Non-Stochastic Lattice Structures for Novel Filter Applications Fabricated via Additive Manufacturing

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Abstract

Non-stochastic lattice structures are widely used in a variety of applications such as biomedical implants and heat exchangers. However, the utilisation of these structures for filtration applications is rather new. Additive manufacturing techniques such as selective laser melting allows lattice structures to be bespoke depending on the type of filter and its intended function. This study considers the flow characteristics and structural strength of a disc filter with a layer of repeated 1.8 mm lattice unit cell as the filter mesh. Computational fluid dynamics simulation is used to analyse the pressure and flow velocity across the filter, while finite element analysis is utilised to analyse the structural characteristics of the lattice mesh under fluid load. The results show a minimal decrease in pressure and small increases in velocity, with the mesh capable of withstanding higher loads. The ultimate failure load of the structure is also determined. These findings indicate that more layers of lattice structures could be used as filter mesh and the flexibility of AM allows the filter properties to be tailored as required for a given application.

Keywords

Non-stochastic lattice structures; Filter applications; Additive manufacturing; Selective laser melting; Customisation

1 Introduction

Cellular metals, also known as metal foams, can be described as solid metals exhibiting cellular structures that form void spaces called pores. These pores take a large volume fraction of the overall structure, which leads to the high porosity characteristic of metal foams. In general, there are two broad categories of metal foams, stochastic (random) and non-stochastic (periodic) geometries [1]. Briefly, stochastic foams have random variations in the shape and size of the cells, where in contrast, periodic cellular structures have repeating lattice structures and can be categorised by their shapes and sizes. Cellular metals have some unique characteristics that make them superior to solid metals. They are lightweight structures with low densities, but they have good strength relative to their weight. These structures also exhibit high surface-to-volume fractions. The characteristics above make certain applications like impact energy absorbers, silencers, heat exchangers, filters and biomedical implants more feasible [2-6]. Non-stochastic metal foams are more preferable as they do not have imperfections such as random variation of cell sizes and shapes. Furthermore, they exhibit better mechanical properties in comparison to stochastic metal foams.

For the past few years, additive manufacturing (AM) technologies have progressed swiftly, and now there are a few processes that focus on near net shape fabrication of metal parts using a layer-based approach. Processes such as Electron Beam Melting (EBM), Laser Engineered Net Shaping (LENS) and Selective Laser Melting (SLM) allow non-stochastic cellular metal structures to be fabricated with any cell shape or geometry, as designed in CAD software. Hence, lattice structures, materials and properties can now be customised, optimised and fabricated in a bespoke manner relative to a product's particular performance specification. One such application that will benefit from the rapid growth of AM technologies is filter fabrication.

Traditionally, metal filters are manufactured using perforated plates, mesh and wedge wire, while others undergo subtractive process such as cutting, punching, rolling and welding [7-9]. However, recently, Banhart [7] and Vijayakumar *et al*. [10] has suggested that AM technology such as SLM could be used not only as an alternative manufacturing process, but also in improving the filters efficiency and in reducing manufacturing costs. Thus, the objective of this research is to design filters with non-stochastic lattice structures and studying their effects both through simulation and experimental study, towards flow and restriction improvement.

2 Non-stochastic lattice structures

Stochastic metal foams have been around as filters for years. They exhibit important filter properties such as fine filtration capacity, good particle retention, cleanability, mechanical properties, corrosion resistance and cost [11]. For instance, Alantum metal foam is used in industrial gas filter applications, particularly in selective catalytic reduction and volatile organic compound systems [12]. In these systems, stochastic Alantum metal foams with a large surface area work as an underlying substance that reduces the quantity of platinum group metal catalyst.

While non-stochastic metal foams fabricated via AM have been widely utilised in various applications such as heat exchangers and biomedical prostheses, only recently have metal AM processes been used to create a filter design with holes in-line to the direction of fluid flow, an improvement over perforated filter plate types [13]. As such, this has enabled the direct production of conical, in-line filter supports using SLM. The experimental results gained indicate that the power consumption is reduced by 57% and almost 53% of the original stock material could be saved by transitioning over to these alternative manufacturing processes [9]. Further studies also show that AM filters have a lower pressure drop than conventional filters for similar flow rates [10].

