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The effect of symmetrical horizontal gradient design on a novel lattice structure

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Abstract

In our former publication a novel Lattice structure was proposed, in hopes of eliminating the buckling behavior of the Auxetic Honeycomb unit cell. For certain designs the buckling behavior is still present. In our current paper symmetrical horizontal gradient design is applied to the buckling specimens in hopes of achieving the desired continuous auxetic behavior. Compressive Finite Element simulations were used to investigate the effect. Only the implementation of extreme horizontal gradient design can in some cases eliminate buckling.

Keywords: Novel lattice, FEM, Gradient design, Lattice design

1. Introduction

Gradient design is a natural form which was not commonly used in product design as conventional manufacturing technologies limit part design. The advent of additive manufacturing (AM) enables the production of complex parts, low density lattices and the implementation of gradient design. Lattice structures in general are lightweight structures which based on their design can provide high strength [1-2], impact resistance [3] and outstanding energy absorption [4-5]. High performance lattice structures can be achieved by gradually changing unit cell parameters, this method is called gradient design. Gradient design can be achieved by changing the material, print and process parameters [6] or by adjusting the geometrical parameters.

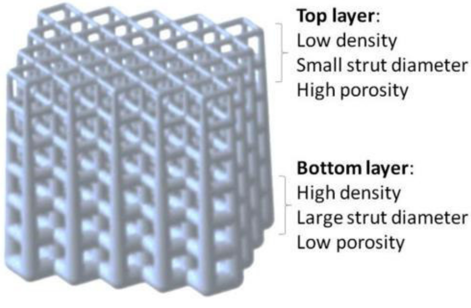

Figure 1. Gradient design examples. [7]

In this study the effect of structural progressivity is examined, the most common and of the most effective structural gradient design is achieved by vertically, continuously, and linearly varying the geometrical parameters of unit cells, making the specimen vertically denser (Figure 1).

Gradient structures absorb more energy [8], can provide large strain protection (before densification) [9], the load bearing capacity also greatly depends on the gradient thickness [10], furthermore the characteristic layer by layer compaction prevent critical sudden failures [11-12].

2. Methods and materials

2.1 Gradient design:

Our aim was to determine the effect gradient design on our novel doubly re-entrant honeycomb Lattie (see Figure 2), in hopes of improving mechanical parameters and deformation behavior of specimens.

When our novel auxetic lattice design was proposed two parameters were used (deg and offset – see Figure 2) to describe it and to evaluate the effect of the novel geometrical design. Mechanical properties and the deformation behavior exhibited parameter dependency, the latter one is not preferred. With gradient design we aim to eliminate the parameter dependency of the deformation behavior, meaning that all specimens exhibit a non-buckling continuous auxetic behavior (the two deformation behaviors are illustrated on right side of Figure 2. Buckling is an unpredictable deformation behavior, not a desired characteristic of high-performance lattices.

