it is the sum of the initial compressive yield stress and the strain hardening:

$$\sigma_y = \sigma_p + R(\hat{\varepsilon}) = \sigma_p + \gamma \frac{\hat{\varepsilon}}{\varepsilon_D} + \alpha_2 \ln\left[\frac{1}{1 - \left(\frac{\hat{\varepsilon}}{\varepsilon_D}\right)^\beta}\right] \tag{3}$$

where:

σ_p = foam plateau stress (initial compressive yield stress)

$R(\hat{\varepsilon})$ = strain hardening

$\hat{\varepsilon}$ = equivalent true strain

ε_D = densification strain (true compaction strain). It is theoretically the strain limit at which the foam density ρ_f equals the density ρ_{f0} of base material. It can be expressed in function of the shape factor α and loading case. For uniaxial compression loading:

$$\varepsilon_D = -\frac{9+\alpha^2}{3\alpha^2}\ln\left(\frac{\rho_f}{\rho_{f0}}\right) \tag{4}$$

α_2, γ, β = material parameters.

The parameters of equation (3) can be calibrated from uniaxial compression tests [2, 5]. As referred in the section dedicated to the calibration strategy, the parameters $\sigma_p, \varepsilon_D, \alpha_2, \gamma, \beta$ have been investigated according to different approaches.

Being required for a crushable foam model a fracture criterion at the goal to provide enough accurate results, especially in uniaxial tension, shear and flexural tests for which fracture do occur [5], in MAT 154 the fracture criterion assumes that elements are removed when the critical value of volumetric strain CFAIL is reached.

Uniaxial Compression FE Model

The uniaxial compression test has been modeled according the following set up:

- aluminium foam sample by a 40x40x10 mm parallelepiped of 1024 solid elements with element formulation equal to 2 (fully integrated S/R solid)
- lower plate by a RIGIDWALL_PLANAR_FINITE
- upper plate by a rigid part (MAT_RIGID steel) of 1936 shell elements with a 1.4 mm thickness
- loading condition provided by a BOUNDARY_PRESCRIBED_MOTION_RIGID. A sinusoidal velocity curve has been exploited so that a zero initial acceleration was attained. By using a velocity of 0.01 mm/sec (quasi static condition), explicit FE model requires too much hours of CPU time to simulate all the compression test. Since the calibration phase needs to run a lot of analyses, CPU time has been dramatically reduced by augmenting the velocity according the scale factor SF. With a SF=-10000 less than 1 min CPU time is required for a 0.015 sec simulation time. It should be noted that MAT 154 does not take into account the strain rate behavior, so only an initial inertial effect arises
- sample-upper plate contact by ASTS (Automatic Surface To Surface) definition. Scale factor for time step TSSFAC has been set to 0.5.

The described FE model (referred here as Cal_Mod) represents the configuration applied during the calibration phase. At the only purpose to check the goodness of a reduced number of calibrated configurations, a more accurate FE model has been developed (Ch_Mod), whose corresponding CPU time is greater than 7 hours. Even if the Cal_Mod is less stable than Ch_Mod (e.g. in terms of energy conservation), the Force-Displacement curves are almost the same, and, above all, Cal_Mod is able to provide the true tendency of the compression behavior versus the examined free parameters. The numerical arrangement of the two models is reported in Table 2.

3 Points Bending FE Model

The 3 Points bending test has been modeled according the following set up:

- aluminium foam sample by a 10x10x100 mm bar of 5120 solid elements with element formulation equal to 1 (constant stress solid element)
- lateral supports by two rigid parts (MAT_RIGID steel) of 1000 shell elements with a 1.4 mm thickness
- central striker by a PART_INERTIA of 1066 rigid shell elements with a 1.4 mm thickness
- loading condition provided by a BOUNDARY_PRESCRIBED_MOTION_RIGID. As done for compression, the sinusoidal velocity curve has been scaled setting SF = -1000, so that a ca. 1 min 30 sec CPU time is required for a 0.06 sec simulation time
- contacts by ASTS (Automatic Surface To Surface) definition. Scale factor for time step TSSFAC has been set to 0.9.

As for the compression case, the above calibration model Cal_Mod has been used for the massive computation phase, while a refined model Ch_Mod to check the goodness of a reduced number of configurations (Ch_Mod CPU time is greater than 10 hours). The numerical arrangement of the two models is reported in Table 3.

The Force-Displacement curves coming from the two models are very similar, as depicted by Figure 3and **Error! Reference source not found.** (the black curve is the experimental one, while the red curves refer to a MAT 154 whose parameters are still not calibrated), where the Ch_Mod seems to be able to reproduce more accurately the ongoing rupture. That suggests the calibration should not be focused on an unnecessary, and potentially misleading, extreme matching of this last part of the curve.

Charpy Pendulum FE Model

The Charpy Pendulum test has been modeled according the following set up:

- aluminium foam sample by a 10x10x100 mm bar of 5120 solid elements with element formulation equal to 2 (fully integrated S/R solid)
- lateral supports by rigid parts (MAT_RIGID steel) of shell elements with a 1 mm thickness
- central striker by a PART_INERTIA of rigid shell elements with a 1 mm thickness
- loading condition, embedded in PART_INERTIA, is given by an initial velocity=2.20 m/sec with a mass=3.44 kg (initial energy is equal to 8.333 J)
- sample damping by DAMPING_PART_MASS with a constant damping coefficient equal to 800
- contacts by ASTS (Automatic Surface To Surface) definition. Scale factor for time step TSSFAC has been set to 0.9.

The average absorbed energy by the 10 experimental samples is equal to 0.266 J (standard deviation = 0.039 J), so it is an order of magnitude lower than the initial one. Unfortunately, due to the housings geometry of the equipment, it was not possible to arrange samples with larger dimensions.

In the current case, a unique FE model (Cal_Mod) has been developed since it provides at the same time good accuracy of results and reasonable CPU time (ca. 1 min CPU time is required for a 0.01 sec simulation time). The numerical arrangement of the FE model is reported in Table 4.

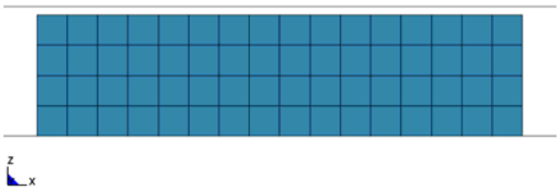
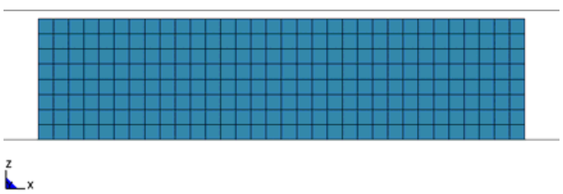
Compression FE model for Calibration (Cal_Mod)			
FE model	**sample elements**	**contact**	**loading**
	• **1024 solids (element size = 2.5 mm)** • fully integrated S/R solid (elf=2)	ASTS tssfac=0.5	BOUNDARY_ PRESCRIBED_ MOTION_RIGID 0.01 mm/sec velocity with **SF=-10000**
Compression FE model for Check(Ch_Mod)			
FE model	**sample elements**	**contact**	**loading**
	• **8192 solids (element size = 1.25 mm)** • fully integrated S/R solid (elf=2)	ASTS tssfac=0.5	BOUNDARY_ PRESCRIBED_ MOTION_RIGID 0.01 mm/sec velocity with **SF=-100**

Table 2: uniaxial compression FE models

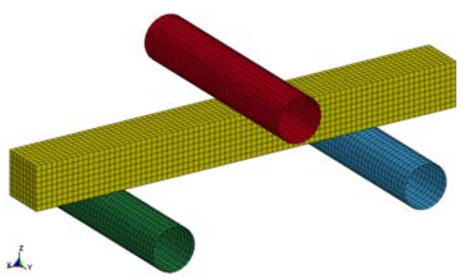
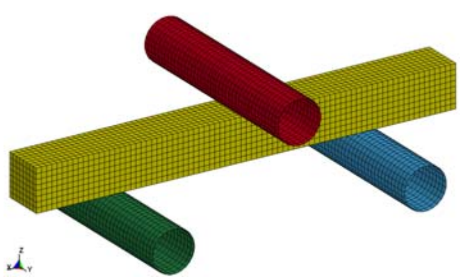
3 Points Bending FE model for Calibration (Cal_Mod)			
FE model	**sample elements**	**contact**	**loading**
	• 5120 solids (element size = 1.25 mm) • **constant stress solid (elf=1)**	ASTS tssfac=0.9	BOUNDARY_ PRESCRIBED_ MOTION_RIGID 0.166 mm/sec velocity with **SF=-1000**
3 Points Bending FE model for Check (Ch_Mod)			
FE model	**sample elements**	**contact**	**loading**
	• 5120 solids (element size = 1.25 mm) • **fully integrated S/R solid (elf=2)**	ASTS tssfac=0.9	BOUNDARY_ PRESCRIBED_ MOTION_RIGID 0.166 mm/sec velocity with **SF=-10**

