Design and application of aluminum foams for car body structures

Supervisor： prof. Giovanni Maizza

Zhao Yue

JULY 2021

ACKNOWLEGEMENTS

I would first like to thank my thesis advisors, Professor Giovanni Maizza of Politecnico di Torino for helping me in the research and accompanying me in writing. During this tough period 2020-2021, It is my great honor to follow such kind and responsible tutor to finish my final project. He is not only my study conductor but also bring large moral encouragement that I could not appreciate no more.

To my roommates, all my close friends, my boyfriend and my family for the great mental support and understanding letting me finish this job.

This accomplishment would not have been possible without them. Thank you.

Abstract

The objective of this research is to investigate on available aluminum foam samples properties software to determine whether their characteristics are suitable for car crash energy absorbing use. If not good fit with the target, design possible solution in Abaqus together with CES Edupack (a software selection of materials, manufacturing processes, joining, and finishing).

Three points bending test and compression tests were performed on samples. Applying MATLAB image analysis tool to recognize foam surface porosity and relevant calculation based on the Ashby theory (metal foam constitutive law are considered). Moreover, specimens were modeled for the finite element analysis in Abaqus to compare simulation results against experiments data. Applying the reasonable properties range provided by CES Edupack for foam building in Abaqus, the design phase will represent a reliable evaluation and good prediction for foam energy-absorbing ability during crash condition. Some possible improvements are discussed at the end.

Table of Contents

Intro

Aluminum foams are lightweight components and show excellent impact energy absorption.

Many efforts for the improvement in quality of metal foams have been made over the recent years. However, some deficits such as nonuniformities and imperfect mechanical properties in aluminum foams were observed. Fabrication method, architecture signifies the foam mechanical properties that, also improved by matrix reinforcement, e.g., adding fine ceramic particles or alloying elements in the base powder in the powder metallurgical route.

The most important characteristics that affects the mechanical properties of the foam is relative density (Relation Between the density of the form and that of the solid), we will discuss more details later.

Brief description of material of samples

ALUSION™ Architectural Stabilized Aluminum Foam is produced by injecting air into molten aluminum, which contains a fine dispersion of ceramic particles. These particles stabilize the bubbles formed by the air, much like dry cocoa powder stabilizes bubbles when it is added to milk. Produced naturally, with a shiny shimmering silver skin, and featuring a unique waved pattern on the surface (most dense product). The higher the density, the smaller the cell size, the heavier and more robust the material is.

1 Details of experiments

1 Three-point flexural (bending) test

1.1 test machine

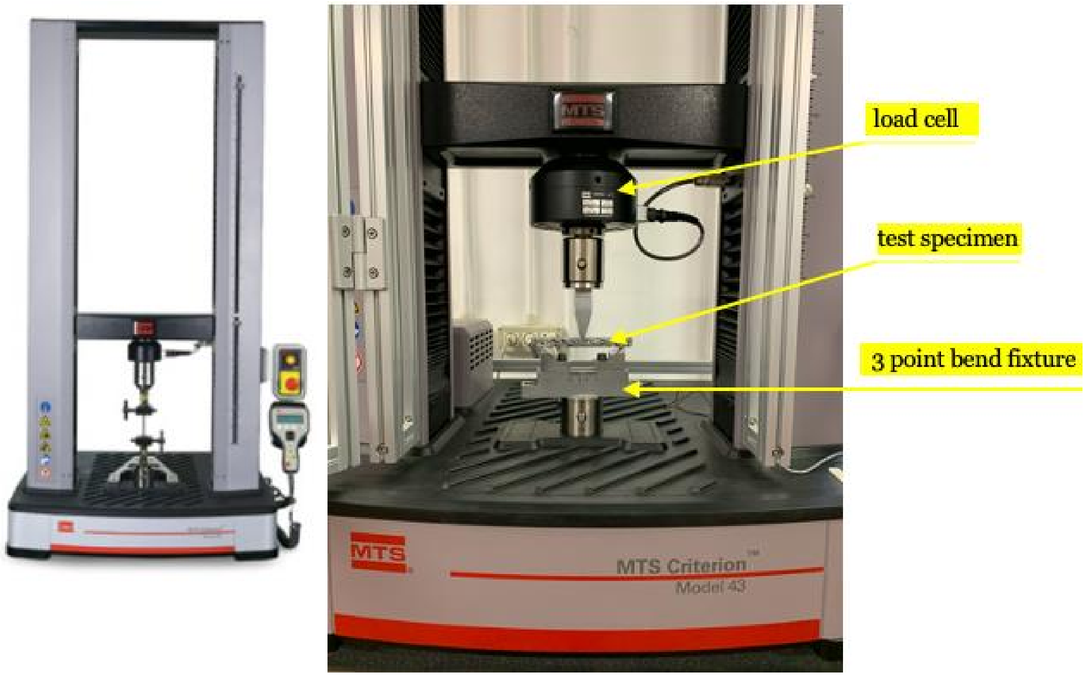


Figure 1 The test machine MTS Criterion model 43 equipped with maximum load of 50 KN

1.2 Sample dimension and procedure

width	Thickness	Support span
25.4 mm	12.7 mm	120 mm

Table 1 bending sample dimension

1) Measure the dimension of specimen (w=25.4mm, t=12.7mm). Then place it on the support, center of the specimen is aligning with the upper load point.
2) Start the test and observe the relation between load applied and deflection of the specimen.
3) Stop the test when crack occur obviously.

1.3 experiments results

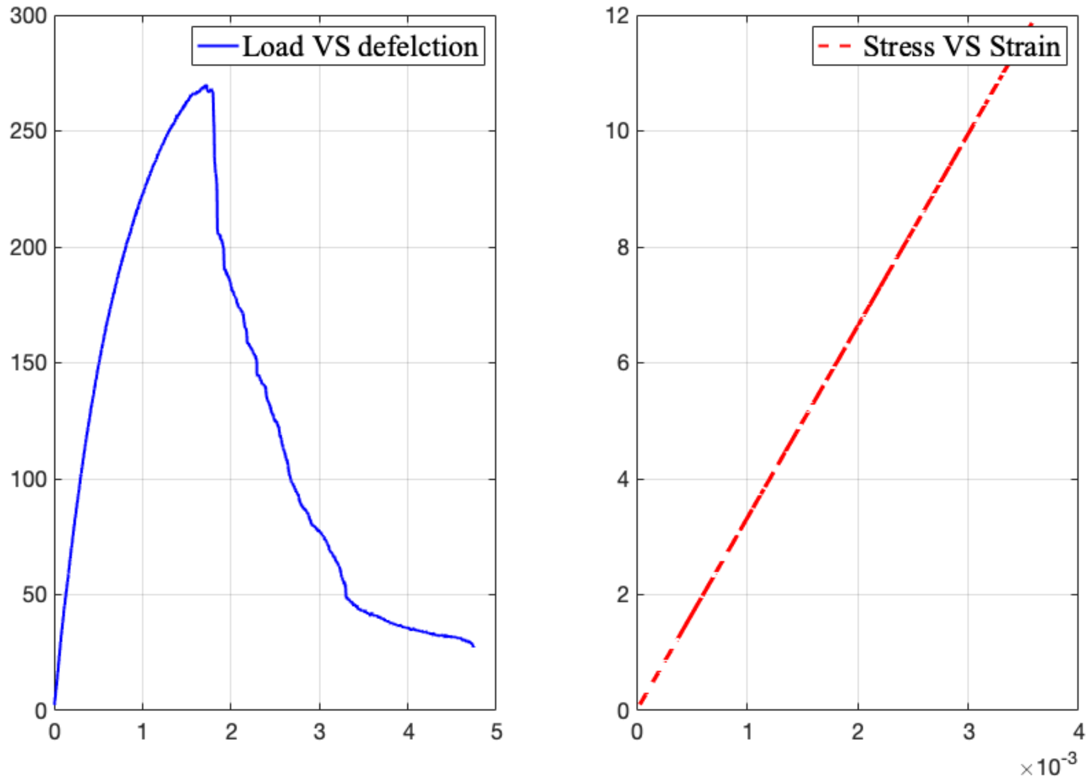


Figure 2 loads versus elongation (left) and maximum strain versus maximum stress (right)

