

# Deformation Taxonomy of Additively Manufactured Lattice Structures

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## Abstract

Additive manufacturing offers opportunities for designed mechanical deformation within parts by integrating lattice structures into their designs. This work re-analyses and translates data on lattice structure deformation behaviours into a novel taxonomy, enabling their actions to be understood and controlled. Parallels between these actions and the four basic types of mechanical motion are identified. Creating a taxonomy method using these motions enables the future development of a DfAM framework that assimilates controlled anisotropy via lattices and aids the design of compliant mechanisms.

*Keywords: additive manufacturing, design for x (DfX), research methodologies and methods, controlled anisotropy, compliant mechanisms*

## 1. Introduction

Anisotropy can be defined as a materials tendency to react differently to forces applied in different directions (Huber, 2018) instead of a uniform behaviour in all directions. This is a critical consideration for form and material selection in engineering applications. Its presence is typically seen as a weakness. For example, in Additive Manufacturing (AM), mechanical anisotropy commonly occurs from lowered strength transverse to the printing direction caused by poor adhesion between the individual layers of printed material. Insufficient adhesion causes poor mechanical performance; however, it is less common in advanced AM machines (Wang et al., 2020).

### 1.1. Controlled Anisotropy in Additive Manufacturing

In this work, the term "lattice structures" refers to the external form and tessellation of an AM part's geometry. What makes lattices unique is their ability to form ideal structures that comprise of small architectures with a network of nodes and beams or struts. This format dramatically reduces weight while retaining structural integrity and giving more control over specific qualities. As a result, mechanical performance could be enhanced and use less material without weakening the part, maintaining a high strength-to-weight ratio (Loginov et al., 2019).

This work is interested in the potential for controlled anisotropic forms in AM and its utilisation in part reduction and improved mechanism reliability (Howell et al., 2013). Take a mechanical hinge, generally consisting of multiple parts. Controlled anisotropic lattice structures (AniLaSts) in AM could manufacture a single-part mechanism that still possesses the same behaviours and functionality. A compliant hinge, designed to be more flexible and deform in a controlled way that replicates that of a mechanical hinge (Loginov et al., 2019). Furthermore, AM has given lattices new levels of accessibility. AM lattice structures are far easier to produce due to control over their internal geometries with this technology ("3D Printing", 2021). Additionally, the layering style of deposition allows greater control

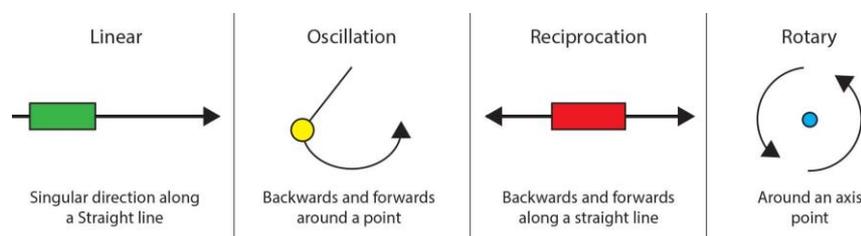
over hollow or porous sections, which are crucial for creating a network of nodes, beams, and struts within the geometry of build parts (Loginov et al., 2019; "3D Printing", 2021).

Another advantage 'AniLaSts' possess is utilising build volumes with lower material usage. As a result, lattices can improve designs by enhancing their surface area, reducing material costs but improving structure properties by stretching beams across nodes with minimal fill in-between (Zheng et al., 2014). Moreover, by adjusting the thickness and position of the nodes, beams or struts, designers can integrate some unique features related to how the component interacts with applied forces, allowing greater control over its deformation behaviours (Loginov et al., 2019; "3D Printing", 2021). Pre-existing lattice structure geometries exhibit different behaviours when exposed to similar forces (Maconachie et al., 2019). Developing our understanding of these forms, their deformation behaviour, and how they interact with each other enables the creation of process principles to include controlled anisotropy in DfAM.

