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Determination of the optimal FEM test environment for the characterization of large deformation Lattice behavior for 2.5 dimensional structures

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Abstract

Selecting the optimal Lattice structure for a certain application is a complex task, which requires knowing the behavior of a plethora of structures. Homogenization is a powerful tool that can provide us with the required information without having to analyze complex structures filled with even more complex Lattice structures. The homogenization method, unfortunately, has its limitations, one of which is its inapplicability for large deformation. In this study, we investigate the optimal test environment for the characterization of large deformation Lattice behavior.

Keywords: Lattice, homogenization, large deformation

1. Introduction

Recent advances in additive technologies granted Engineers unprecedented design freedom. Not only can complex, previously unfeasible geometries be designed, but structures with infill, Lattices can also be manufactured. Lattices can be implemented into a design for a plethora of reasons, such as improved energy absorption, lightweighting, improved thermal properties, etc. It is not the wide range applicability of Lattice structures that makes them so unique but the achievable behaviors. This is where the miracle ends. Selecting and designing the appropriate Lattice structure with the appropriate parameters and then inserting it into our 3D CAD model are challenging tasks that are fundamental to achieving an optimal design.

In this paper, we will focus on the "bedrock" of selecting and designing the optimal Lattice structure, which is the characterization of Lattice structures. In order to choose the optimal structure, first, its properties and behavior characteristics must be known. Simulating complex lattice structures is difficult and time-consuming; thus, several homogenization methods are created.

The homogenization method is based on the idea that a heterogeneous medium can be characterized by the properties of the Representative Volume Element (RVE) [1]. In the case of Lattice structures, the RVE is the unit cell, as a region is filled by allocating unit cells along the x, y, and z axis – depending on the application. The concept of Homogenization can be seen in Figure 1. With homogenization, we only need to study/simulate the behavior of a single unit cell, and the results can be extended to the entire Lattice filled region, obviously. Homogenization has its limitations as well.

For simpler 2.5-dimensional Lattice structures, there were attempts to model the elastic deformation of these structures. Beam theory was used on the standard and the auxetic honeycomb structure to define its behavior [3].

The model is quite simple and does not require large computation power. However, only valid for small deformation and low density.

There are several homogenization methods for 3-dimensional Lattices, one of the methods is defined for 3-dimensional beam-based lattices [3]. This method is applicable to more complex lattices as well, as long as they are beam based.

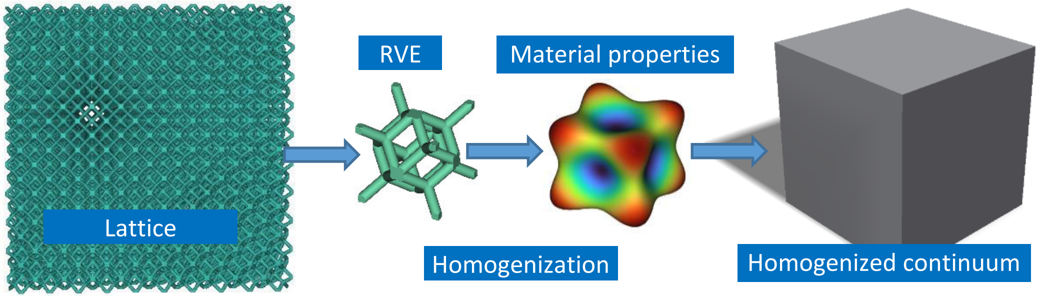


Figure 1. The concept of the homogenization approach

Homogenization, in general, can be considered accurate if the homogenized continuum under investigation consists of infinite unit cells. The method will yield the same results regardless of the number of elements. Studies [2] showed that homogenization can be considered accurate enough for compression load if there are 6 or more elements in one direction. In our case, as we will describe in this study later, far fewer elements can be fitted to the design.

Software, such as Ansys's Material Designer module, offers a homogenization method as well. For a 3-dimensional unit cell the software will create 6 separate load cases to determine 9 individual material constants (3 Poisson ratios, 3 elastic moduli, and 3 shear constants) [6]. This method is only valid for small deformation and an infinite number of elements.

2. Methods and materials

2.1 The scope of this study

Our aim was to determine the minimum number of elements that can represent the behavior of infinite elements accurately enough. In our project, we design passive safety elements for vulnerable road users for a variety of vehicles. During unfortunate road accidents, vulnerable road users experience immersed force and acceleration loads. These loads should be absorbed by the system we design. The absorption of energy, force, and acceleration happens under milliseconds, resulting in relatively large deformations on the safety elements. Furthermore, any product you install into a vehicle takes up space from the passengers resulting in a less comfortable travel experience. Thus, when designing the elements, we also have to consider certain dimensional constrains. The maximum enclosing depth dimension is defined at 5 cm.

