This is the published version of a paper presented at 9th Conference on Industrial Computed Tomography (iCT) 2019, 13-15 Feb, 2019, Padova, Italy.

Citation for the original published paper:

In-situ computed tomography investigation of the compression behaviour of strut, and periodic surface lattices
In: Rolf Diederichs (ed.), iCT 2019

N.B. When citing this work, cite the original published paper.

Permanent link to this version:
http://urn.kb.se/resolve?urn=urn:nbn:se:oru:diva-72514
In-situ computed tomography investigation of the compression behaviour of strut, and periodic surface lattices

Anton Jansson\textsuperscript{1}, Lars Pejryd\textsuperscript{1}

\textsuperscript{1}Örebro University, fakultetsgatan 1, 701 82 Örebro, Sweden, e-mail: anton.jansson@oru.se, lars.pejryd@oru.se

Abstract

In this work the effects of fabrication errors in the Body Centered Cubic strut lattice, and the periodic surface lattice Schwarz Diamond has been investigated. The lattices were both fabricated as-is and with induced errors to evaluate the lattices response to fabrication errors. The behaviour of the lattices were studied using compression test and in-situ computed tomography investigation. The results show that the Schwarz Diamond lattices in general are stronger than the Body Centered Cubic lattices in all of the measured aspects. Often up to five times stronger. It was also found that the elastic behaviour of the Schwarz Diamond lattices were mainly unaffected by fabrication errors while the Body Centered Cubic lattices experienced severe losses in performance. The behaviour of the lattices under compression could be followed using computed tomography which aided in the understanding of their behaviour.

Keywords: Additive manufacturing, computed tomography, periodic surface lattices, in-situ compression, fabrication error

1 Introduction

Additive manufacturing (AM) has brought upon a shift in the fabrication industry where it is now possible to lighten almost any component with the use of lattice structures. The lattice structures provide a high stiffness to weight ratio and can be included anywhere in AM parts, providing great flexibility in design options. Typically, the lattices that have been used so far in components are based on struts and vary from simple cubic lattices to topology optimized lattices that alter their shape to increase the stiffness to weight ratio \cite{1}. In recent years a new contender for the strut lattices has appeared in the periodic surface lattices (even though the concept has been around for a long time \cite{2}). These lattices are made up from a single surface that wraps around itself to create a cubic surface lattice structure. The surface networks appears to be stiffer than the strut lattices but they could also provide a higher redundancy to fabrication errors \cite{3}. Pores and inclusions present in a thin strut reduce the load bearing capability of that strut significantly, while the same defect in a surface lattice is likely to behave differently. Further, it is less likely to experience problems during the fabrication of a surface due to rake interaction and thermal stress than it is when fabricating a strut. An illustration of the fabrication of strut vs surface can be seen in figure 1.

![Fabrication of a strut vs surface](image1)

Figure 1: a) Fabrication of a strut in a power-bed. The structure is exposed to both heat accumulation as the main conduction of heat travels through the thin strut. It is also exposed to rake interaction that can distort the strut b) Fabrication of a surface in a powder-bed. The structure can conduct heat through an entire wall. The structure is also more resilient to rake interaction as it is less likely to bend.
In recent years the periodic surface lattices have started to receive interest from researchers but the use in industry is still scarce [4]. Inspecting the behaviour of lattices is a challenging task as the field of view is obstructed as to what is occurring inside of the lattice. However, using computed tomography (CT) it is possible to follow and study the behaviour of an entire structure through its deformation [5]. In this work, the difference of behaviour between the strut and surface lattices are investigated with respect to the effect of fabrication errors. This was done to confirm the hypotheses that surface lattices have a higher redundancy towards fabrication errors than the strut lattices. Following this introduction is a short description of the methods used and the results that were acquired.

2 Materials and Methods

This section is divided into two sections, the first describes the structures and materials used in this study as well as how errors were distributed throughout the structures. The second section describes how the structures were tested and investigated.

2.1 Materials and design

Two structures were investigated in this study, the Body Centered Cubic (BCC) lattice and the Schwarz Diamond (Schwarz D) lattice. The BCC lattice is comprised of struts while the Schwarz D lattice consists of periodic surfaces. The structures were designed to have a relative density of 12.5%, this resulted in a strut diameter of 0.69 mm in the BCC lattice and a surface thickness of 0.27 mm in the Schwarz D structure. The unitcells, dimensions, and overall design can be seen in figure 2.

The material, and fabrication process, chosen for this study was the FullCure 720 photopolymer material printed with the PolyJet method in an EDEN250 printer. This process was chosen as it allows for highly accurate prints (layers can be produced as thin as 15 µm) so that defects could be controlled with high accuracy. Each of the structures were printed in four editions, as is, and with three different error distributions. The errors were placed randomly using the following schemes, figure 3.