## 1.2. Mechanical Motion

In mechanics, there are four basic types of motion: Linear, Oscillation, Reciprocation, and Rotary motion. Each is achieved using different mechanical means that help us understand linear motion and motion control (Donohue and Richards, 2015; "Changing speed - Mechanical devices", 2021). An explanation of these motions is listed below and illustrated in Figure 1:

- Linear motion: Moves something in a straight line, such as linear rail guides or trains.
- Oscillation motion: A curved backwards and forward movement that swings on an axis or pivot point, such as a swing or pendulum.
- Reciprocation motion: A repeated up and down motion or back-and-forth motion along a straight line, such as a piston or drawer slides.
- Rotary motion: Where an object moves around an axis, and its body moves at different distances in a given period, such as a wheel or hinge (Donohue and Richards, 2015; "Changing speed - Mechanical devices", 2021; "1-D Kinematics: Describing the Motion of Objects", 2021).



**Figure 1. The four basic motion types and their behaviours (Air and Wodehouse, In preparation)**

Understanding different lattice structure types and predicting their behaviours is crucial to the theory that anisotropy can be controlled and engineered as a benefit in AM processes (Hossain et al., 2021). Despite not being a usual classification method, these motion types present parallels with the deformation behaviours of anisotropic lattice structures in AM and thus are suitable to be adopted.

## 1.3. Compliant Mechanisms

Compliant mechanisms are flexible mechanisms that transfer an input force or displacement to another point through elastic body deformation. The idea of a compliant mechanism is to integrate controlled flexibility into a single, compact, and precise component, replacing rigid multi-part mechanical assemblies. The absence of mechanical coupling eliminates contact, play, friction, wear, lubrication, or dispersions. ("Compliant Mechanisms Explained", 2021; Howell and Midha, 1995)

The benefit of compliant mechanisms is that they can integrate different functions into fewer parts and accomplish complex tasks. However, they can also be more challenging to design (Howell et al., 2013). Therefore, understanding the deformation behaviours of AM lattice structures concerning mechanical motion and creating a classification system could aid the development of compliant mechanisms using controlled anisotropy via lattice structures. In addition, this taxonomy could be integrated into a novel DfAM framework, simplifying the process (Hossain et al., 2021; Howell et al., 2013; Ion et al., 2016).

## 2. Material and Methods

This work re-analyses and augments a database developed by the authors (Air and Wodehouse, In preparation), which addresses a deficiency in the deformation behaviour data of AM lattice structures. Re-analysis of previous work is key to this paper's contribution. Large data pools can be hard to decipher and utilise. Therefore, a classification method for translating and presenting this data was crucial in its value to designers and engineers. During testing, parallels with lattice deformation behaviours and the four basic types of mechanical motion in mechanics were identified. A taxonomy classification method was developed to link lattice deformation behaviours to the motion themes they could replicate. The impact of this finding indicates that if the deformation behaviours of the lattices can be predicted, they can be utilised to replicate mechanical motions in AM compliant mechanisms. Further, during a post-experiment re-analysis, it was discovered that there were variations of motions possible within the rotary motion theme that were not interchangeable. A more in-depth classification of motion themes is required to address this, prompting a further re-analysis of the author's data (Air and Wodehouse, In preparation) to identify additional mechanical motion categories for an AM deformation and a motion taxonomy.

This proposed approach is a result of discussions with industry experts, where multiple directions were identified. First, the authors aim to study this taxonomy's feasibility and potential application in translating AM lattice structure deformation behaviours related to mechanical motion, building a conceptual framework. The next stage is the application, case studies, and validation, but this work is based on the initial raw discussion. At this stage, the validation is not terministic but rather a predetermined initial method.

### 2.1. Method for Previous Experiments

It is essential to understand the aim and findings of the authors' previous work (Air and Wodehouse, In preparation) that led to the AM motion taxonomy's need for expansion. This work aimed to find evidence that anisotropy can be controlled via lattice structures and utilised to benefit AM. For this, their deformation behaviours need to be understood to be predicted and thus controlled. This knowledge is how the authors initially plan to create controlled anisotropy via the mechanisms' external form. Experiments to achieve this subjected the lattices to five types of mechanical tests (MTs).