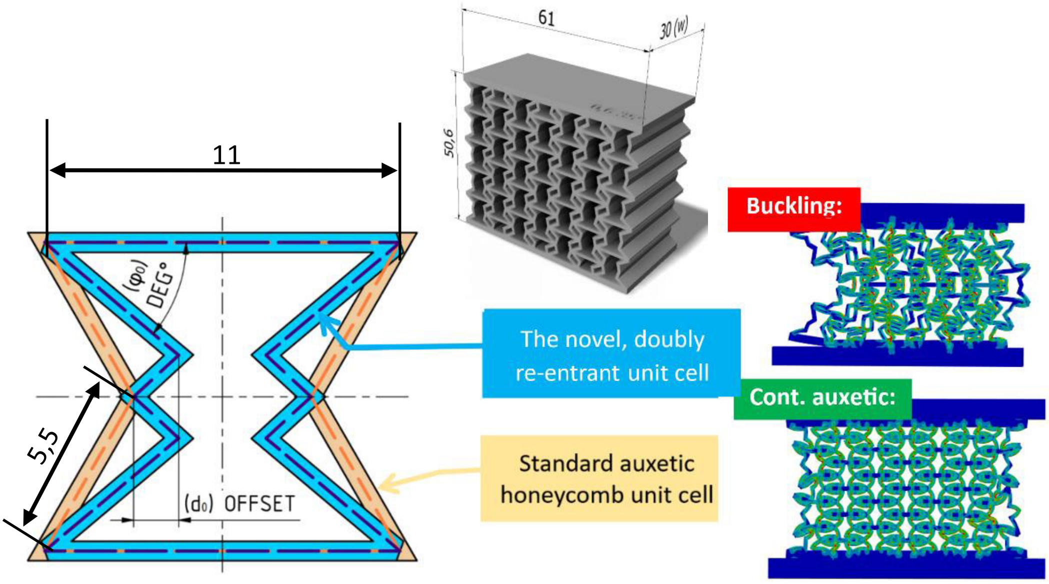

Figure 2. The novel auxetic unit cell and the two parameters used to describe the geometry modification (left side); the two characteristic deformation behaviors (right side).

During the desired auxetic behavior unit cells are pulled towards the center of the specimen when compressed. In prospect of reproducing this behavior on specimens prone to buckling the outer segments (Horizontally speaking) of the specimens were thinned out. In other words, horizontal gradient design was applied to specimens. Figure 3. illustrates the design change.

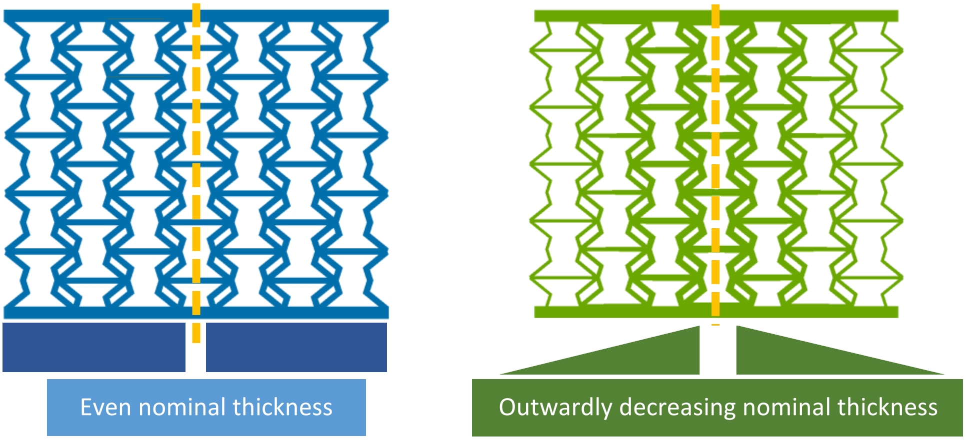

Figure 3. Even thickness, (left) and horizontally graded specimen – with outwardly decreasing nominal thickness (right)

2.2 Specimen modelling:

In this study a linear horizontal gradient design was applied to the specimens. Each specimen consists of 5 by 7 unit cells. To achieve a seamless gradient design the specific thickness of the unit cells changes linearly between two boundary values. These boundary values are the specific thickness values at edge of the unit cells, which are calculated by dividing the desired gradient scale by the horizontal unit cell numbers. Figure 4. illustrates the CAD modelling principle of this horizontal gradient design.