Table 3: 3 points bending FE models

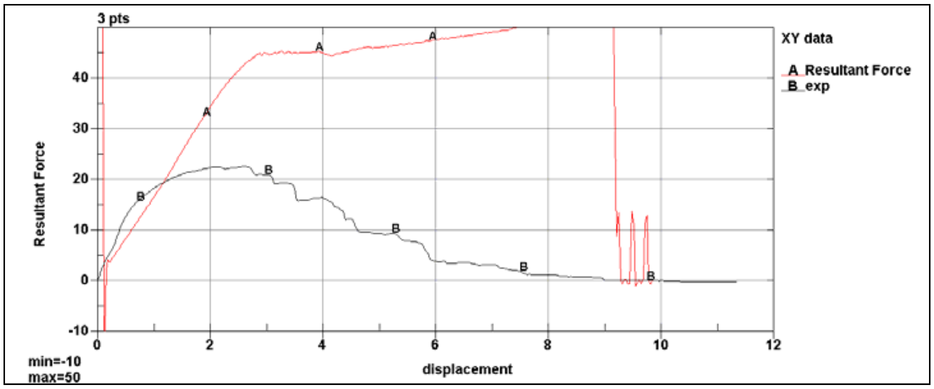


Figure 3: 3 pts bending with Cal_Mod

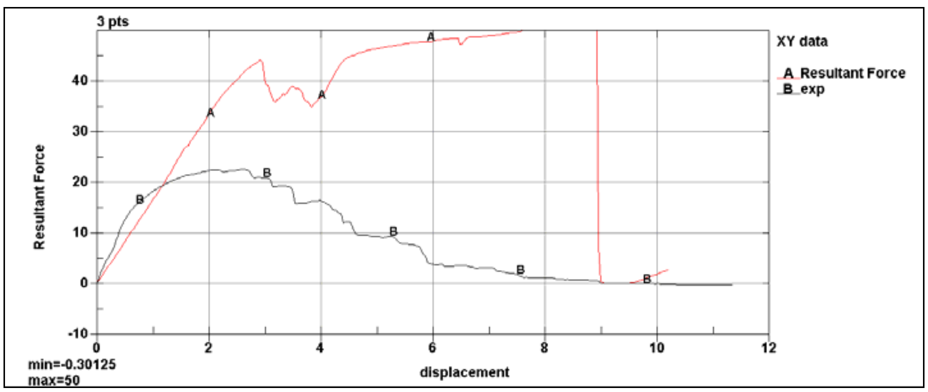


Figure 4: 3 pts bending with Ch_Mod

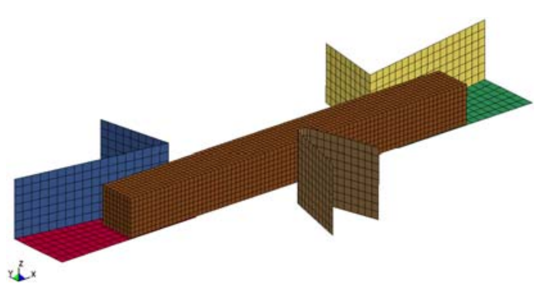
Charpy Pendulum FE model for Calibration (Cal_Mod)			
FE model	**sample elements**	**contact**	**loading**
	• 5120 solids (element size = 1.25 mm) • fully integrated S/R solid (elf=2)	ASTS tssfac=0.9	PART_INERTIA velocity=2.20 m/sec with a mass=3.44 kg

Table 4: Charpy Pendulum FE model

2.3 modeFRONTIER workflow

Once built up the FE models, the material model calibration requires to perform a fitting between the numerical data and the experimental ones, basically the Force-Displacements curves for uniaxial compression and 3 point bending tests, and the Force-Time curves for the Charpy test. Generally speaking that is a multi-objective problem since several objective functions can be defined for pursuing the best compromises amongst the different matchings. As described in detail in a previous activity [1], such multi-objective problem has been faced by using modeFRONTIER, integration platform for multi-objective optimization and advanced data mining. It enabled firstly to integrate in a unique and automatized data flow all the three FE models and then to perform, according to a smart and flexible strategy, the optimization process. The outcoming results have been evaluated by using the multivariate data analysis (i.e. data depending on multiple variables) tools available in modeFRONTIER.
The workflow depicted in Figure 5 shows the process integration of the three FE models. Every process element is associated to a so-called “node” and the connection between the nodes provides the data flow (sequence according to data are elaborated and transferred) and the logic flow (sequence according to operations are accomplished).
Once the MAT 154 free parameters (further input variables, as referred within modeFRONTIER, are related to run set up) are updated, their values are written into the .dyn files (*PARAMETER keyword is definitely helpful) and then the batch runs of the numerical models are executed. Being the process integration completely automatized, also the handling of the results files is made in batch modality. At this purpose three .cmd macros have been registered within LS-PrePost® environment and then integrated in the same batch run node where LS-DYNA model is launched (in the current case a Cygwin node has been exploited). Basically the LS-PrePost operations export the Force-Displacement and Force-Time curves into ASCII files so that modeFRONTIER can compare them with the experimental ones. The results coming from such evaluations are stored into the so-called output variables and eventually addressed by suitable objective functions. In the current case, the comparison between numerical and experimental curves has been implemented by the least squares minimization. At the aim to get a local insight of the correlation amongst the MAT 154 parameters and the curve trends, for the same curve more than one objective function has been defined. In particular, the experimental curves have been subdivided into appropriate sub-dominions and for each of them a dedicated objective function has been defined. For uniaxial compression test three regions have been assessed: the first one is where the stress rises almost linearly until maximum value is achieved, the second one is characterized by a constant stress (plateau region), the third one located after the densification strain (#3 obj. functions labelled as *mc_err1,2,3*). For 3 points bending and Charpy pendulum tests the first region lasts until maximum force is reached, while the second one until force vanishes (#2 obj. functions, labelled as *m3_err1,2* for 3 points and *mch_err1,2* for Charpy). Finally, for all three tests, an objective function spanning through all dominion (labelled with *tg_*) has been built up with the intention to globally check the fitting goodness. In this last case, for a more efficient addressing of the optimization process, no square root has computed (it should be taken into account for the following results evaluation).
Additional output results are available within workflow, like the absorbed energy for Charpy test, an index providing normal (0) or error (1) termination condition for the ongoing analysis, the slope of compression initial region.

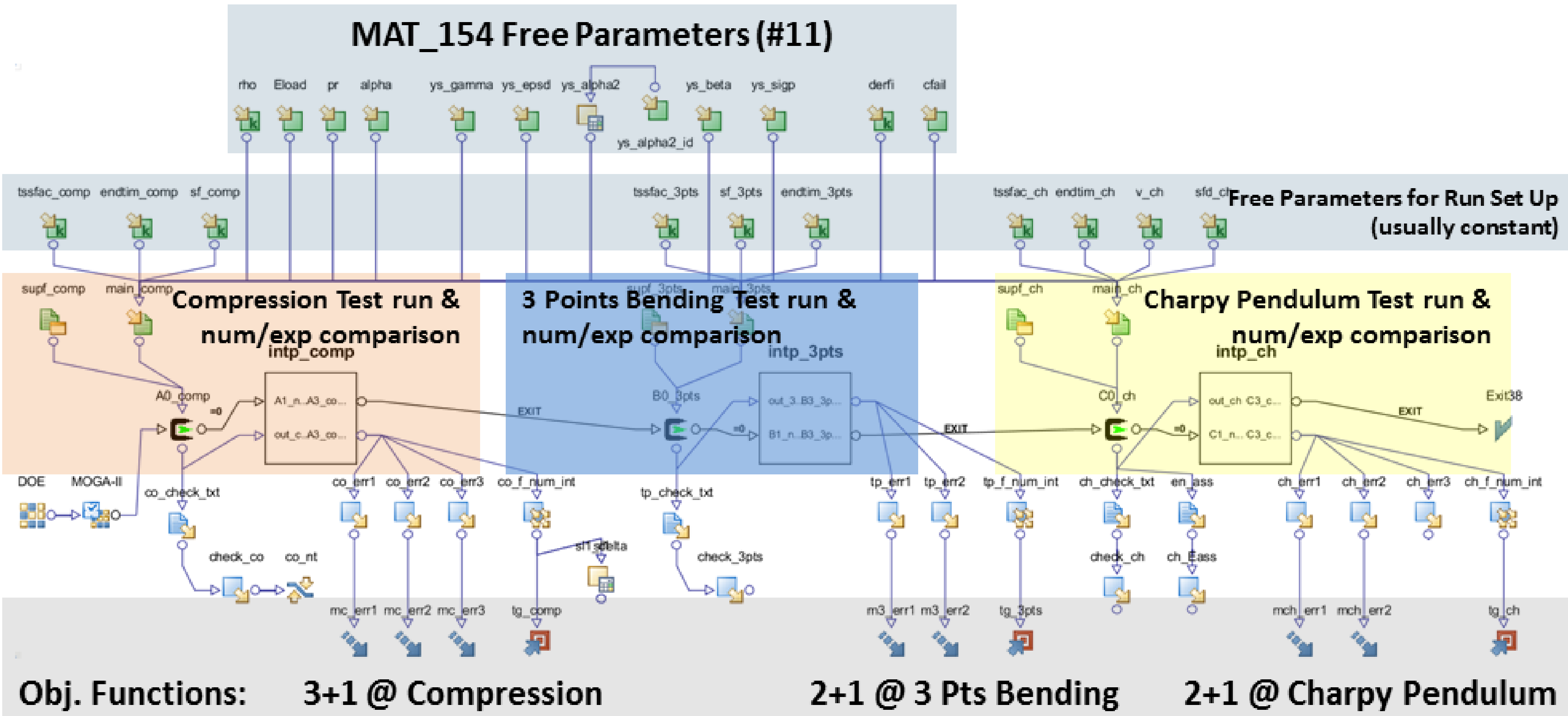


Figure 5: modeFRONTIER workflow

2.4 Calibration and Optimization Strategy

The material model calibration has been performed both according to the literature practices, approach that is more correct from a theoretical point of view, and according to an independent methodology, aimed to assess the relationships between the investigated phenomena without a priori constraints. Basically the two approaches have been designed as in the following:

a) the “Standard Methodology” exploits the uniaxial compression test to calibrate the parameters embedded into equation (2), that is $\sigma_p, \varepsilon_D, \alpha_2, \gamma, \beta$, but also to investigate the MAT 154 remaining parameters. Later, the calibrated material model is used for 3 points bending and Charpy pendulum simulations and discrepancies are evaluated
b) the “Experiments Driven Methodology” exploits contemporaneously for calibration all three experimental tests with the intention to identify the parameters values providing the best trade-offs between all configurations.

The workflow shown in Figure 5 holds for both methodologies, being the not required FE models batch runs switched off according the ongoing analysis.
Along the post-processing of the results, ranges and influences of parameters have been evaluated. For the MAT 154 parameters, some mutual relationships exist as shown by equation (2,4) and according to literature [2-5]. Essentially the different studies advise the following correlations amongst the “free” parameters:

$$\alpha = \alpha(\nu_p)$$
$$\varepsilon_D = \varepsilon_D(\alpha, loading\ \ condition, \rho_{f0}, \rho_f)$$

The present study, in both two methodologies, did not exploit such correlations, letting on the contrary the calibration driven only by numerical/experimental fitting. Even if this approach is less theoretically correct, the idea behind was to explore the design space (i.e. the dominions of the free parameters) in an extensive way and looking for different values arrangements.
Some typical MAT 154 parameters values were gained (even if not for M-PORE aluminium foams) in literature [2, 6, 7]. At the same the experimental tests carried out for the current activity provided the data in Table 5.

Specimens Data – M-PORE 45 ppi		
Uniaxial Compression	**3 Points Bending**	**Charpy Pendulum**
av. density $\overline{\rho}_f$ =283.39 [kg/m^3] st_dev=11.59 [kg/m^3] av. Young’s modulus $\overline{E}$ =72.28 [MPa] st_dev=15.32 [MPa] av. plateau stress σ_p =2.63 [MPa] st_dev=0.13 [MPa]	av. density $\overline{\rho}_f$ =284.33 [kg/m^3] st_dev=40.17 [kg/m^3]	av. density $\overline{\rho}_f$ =287.60 [kg/m^3] st_dev=24.74 [kg/m^3] av. absorbed energy $\overline{E}_{ABS}$ =0.266 [J] st_dev=0.039 [J]

Table 5: specimens data vs. experimental test

Accordingly to the number of MAT 154 parameters, 11 input variables have been inserted into modeFRONTIER workflow, as the previous Figure 5 highlights, and the their initial dominion is given in Figure 6. The variables related to the yield stress function σ_y are categorized by “ys” prefix. The plateau stress has been studied in respect of a range whose width is coherent with its standard deviation. The DERFI parameter selects the type of derivation (0/1 for numerical/analytical) used in material subroutine [10] and it has been checked to detect its best choice.
The parameters set to a constant value are denoted in modeFRONTIER by a “k” label. The density (rho) and Young’s modulus (Eload) values come from the test selected for the numerical-experimental fitting, while the CFAIL parameter is equal to zero since it is calibrated versus 3 point bending and Charpy pendulum tests. Clearly such dominions have been updated in respect of the out coming results. Values of variables have been discretized by suitable steps.

	Name	Variable Type	Value	...	...	...	Lower Bound	Upper Bound
0	k rho	Constant	2.8663E-10		...	0	2.7E-10	3.5E-10
1	k Eload	Constant	73.1		...	0	65.0	75.0
2	pr	Variable	0.3		...	0	0.0	0.2
3	alpha	Variable	0.0		...	0	0.0	2.121
4	ys_gamma	Variable	0.0		...	0	1.0	7.0
5	ys_epsd	Variable	2.28		...	0	1.3	2.7
6	ys_alpha2	Variable	0.0		...	0	0.0	5000.0
7	ys_beta	Variable	0.0		...	0	2.0	6.0
8	ys_sigp	Variable	2.6		...	0	2.5	2.7
9	derfi	Variable	1.0		...	0	0.0	1.0
10	k cfail	Constant	0.0		...	0	0.01	0.71
11	k tssfac_comp	Constant	0.5		...	0	-1000.0	1000.0
12	k endtim_comp	Constant	0.015		...	0	-1000.0	1000.0
13	k sf_comp	Constant	-10000.0		...	0	-1000.0	1000.0

Figure 6: MAT 154 parameters dominion in modeFRONTIER workflow – unit system in [N, mm, tons, sec]

The optimization strategy has been designed taking into account the requirement that all the analyses were multi-objective. The genetic algorithm MOGA-II (Multi Objective Genetic Algorithm) coupled with a SOBOL DOE (Design Of Experiment) has usually been exploited for the optimization process, while for sensitivity analyses suitable combinations of the factorial DOEs available in modeFRONTIER.
Some of the post processing tools have been already presented previously [1], and in the following they will be applied for multivariate analysis as something almost established.

3. Results

The results here presented are focused on identification of suitable material parameters values for the calibration of the FE models for the three investigated loading conditions. Additionally, how the free parameters dominions affect the numerical/experimental fittings is shown.

3.1 Standard Methodology

1st Optimization

The analyses performed by using the FE model of uniaxial compression test can be straightaway evaluated by plotting into a 3D bubbles chart the three objective functions (OFs) mc_err1,2,3 (i.e. the least squares minimizations associated to the three typical regions produced by such test, as already explained in section 2.3), whose picture is provided in Figure 7.
Definitely the best configurations have to minimize them contemporaneously, so the regions in the left lower zone have to be checked. Apparently a trade-off between mc_err1 and mc_err2 exist since it is no possible to reduce both at same time. A further feature is the occurrence of some clusters: for mc_err1 at least three main groups can be noted. At the purpose to get a deep insight of the correlations between input and output, the 3D bubbles chart has been combined with a vector plot chart where the numerical Force-Displacement curves are superimposed to the experimental one (black curve), and with a parallel coordinates chart where input and/or output values can be filtered at the goal to assess how they affect each other [1, 13]. An arrangement of such charts is depicted in Figure 8, in which a first reduction of the OFs has been already done, removing the worst solutions. Filtering out alternatively the greater values of mc_err1, mc_err2, mc_err3, as shown sequentially in Figure 9-Figure 11, the more suitable input dominions for the three OFs appear (framed in red). For the input labeled with "ys", the charts are in agreement with the structure of the equation (3) and with literature data [2], that is mc_err1 is strictly dependent on σ_p, mc_err2 by γ, ε_D and β as well, while for mc_err3 some influence of α_2 can be noted too.