#### 2.1.1. Experimentation and Mechanical Tests

Experimentation for this database comprised of 17 (lattice types) x3 (wall thicknesses 0.4, 0.6, 0.8mm) equalling 51 lattice samples, subjected to 5 MTs (Table 1), repeated x3 per sample, resulting in 765 data points. Nine lattice types were tested at two orientations for MTs 3-5 due to differing tessellations along their x and y axes, producing different results.

**Table 1. Summary of mechanical test types and variations**

Test No.	Mechanical Test Type	Mechanical Force(s)	Axis Movement	Test Angles	Test Orientations	Newton Force(N)	Snapshots per Test
MT1	Planar Compression	Compression	X,Y (simultaneous)	0°	1	100N	3
MT2	Planar Tension	Tensile	X,Y (simultaneous)	0°	1	100N	3
MT3	Non-Planar Compression	Compression; Shear	X only	45° (torsion)	2	100N	3
MT4	Non-Planar Tension	Tensile; Shear	X only	45° (torsion)	2	100N	3
MT5	Planar Bending	Shear	X only (Manual)	0° 30° 45°	2	NA	3

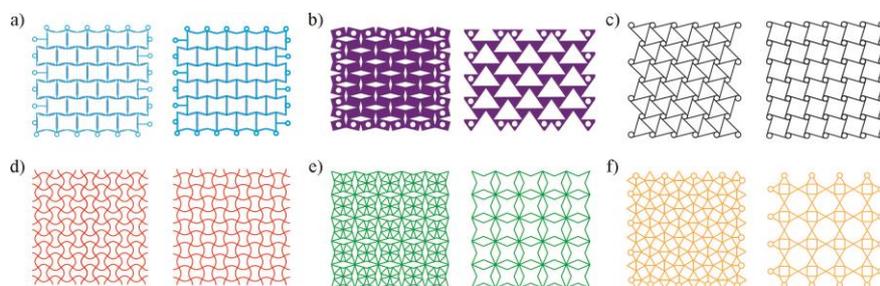
Total data points equalling 1008, plus peak deformation snapshots for each test. Greater wall thickness (WT) generally means a higher strength part (O'Connell, 2021). However, lattice sizes and thus WTs

will vary depending on user requirements in application. Therefore, it was essential to understand its effect on performance, even in minor thickness variations of 0.2mm.

There are three main types of mechanical force: Tensile, Compression, and Shear ("[Types of Mechanical Forces](#)", 2021). MT1 and 2 test the compression and tensile strength of 2D lattices, simultaneously expanding/compressing on the x and y axes. Results from these MTs can be utilised in the applications of controlled anisotropy where planar unilateral reciprocating or linear motion are behavioural requirements, such as suspension or energy absorption. For MT2, rotary motion is also applicable where centrifugal force is required due to its simultaneous expansion on the x and y-axis. MTs 3-5 analyse how these 2D samples perform under non-planar or shear forces. These tests are less typical but helped to attain a more comprehensive dataset. MT3 and 4 also test the compression and tensile strength of 2D lattices, but in a non-planar state where shear force is apparent through torsion exerted on the sample. For this work, there are applications in reciprocating motion in environments where 2D lattices may be subject to additional external forces. Finally, MT5 tested planar bending deformation with rotary motion alternatives in mechanisms that pivot on an axis.

### 2.1.2. Lattice Samples

The 17 lattice types comprised six structure types: Re-entrant; Semi-rigid; Chiral; Sinusoidal; Quadratic; and Kagome. All six have distinctions in design and classification. Figure 2 visualises distinctions with two examples for each of the six categories, communicating the difference between categories and providing examples of commonalities between variations of each type.



**Figure 2.** a) Re-entrant; b) Semi-rigid; c) Chiral; d) Sinusoidal; e) Quadratic; f) Kagome

Lattices samples with base measurements not exceeding 90×90×10 mm were fabricated using a Stratasys J850 Prime, a material jetting AM machine. Each sample had 3x versions with different WTs of 0.4, 0.6 and 0.8 mm. AM material used was Agilus30 (FLX935) which possesses a shore value of A30 ([Körner and Liebold-Ribeiro, 2014](#)). Samples were designed and manufactured using Rhinoceros 7 (surface 3D modeller); and Grasshopper (graphical algorithm editor) software.