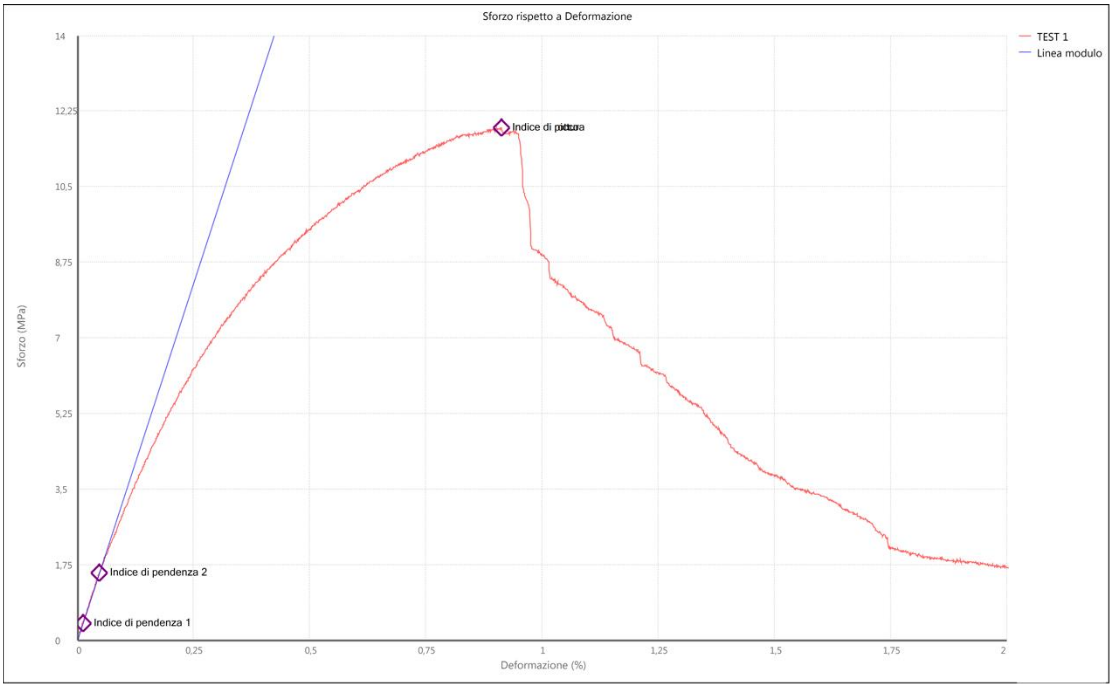


Figure 3 stress versus deformation [%]

1.4 data record

the mechanic properties obtained from the test: peak force, peak stress, flexural stress and young's modulus.

$F_{peak}[N]$	$\sigma_{peak}[Mpa$	$\sigma_f[Mpa]$	E [Mpa]
269.99	11.9	11.86	3315

Table 2 the mechanical properties of bending sample

2 Compression tests with 3 samples

2.1 Test machine and sample installation presentation

The test machine MTS Criterion model 43 with a maximum load of 50KN was employed for compression test. uniaxial test with initial strain rate of 5 mm/min was conducted at room temperature.

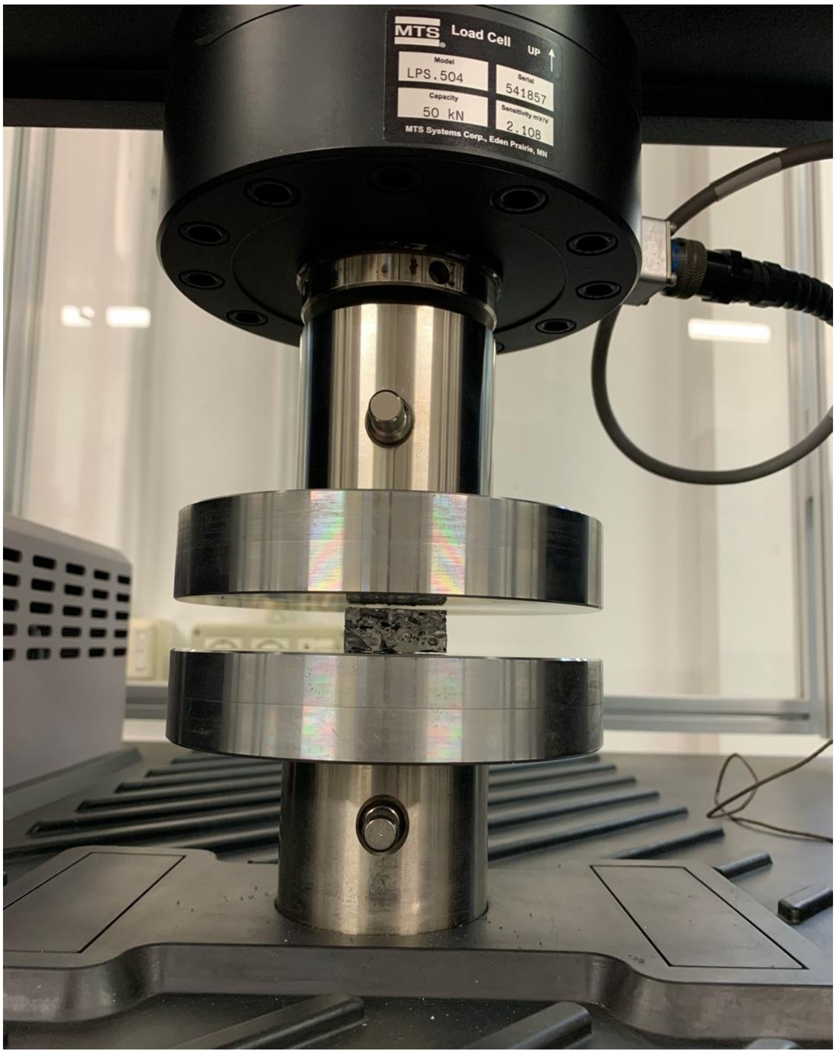


Figure 4 compression set up.

2.2 Sample dimension and procedure

	Thickness [mm]	Length [mm]	Width [mm]
Sample 1	13.02	30.65	30.45
Sample 2	13.17	30.08	30.85
Sample 3	13.17	31.36	31

Table 3 dimension of samples used in compression test.

1) Measure the width and thickness of 3 samples.
2) Place the specimen in the test fixture and carefully align the specimen to the fixture to ensure concentric loading.
3) set the machine to strain the specimen at a rate of 5 mm/min.
4) As shown in the figure, sample 1 had been partially compressed, and other two are completely crushed during the test.

Figure 5 only first sample has been partially compressed, the others have totally been compressed.