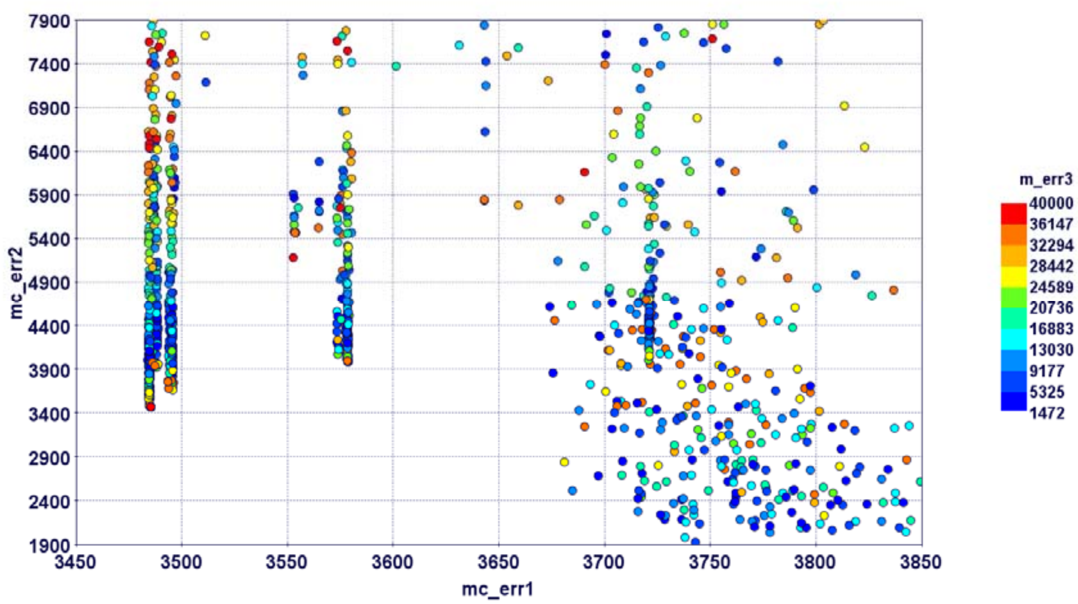


Figure 7: 3D bubble chart for uniaxial compression OF

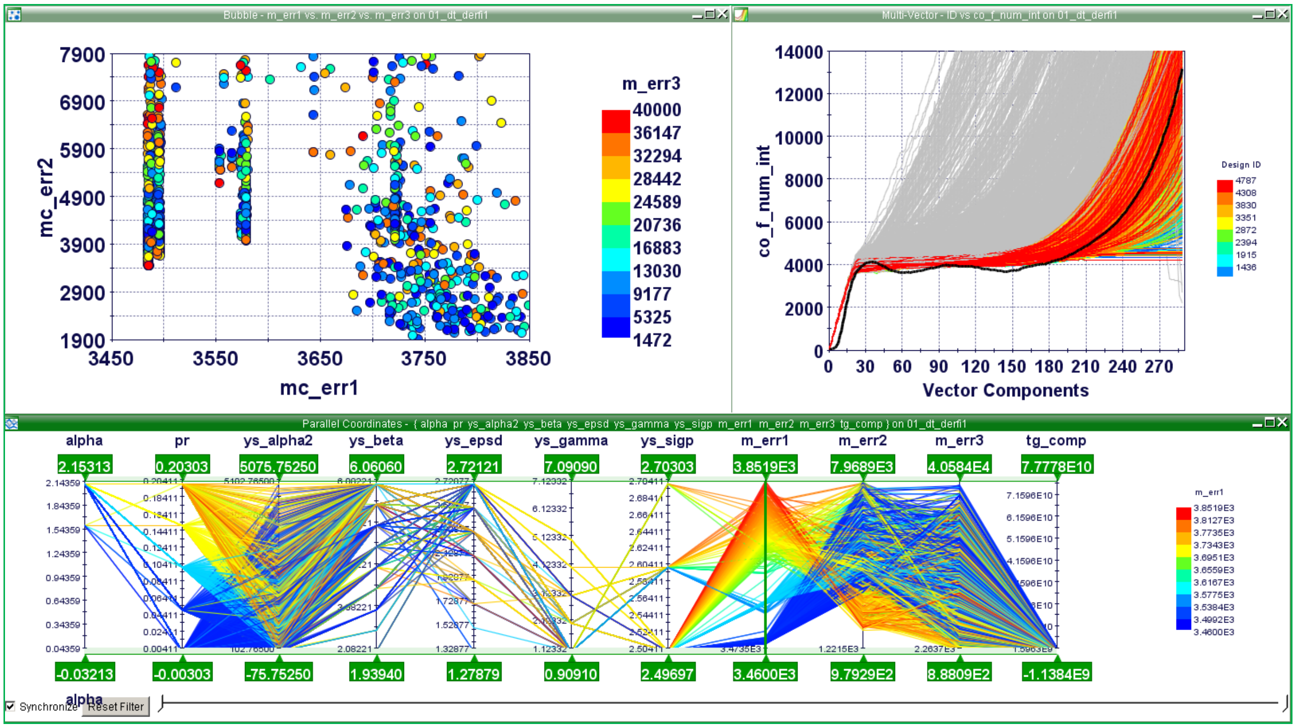


Figure 8: integration of 3D bubbles, vector plot and parallel coordinates charts for uniaxial compression