### 2.1.3. Process Parameters

Although process parameters of AM produce many variables, this research aims to understand the deformation behaviours of the tested lattice structures. In experiments, great care was taken to ensure that each test sample was produced under the same conditions to ensure consistency and focus on how the structures deformed compared to the other samples. Understanding this behaviour is how the authors initially, in this instance, plan to create controlled anisotropy; via the mechanisms' external geometry. In addition, certain variables were considered in terms of the tessellation and sample WTs, contributing to our understanding of how the geometry of the lattice may deform at different scales. Materials and build quality will, of course, impact how the lattices may perform. However, the authors believe it is crucial to first understand how different lattices perform under the same conditions before investigating these other factors. Still, other variables must be considered in the future to enhance our understanding.

## 2.2. Results of Previous Experiments

Deformation themes in experiments uncovered parallels with the four basic types of mechanical motion: Linear, Oscillation, Reciprocation, and Rotary. As discussed, there was a value proposition for a taxonomy for AM lattice structure deformation behaviours. Within the database, these motion



rotations  $<360^\circ$ , like a door hinge and vice-versa. Therefore, a more specific taxonomy method is required, though expanding the motion themes available in parallel or perhaps sub-motion themes.

Data from previous experiments was re-analysed to ascertain further disparities in the rotary motion theme. The definitions of the four pre-existing will be re-considered to help achieve a more specific categorisation. A further example of this is Reciprocation motion, previously defined as lattices that possess mirrored compression and tensile strength values - i.e., 100N vs -100N. Some applications in Reciprocation may be more successful with an imbalance of compression and tension values. Similar imbalances may also be prevalent in Linear motion for tasks where Linear compression is preferred over Linear tension. These examples and more are investigated in this research.

This work initially investigates the addition of new motion themes, in parallel with the pre-existing four, by ascertaining what 'non-basic' motions are possible in motion mechanics. Once this was concluded, further analysis was conducted into creating subcategories within the motion themes, taking influence from the 'non-basic' motions, observations of the experiments in practice and the data.

### 3. Results

This section will first discuss exploration into parallelly expanding on the four basic motion themes of Rotary, Oscillation, Reciprocation and Linear before investigating how all motion themes can be divided to specify potential motions in greater detail. Thus, developing a more comprehensive taxonomy for understanding the deformation behaviour of AM lattice structures concerning mechanical motion and their potential in creating controlled anisotropy in AM parts.

#### 3.1. Motion Themes and Expansion

Initial plans aimed to expand the number of motion themes available, providing greater information on what motions and behaviours are available when using lattice structures to create controlled anisotropy within AM part designs. As a result, seven motions were selected for consideration and referred to as non-basic motions: Flexure; Translational; Rectilinear; Curvilinear; Circular; Uniform; Non-uniform.

The studied non-basic motions presented no clearly defined independence of the four basic motions, making them unsuitable for working as parallel additions to the taxonomy. However, some of these non-basic motions did show potential for subcategories (sub-motions) within the pre-defined basic motions. This provides a more specific specification of the applications possible with each lattice, giving engineers and designers a better understanding of which lattices are ideal for their needs.

#### 3.2. Sub-Motion Themes

Although no additional motion categories were suitable for this work, providing more specific detail within the four motion themes via "sub-motions" was deemed suitable. In addition, a re-analysis of results from previous work revealed that all four motion types offer opportunities for refinement.

##### 3.2.1. Rotary Sub-Motions

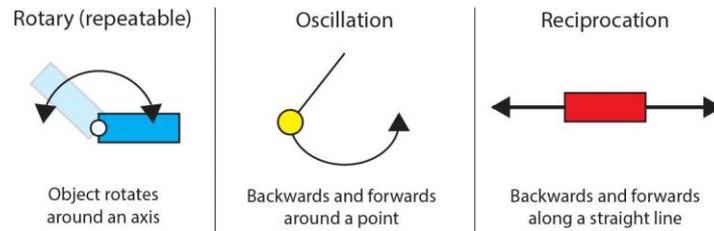
In experimentation, Rotary motion was apparent in two forms of mechanical tests, MT2 and MT5. These Rotary motions differ significantly, with results from MT2 showing themes related to centrifugal force and MT5 results relating to short pivots, such as a hinge. However, there was a clear distinction between the behaviours of the two movements, and thus two rotary sub-motions were defined:

- $\geq 360^\circ$  Rotation: motion that spins on an axis and completes rotations greater than  $360^\circ$ ; typically, motions will rotate continuously, either clockwise or anti-clockwise (e.g., a wheel).
- $< 360^\circ$  Rotation: Motion that pivots on an axis with rotations less than  $360^\circ$ ; typically, these motions are repeatable (e.g., a door hinge).

