Modeling of lattice structures energy absorption under impact loads

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***Abstract*—Lattice structures are promising design solutions for lightweight components in many industrial fields as aeronautics and space. The multifunctional design approach aims to combine in the same component several capabilities, including the ability to absorb impact energy with high efficiency. The additive manufacturing of metals is presently opening to innovative constructive approaches where static strength, lightweight and impact behavior must be considered together in design and simulation. This paper introduces the modeling results of the energy absorbed by different lattice cells topologies under impacts.**

Keywords-additive manufacturing; lightweight design; energy absorption; lattice structures; smart structures.

I. INTRODUCTION

Metal lattice structures fabricated by additive manufacturing (AM) processes have wide range of applications in the mechanical field. The ability to provide high-energy absorption in small volumes, in particular, has potential interest for vehicles, aeronautics and space engineering. For instance, the leading edge area of aircraft wings is subjected to accidental loads as bird strikes. The application of lattice structures is able to provide high strength/weight ratios and improved capability of absorbing impact energy, in addition to other functions (as thermal exchange for anti-icing systems). The cell shape can be theoretically optimized to increase the elasto-plastic energy absorption in the unit volume. This leads to optimized impact-absorbing components with lightweight property and reduced volume. Both static and dynamic behaviors of metal lattice structures have been investigated under the constraints imposed by the complex shape and the high topology variability. The evaluation of strain energy dissipated in presence of impulsive forces requires dedicated calculations in the dynamic regime. However, the preliminary analysis of the lattice behavior in the static loading condition can provide, in first approximation, the comparative estimation of the energy absorption capabilities among cells topologies as already observed in [1]. The reduced-order modeling method is used in this work to provide efficient solution in maximization of the energy absorption in lightweight design.

The present study introduces the analysis and compact modeling of the energy absorption behavior of truss-lattice structures subjected to non-linear static loads and impact loads at high strain rate. Firstly, the performance of several unit cell topologies is assessed in order to identify the role of different struts types in the energy absorption capability. Secondly, multi-cells high speed crashing simulations have been performed in order to gather information about the plastic energy absorption until densification point. The results from static simulations can be used to predict qualitatively the energy absorption in the dynamic field.

II. STATIC TESTS

As starting point for investigating the influence of different struts on the energy absorption capability, the basis unit cells *bcc* (body-centered cubic) and *fcc* (face-centered cubic) are selected as the respective representative of the bending and stretching dominated behavior among the lattice structures with reference to previous works [1-5]. Additional cells topologies are then considered, including *bccz* and *fccz* (body/face centered cubic with reinforcement), *fbcc* (face-body-centered cubic) and its reinforced counterpart *fbccz* (face-body-centered cubic reinforced): these topologies are studied to investigate the influence on energy absorption of the combination of different cells morphologies and load-oriented struts. The mechanical performances of the different lattice representative volume elements (RVEs) are compared numerically. The tool Ansys Workbench 20 R1 is used for the modeling and simulation. The material considered for the numerical simulations is AlSi10Mg due to the consolidated AM fabrication processes and low density [6].

The energy absorption in static domain is calculated by considering nonlinear material behavior with the bilinear modeling assumption. The comparison between the cells topologies is performed based on the specific (SEA) and volumetric (VEA) energy absorptions as well as the maximum equivalent reaction force (Fz_0) of the RVE for a given displacement. To compare the results, the cell size (3 mm), the struts diameter (0.370 mm), and the applied displacement are kept constant for all configurations. The displacement imposed is able to induce the plasticization of the cell for each topology considered. Then, the elasto-plastic energy absorption associated to constant displacement among cells is calculated. The results of static models with bilinear material behavior are reported in Fig. 1.

III. HIGH SPEED IMPACT TESTS

All of the topologies statically tested are considered in the simulations of high speed crashing. Test configuration is very similar to the one applied in [7], but instead of using a 5x5x1 sample, a 3x3x1 has been used to reduce the computational heaviness of the model. Beside the sample, where cells are modelled in the same way used for the static tests, the configuration also make use of two rigid plates: the upper plate is the one applying the load (crashing the sample at 200 m/s), while the lower plate is fixed. Frictionless contact has been imposed at the connection between the plates and the sample by means of the contact algorithm for rigid bodies embedded in Ansys Explicit Dynamics solver. The model considering the *fcc* topology is reported in Fig. 2 as an example. The RVE is selected in order to manage the proper modeling of nodes, with no struts hanging like oriented cantilever beams.