2.3 experiments figures and results

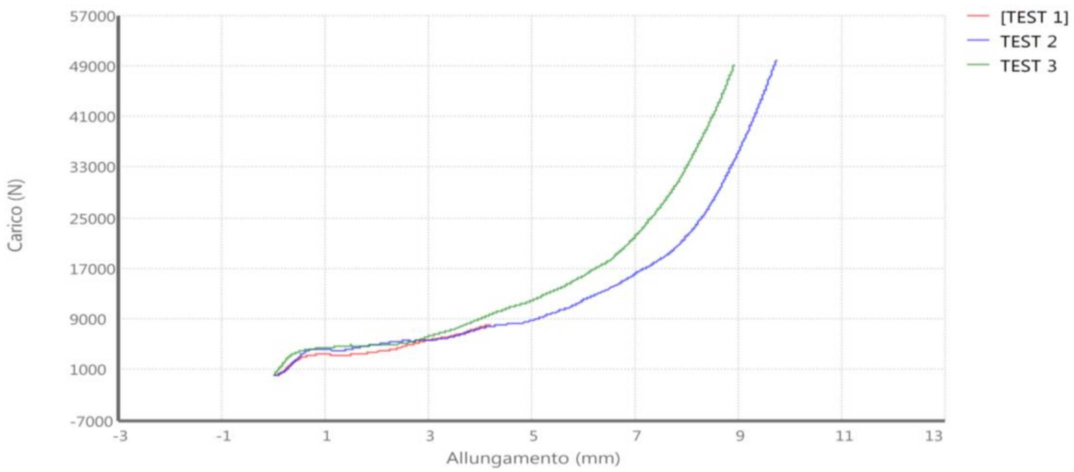


Figure 6 load versus deformation for 3 samples

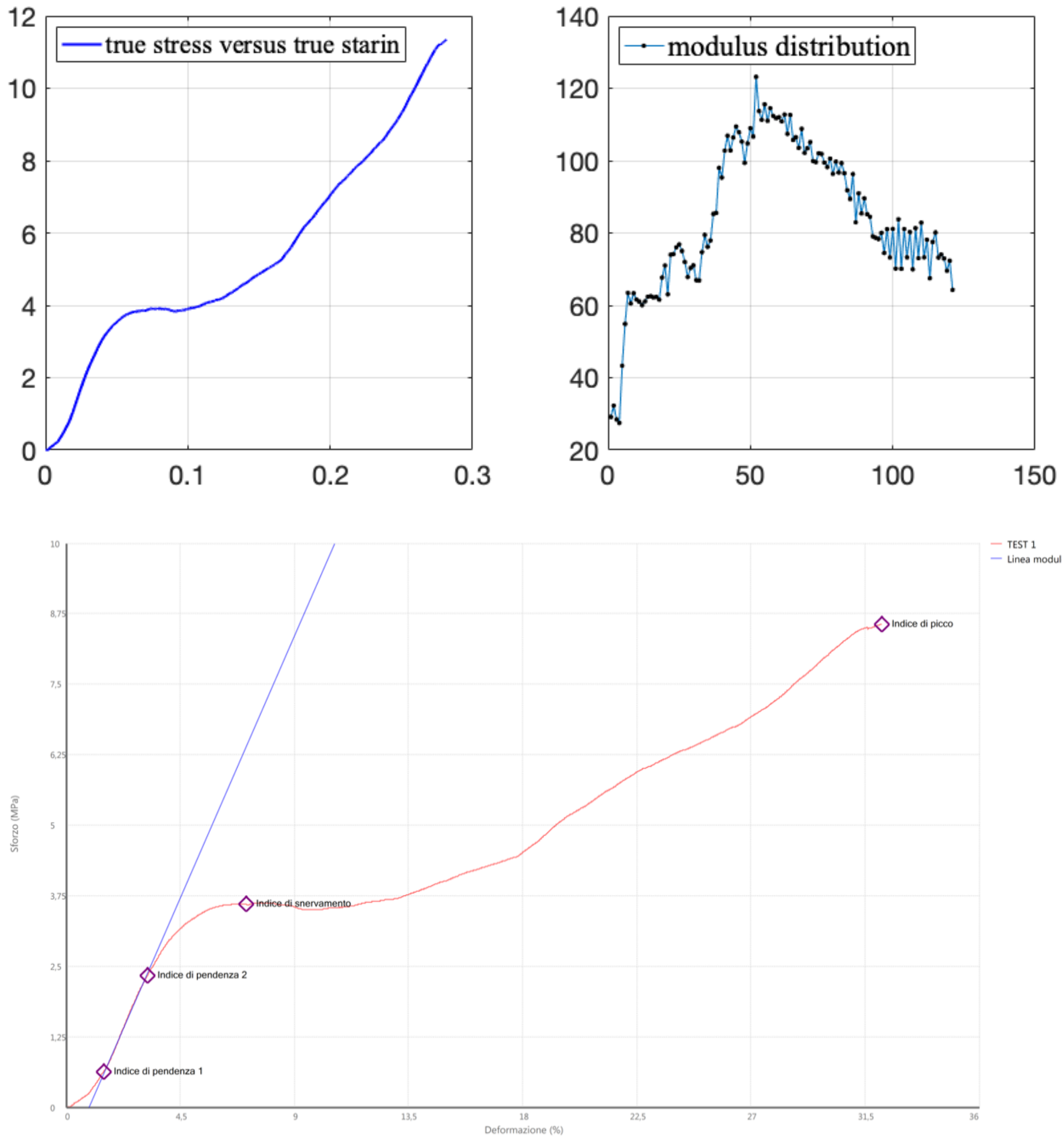


Figure 7 stress versus strain (above left), young modulus variation (above right), stress versus deformation for sample 1(below)