Rotary sub-motions could potentially utilise subcategories of their own:

- Continuous rotation: motion that consistently pivots either clockwise or anti-clockwise
- Repeatability: motion that pivots backwards and forwards, distinctly from oscillation motion.

Although Repeatability is distinct from Oscillation and Reciprocation, clarity on their differences would be prudent. This is illustrated below in Figure 4.



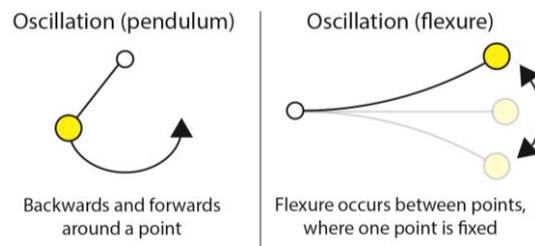
**Figure 4. Distinctions between Rotary (repeatable), Oscillation and Reciprocation motions**

Reciprocation repeats motion along a straight line. Oscillation repeats motion along a curve. However, this is regarding the entire body. Rotary revolves the body around the axis at differing speeds, and velocity increases further away from the axis. This is because the body is part of the axis point.

### 3.2.2. Oscillation Sub-Motions

Oscillation was present within some samples in MT5 experiments. Due to the nature of oscillation motion, it is challenging to place lattice structures into this category because typical oscillation motions are not directly attached to their pivot point. However, oscillation motion is also present in flexure—a motion involving a structure being bent between its pivot point and an endpoint. A comparison and definition can be seen in Figure 5 below. Results from MT5 show that this motion is possible through lattices, and as such, Oscillation can be divided into two sub-motions, defined as:

- Flexural Oscillation: Occurs when structures are bent between their endpoint and a fixed pivot point. More likely to be present in lattice structures.
- Pendulum Oscillation: The endpoint is disconnected from the pivot point, connected by a rigid or straight body. The connector is typically subjected to tensile stress. This sub-motion is less common in lattice structures but contrasts flexural Oscillation.



**Figure 5. Distinctions between oscillation sub-motions, pendulum and flexural, where white is a fixed pivot point, and yellow is the endpoint**

### 3.2.3. Reciprocation Sub-Motions

Typical yield strength values in tensile and compression tests for reciprocation motion are mirrored. This is true for applications where a repeated motion is desired, such as a drawer slider. However, there are applications where an imbalance is preferable, either biased toward greater compression or tensility. Therefore, sub-motions of the Reciprocation theme would be useful:

- Compressive Reciprocation: Good tensile value but possesses greater compression value.
- Tensile Reciprocation: Good compressive value but possesses greater tensility value.
- Balanced Reciprocation: Traditional reciprocation values are mirrored.