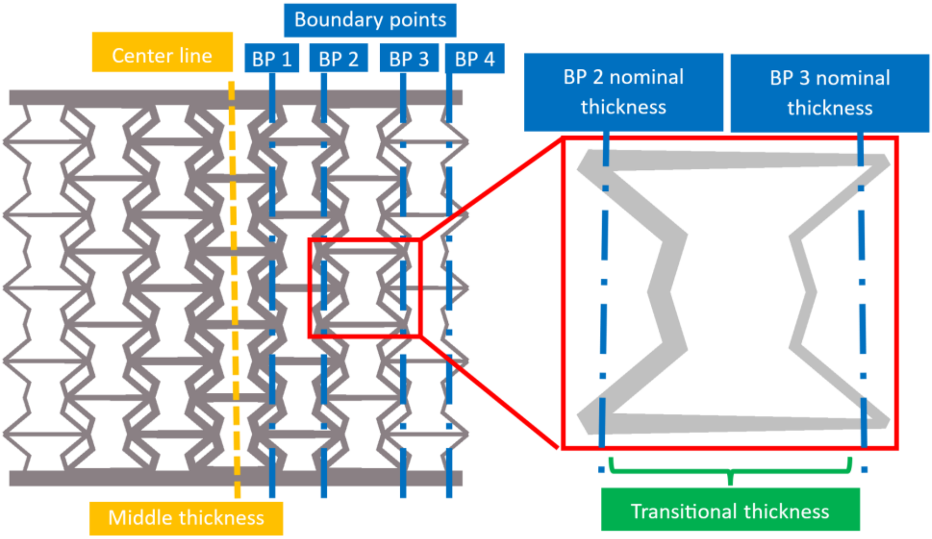

Figure 4. Specimen modelling – nominal thickness

In our previous work where the novel unit cell was proposed one can see that specimens with the following parameters listed in Table 1 buckled laterally, thus only these specimens form the scope of our recent study.

Table 1 Geometrical parameters of specimens prone to buckling based on our previous research

Specimen no.	**1**	**2**	**3**	**4**
φ_0 (0) d_0(mm)	30 0.6	35 0.6	40 0.6	30 1.0
Behavioral mechanism	Buckling	Buckling	Buckling	Buckling

2.3 Series of experiments:

The effect of horizontal gradient design was investigated in three grades. Mild, Modest and Extreme horizontal gradient design was applied to each specimen. Mild horizontal gradient design refers to 33% decrease in nominal thickness of specimens, while mild and modest refers to 50% and 66% respectively. The nominal thickness at the edge boundary points (BP1 and BP4) are show in Figure 5, the nominal thickness between these boundary points were calculated following and even distribution. In total 12 specimens formed the scope of our study.

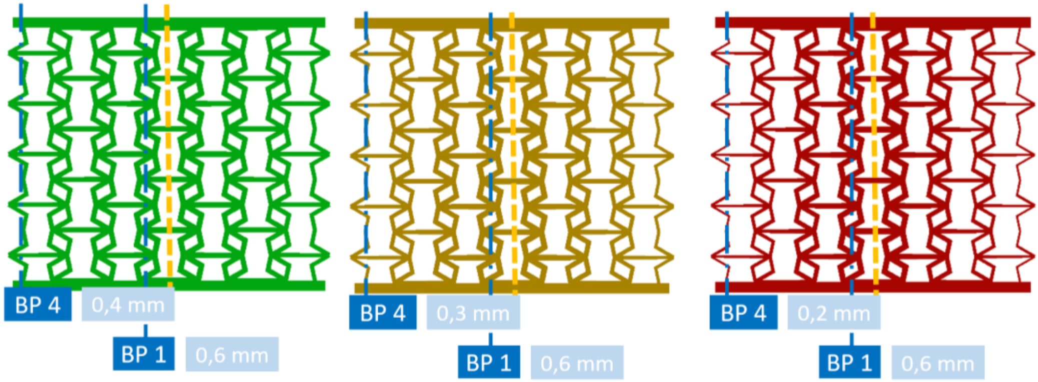

Figure 5. Representation of the three gradient design grades, with nominal thickness values at the edge boundary points.

2.4 FEM simulations

Compression testing was chosen to evaluate the effect of horizontal gradient design. Compressive Finite Element Method (FEM) simulations were carried out on each specimen. The established FEM test environment is shown on Figure 6. Our aim was to represent a real compression testing environment accurately enough; thus, the mowing and stationary jaws of a compression testing machine were included in the FEM model.