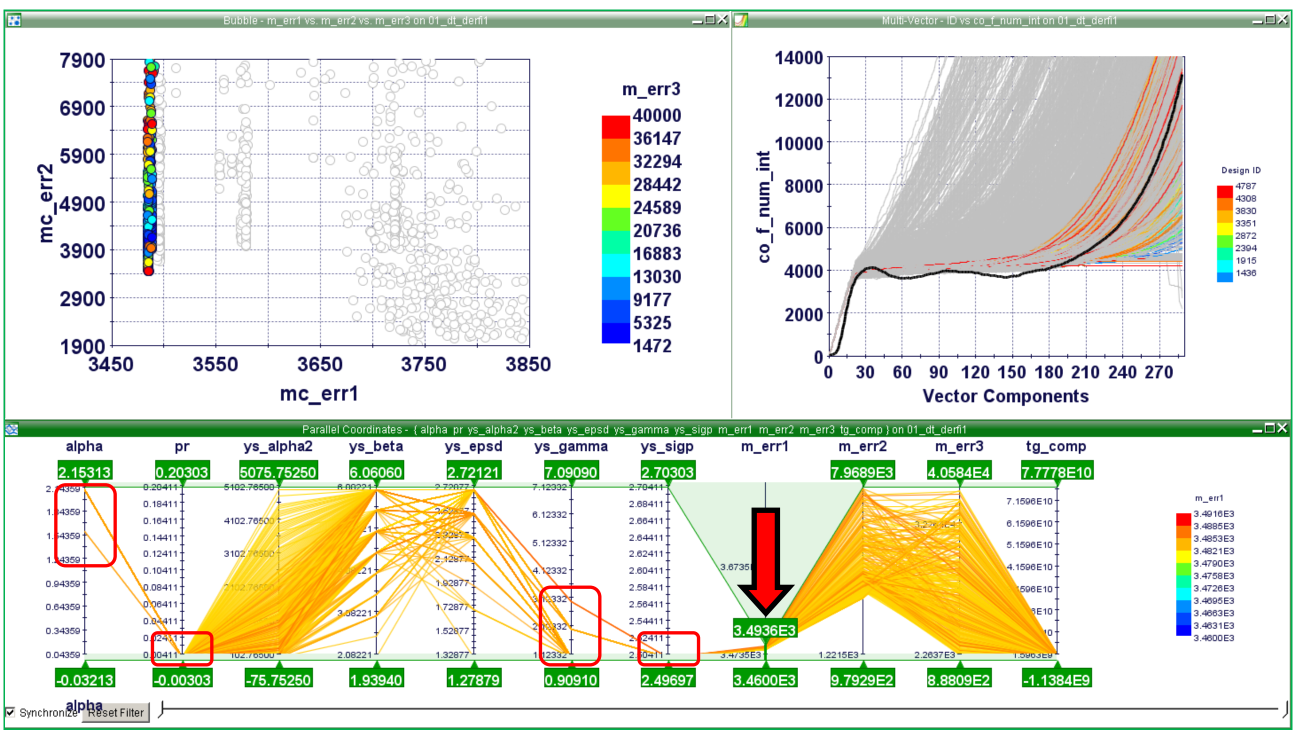


Figure 9: uniaxial compression – filtering out mc_err1

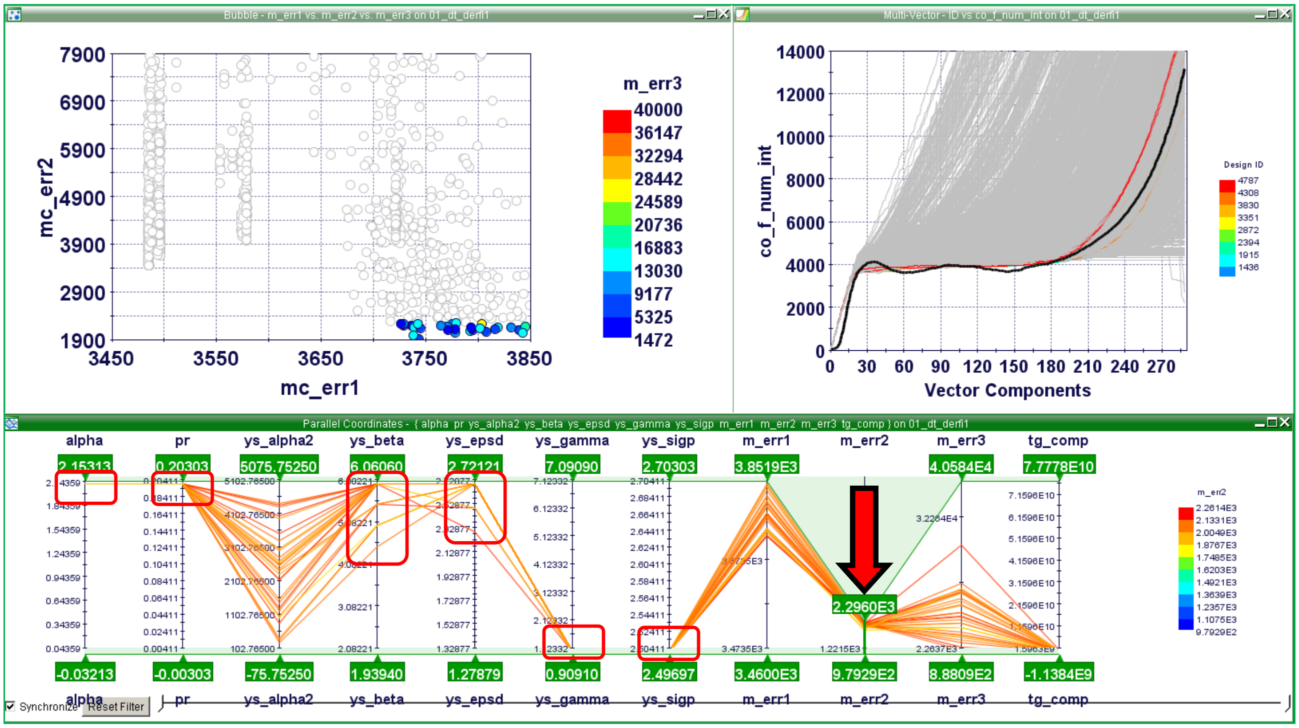


Figure 10: uniaxial compression – filtering out mc_err2

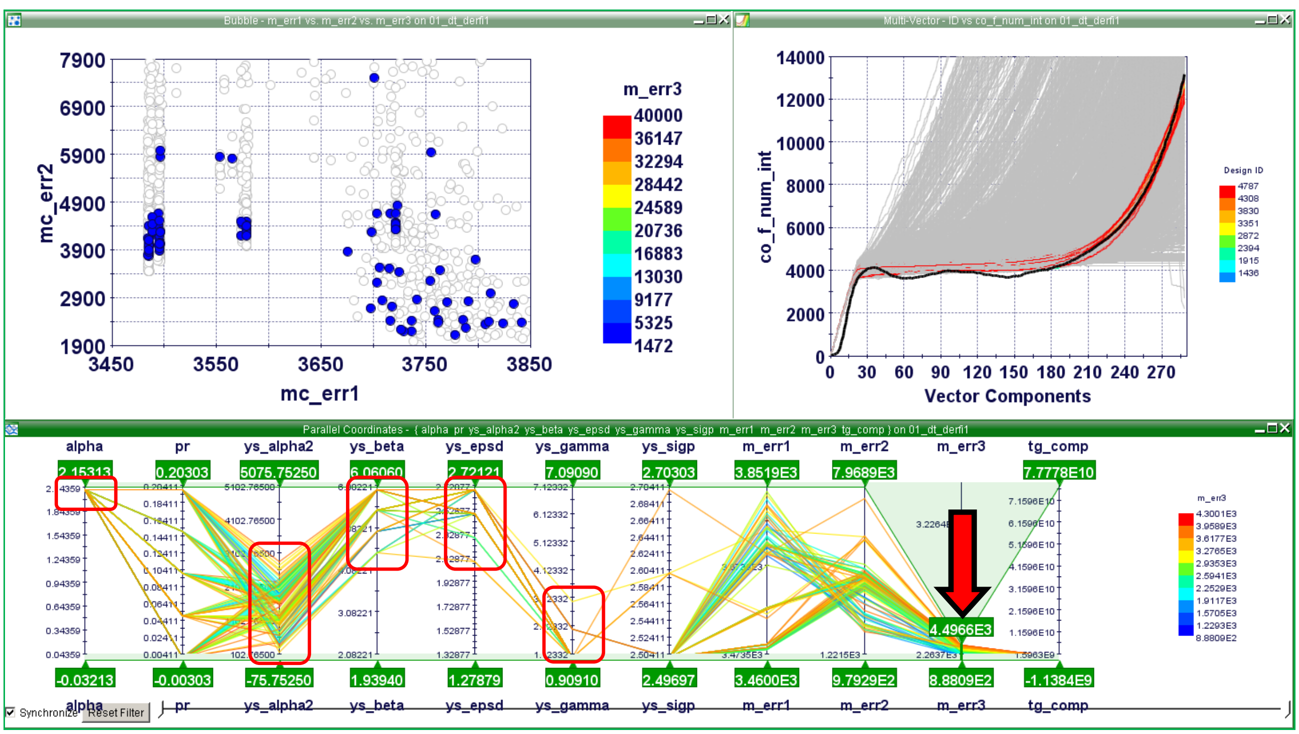


Figure 11: uniaxial compression – filtering out mc_err3

For the remaining parameters, α is pushed to assume its maximum value (2.121), while the Poisson ratio, within the selected dominion, “jumps” between opposite values in respect of mc_err1 and mc_err2 minimizations, being on the contrary substantially indifferent for mc_err3 minimization. A sensitivity analysis relied on a factorial DOE, here not reported for sake of shortness, confirmed the previous results. Taking into account these conflicting trends between mc_err1 and mc_err2, the reason of their trade-off comes out.
Applying filtering on the input variables, it has been possible to reveal that the Poisson ratio and plateau stress are the main parameters inducing the clusters formation for mc_err1: according to their values not only the main three groups arise but also further sub-groups within them can be identified (as can be discerned looking at Figure 7).
To be sure about the appropriate selection of the input dominions, and consequently of pursuing the best possible configurations, the convergence values of the free parameters have been searched for. By using history and distribution bars charts, the most wanted values have been verified and for the parameters in Table 6 the dominions updated.

Free Parameter	1st Optimization	2nd Optimization
γ [MPa]	[**1**-7]	[**0.1**-7.1]
ε_D [-]	[1.3-**2.7**]	[1.3-**3.0**]
β [-]	[2-**6**]	[2-**10**]

Table 6: new dominions for free parameters

Before going to next step, it should be remarked the DERFI behavior. All the analyses executed with zero value (numerical derivation) are characterized by an error termination condition falling into the region where the stress rises almost linearly, hence a constant value equals to 1 has been set.

2nd Optimization

Once the new dominions have been changed into modeFRONTIER workflow, a second optimization has been started. Pictures in Figure 12, Figure 13 show only the Pareto designs (i.e. the best compromises between all the objective functions) related to 1st and 2nd Optimizations, respectively. A new subset of configurations, located in the left lower zone and framed in red, is being generated and the main parameter involving this performance is γ, as indeed the parallel coordinates chart in Figure 14 points out. A trade-off is still present but it has been reduced since the configurations characterized by γ=0.1 MPa (blue lines) provide at same time low values for all three OFs. A further observation concerns α and σ_p values: at the purpose to get Pareto configurations it is mandatory to set α =2.121 and σ_p = 2.5 MPa.
Looking just for the most fitting curves belonging to the red framed group (with the chart in Figure 14 properly filtered), it comes out that β parameter is peaked around an average value of 7, while ε_D and α_2 are nearly spread all over their dominion (for the last one anyway no values have been detected below ca. 1000 MPa).