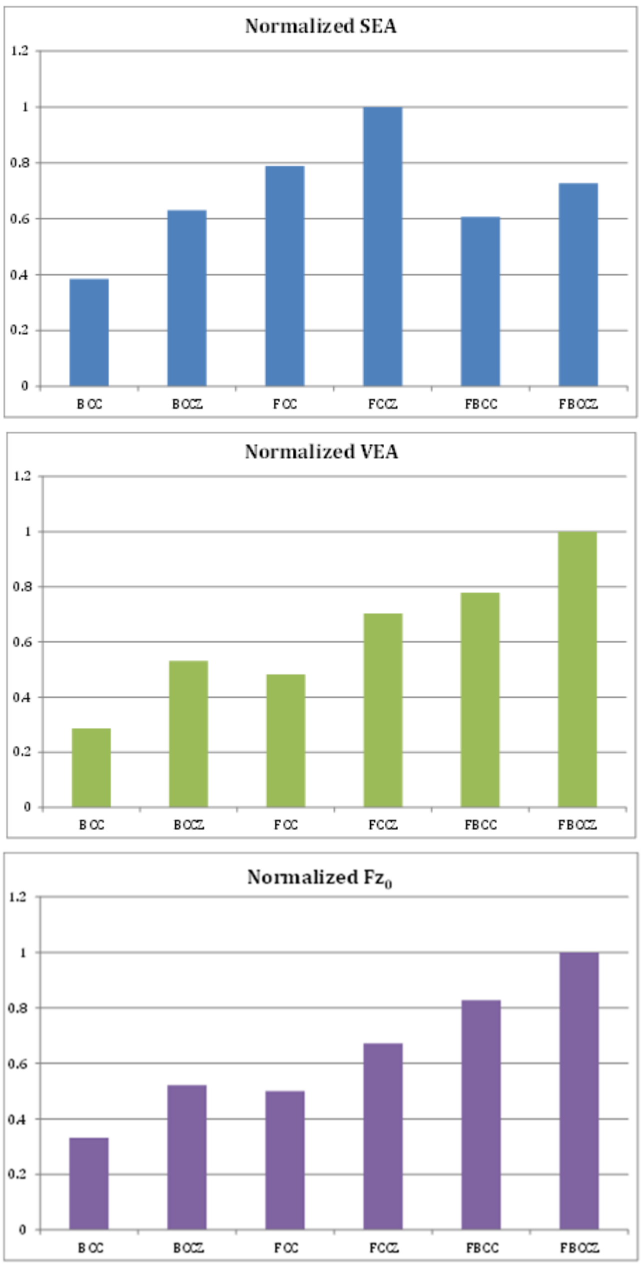

Figure 1. Results of static simulations on different cells with elasto-plastic material assumption, normalized respect the maximum value.

Also, reinforcements are modeled so that there are unique vertical struts (and not halves and quarters of them): in this way buckling phenomenon happens more realistically. The model induces the bending (for *bcc*) and stretching (for *fcc*) loading of struts, which corresponds to the real loading state.

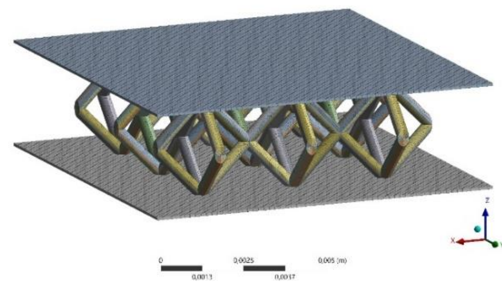

Figure 2. Model of high speed crashing simulations with *fcc* cells.