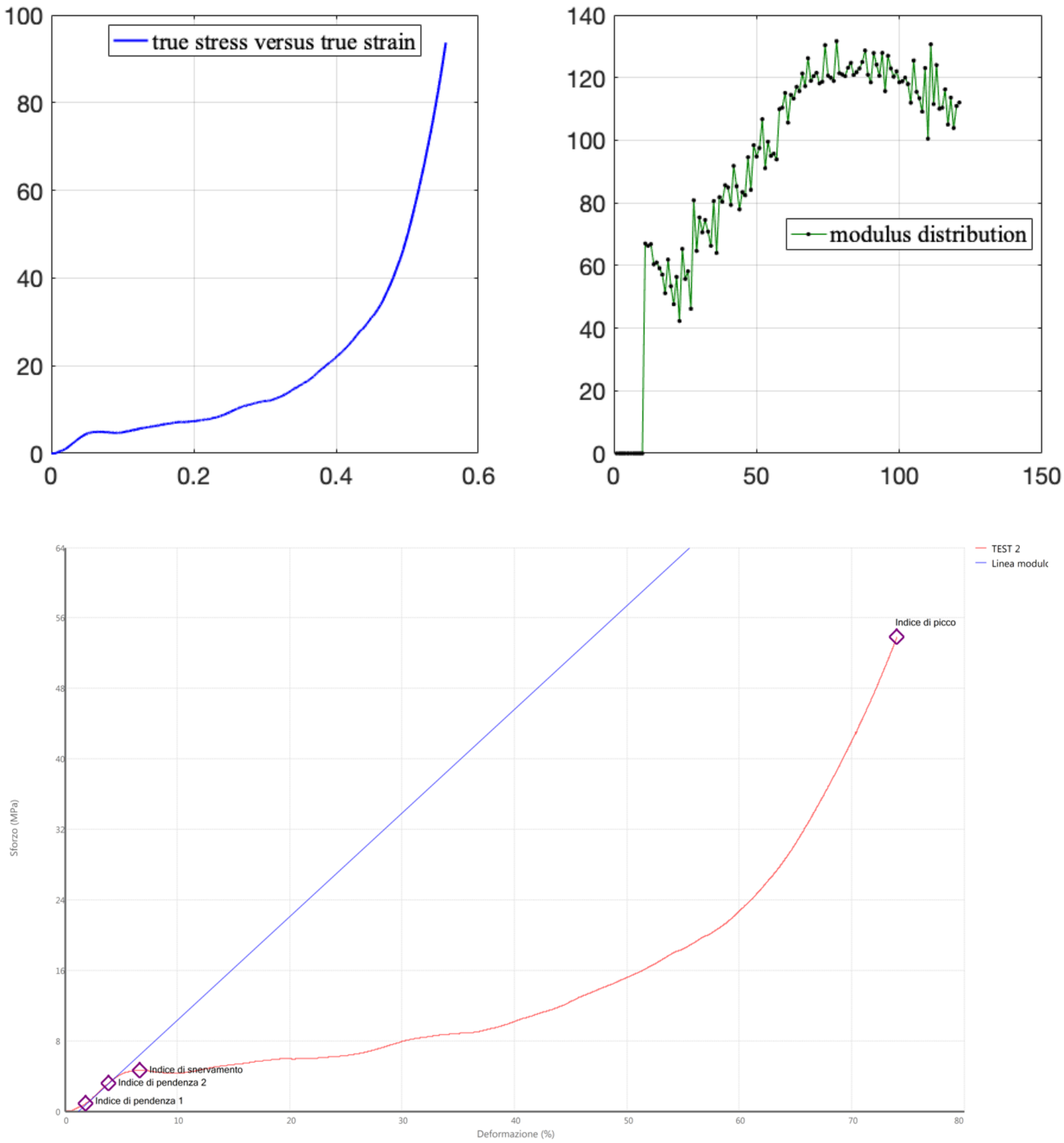


Figure 8 stress versus strain (above left), young modulus variation (above right), stress versus deformation for sample 2(below)

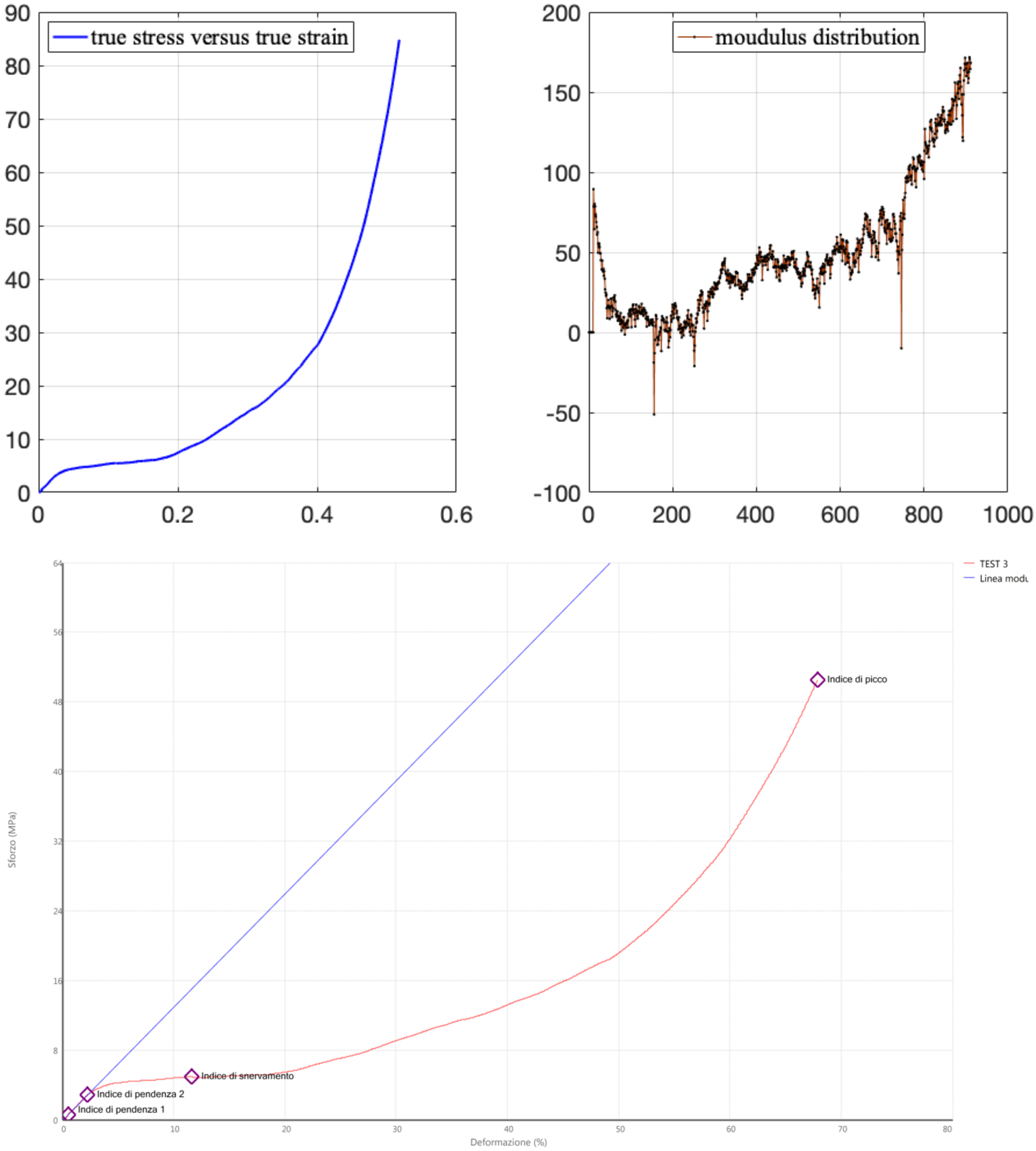


Figure 9 stress versus strain (above left), young modulus variation (above right), stress versus deformation for sample 3 (below)

Yield load [N]	Peak stress [Mpa]	Yield stress [Mpa]	Deformation at peak load (%)	Elastic modulus E [MPA]
3364.2	8.6	3.6	32.2	103
4264.8	53.8	4.6	74.0	118
4791.2	50.5	4.9	67.9	130

Table 4 the mechanical properties of sample been uniaxial compressed

Marking plateau stress and densification strain of compression tests for 3 samples, aim to evaluate the Energy of absorption characteristics.

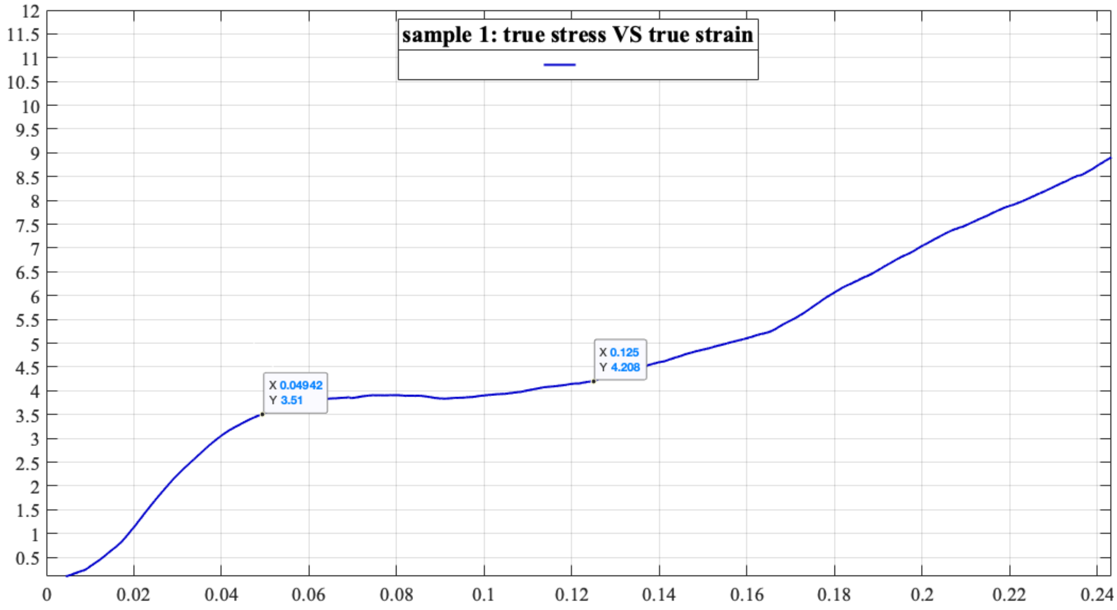


Figure 10 Compression test for sample 1: true stress [Mpa] versus strain: we could assume reasonably plateau stress and densification $\sigma_{pl1} = 3.51\ Mpa, \varepsilon_{D1} = 0.125$