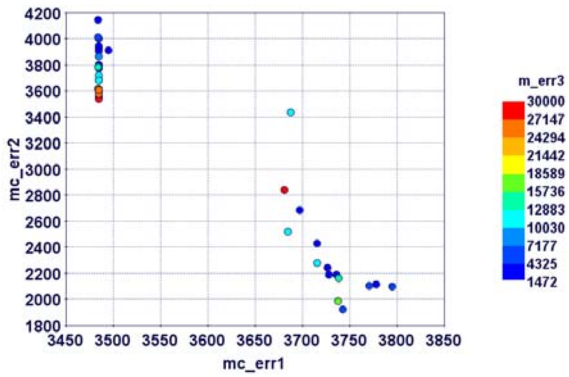


Figure 12: 1st Optimization - Pareto designs

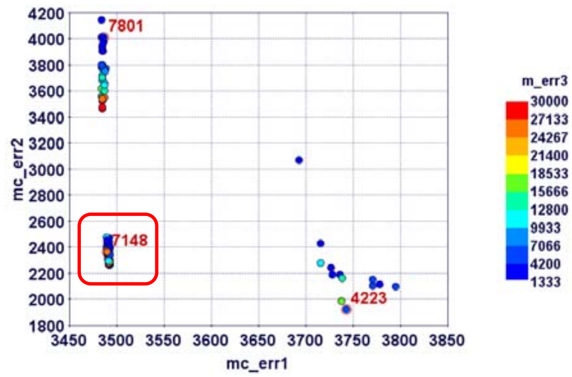


Figure 13: 2nd Optimization - Pareto designs

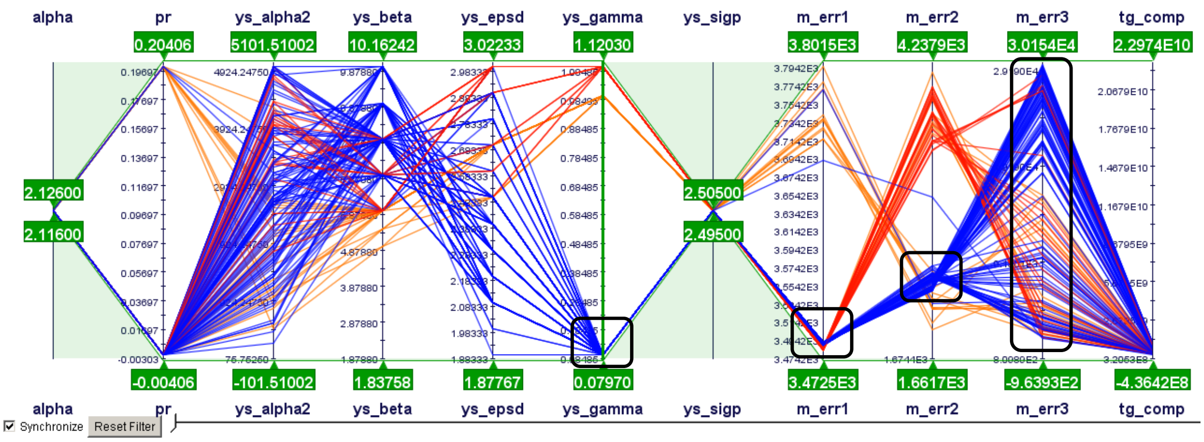
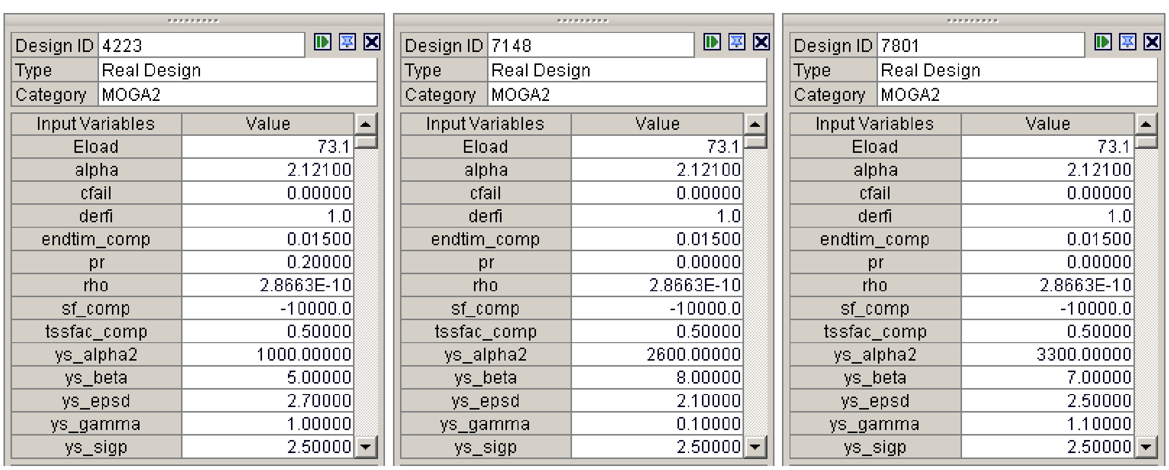


Figure 14: parallel coordinates chart with γ highlighted at 0.1 MPa (blue) and 1.1 MPa (red)



Design ID	4223
Type	Real Design
Category	MOGA2

Input Variables	Value
Eload	73.1
alpha	2.12100
cfail	0.00000
derfi	1.0
endtim_comp	0.01500
pr	0.20000
rho	2.8663E-10
sf_comp	-10000.0
tssfac_comp	0.50000
ys_alpha2	1000.00000
ys_beta	5.00000
ys_epsd	2.70000
ys_gamma	1.00000
ys_sigp	2.50000

Design ID	7148
Type	Real Design
Category	MOGA2

Input Variables	Value
Eload	73.1
alpha	2.12100
cfail	0.00000
derfi	1.0
endtim_comp	0.01500
pr	0.00000
rho	2.8663E-10
sf_comp	-10000.0
tssfac_comp	0.50000
ys_alpha2	2600.00000
ys_beta	8.00000
ys_epsd	2.10000
ys_gamma	0.10000
ys_sigp	2.50000

Design ID	7801
Type	Real Design
Category	MOGA2

Input Variables	Value
Eload	73.1
alpha	2.12100
cfail	0.00000
derfi	1.0
endtim_comp	0.01500
pr	0.00000
rho	2.8663E-10
sf_comp	-10000.0
tssfac_comp	0.50000
ys_alpha2	3300.00000
ys_beta	7.00000
ys_epsd	2.50000
ys_gamma	1.10000
ys_sigp	2.50000

Figure 15: free parameters values for candidate solutions 4223, 7148, 7801

Eventually, amongst the Pareto designs three candidate solutions (des 4223, 7148, 7801 shown in Figure 13) have been selected an evaluated with Ch_Mod models for uniaxial compression and 3 points bending tests, and with Cal_Mod model for Charpy pendulum test. The corresponding free parameters values are provided in Figure 15.
The Force-Displacement curve coming from the uniaxial compression Ch_Mod model is practically the same given by Cal_Mod model. On the contrary, mismatches arise for the remaining two tests, for which a remarkable difference does exist in terms of force values. The pictures in Figure 16 and Figure 18 bring out such discrepancy for configuration 7148, but similar results occur for the other ones (being not still calibrated, CFAIL was also set to 0.2 to assess its influence).
In literature analogous trends in terms of different magnitude of loads have been reported, e.g. by Reyes et al. [2] and Styles [6], and possible reasons of phenomenon have been ascribed both to cell size effects and to the stress concentrations at specimen supports when acting loadings are not uniformly distributed (like in 3 points bending or Charpy pendulum test).
In the current case, it easy to check that a better fitting can be achieved, from numerical point of view, by reducing the plateau stress σ_p, even if such condition makes worst at same time the uniaxial compression performance. The best balance between all these conflicting goals can be pursued by a multi-objective optimization involving all three experimental tests.

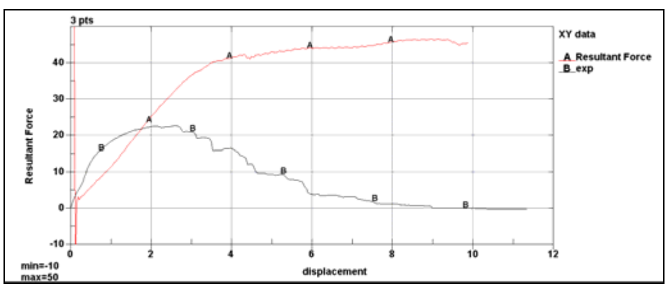


Figure 16: des 7148 – 3 pts bending with Cal_Mod CFAIL=0 (no failure)

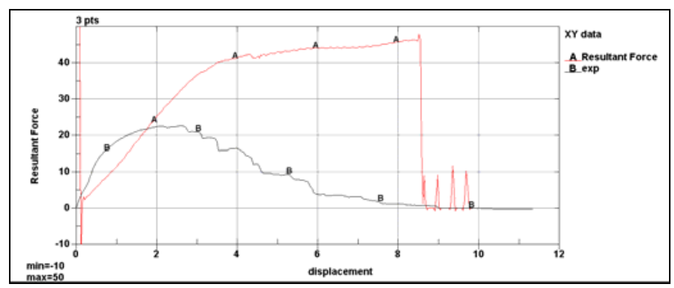


Figure 17: des 7148 – 3 pts bending with Cal_Mod CFAIL=0.2

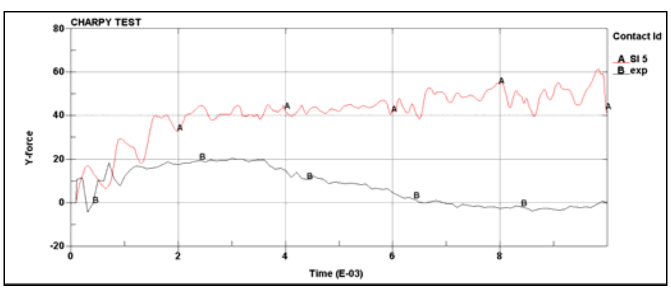


Figure 18: des 7148 – Charpy pendulum with Cal_Mod CFAIL=0 (no failure)

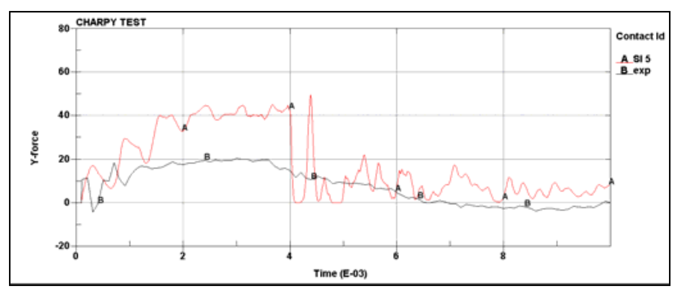


Figure 19: des 7148 – Charpy pendulum with Cal_Mod CFAIL=0.2

3.2 Experiments Driven Methodology

Once the modeFRONTIER workflow has been updated in respect of free parameters dominion, whose range is provided in Figure 20, the optimization process has been addressed at the aim to minimize the three global OFs (labelled with *tg_*) representing the fitting of three experimental curves.
Regarding the new dominions, they have been modified taking into account the results coming from previous analyses. In particular, to get a better matching of initial slope for 3 points bending curve (as recognizable in Figure 16), Young's modulus is no more constant but assumes a value equal to 73.1 or 146.2 MPa. For the CFAIL parameter a reasonable range has been set (an initial upper bound of 0.71 was changed to 0.41 after first runs), while α_2 value is being selected according to an index so that a not uniform sampling can be exploited.