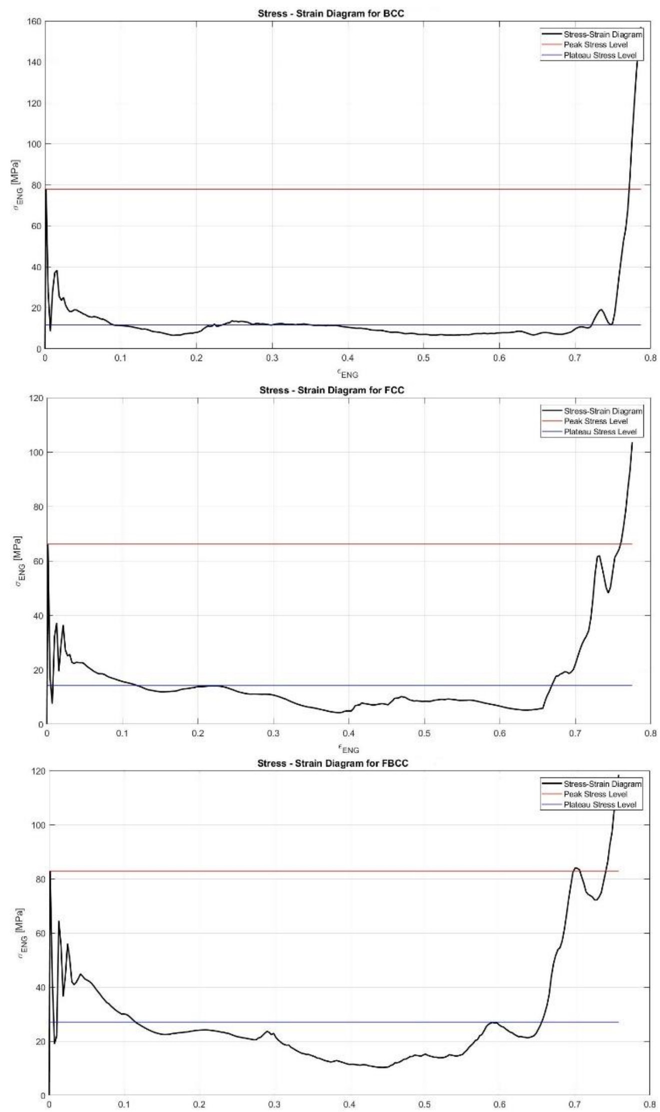

Figure 3. Stress-strain diagrams for *bcc*, *fcc* and *fbcc* cells from impact loading simulations.

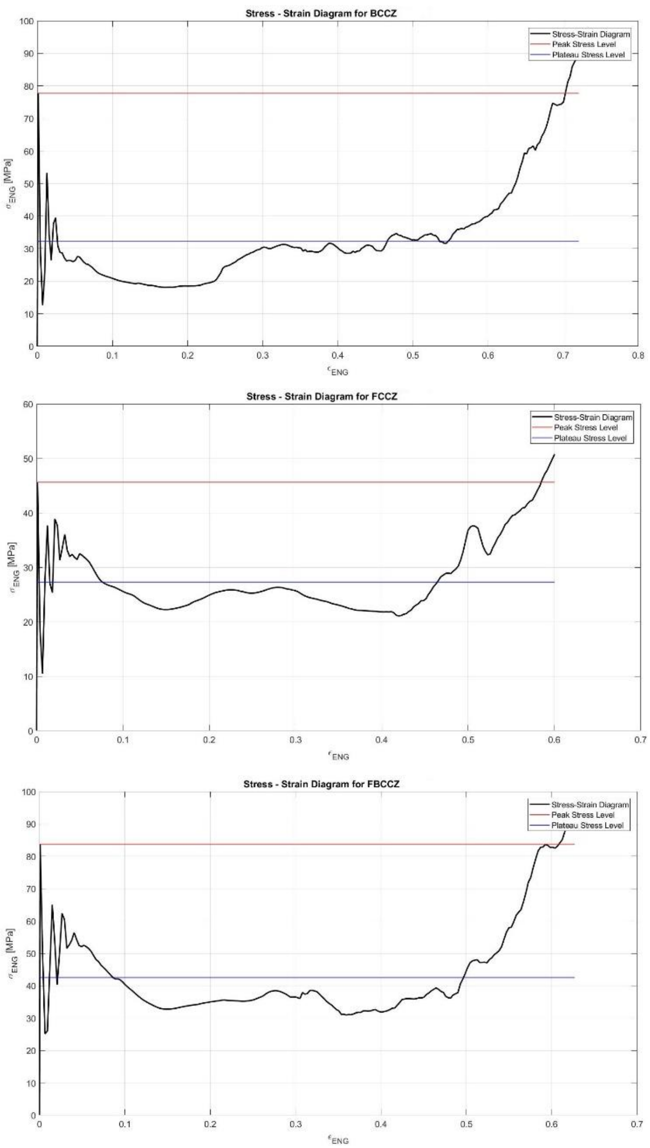

Figure 4. Stress-strain diagrams for *bccz*, *fccz* and *fbccz* cells from impact loading simulations.