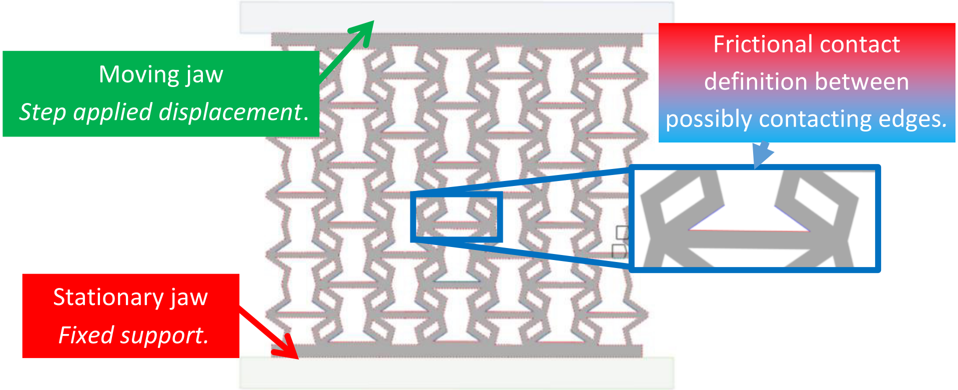

Figure 6. The FEM test environment

Step applied displacement was added at the upper edge of the mowing jaw, while the lower edge of the stationary jaw was fixed rigidly. Appropriate contact definition is indispensable, frictional contact was applied between the specimen and the jaws of the compression machine (coefficient of friction: 0,2). Frictional contact was also applied between the potentially contacting edges of the specimen (coefficient of friction: 0.35). Titanium alloy was set as the jaw material, the specimen material model is a Money Rivlin model fitted on the tensile test results of a unique resin mixture. We have chosen to use the aforementioned material model so the effects of horizontal gradient design can be compared against previous measurements. Simulations were carried out in Ansys Workbench 2023.

3. Results:

Compression force, absorbed energy and specific absorbed energy (SAE) are common metrics for result evaluation, thus our assessment is also based on these metrics. Figure 7. shows the compressive force in function of displacement.

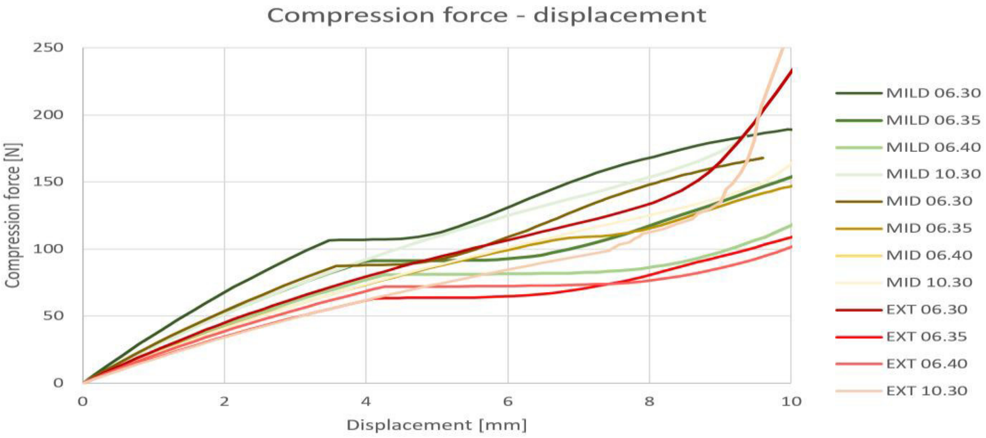

Figure 7. Compression test results.

One can clearly see that although the curves differ, their characteristics with two exceptions is similar. In order to understand the underlying effect, the deformation behavior of the specimens needs to be considered.