There are several possible challenges that are related to filter fabrication via AM with non-stochastic lattice structures. One of them is the structures accuracy and consistency. Yan *et al*. [14] has investigated the manufacturability and performance of 316L stainless steel lattice structures fabricated via SLM. The results showed that the structures were well made according to the CAD geometric data, but the struts exhibit rough surfaces with curvatures and corrugations. The struts produced are also slightly larger than the initial CAD dimensions. Besides, it was also found that SLM could not repeatedly manufacture cellular structures with a strut size of 0.5 mm, as structural defects cannot be avoided [15]. Results of another study by Kim *et al*. [16] showed that it is possible to reproduce virtually identical structures repeatedly from the same CAD data by using SLM.

Also of concern is the structural integrity of the structures. Filters are susceptible to pressure applied by the fluid flowing through them. Lattice structures with micro pores have very fine strut geometries that could easily be bent or broken. Kim *et al*. [16] found that titanium structures fabricated using SLM having struts with diameters less than 180 μm are prone to bending and breaking due to the cleaning process using jet blasting. The structural strength of metal lattices is also affected by their fabrication build angle. The limitation of build angle is illustrated in **Figure 1** below, where structures with their struts built at narrow angles with respect to the build plane showed poor structural integrity due to very small overlaps between adjacent layers [17]. Besides structural strength, the build angle also affects the support structure requirements. To negate support structure requirements in SLM, build angles greater than 45° should be used.

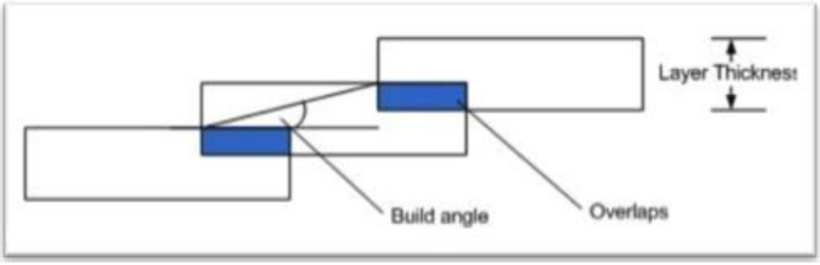


Figure 1: Overlaps between adjacent layers

Another consideration is the selection of the lattice structure design. There are numerous designs for these structures, including octahedron, hexagon and rhombic dodecahedron (**Figure 2**). These structures exhibit different mechanical properties while having similar struts and pore sizes [4]. However, other properties such as filtration capacity and flow characteristics need to be studied further. It is also possible to categorise these structures based on their best applications once the filtration characteristics have been obtained.

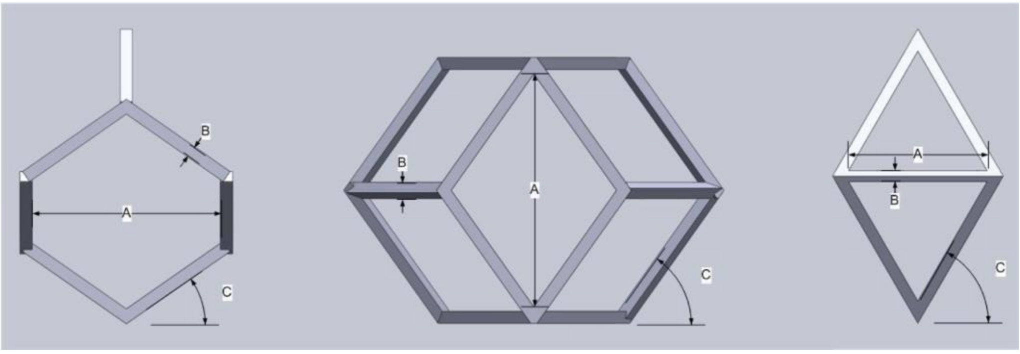
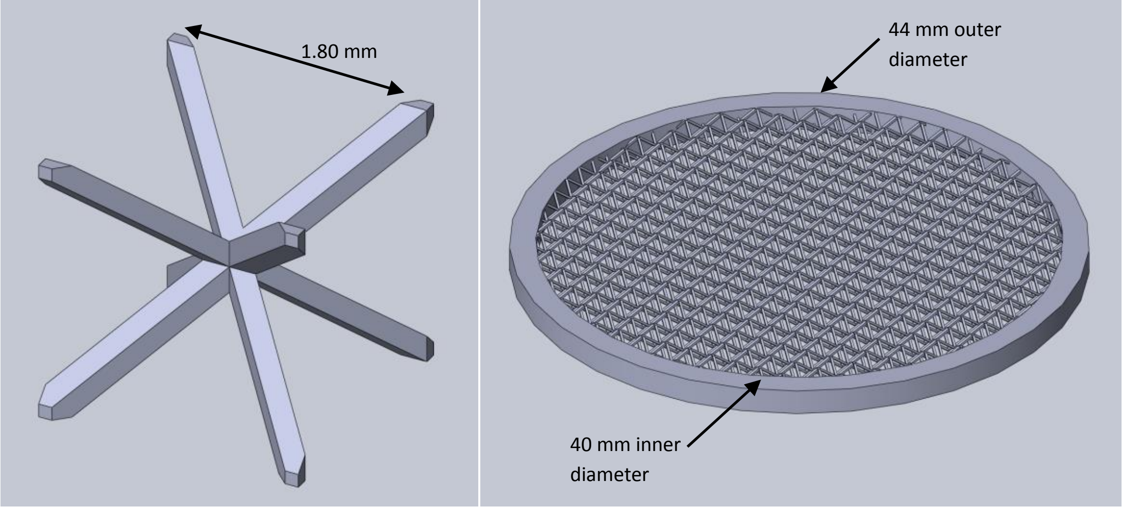