	Name	Variable Type	Value	...	...	...	Lower Bound	Upper Bound
0	k rho	Constant	2.8663E-10		...	0	2.7E-10	3.5E-10
1	Eload	Variable	73.1		...	0	73.1	146.2
2	pr	Variable	0.3		...	0	0.0	0.3
3	alpha	Variable	0.0		...	0	1.621	2.121
4	ys_gamma	Variable	0.0		...	0	0.1	5.1
5	ys_epsd	Variable	2.28		...	0	1.3	3.0
6	ys_alpha2_id	Variable	0.0		...	0	0.0	9.0
7	ys_beta	Variable	0.0		...	0	3.0	10.0
8	ys_sigp	Variable	2.6		...	0	1.0	2.6
9	k derfi	Constant	1.0		...	0	0.0	1.0
10	cfail	Variable	0.0		...	0	0.01	0.41
11	k tssfac_comp	Constant	0.5		...	0	-1000.0	1000.0
12	k endtim_comp	Constant	0.015		...	0	-1000.0	1000.0
13	k sf_comp	Constant	-10000.0		...	0	-1000.0	1000.0
14	k v_ch	Constant	2200.0		...	0	-1000.0	1000.0
15	k tssfac_ch	Constant	0.9		...	0	-1000.0	1000.0
16	k sfd_ch	Constant	800.0		...	0	0.0	1000.0
17	k tssfac_3pts	Constant	0.9		...	0	-1000.0	1000.0
18	k endtim_3pts	Constant	0.06		...	0	-1000.0	1000.0
19	k endtim_ch	Constant	0.01		...	0	-1000.0	1000.0
20	k sf_3pts	Constant	-1000.0		...	0	-1000.0	1000.0

Figure 20: MAT 154 parameters dominion in modeFRONTIER workflow – unit system in [N, mm, tons, sec]

Getting to the point, the new candidate solutions have been selected firstly looking for the best for every single FE model (the corresponding $m_x\_err_i$ objective functions have been plotted at this purpose), then searching for a suitable compromise among them.
Taking into account only the Pareto designs, Figure 21 and Figure 22 show for the 3 points bending and Charpy pendulum models, respectively, the most advantageous solutions as picked within a 3D bubble chart and as compared with the three experimental curves (the Ch_Mod models gave same results for the configurations selected in the following).
For the 3 points bending case (Figure 21), two solutions belonging to 2 different groups have been chosen, as the 3D bubble chart points out: des 598 is characterized by a Young's modulus equals to 146.2 MPa, while for des 992 it is 76.1 MPa. Both configurations provide a good fitting for the current model, while for the remaining ones deviations occur. In the uniaxial compression test, in particular, the plateau force is approximately ½ of the experimental value, owing to σ_p=1.2 MPa. In the Charpy pendulum test, the mismatch is lower but the volumetric strain CFAIL (e.g. 0.11 for des 598) seems to underestimate the real value.
For the Charpy pendulum case (Figure 22), the best solution is univocally identified in terms of des 1876. Further, a similar consideration about σ_p in the uniaxial compression test, the analysis of CFAIL value with respect its influence on 3 points bending and Charpy pendulum models seems to be confirmed, being now definitely oversized in the 3 points bending case.