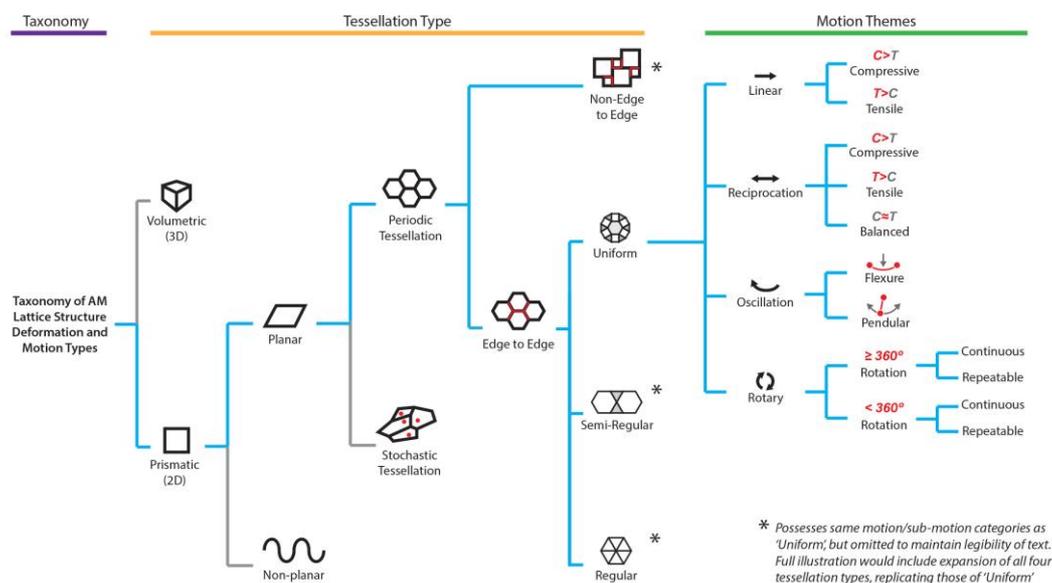
### 3.2.4. Linear Sub-Motions

Linear categorisation depends on whether a lattice is more suited to compression or tensile forces. For example, pulling tension applications and uses where low or zero spring back is desired for compression. It is noteworthy that lattices may be suitable for both and overlap with reciprocating themes. As such, linear categories share some similarities with reciprocation motion. Thus, linear lattices can be sub-categorised as Compressive Linear; and Tensile Linear.

### 3.3. Visual Representation of the Taxonomy

A simple translation of an AM lattice deformation and motion taxonomy is crucial in its usefulness to designers and engineers, indicating what motion each lattice can replicate. An ideal method of doing this is through a visual illustration in the form of a dendrogram, as previously utilised in Figure 3. A taxonomy of lattice tessellation types and their basic motion themes (Figure 3) aided in developing a database in previous work. This facilitates a breakdown of the behaviours, properties, and categorisation of structures available. A dendrogram of this nature can be taken further when considering the sub-motions concerning the four basic motion themes in section 3.2.

Figure 6 below augments Figure 3 to produce an enhanced dendrogram for AM lattice structure deformation and motion types, including sub-motions. For this work in 2D tessellation patterns, only areas relevant have been expanded on thus far: Prismatic, Planar, and Periodic Tessellation. All tessellation types share identical motion theme categories. In addition, there has been a rearrangement with the colour coding used in Figure 3 to create greater clarity. Sections are now deciphered using the coloured lines above the dendrogram. The headers correspond directly with the sections below.



**Figure 6. Taxonomy dendrogram updated to include tessellations, motions, and sub-motions**

In this dendrogram, two sections represent visual and behavioural elements. The yellow section details the key underlying concepts that describe each structure's tessellation type and how these geometries are arranged and constructed. The green section highlights suitable motion themes for each lattice. In addition, sub-motion themes have been added to further detail the types of motions each lattice can achieve. The lattices may be deemed suitable for more than one motion type depending on experimental results. This helps identify more adaptable samples and does not signal any drawbacks within a sample should it qualify or not for multiple types.

## 4. Discussion

Understanding lattice structure types and their deformation behaviours are key to understanding how controlled anisotropy could benefit the design of AM parts (Hossain et al., 2021) and not be a defect. Experiments developed this understanding by creating an extensive database on AM lattice structures, with various structure types, all subjected to the same five mechanical tests. This data helps designers and engineers to see what lattices are available in AM and how they can be controlled and compared. Such a large and consistent dataset was not previously found and was crucial in developing the foundations to achieve the aim. However, a categorisation method for translating and presenting this information was crucial to its usefulness. At this stage, parallels with the lattice deformation behaviours and the four basic types of mechanical motion in engineering were discovered. A novel classification method lays the foundations for developing a DfAM framework that utilises lattice structures to create

controlled anisotropy within parts. Furthermore, information can be taken from the database to influence the development of AM compliant mechanisms by integrating suitable lattices into their designs, replacing multi-part mechanisms by replicating their intended motions with flexible sections, possessing designed mechanical deformation. Future research by the authors will focus on developing this further.