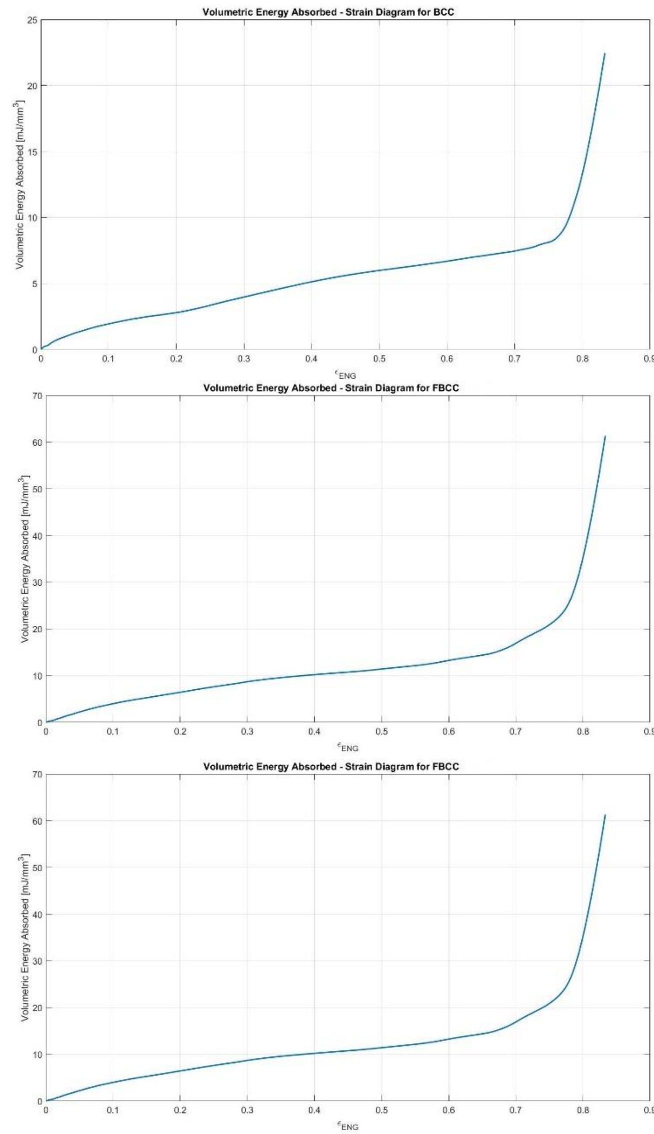

Figure 5. VEA – strain diagrams for *bcc*, *fcc* and *fbcc* cells from impact loading simulations.

The data analysis criteria used in the post-processing of results are the same used in [8] and [9]. The stress σ is defined through the force calculated at the rigid upper plate (by means of the reaction force output), while strain ε is obtained as ratio between height variation and the original height. The volumetric energy absorption (VEA) is defined with the following expression:

$$EA = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \qquad (1)$$

The SEA can be calculated by dividing the absorbed energy (EA), evaluated using VEA, by the mass. The efficiency parameter can be expressed as:

$$\eta = \frac{\int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{\sigma_{pk}(\varepsilon)} \qquad (2)$$

where $\sigma_{pk}(\varepsilon)$ is the peak stress calculated in correspondence to the displacement imposed to the cells (constant among all simulations). The densification strain ε_{cd} is calculated as the strain where the efficiency parameter is maximum. Then, the plateau stress can be defined as:

$$\sigma_{pl} = \frac{\int_0^{\varepsilon_{cd}} \sigma(\varepsilon) d\varepsilon}{\varepsilon_{cd}} \qquad (3)$$

The energy absorbed before the stress plateau can be considered as negligible and is not accounted. Finally, the crash load efficiency can be determined as $CLE = \sigma_{pl}/\sigma_{pk}$. Numerical quadrature over the data gathered via FEM has been performed by using Matlab script.

The stress-strain curves (including peak and plateau stress levels), volumetric energy absorption and efficiency parameter diagrams are shown from Fig. 3 to Fig. 8. The values calculated by the simulations are listed in Tab. 1 and graphed in Fig. 9-14, where EA, VEA and SEA are evaluated at the densification strain (allowing a valid comparison).