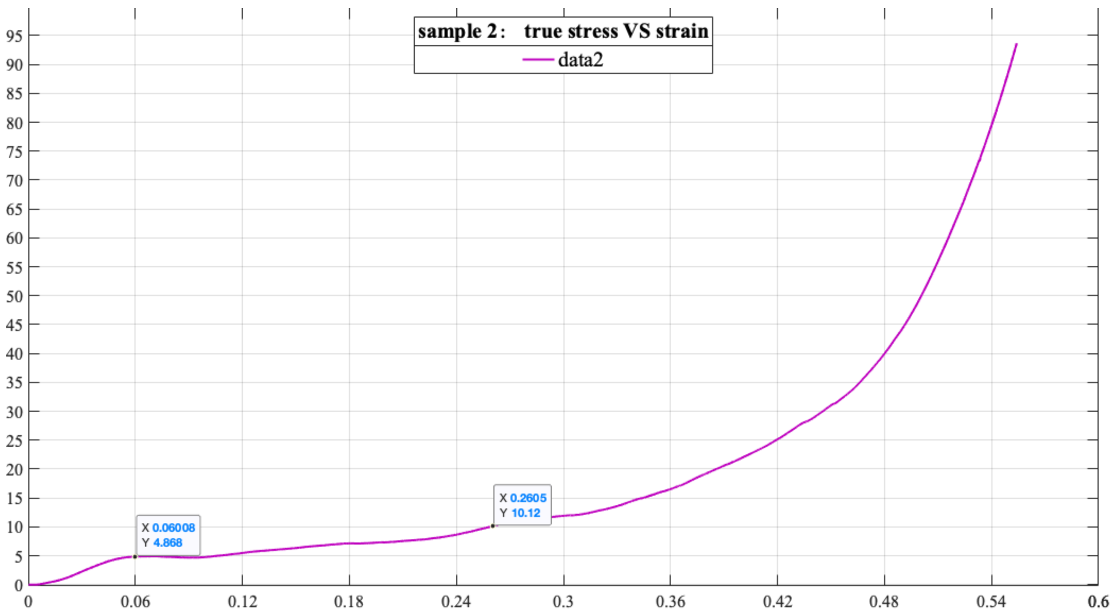


Figure 11 Compression test for sample 2: true stress [Mpa] versus strain: we could assume reasonably plateau stress and densification $\sigma_{pl2} = 4.868\ Mpa, \varepsilon_{D2} = 0.26$

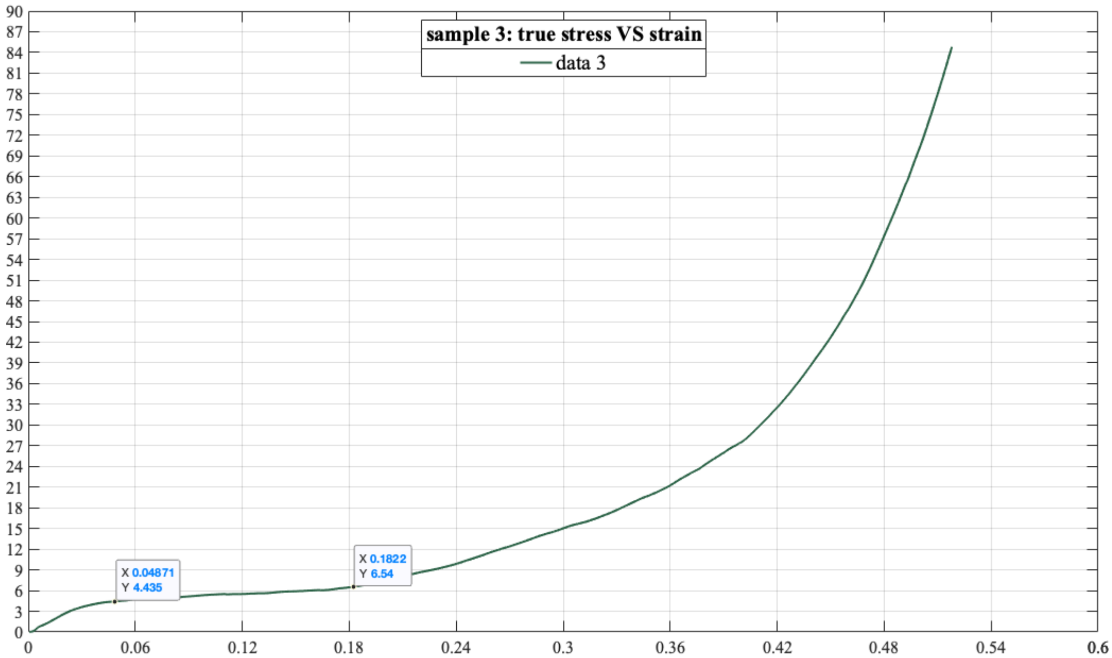


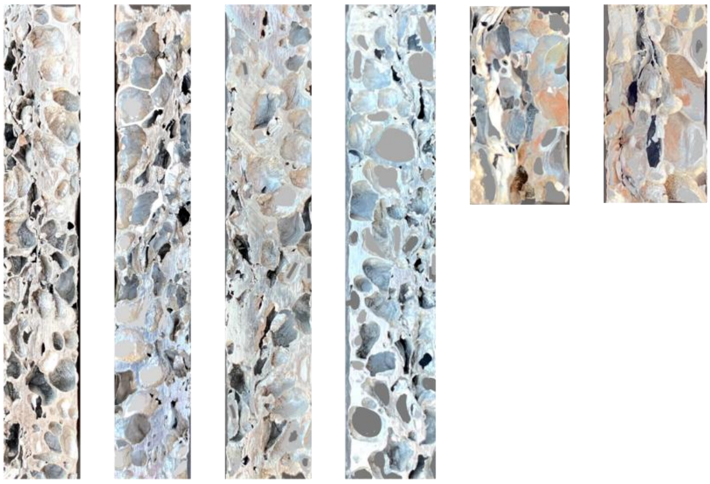
Figure 12 Compression test for sample 3: true stress [Mpa] versus strain: we could assume reasonably plateau stress and densification $\sigma_{pl3} = 4.435\ Mpa, \varepsilon_{D3} = 0.182$

	1	2	3
plateau stress σ_{pl}	$3.51\ Mpa$	4.868	$4.435\ Mpa$
densification strain ε_D	0.125	0.26	0.182

Table 5 plateau stress and densification strain of compression tests for 3 samples

We could find that, every stress-strain cure has 3 stages, which a typical characteristics of metal foam: linear grow stage, where stress increases linearly with strain until reach the upper yield point; more or less saturation stage, where the flow stress changes little with the strain increasing; sharpe stage, where stress steeply with the string increasing slightly. Load and displacement were recorded automatically by computer. Stress and strain were calculated in MATLAB for each test parameters by take account initial dimensions of specimens.

2 MATLAB image analysis tool



Foam images recognized by Matlab

Surface	1	2	3	4	5	6
Pore area %	53.01	40.82	53.11	58.08	73.90	60.06

Average porosity fraction
56.49

Figure 13 image recognition by MATLAB

To determine more properties of foam during deformation, the key factor is knowing relative density of metal foam. Image analysis tool embed in MATLAB is capable to recognize foam surfaces and give rough approximation of pore area percentage, with assumption that every surface has similar pore distribution and neglect the pore inside the foam which brings the error between recognition by tool and real condition. By applying relevant expression, we could get relative density of sample.