#### **4.1. Motion Taxonomy of AM Lattice Structures**

In the taxonomy, four motion types are used to categorise the lattices' behaviours, indicating which lattices may be suitable alternatives to multi-part mechanisms. Furthermore, the tessellation patterns of each lattice are detailed. A route of discussion is how Figure 6 can be developed further—adding new lattice samples and exploring new tessellations yet expanded upon in the dendrogram through periodic (2D) non-planar and stochastic patterns and volumetric (3D) lattices. What behaviours these structures may exhibit will enhance our understanding of controlled anisotropy in AM, expanding the usefulness of this taxonomy classification method to both designers and engineers.

There is potential for new lattices to be added to the current 'tessellation' section without the need for testing. However, as motion theme capabilities are based on MT results, it would be challenging to assign lattices to motions without first testing them. Still, it is possible lattices could be added based on their tessellation make-up by predicting how they will deform and, therefore, which motions they could be used to replicate without the concrete need for them to get tested. Kagome and Sinusoidal lattices are potential examples of this in practice. Their tessellation construction and symmetry allow for their deformation to be predicted. This is due to the 'spare material' between nodes that influence their deformation, particularly in Reciprocation and Linear tests such as MTs 1-4. With enhanced experiments, other lattice types may reveal further deformation predictability.

#### **4.2. Design for AM + Controlled Anisotropy**

This work aims to create a method for translating data on lattice deformation behaviours into useable data to assimilate controlled anisotropy into a novel DfAM framework. To achieve this, a taxonomy was synthesised. The four basic mechanical motions serve as categories within the taxonomy and indicate what motion applications each lattice can perform—further enhanced by adding 13 sub-motions across two additional tiers. Understanding lattice deformation behaviours allows us to control and predict lattice behaviours, demonstrating anisotropy as a benefit and not a defect within AM. More so, it can be utilised to enhance the properties of AM parts and optimise designs to require minimal assembly time, processes, and materials. The AM lattice structure deformation database will be utilised to support this parametrisation as an integrated DfAM tool, providing engineers and designers with a large dataset of lattices available and aiding them in selecting an appropriate lattice for their desired properties and behaviours. Future works will develop a novel DfAM framework that assimilates controlled anisotropy into AM parts via lattice structures, utilising the taxonomy created.

### **5. Conclusion**

This work builds on a database developed by the authors, which addresses a deficiency in deformation behaviour data of AM lattice structures. A categorisation method for translating and presenting this data was vital in its usefulness to users. It was also crucial to the theory that anisotropy can benefit AM. A novel approach to lattice structure classification in AM was developed, adopting the four basic types of mechanical motion: Linear, Oscillation, Reciprocation, and Rotary. These motions contain parallels with lattice deformation behaviours, allowing for the creation of a motion taxonomy.

Data re-analysis showed disparities in Rotary via two non-interchangeable motion variants within the categories, signalling that a more in-depth taxonomy was required. However, additional motion themes would be challenging to achieve and not a viable solution. Nevertheless, 'sub-motions' within these motion themes would be an appropriate expansion method. Nine sub-motions were identified, with a further four sub-motions in a third rotary tier. This taxonomy can aid in developing a novel DfAM framework that assimilates controlled anisotropy into AM part designs via lattice structures.

In summary, this unique classification of lattice structures will enable designers and engineers to find ideal structures for controlled anisotropy in their AM part designs based on the types of motions and

deformation behaviours they want to adopt. There are applications in developing AM compliant mechanisms, improving part properties, functionality, and reliability, whilst reducing materials, parts, and processes. Data would be taken from the database to influence the development of AM compliant mechanisms by integrating suitable lattice structures into their designs, an alternative to multi-part mechanical assemblies by replicating their intended motions with flexible, controlled sections. AM is growing as a manufacturing process, and compliant mechanisms will become increasingly prevalent. It is an ideal partnership, but there is still a need for a process to incorporate controlled anisotropy into a DfAM framework. This work's taxonomy, paired with the author's database, is key to this.

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