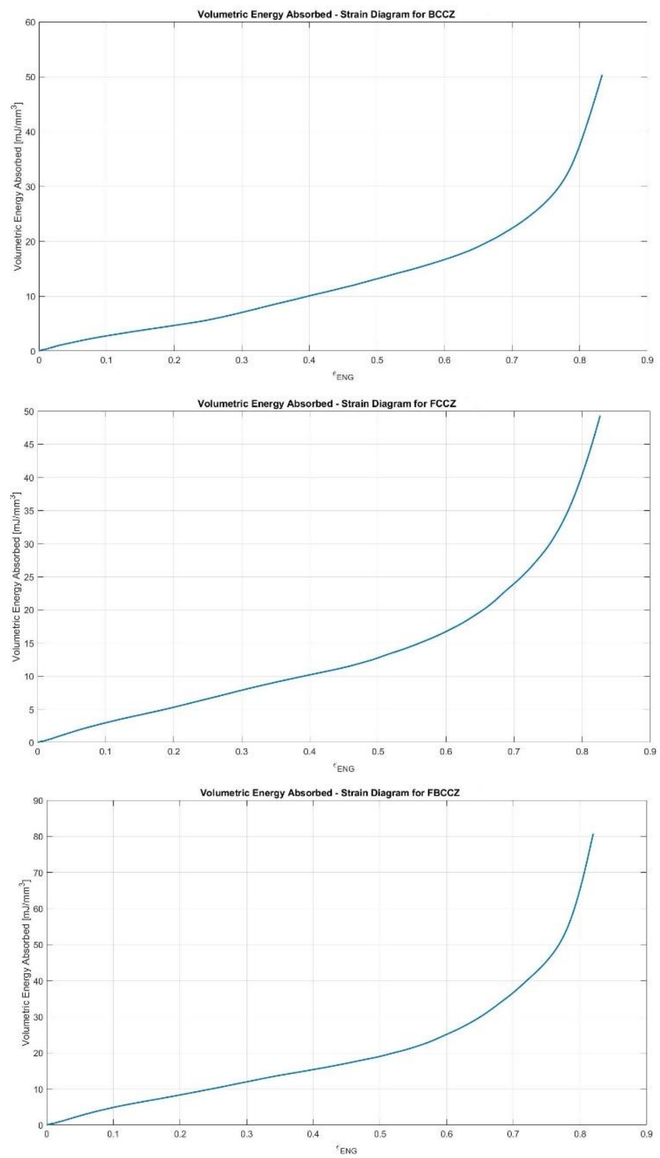

Figure 6. VEA – strain diagrams for *bccz*, *fccz* and *fbccz* cells from impact loading simulations.

TABLE I. RESULTS FROM HIGH SPEED IMPACT SIMULATIONS

Cell	σ_{pk}	σ_{pl}	ε_{cd}	EA	VEA	SEA	CLE	$\bar{\rho}$	mass
	MPa	MPa	/	mJ	mJ/mm^3	mJ/g	/	/	g
bcc	77,86	11,56	0,7698	2161,434	8,8948	45107,17	0,1484	0,0736	0,0479178
bccz	77,75	32,19	0,7034	5501,207	22,6387	101549,71	0,4139	0,0832	0,0541726
fcc	66,20	14,21	0,7583	2618,289	10,7749	66734,26	0,2147	0,0602	0,0392346
fccz	45,62	27,28	0,5830	3864,292	15,9024	85590,18	0,5979	0,0693	0,0451488
fbcc	82,91	27,08	0,7409	4876,338	20,0672	59222,75	0,3267	0,1264	0,0823389
fbccz	83,74	42,49	0,6095	6293,851	25,9006	71340,05	0,5074	0,1355	0,0882232

IV. DISCUSSIONS

According to the results of the static modeling, the *fcc* cell type demonstrates the highest specific energy absorption, together with the *bcc* cell. The *fbcc* cells do not show high performances in terms of energy absorption although displaying good overall VEA. The addition of one vertical strut to the RVE offers apparently supplementary energy absorption capability in terms of SEA and VEA as well as force reaction.