We also use the density determination kit to detect foam density which value is closer to the practical case. We measure the pure weight of samples at the beginning and immerse it in the water completely, according to the weight change on the balance. The apparatus could calculate the foam density automatically, with smaller error compared to the MATLAB. but still cannot reach the pore deep inside the material.

Figure 14 configuration of Sartorius YDK03 and sample been immersed to read density

We got the final mechanical properties based on Ashby theory with reasonable relative density, see following table :

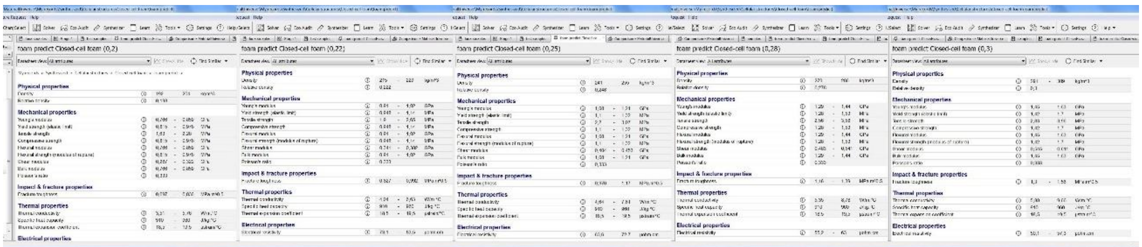
average value of porosity P_{avg}	0.75		plateau stress σ_{pl} (from theoretical formula)	4.11e+06	Mpa
standard deviation of pore area fraction ρ_{std}	0.1084		densification strain ε_D (from theoretical formula)	0.59	
relative density ρ_{rela}	0.25		yield strength of foam	5812500	Pa
density of foam ρ_{avg}	675	kg/m^3	tensile strength of aluminum σ_t (too large)	4.09e+07	Pa
young's modulus E *	5.96e+09	Pa	hardness H (too large)	5.12e+07	Pa
young's modulus for compression of foam E_c*	3.6e+09	Pa	compressive strength of aluminum σ_c (too large)	3.41e+07	Pa
shear modulus for compression of foam G_c	5.62e+08	Pa	bulk modulus (chosen not calculate)	5	Gpa

* With standard deviation of porosity, also have exist max and min of young's modulus E , Ec

Hardness and tensile strength of aluminum σ_t both are related to compressive strength

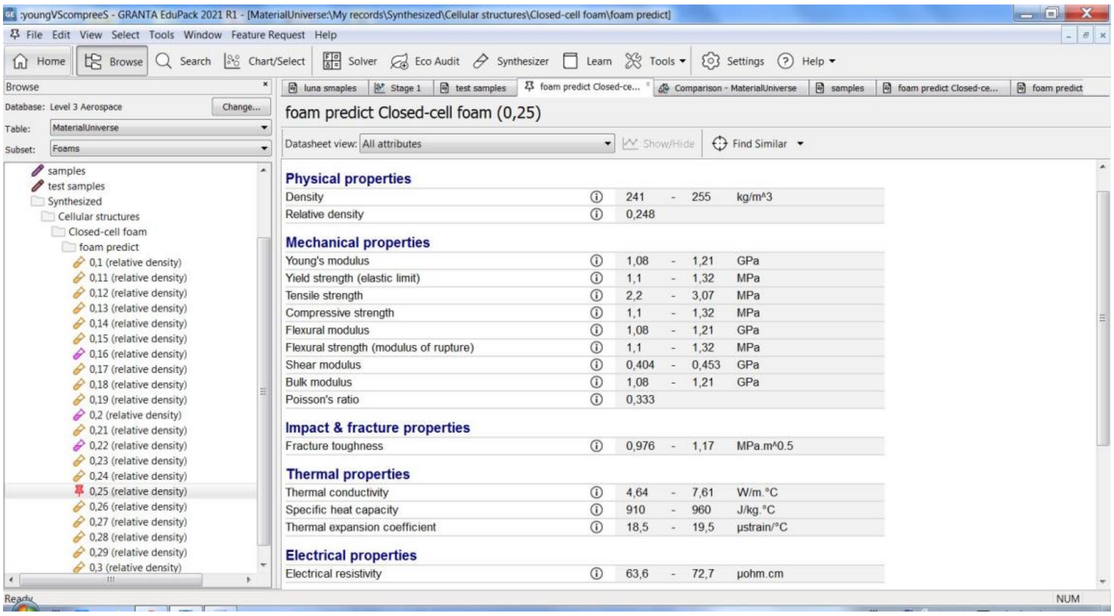
Table 6 mechanical properties of test samples

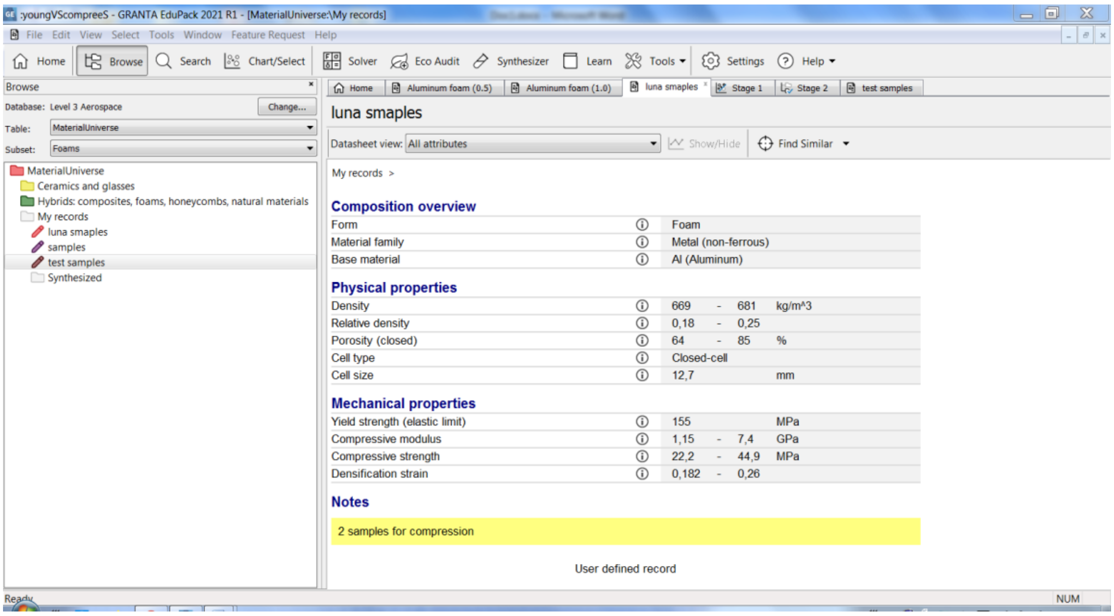
We compared the results with CES:
Brief description for CES
ADD CES figure, edit into excel summation.