In light of the above, our task is to determine the minimum number of elements that can represent the behavior of infinite elements, which are subjected to relatively high deformation with the maximum height of 5 cm.

First, an etalon specimen was created, forming the base for result evaluation. The etalon was created so that it has "infinite" elements. For the study, we created specimens with 7 (6) *(horizontal)* by 5 *(vertical)* elements, 5 (4) (horizontal) by 5 *(vertical)* elements, and a specimen with 5 (4) *(horizontal)* by 3 *(vertical)* elements. The etalon alongside the investigated specimens can be seen in Figure 2.

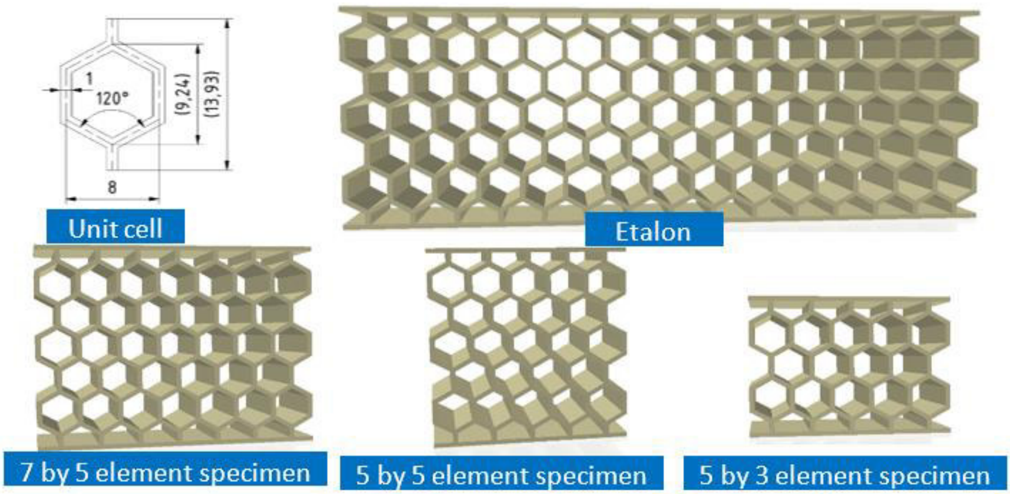


Figure 2. Unit cell dimensions and the investigated specimens

Based on the results, we can determine which of the above specimens can accurately represent the etalon so that we can carry out simulations on other Lattice structures with the determined element number. Our aim is to build a decision preparation database upon which the appropriate Lattice structure can be selected for certain applications. For determining the FEM test environment, the standard honeycomb structure was selected, with the dimensions shown in Figure. 2. The dimensions are given in [mm] unit.

2.2 FEM simulation

The energy-absorbing passive safety elements are subjected to compressive load during an accident, thus, in the finite element method (FEM) simulations, the specimens are also subjected to compressive load. For the FEM simulations, Ansys Workbench 2022 R2 software was used, and the studies were completed in static structural systems; large deformations were allowed.

The load is displacement-based, exerting its effect on the top edge of the specimens, as can be seen in Figure 3. The load is step applied to achieve a more reliable convergence and to obtain the results at several points. The bottom edge of the specimens is fixed rigidly. Vertical and lateral displacements are not allowed. Considering that the specimens are 2,5-dimensional 2-dimensional FEM simulations were created, further decreasing the simulation time.

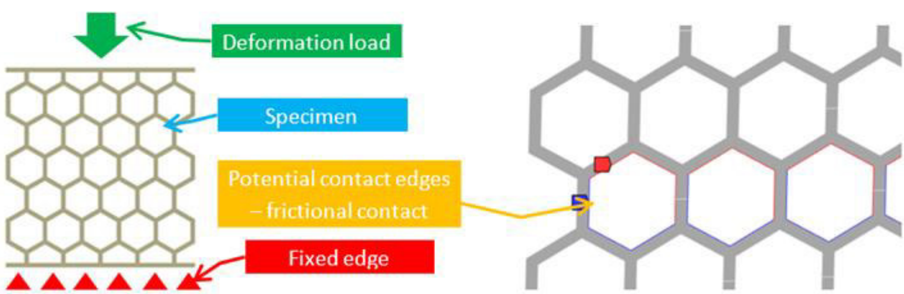


Figure 3. FEM model with boundary conditions.