An error in the BCC structure was introduced as a cut in a truss or vertex point with the thickness of 0.27 mm (the thickness of the surface structure). An error in the Schwarz D structure was introduced as a cylindrical hole normal to the surface with a
Figure 3: Illustration of the error placement in the lattices a) The position annotation for the errors in the BCC lattice. On top there is a side view of the lattice with the dashed lines indicating layers of cross-section. Beneath there are three cross-sections indicating where the errors are placed in the structure b) The error locations in the Schwarz D lattice. On top there is a side view of the lattice indicating the positions of cross-sections. Beneath there are cross-sections indicating where the errors were placed in the lattice.

diameter of 0.67 mm (the diameter of a strut). The errors were uniformly distributed randomly, the distributions can be seen in figure 4. For each of the error distributions (and the as-is structure) two structures were printed and evaluated.

Figure 4: Schematic of the distribution of errors in the BCC and Schwarz D lattices.
2.2 Evaluation
The first set of structures were compressed outside of the CT machine with a compression test at a displacement speed of 2 mm/min using a Lloyd LR 50K. The results from these compression tests were then used to decide at which deformation steps to evaluate the structures in the in-situ tests. In the in-situ testing each of the structures were scanned four times, once unloaded, once close to the yield point, and finally once in the plastic region. The in-situ compression was performed in a SkyScan 1272 with a voxel size of 9 $\mu m^3$. The evaluation of the CT data was performed in VGstudioMAX 3.0.

3 Results
The results from the compression test performed outside of the CT equipment can be seen in table 1 and figure 5. The energy needed for the deformations were also calculated of each of the structures and can be seen in table 2, this is important for impact attenuation.

Figure 5: Compression test results from the Schwarz D and the BCC lattices. The results show the compression of the as-is structures together with the lattices with induced errors.

From the results it can be seen that, in general, the Schwarz D lattices all achieved a higher max load, stiffness, and energy absorption than the BCC lattices. The differences in max load capacity for the Schwarz D lattices were almost negligible while for the BCC lattice they were as high as 30%. When comparing the max load of the Schwarz D lattices and the BCC lattices it can be seen that the max load that the Schwarz D lattices could withstand was more than 5 times higher than the BCC lattices. The differences in stiffness for the Schwarz D lattices was also small, and for one of the error distributions it was even higher than the as-is structure. In the BCC lattices the differences in stiffness were significant, consistently showing a loss of around

Table 1: Results from the compression tests of the of the Schwarz Diamond and Body-Centered-Cubic structures. The results for the maximum load (before yield) and the stiffness of the structures are presented and compared between the as-is and error distributions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Max load (N)</th>
<th>Diff. (%)</th>
<th>Stiff (N/mm)</th>
<th>Diff. (%)</th>
<th>Max load (N)</th>
<th>Diff. (%)</th>
<th>Stiff (N/mm)</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-is</td>
<td>155.3</td>
<td>N/A</td>
<td>226.8</td>
<td>N/A</td>
<td>30.1</td>
<td>N/A</td>
<td>43.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Dist. 1</td>
<td>153.5</td>
<td>-1.2</td>
<td>221.4</td>
<td>-2.4</td>
<td>21.7</td>
<td>-27.8</td>
<td>9.4</td>
<td>-78.5</td>
</tr>
<tr>
<td>Dist. 2</td>
<td>152.9</td>
<td>-1.6</td>
<td>223.5</td>
<td>-1.4</td>
<td>24.9</td>
<td>-17.2</td>
<td>7.4</td>
<td>-82.9</td>
</tr>
<tr>
<td>Dist. 3</td>
<td>151.7</td>
<td>-2.4</td>
<td>240.3</td>
<td>6.0</td>
<td>21.1</td>
<td>-29.9</td>
<td>6.4</td>
<td>-85.4</td>
</tr>
</tbody>
</table>

Table 2: The energy required to compress each of the structures to 50% deformation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Energy (mJ)</th>
<th>Diff. (%)</th>
<th>Energy (mJ)</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-is</td>
<td>791.1</td>
<td>N/A</td>
<td>228.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Dist. 1</td>
<td>790.5</td>
<td>-0.1</td>
<td>121.9</td>
<td>-46.6</td>
</tr>
<tr>
<td>Dist. 2</td>
<td>713.4</td>
<td>-9.8</td>
<td>181.3</td>
<td>-20.5</td>
</tr>
<tr>
<td>Dist. 3</td>
<td>735</td>
<td>-7.1</td>
<td>135.4</td>
<td>-40.6</td>
</tr>
</tbody>
</table>
Figure 6: CT volumes from the compression of the, as-is, Schwarz D lattice a) 0% deformation b) 2.8% deformation c) 8% deformation d) 20% deformation.