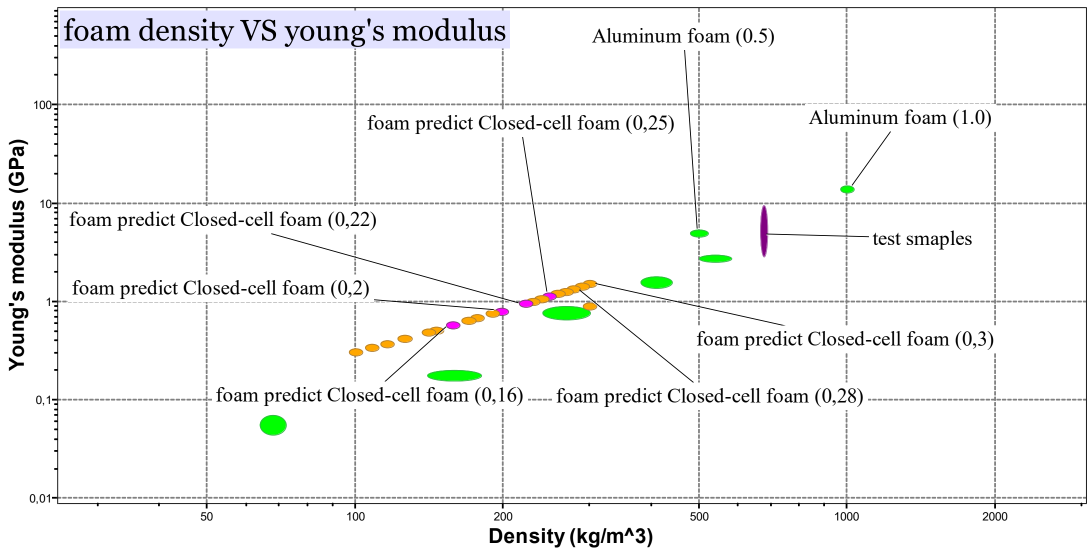
As we mentioned before, relative density is crucial to the mechanical properties. lower the relative density of foam, which means lower the porosity, brings higher young's modulus and strength.

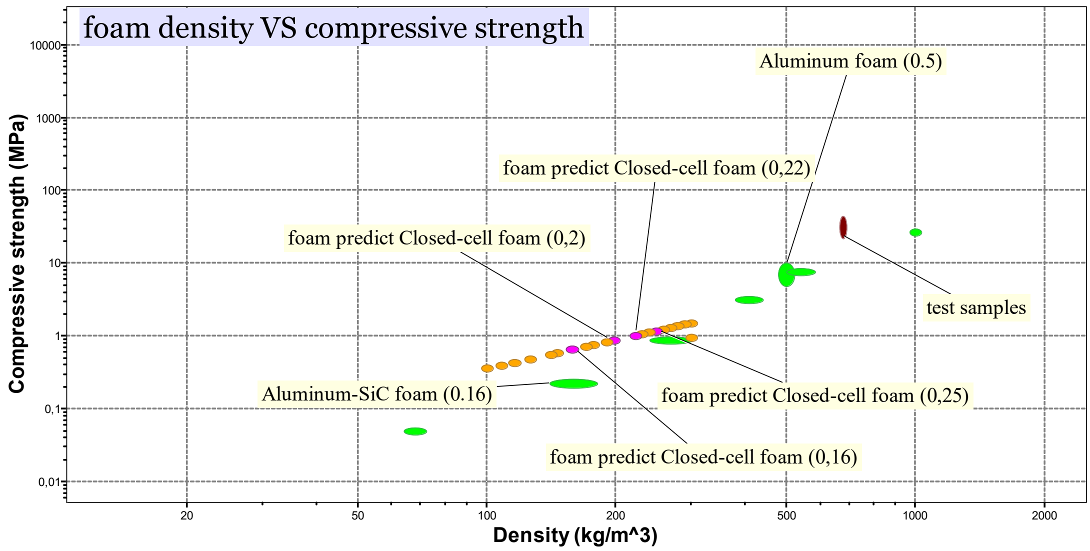
Some of values are difference from CES predict range + explanation.





Description of How I obtain the following charts.





Yong's modulus and compression strength calculated by Ashby formula are much higher than Abaqus.

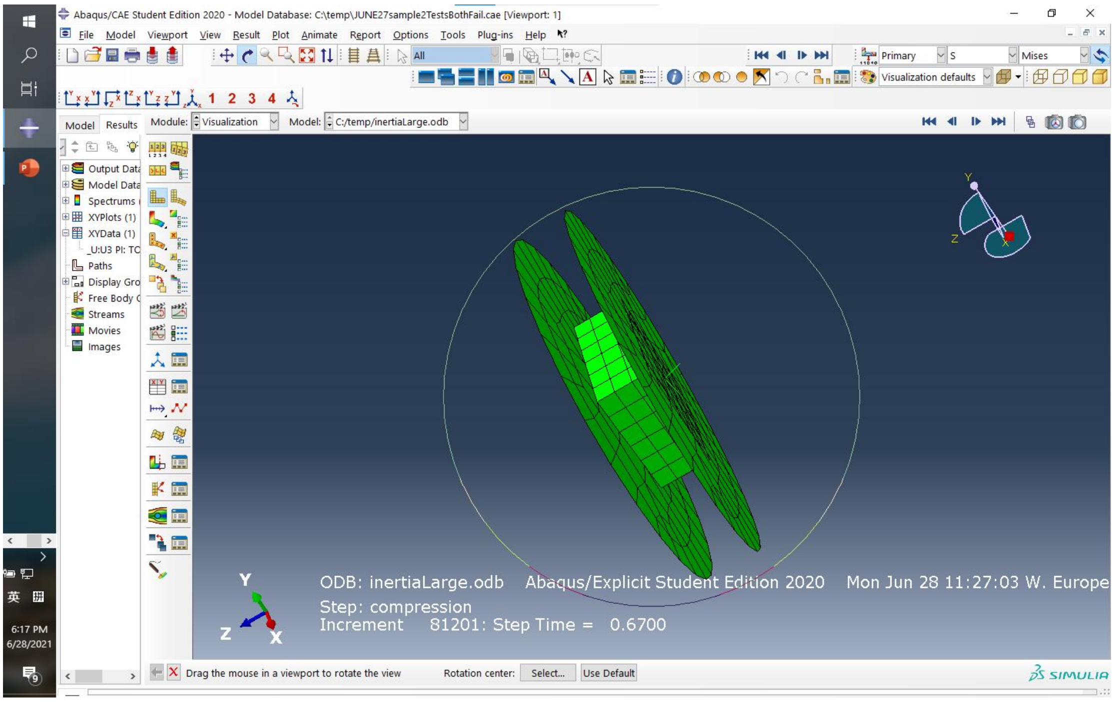
3 Abaqus simulation

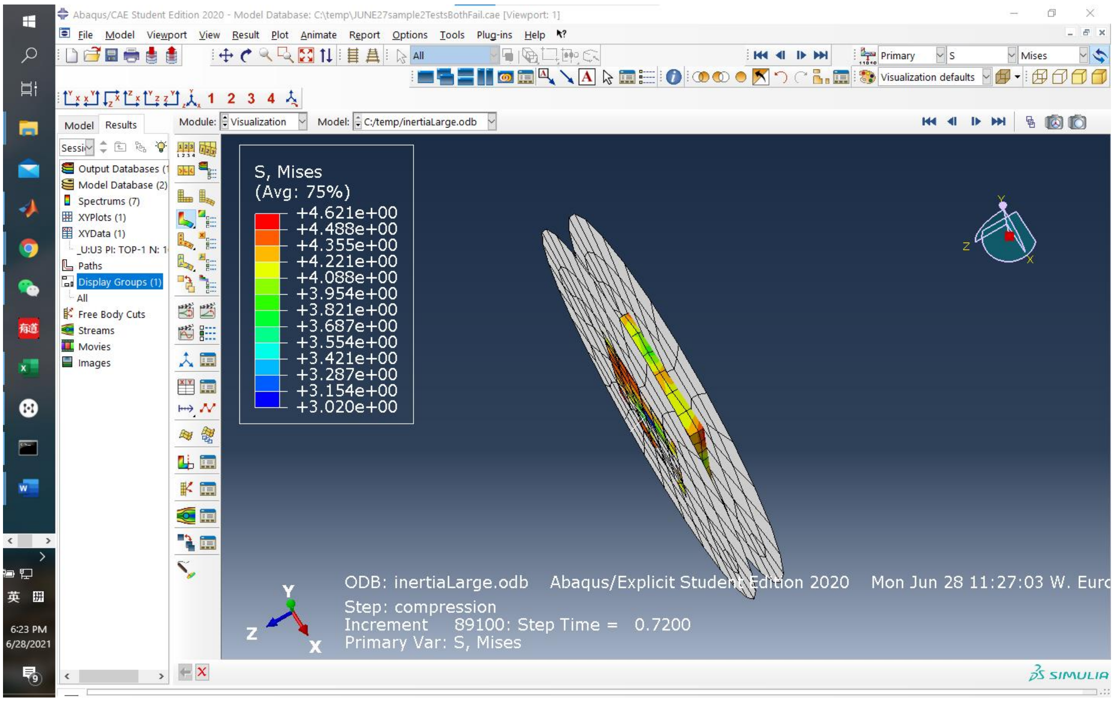
The constitutive models described here are available in ABAQUS for the analysis of crushable foams typically used in energy absorption structures. Two phenomenological constitutive models are presented: the volumetric hardening model and the isotropic hardening model. And in my case, is volumetric hardening.