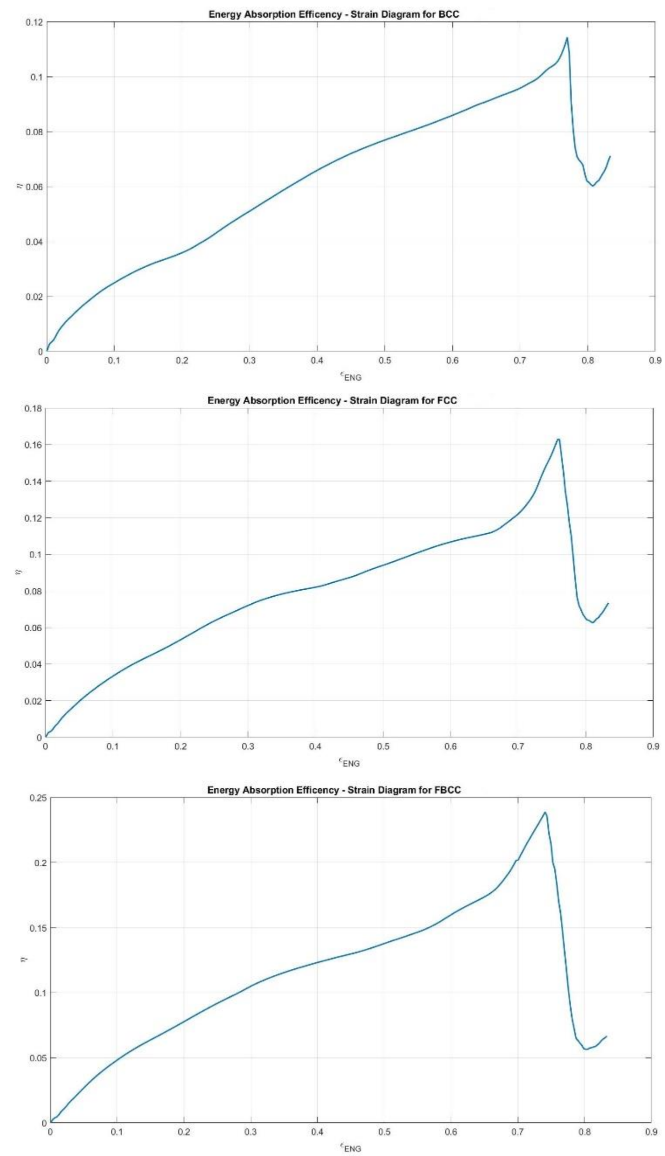

Figure 7. η – strain diagrams for *bcc*, *fcc* and *fbcc* cells from impact loading simulations.

These results will be compared to those ones obtained from high speed crashing simulations, presented in the next section.

The results obtained from impact simulations are well representative and extremely close from the point of view of the stress-strain behavior to the ones presented in [7]. The results seem to be quite following the trend shown for the static tests. The following considerations are relevant.

- Stress-strain diagrams perfectly represent typical cellular solids behavior: plateau stress follows a linear elastic section and the point where densification happens is clearly defined for every cell analyzed. The method for the evaluation of σ_{pk} and σ_{pl} seems to be respectful of the actual stress level, as shown by Fig. 3 and 4 which indicates that energy absorbed before the stress plateau was an acceptable assumption as for [8]. From data shown in Fig. 9 it is clear that plateau stress is evidently higher for reinforced cells: trend for this parameter follows the force reaction one from static analyses; it can be concluded therefore that force reaction can anticipate the evaluation of dynamic plateau stress. Peak stress does not seem to be dependent on vertical reinforcement, but the trend (for non-reinforced cells) is quite similar to the relative density one.