Figure 2: Unit cell characteristics for hexagonal, rhombic dodecahedral and octahedral; A is the pore size, B is the strut size and C is the build angle

3 Filter design and analysis

Functionally graded non-stochastic lattice structures have been used in other applications, for example, biomedical implants. These structures were tailored in various ways to achieve the desired mechanical properties. Previous research by Emmelmann *et al*. [18] successfully integrated a functionally graded lattice structure onto a hip endoprosthesis. This was achieved by applying mathematical equations to create the structure in the shape of a curved surface. The lattice structure was fabricated via SLM, starting with bigger pores at the bottom of the curve and gradually getting smaller towards the top.

Such customisation could be applied on filter media. By designing filters with bespoke, functionally graded, non-stochastic lattice structures, not only will the flow characteristics be altered, but the filter's strength as well. In this study, a 44 mm diameter disc filter was designed with a layer of repeated 1.80 mm lattice unit cells as the filter mesh, as shown in **Figure 3**, while **Figure 4** depicts such structures built using SLM:



(a) (b)

Figure 3: Dimensions of (a) lattice unit cell, and (b) disc filter

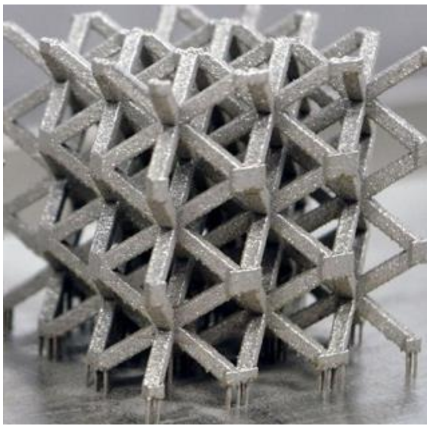


Figure 4: Lattice structures fabricated via SLM

Next, the filter design was used for a CFD simulation using SolidWorks Flow Simulation as shown in **Figure 5**. The disc filter was subjected to an inlet velocity of 1.55 m/s and atmospheric pressure in the outlet. These conditions are similar to that of [9], as the fabricated filter was to be evaluated on the same test rig, which has a maximum flow rate capacity of 500 litres/min.