80 % stiffness. This can also be seen in the results displayed in figure 5 where the elastic behaviour of the Schwarz D lattices are highly similar while the opposite can be said for the BCC lattices. Comparing the stiffness between the Schwarz D lattice and the BCC lattices show that the stiffness of the Schwarz D lattices were more than 5 times higher than that of the BCC lattices. In the energy absorbing perspective the results are again that the Schwarz D lattices show significantly higher values. In the case of the as-is structures the Schwarz D lattice absorbed almost 3.5 times more energy than the BCC lattice. The loss in energy absorption was also lower in the Schwarz D lattices compared to the BCC lattices when errors were induced.

Figure 7: Slices from the Schwarz D volumes for each deformation step a)-d) shows the compression of the as-is structure e)-h) shows the deformation of the dist. 1 structure i)-l) shows the deformation of the dist. 2 structure m)-p) shows the deformation of the dist. 3 structure. The dashed red lines highlights the behaviour of the surface.
Figure 8: CT volumes from the compression of the, as-is, BCC lattice a) 0% deformation b) 2.8% deformation c) 8% deformation d) 20% deformation.

From the compression behaviours found in figure 5 it was decided to perform the CT investigations at the following deformations: 0%, 2.8%, 8%, and 20%. Both the Schwarz D and the BCC lattices were investigated at these deformations. The general compression behaviour of the Schwarz D lattice can be seen in figure 6.

To analyse the behaviour of the lattice a slice was selected at the same position in each volume. The slice was selected to be normal to one of the sides of the lattice. This slice, from all of the Schwarz D lattices, for all deformations, can be seen in figure 7. From the slices it can be seen that the behaviour of the structure in the elastic region seems to be the same in the as-is structure as in the ones with induced errors. Once the structures reach their peak loading capacity the behaviour change. In the final

Figure 9: Slices from the BCC volumes for each deformation step a)-d) shows the compression of the as-is structure e)-h) shows the deformation of the dist. 1 structure i)-l) shows the deformation of the dist. 2 structure m)-p) shows the deformation of the dist. 3 structure. The dashed red line highlights the behaviour of the trusses and vertex points.
9th Conference on Industrial Computed Tomography, Padova, Italy (iCT 2019)

deforamation slice it can be seen that all of the structures have gone through the plastic deformaton differently. The general compression behaviour of the BCC, as-is, lattice can be seen in figure 8. To analyse the behaviour of the lattice a slice was selected at the same position in each volume. This slice was selected as a diagonal passing through the centre of the lattice. The slice, from all of the BCC lattices, for all deformations, can be seen in figure 9. In the BCC slices it can be seen that the behaviour of the lattices is different already in the elastic region. The behaviour continues to be different for lattices throughout the deformation.

4 Discussion

The mechanical results show that the Schwarz D are stronger than the BCC lattices in general when it comes to all aspects that were measured. In both maximum load and stiffness the Schwarz D lattices were up to 5 times stronger than the BCC lattices. In energy absorption the difference was a factor of 3. When errors were induced into the lattices it could be seen that the elastic behaviour of the Schwarz D lattices were almost unchanged. For the BCC lattices the loss of strength was, however, severe. Inspecting the CT data it can be seen that the behaviour of the Schwarz D lattices in the elastic region is the same, regardless of errors. For the BCC lattices the behaviour is changed depending on errors. The reason for this is that the Schwarz D lattice is a continuous surface that for each "layer" of the structure carries the load over an entire, connected, surface. This gives the structure the ability to redistribute the load over this surface if there is an error somewhere in the plane. This causes even larger defects to have a small impact on the elastic behaviour of the structures. However, during the plastic deformation the errors seem to have an effect on the behaviour of the structures. This is likely caused by stress concentrations around the defects that shifts the initiation points for buckling of the surface.

In the case of the BCC lattices an error in a truss causes the truss to completely lose the capacity to carry load. This causes the behaviour of the lattice to be changed even in the elastic region as there will be regions in the structure that offer no resistance to the initial compression.

It is difficult to make "fair" comparisons of fabrication errors in these lattices as they are highly different in their geometrical structure. To some extent, the errors induced in this work might favour the Schwarz D lattices in an unfair way as they were designed in a way that allowed a broken truss to be supported by the truss underneath it. If the errors had been placed in a lateral fashion instead this effect would have been prevented. However, layered type of defects are the most likely to appear in the powder AM processes where the defects can be caused by uneven powder layers and rake/part interaction.

5 Conclusion

The aim of this work was to study the behaviour of the Schwarz D, and BCC lattice. Both in the as-is state but also when subjected to induced fabrication errors. It was found that the Schwarz D lattice in general was stronger, stiffer, and could absorb more energy than the BCC lattice. For most of the measured aspects the Schwarz D lattice was more than 5 times better than the BCC lattice. It was also found that the elastic behaviour of the Schwarz D lattice was the same independent of the induced errors. This was not the case for the BCC lattices. This could be seen both in mechanical results and in the CT results.

Thus it can be concluded that the Schwarz D lattice has a high redundancy towards fabrication errors while the BCC lattice does not.

References