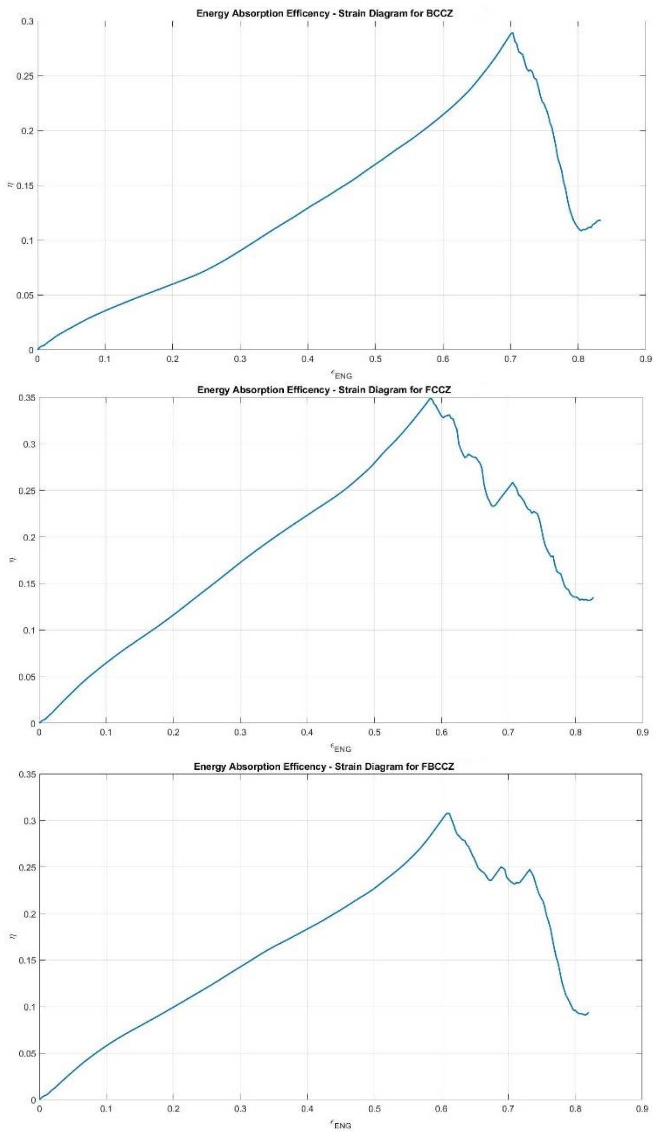

Figure 8. η – strain diagrams for *bccz*, *fccz* and *fbccz* cells from impact loading simulations.

Among the topologies, struts loading varies: the bending dominated cell (*bcc*) shows a higher peak stress and a lower pleateau stress than the stretching dominated cell (*fcc*). Also, the 45° oriented struts are more efficient than the struts with 35.26° orientation in terms of load path. Their combination offers excellent results with regard to the single orientations. Effects of these parameters are evident on CLE.

- CLE trend (Fig.10) can be qualitatively compared with force reaction from static analyses, just like plateau stress (being the two properties directly related each other): it can be seen, in fact, as a non-dimensional force parameter. *Fccz* achieved best CLE, having a high plateau with regards to the peak stress. A good result is by the way obtained by *bccz*: situation will improve with energy parameters as well, allowing a revaluation from static results.

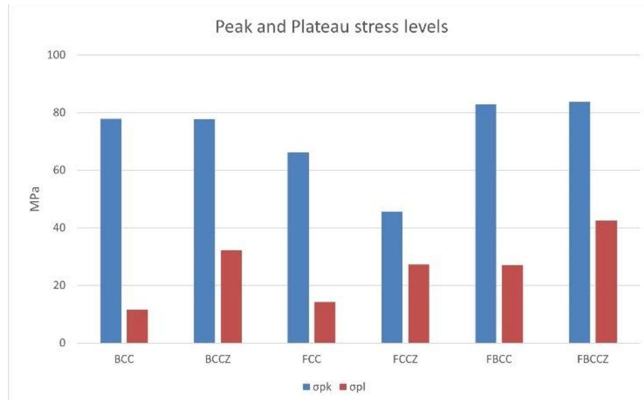

Figure 9. Peak and plateau stresses.

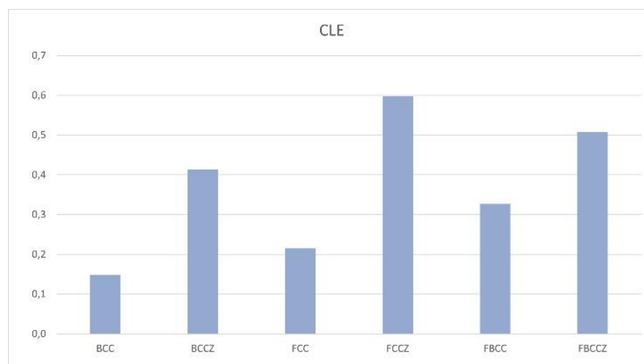

Figure 10. Crashing load efficiencies.

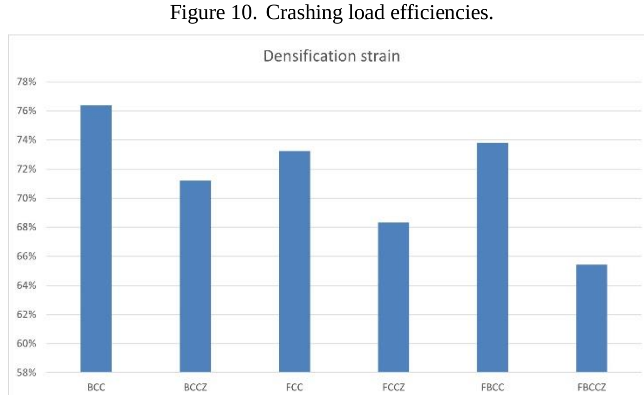

Figure 11. Densification strain.