As the deformation load progresses, the specimens will distort, and considering the large deformation load certain edges of the specimens will come into contact with one another. For the potential contact regions, frictional contact pairs were defined with a friction coefficient of 0,3 (polyamide – polyamide) [5]

Under real conditions, the passive safety elements will be manufactured by implementing additive technologies. On that note, HP's PA 12 material was set for the simulations, the material parameters were obtained from a recent study [7], and a bilinear material model was used. The tests were carried out until the central unit cell was fully flattened out in all cases, which meant a 10 mm deformation between the marked lines in Figure 4.

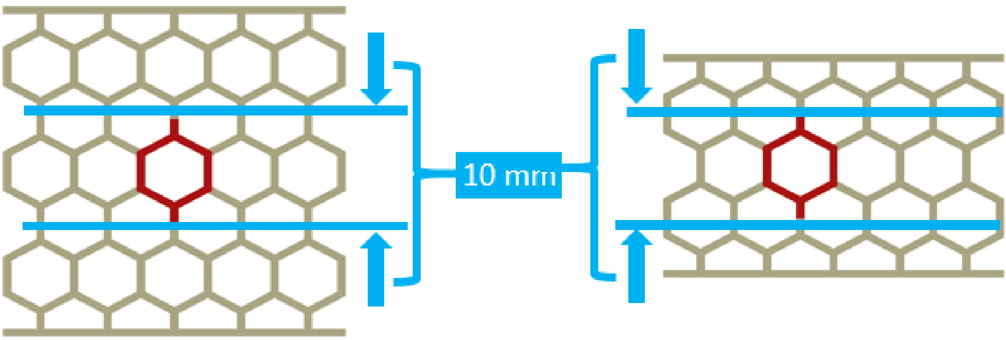


Figure 4. Representing the two control points for the deformation load

2.3 Basis for comparison and evaluation

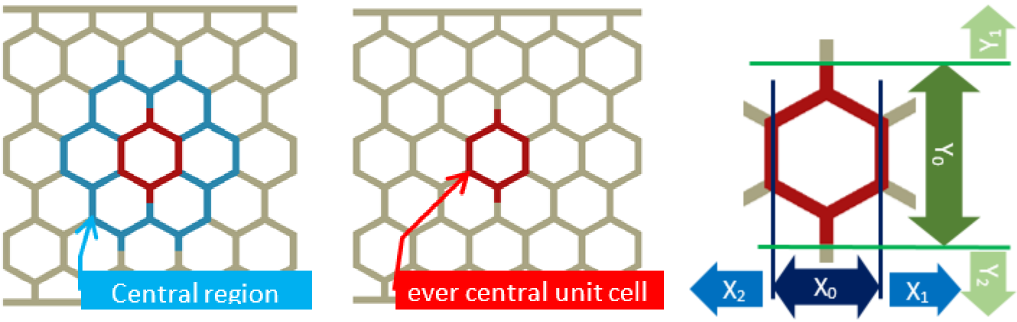
The basis for comparing and evaluating the results was the ever-central unit cell and the central region (Fig.5.a), to be more specific the Poisson's ratio of these elements/regions in the function of the deformation. The absorbed force was also considered for evaluating the results.

The passion ratio was calculated using the following equation:

$$\mu = -\frac{\varepsilon_x}{\varepsilon_y} \tag{1}$$

Where ε_x is the specific displacement in the x direction, while ε_y is the specific displacement in the y direction, as shown in Figure 5.b The specific displacement can be calculated by using equation (2) and the displacement data from the simulations illustrated in Figure 5.b

$$\varepsilon_x = \frac{\Delta x}{x_0}; where\ \Delta x = \frac{x_1 + x_2}{2} \tag{2}$$



a) *b)*

Figure 5. a) representation of the central regions, forming base for the evaluation; b) deformation components used to calculate the Poisson's ratio

3. Results and discussion

The results of the FEM simulations were first evaluated on the ever-central unit cell, as can be seen in Figure 6. At smaller deformation levels, the specimens with a smaller number of elements seem to be more accurate; however, as the deformation progresses, the 5 by 5 and the 5 by 7 specimens are more accurate at characterizing the behavior of Lattices.