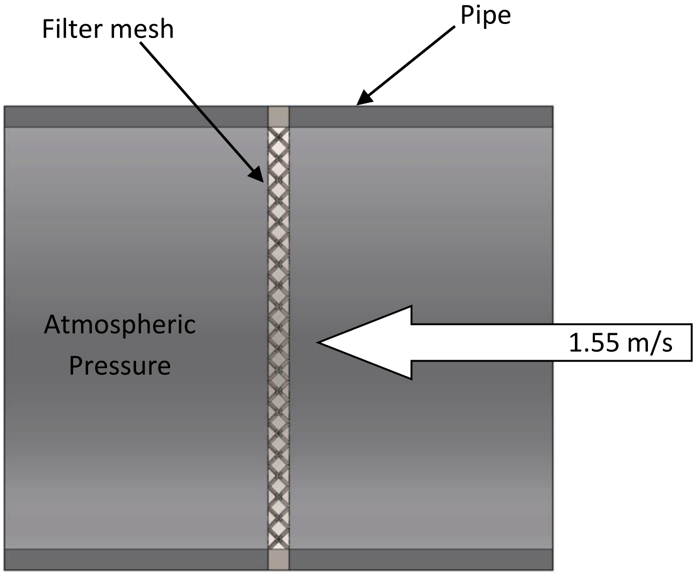


Figure 5: Flow simulation conditions of the filter

Finally, the Flow Simulation results were exported into SolidWorks Simulation for static analysis using FEA to analyse the structural characteristics of the lattice mesh under fluid load.

4 Results

4.1 Flow simulation results

The fluid flow is parallel to the axis of the filter, as depicted by **Figure 5** above. Two important characteristics of the flow simulations, pressure and velocity, have been observed in this study. Based on the pressure plot shown in **Figure 6**, the pressure drop across the filter is minimal (approximately 0.05%) and the pressure seems to be evenly distributed throughout the pipe cross-section. Observation on fluid velocity changes across the filter (**Figure** 7) indicating a small velocity increase (approximately 1.22%). These values are expected to be greater with the use of two or three layer lattice structures as the filter mesh, but these small drops in pressure and increases in velocity are crucial as they indicate the opportunity to further design such filters with minimal loss in the aforementioned characteristics. However, there is an area around the pipe wall, just after the fluid passes through the filter, which show a significant velocity drop to 0.59 m/s. Interestingly, this velocity drop does not show any significant changes in pressure.