- ε_{cd} (Fig. 11) is almost the same for every cell: this allows comparing the EA, SEA and VEA values, being almost at the same strain level. As an alternative to the definition previously provided, the final cell height can be also obtained by subtracting two times the strut diameter from the RVE initial height in the specific case of the considered lattice unit cells. It has to be stated though that, among non-reinforced cells, *bcc* performs highest densification strain and same thing happens for *bccz* when it comes to their reinforced versions. Even if differences are small, effects on EA and SEA is relevant.

- EA, SEA and VEA (Fig. 12 – 14) from impact simulations also present a qualitative similarity with static result, exception made for *bccz*, that performs an exceptionally high pure EA (even surpassing *fcc*z), and the highest SEA above all. Motivation for this result has to be searched into high densification strain coupled with high plateau stress. *Fbccz* still is the cell performing highest pure EA.

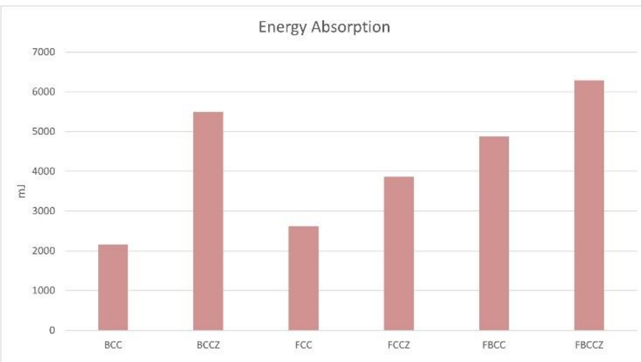

Figure 12. Energy absorption at densification strain.

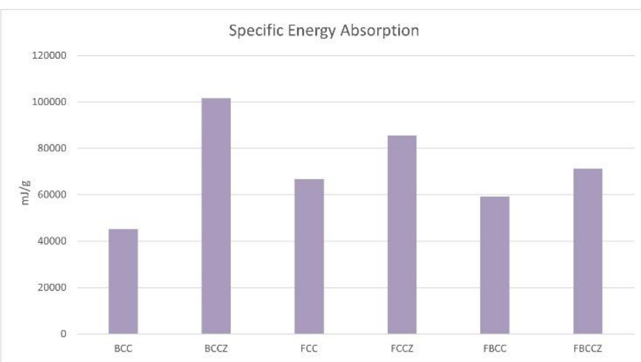

Figure 13. Specific energy absorption at densification strain

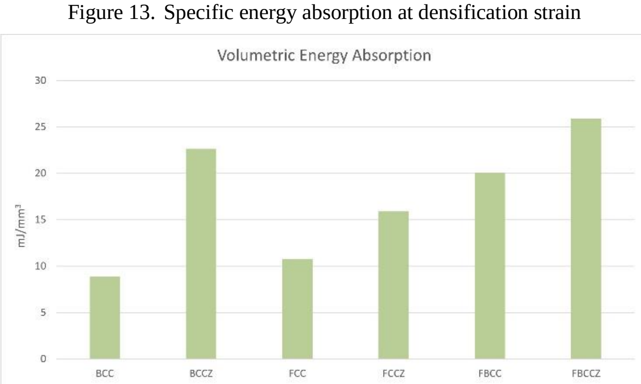

Figure 14. Volumetric Energy absorption.

VEA once again follows the exact same trend as EA, being the volume considered the same for all analyses.

V. CONCLUSIONS

In conclusion, with reference to the cells topologies considered, the comparisons between static and dynamic simulations provides repeatable results in terms of energy absorption capability. Static simulations are significant in terms of preliminary benchmark analysis and allow the prediction of basic cells properties. In conclusion, the *fbccz* topology provides the highest value of EA. Both static and dynamic analyses identified the *fccz* as a very efficient topology for high EA with reduced mass. Finally, the *bccz* topology is also suitable for efficient EA due to the high densification strain.

The simulations presented here do not consider strain-rate dependency in the results, and this effect requires more deep investigations in the next activities, that will include also experimental tests.

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