3.1 Deformation behavior of specimens:

In our original article where we proposed this novel lattice structure two deformation behaviors and their parameter dependency were observed. Unfortunately, the parameter dependency of behavioral mechanism persists. The observed deformation behaviors are listed in table 2. All but three specimens buckle during compression. It can be stated that horizontal gradient design can not eliminate buckling behavior, however with extreme horizontal gradient design more specimens exhibited the preferred auxetic behavior. In summary extreme gradient design can slightly improve the deformation behavior of certain specimens originally prone to buckling.

Table 2 Deformation behaviour of specimens

Gradient grade	Mild				Modest				Extreme			
d_0 (mm)	0.6	0.6	0.6	1.0	0.6	0.6	0.6	1.0	0.6	0.6	0.6	1.0
φ_0 $(^0)$	30	35	40	30	30	35	40	30	30	35	40	30
Deformation behavior	Buckling	Buckling	Buckling	Cont. aux.	Buckling	Buckling	Buckling	Buckling	Buckling	Buckling	Cont. aux.	Cont. aux.

Figure 8. illustrates the force displacement curve of a buckling and a non-buckling specimen.

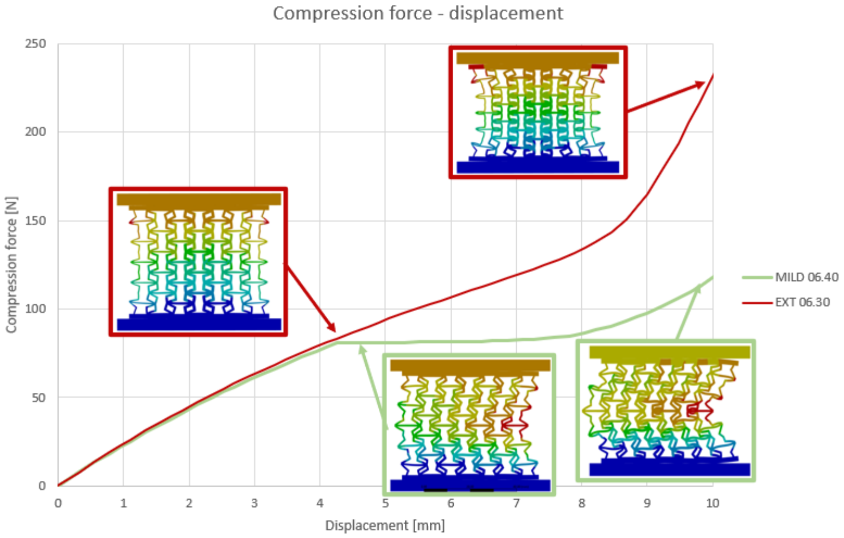

Figure 8. Force displacement curve of a buckling and non-buckling specimen

Figure 8. clearly shows the effect of buckling on the force curve and thus its effect on the absorbed energy. One can see based on the aforementioned parameters why buckling should be avoided.

3.2 Maximum compression force and specific compression force:

For a more transparent comparison of results, the effect of parameters on the maximum compression force were plotted in 3D. Figure 9 shows that maximum compression forces have a local minimum, with modest gradient grade the force values are the lowest, while extreme gradient grade results in the greatest force values. Figure 5 shows, that the more extreme the gradient effect the lower the mass, thus weight specific results must be considered as well. Figure 9 shows the weight specific results, showing the outstanding specific force values of the extreme gradient grade design.