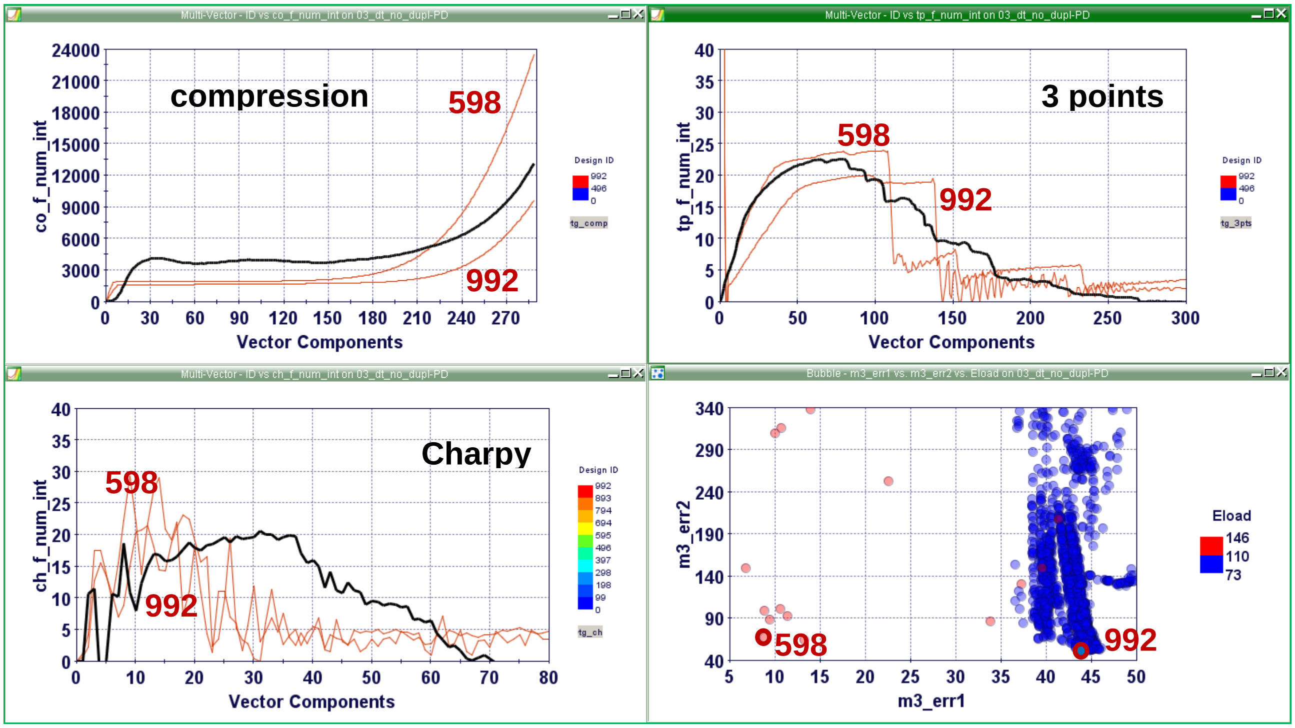


Figure 21: candidate solutions for 3 points bending – des 598 and 992

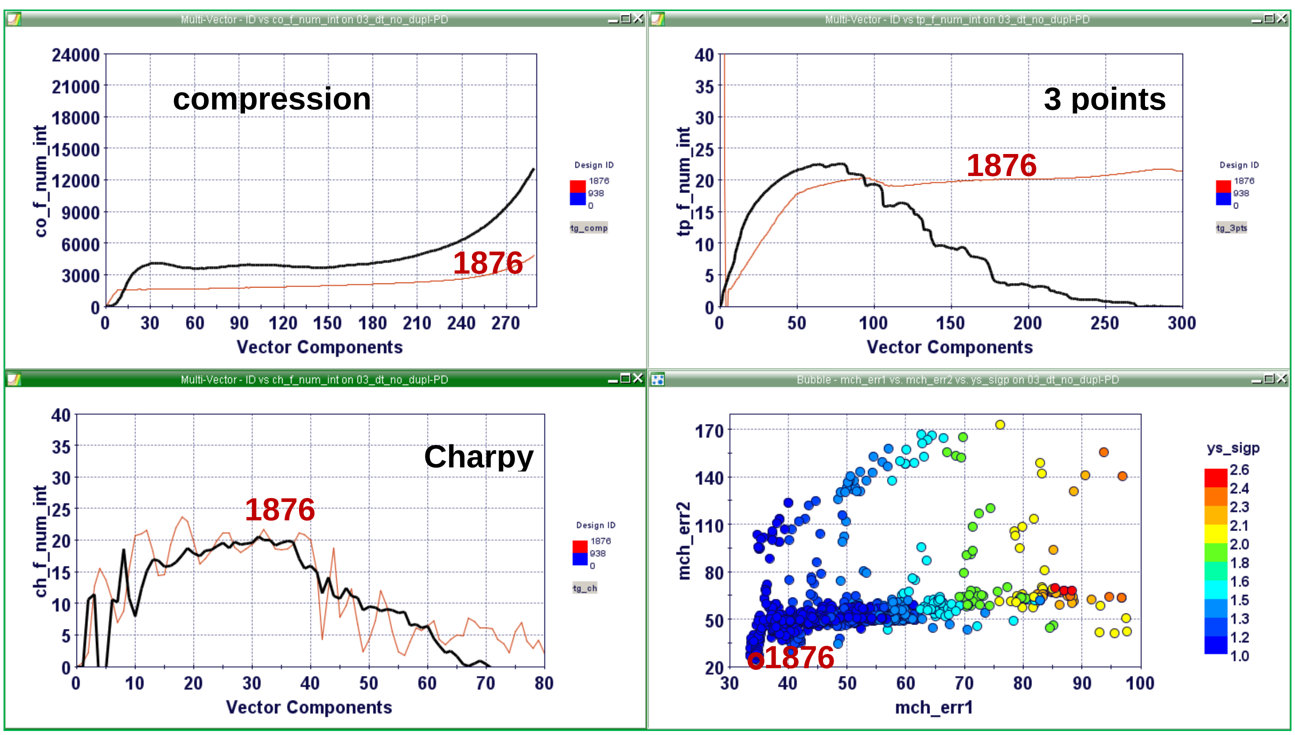


Figure 22: candidate solution for Charpy pendulum – des 1876

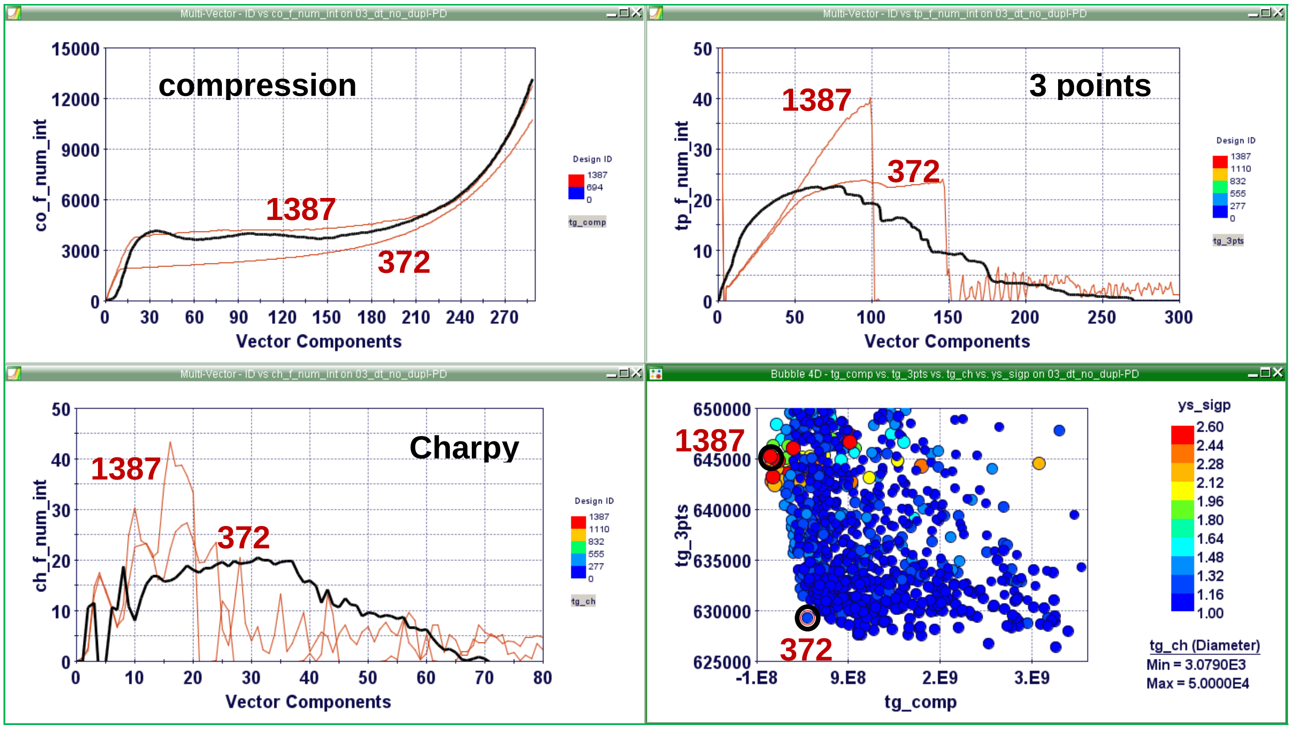


Figure 23: two trade-off solutions between all three FE models – des 372 and 1387

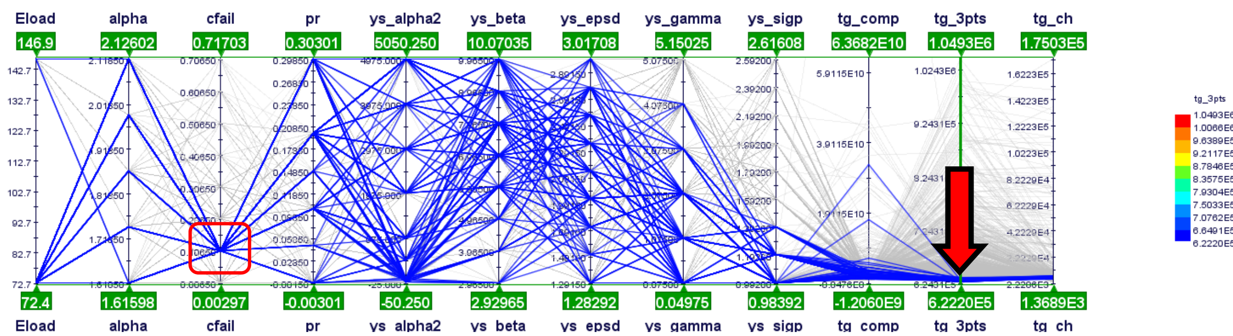


Figure 24: best inputs dominion vs. reducing m3_err1 & m3_err2 (3 points)

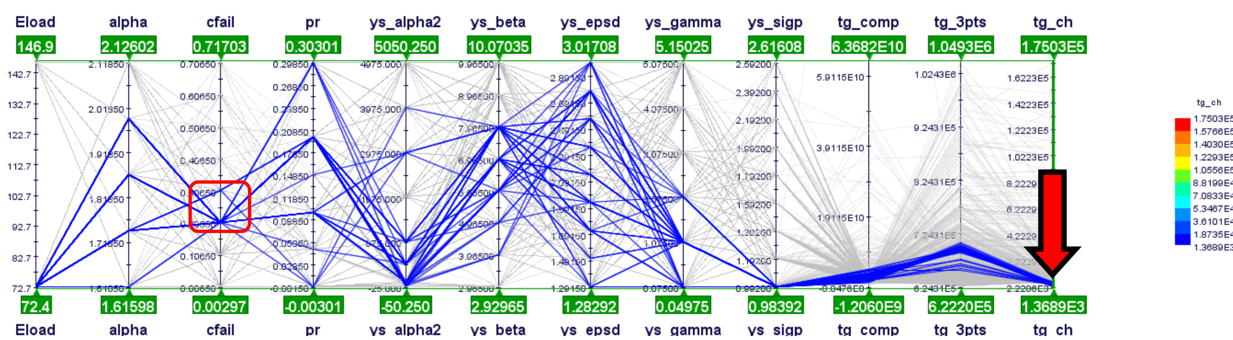


Figure 25: best inputs dominion vs. reducing mch_err1 & mch_err2 (Charpy)

Eventually, while Figure 23 highlights a couple of trade-off solutions between all three FE models, i.e. des 372 and 1387, the parallel coordinates charts sketched in Figure 24 and Figure 25 point out the best inputs dominion for 3 point bending and Charpy pendulum models, respectively. Even if the selection of the solutions providing such dominions has been performed qualitatively, that is until filtering of OFs allowed to choose numerical curves "enough" close to the experimental ones, the previous assessment of CFAIL is again recognized and, more in general, the Charpy dominions are more demanding than the 3 points ones.

4. Conclusions

A flexible and efficient methodology has been applied for MAT 154 material model calibration of M-PORE open cells aluminium foam at three different loading conditions.
Relying on efficient FE models of simple and cheap experimental tests, whose behavior has to be matched, the methodology has been implemented into modeFRONTIER, that allows an immediate LS-DYNA integration and a very intuitive and powerful data mining of the outgoing multi-objective optimization analyses.
Material calibration has been performed firstly with respect to only uniaxial compression test and later taking into account at same time the 3 points bending and Charpy pendulum tests as well. Accordingly, the most suitable material parameters values have been assessed and investigated in terms of their influence on the different tests.
Further, not only single calibration values have been provided but also the dominions in which the parameter values are "reasonable" for better numerical/experimental fitting.
Being available a wider set of experimental tests (different in terms of foam typology, loading type, loading direction, …), next activities will be dealt with a more extended material models calibration.

Acknowledgements

The experimental tests have been carried out by the Department of Innovation Engineering, University of Salento, Lecce, Italy.

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