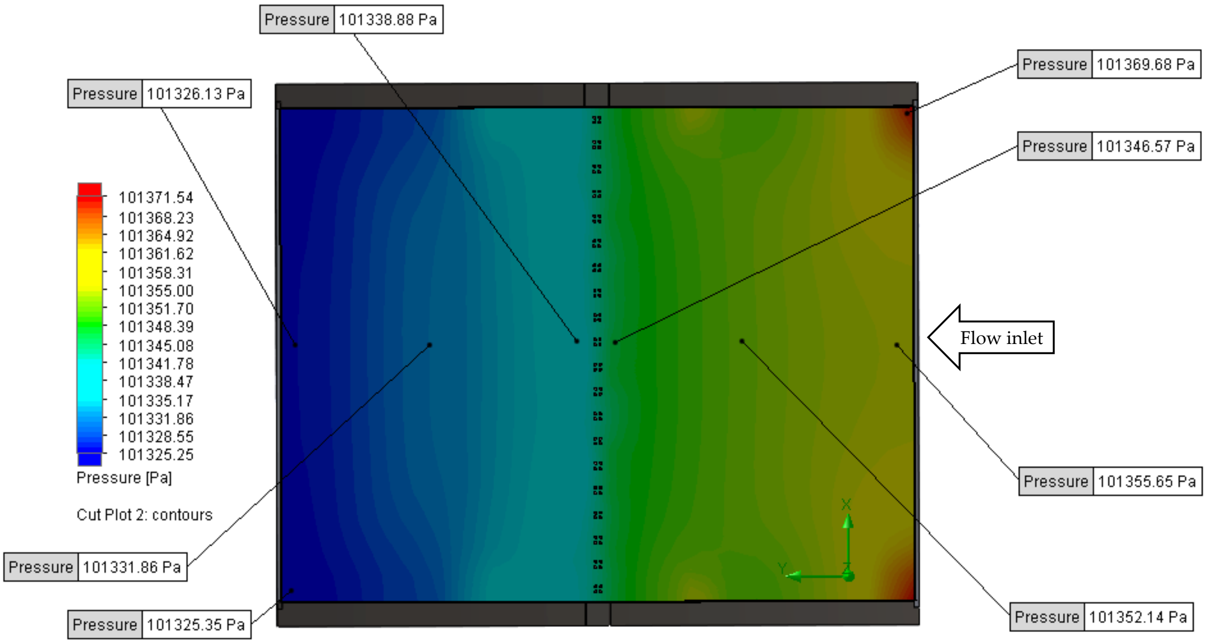


Figure 6: Pressure analysis

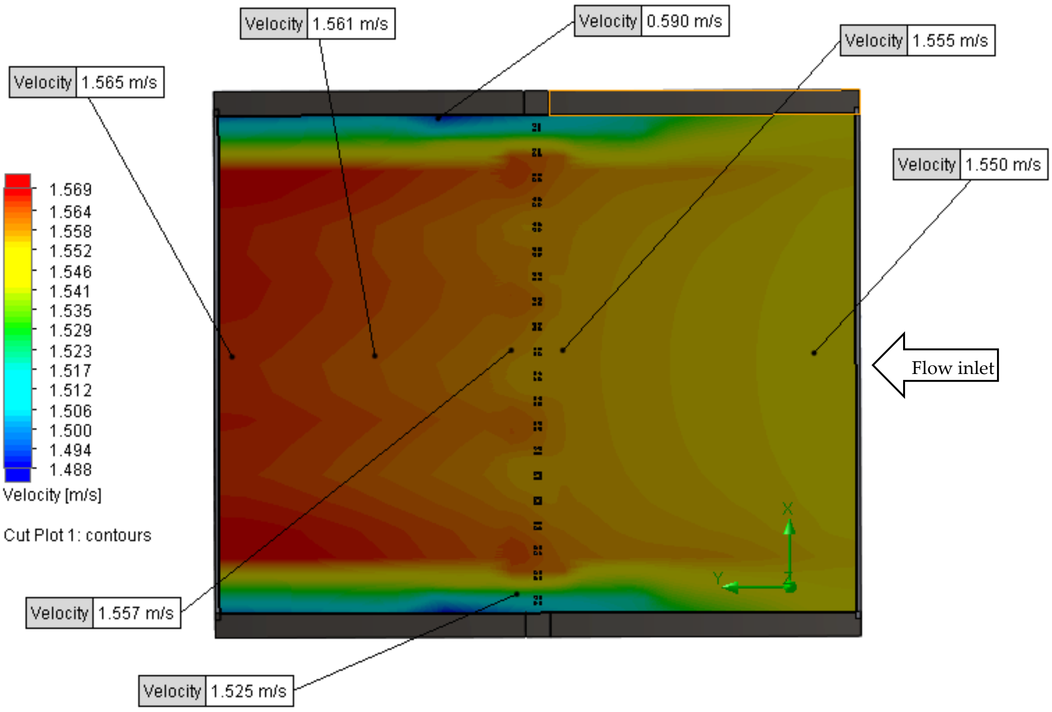


Figure 7: Velocity analysis

4.2 FEA results

A static analysis was carried out in SolidWorks Simulation using the relative load applied by the moving fluid onto the filter mesh surfaces (**Figure 8**). These load values were directly imported from SolidWorks Flow Simulation.

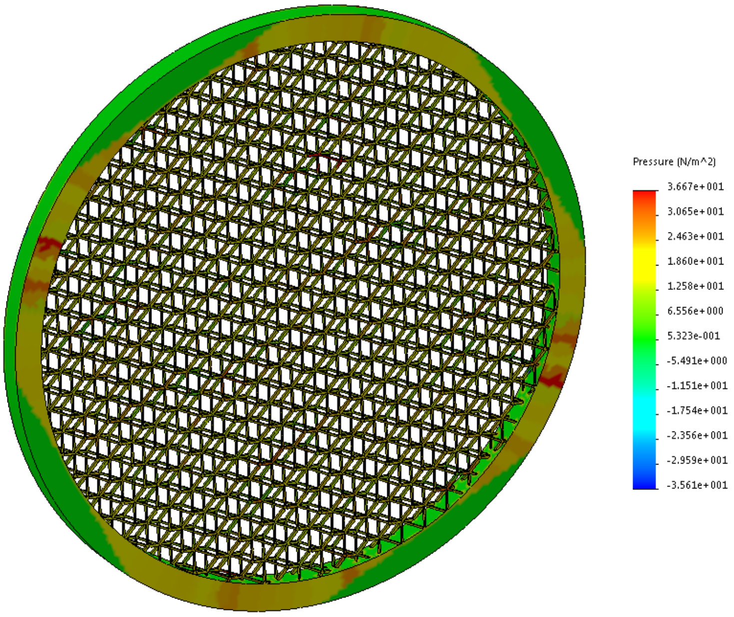


Figure 8: Pressure applied by fluid onto disc filter

The filter was also restrained on both of its flange planar surfaces. The stress distribution result is illustrated by **Figure 9** below:

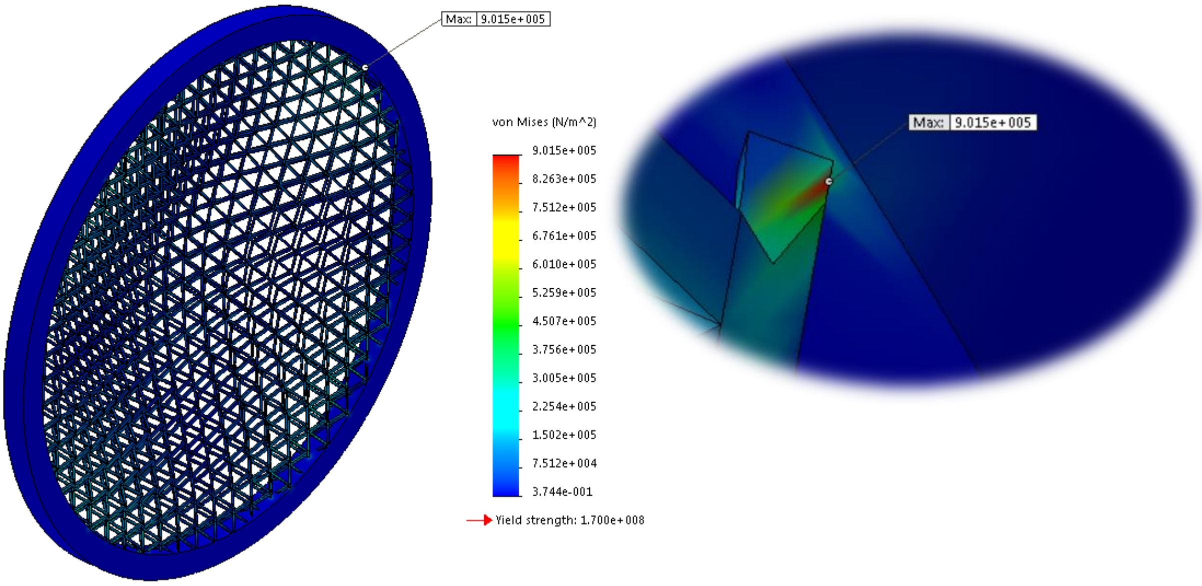


Figure 9: Stress distribution across disc filter

It is clear that the resultant Von Mises stress is concentrated on the lattice strut adjacent to the flange. Further observation shows that there are other struts that are also adjacent to the flange sharing the same condition. On the other hand, the value of the maximum stress is still significantly less than the yield strength, resulting in the factor of safety value of 187. The analysis was then run again with higher flow rates to determine the ultimate failure load of the lattice structure, which is listed in Table 1 below.

Table 1: Failure parameters of filter mesh

Parameter	Value
Flow velocity	47.55 m/s
Fluid pressure (max)	3.634×10^4 N/m^2
Von Mises Stress (max)	1.696×10^8 N/m^2
Factor of safety	1.00

Currently, the discs have been fabricated using SLM and tests are being carried out to determine the collapse pressure of the disc filter. **Figure 10** shows one of the discs which failed during the actual test.

Figure 10: Failed disc filter in collapse pressure test

5 Conclusions and future recommendation

This study has shown the possible benefits of implementing non-stochastic lattice structures fabricated using SLM AM technology as filter mesh. The simulation results indicate that this novel filter has the potential to reduce pressure drop without compromising mechanical strength. Furthermore, the flexibility of AM allows the design of the filter to be tailored to achieve required strength and filter aperture. Applying different lattice unit cell structures could also be conducted, depending on the filters application, in order that it is optimised for functional utilisation.

Immediate future work is further validation of the simulations correlated to experimental results. The collapse pressure will be measured using a customised test rig. The next step is to apply the lattice mesh on cone-type filters, and the eventual production of an algorithm for filters designed with functionally graded lattice structures, fully tailored for specific filtration applications.

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