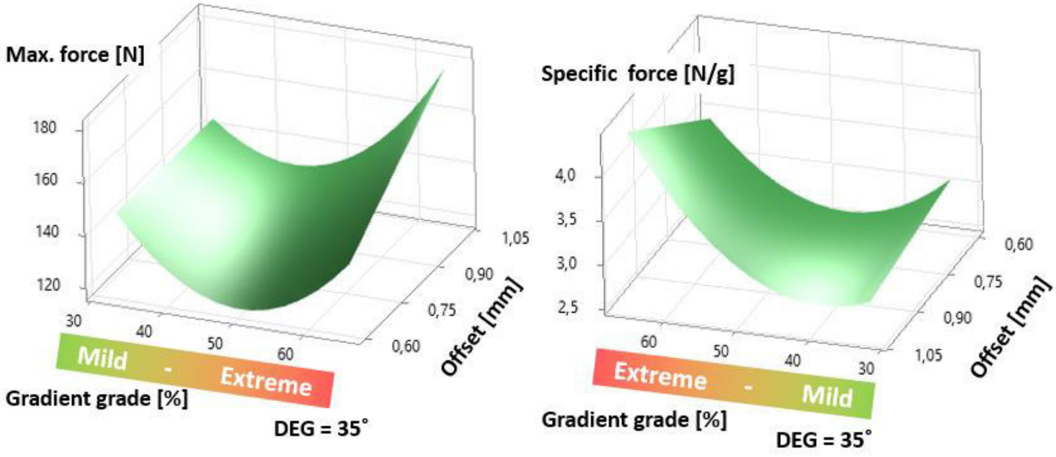

Figure 9. Maximum compression force values

3.3 Absorbed energy and specific absorbed energy:

Absorbed energy is defined by the area under the force – displacement curve, the calculated values are shown on Figure 10. The horizontal gradient design has a negative effect on absorbed energy, which is not necessarily surprising, considering that the specimens with grater gradient grade are lighter (see Figure 5). For a more equal comparison the specific energy absorbed (SEA) should be considered. The right side of Figure 10 illustrates these SEA values, indicating that gradient design has no significant effect on absorbed energy. It can also be stated that at almost all cases specimen 06.30 has the greatest value. This phenomenon can be explained by the geometrical layout of the specimen, figure 10 also shows that this specimen consists of almost straight lines, while the others (for example 06.40) have a much different shape. Straight lines inhibit deformation (until buckling) while in other cases the shape of the specimen predefines the deformation path.

Absorbed energy values were also plotted in 3D, see Figure 11. As one can see, the offset parameter has little to no effect on the absorbed energy, although decreasing the *"offset"* value results in slightly greater energy absorption capability. On the other hand, decreasing the *"deg"* parameter value greatly improves the absorbed energy value.

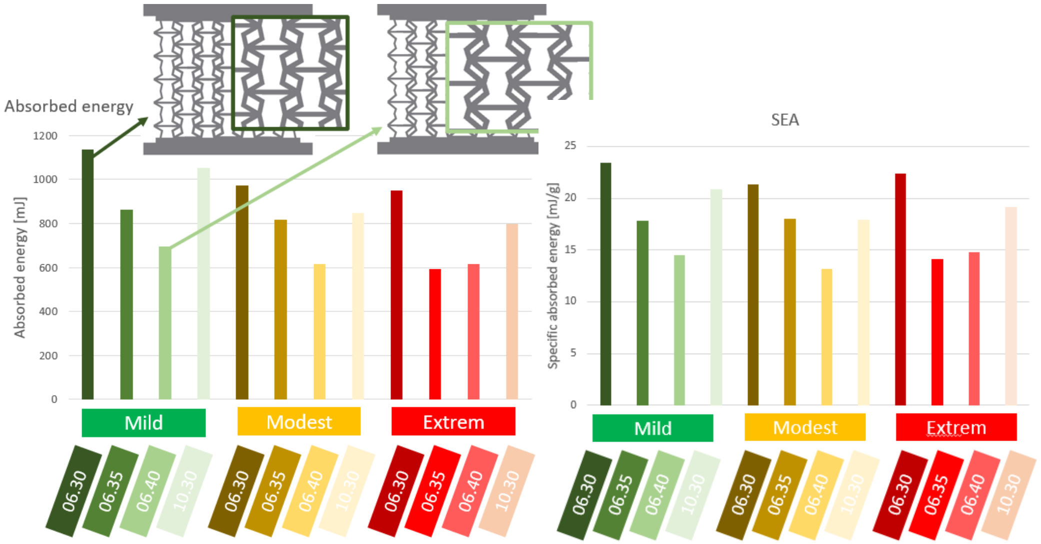

Figure 10. Absorbed and specific absorbed energy values of the studied specimens.