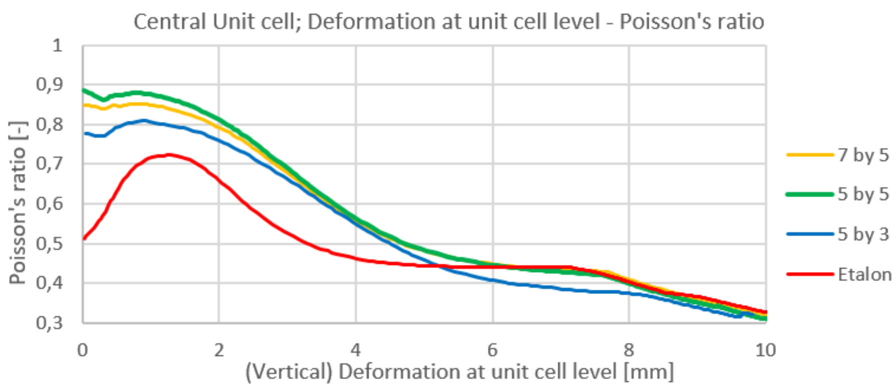


Figure 6. Poisson's ratio as a function of deformation at unit cell level

Considering the central region, which is a wider, a more specific region, it can be seen in Figure 7. that overall, the 5 by 5 and the 5 by 7 specimens follow the etalon specimen's behavior most accurately.

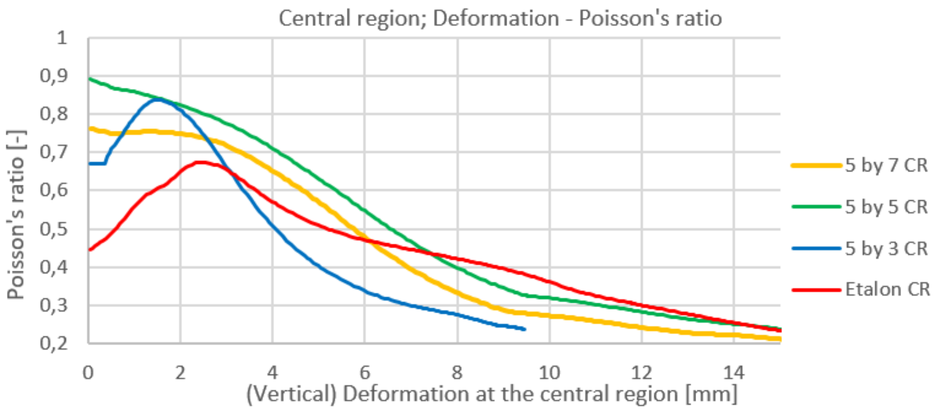


Figure 7. Poisson's" ratio as a function of deformation, evaluated on the central region

By analyzing the evolution of the force as a function of displacement, it can be noted that the 5 by 7 and the 5 by 5 specimens represent the etalon specimen's behavior most accurately (see Fig. 8). Obviously, the specimen with the least number of elements will be selected for representation.

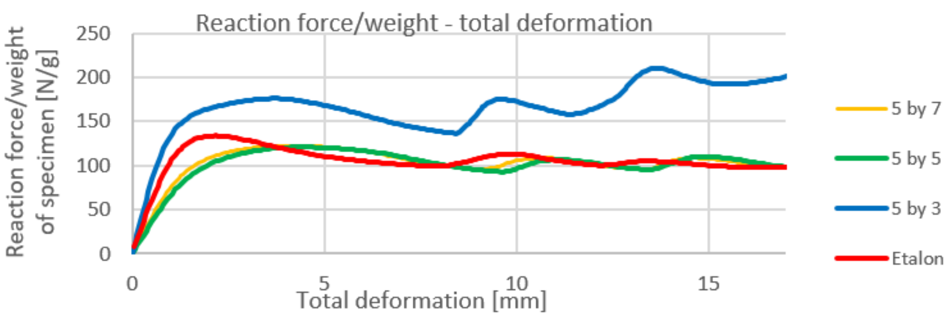


Figure 8. Reaction force as a function test environment

It can be concluded that 2.5-dimensional, non-auxetic Lattice structures subjected to large deformation can be characterized by only preforming simulations on a smaller specimen consisting of 5 by 5-unit cells. It should be noted that further studies will be carried out to further validate the effectiveness of this method.

4. Conclusion

Based on the study introduced in this paper, it can be sad that Lattices subjected to large deformation can be homogenized as well with a different method. In this study, we determined the optional FEM test environment for standard (non-auxetic) 2.5-dimensional Lattice structures. The 5 by 5 element specimen will be the fundamental test environment for our decision preparation database, upon which the optimal Lattice structure can be selected for passive safety elements.

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