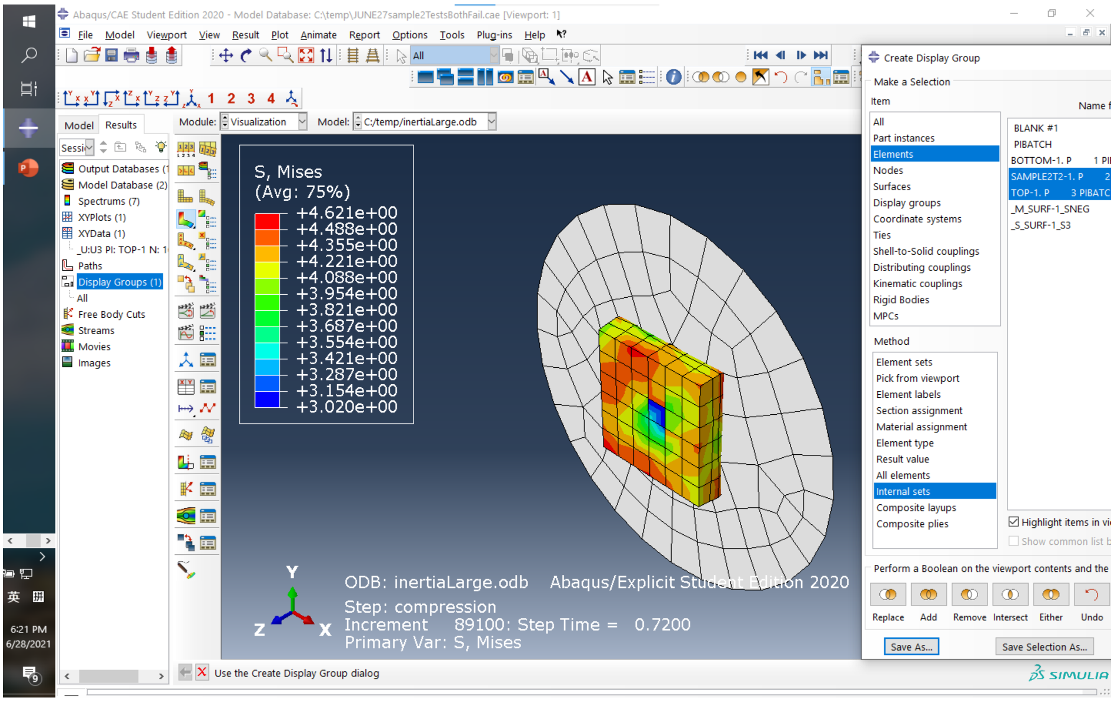
The volumetric hardening model is motivated by the experimental observation that foam structures usually experience a different response in compression and tension. In compression the ability of the material to deform volumetrically is enhanced by cell wall buckling processes as described by Gibson et al. (1982), Gibson and Ashby (1982), and Maiti et al. (1984). It is assumed that the foam cell deformation is not recoverable instantaneously and can, thus, be idealized as being plastic for short duration events.

The volumetric hardening model assumes a perfectly plastic behavior in hydrostatic tension, and the evolution of the yield surface is controlled by the volumetric plastic strain experienced by the material: compactive inelastic strains produce hardening while dilatant inelastic strains lead to softening.

V=10mm/s, inertia1500 [change to standard name]







After above simulations, we may have design concept for our foams to meet some real crash condition.

When talking about automotive crash, there are several entities responsible to access the crash performance of road vehicles. The standard tests regulated by United Nations Economic Commission for Europe (ECE) and National Highway Traffic Safety Administration (NHTSA) in the U.S.A..

In these tests, the setup is defined by standard regulations and the results are compared to maximum values of accelerations and forces suffered by the dummies during the crash. Currently in Europe, 2020 Test Procedures are shown following:

Mobile progressive deformable barrier

The test car is propelled at 50 km/ h (31 mph) into a moving deformable barrier mounted on an oncoming 1400 kg trolley, also traveling at 50 km / h at a 50% overlap. This represent shitting a mid-size family car. Two adult male THOR-50M dummies are seated in the front and two child dummies are placed in the back. The aim is to assess the crumple zones and the compatibility of the test car.

Full width rigid barrier.

The test car is driven into a rigid barrier with full overlap at a speed of 50 km / h (31 mph). A small female dummy is seated in the driving position and in the rear seat. The aim is to test the car's restraint system, such as airbags and seat belts.

Mobile side impact barrier A deformable barrier is mounted on a trolley and is driven at 60 km/ h (37 mph) into the side of the stationary test vehicle at a right angle. This is meant to represent another vehicle colliding with the side of a car.

Side pole [18] The car is propelled sideways at 32 km / h (20 mph) against a rigid, narrow pole at a small angle away from perpendicular to simulate a vehicle traveling sideways into roadside objects such as a tree or pole.

4 Conclusion

Over on the results show good agreement Between the numerical simulation and the experiment test .in numeric simulations Some factors are not take into account such as the friction Between the test machine and foam faces, pore deep inside the materials, etc. these factors can also consume the energy in the compression test.

Various studies were tried out to increase the energy absorption of thin-walled tubes with the use of fillers. The filling of cellular materials, such as Honeycombs and foams to the tubular structures is a common method which may tremendously improve energy absorption efficiency of the tubes. Not Only the filler itself absorb Energy by plastic deformation but also the interaction Between the tube and filler make change The Original collapse mode of the tube Into a More efficient collapse mode.

5 Reference

1. Crashworthiness and lightweight optimization to applied multiple materials and foam-filled front end structure of auto-body Zhaokai Li, Qiang Yu, Xuan Zhao, Man Yu, Peilong Shi and Cilei Yan. Advances in Mechanical Engineering 2017, Vol. 9(8) 1–21
2. Deformation and energy absorption of aluminum foam-filled tubes subjected to oblique loading Zhibin Li a , Jilin Yu a,n , Liuwei Guo a,b. Available online 28 September 2011
3. Effects of porosity and pore size on the compressive properties of closed-cell Mg alloy foam. X.C. Xia a, *, X.W. Chen a , Z. Zhang a , X. Chen a,b , W.M. Zhao a, *, B. Liao a , B. Hur
4. A-242 Aluminium Alloy Foams Manufacture from the Recycling of Beverage Cans Nallely Montserrat Trejo Rivera * , Jesús Torres Torres and Alfredo Flores Valdés
5. Mechanical Properties of Aluminum Foam Fabricated by Aluminum Powders with Na or Carbamide Replica G. Kavei
6. Numerical study on mechanical behavior of foam core sandwich plates under repeated impact loadings Kailing Guoa,b , Ling Zhua,c,⁎ , Yinggang Lia,b , T.X. Yud
7. CES edupck guide
8. Abaqus user’s manual and online vedieo
9. Metal Foams: A Design Guide M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson,

J.W. Hutchinson and H.N.G. Wadley
10. Applying the investment methodology for materials(IMM) to aluminum foams