At bottom section of Figure 11, the specific energy and maximum absorbed energy values are displayed as a function of gradient grade, gradient grade having little effect on the specific absorbed energy and negative effect on the total absorbed energy value.

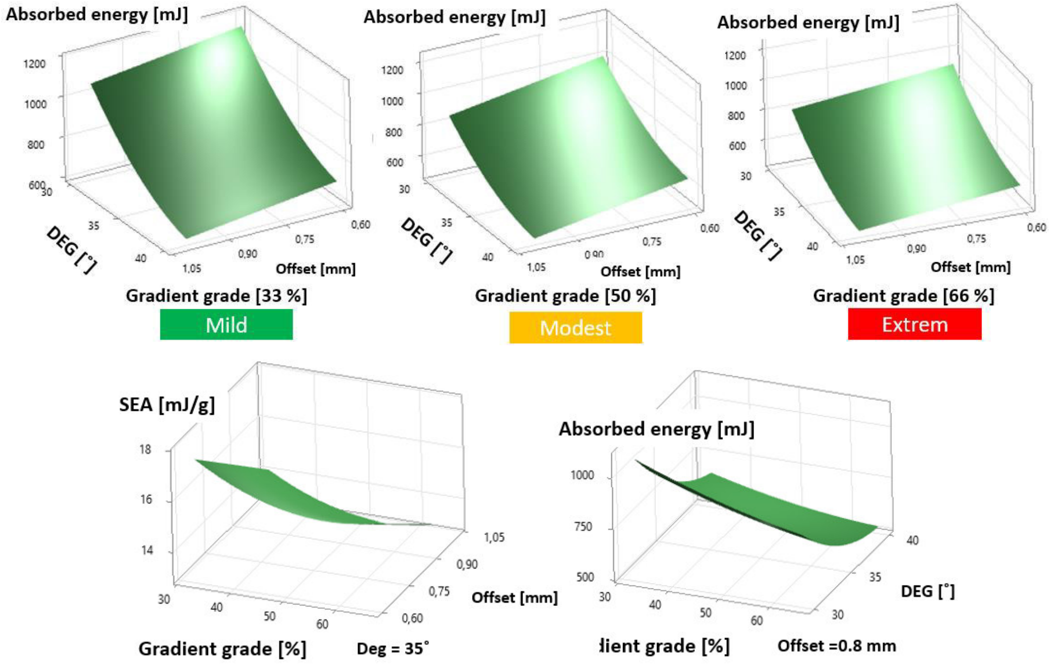

Figure 11. Absorbed and specific absorbed energy values of the studied specimens.

4. Conclusion:

In conclusion the horizontal symmetrical gradient design is not a widely researched, promising way of improving certain parameters of Lattice structures. Although our present research did not achieve the desired objective, the following conclusions can be drawn:

- The horizontal gradient design overall did not achieve the desired parameter independent continuous auxetic deformation behavior for the novel doubly re-entrant honeycomb unit cell.
- Extreme gradient design increases the maximum compressive force.
- Increasing the gradient grade decreases the energy absorption capacity of the specimens.
- Decreasing the "deg" parameter results in increased energy absorption
- Solely the extreme gradient design improved the deformation behavior of the specimens, however the manufacturability of such specimens is difficult.
- The effect of gradient design can be investigated at higher specific deformations.
- It may be of interest to investigate the effect of horizontal gradient design on other samples that behave auxetically by default.

Acknowledgments

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5. References

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