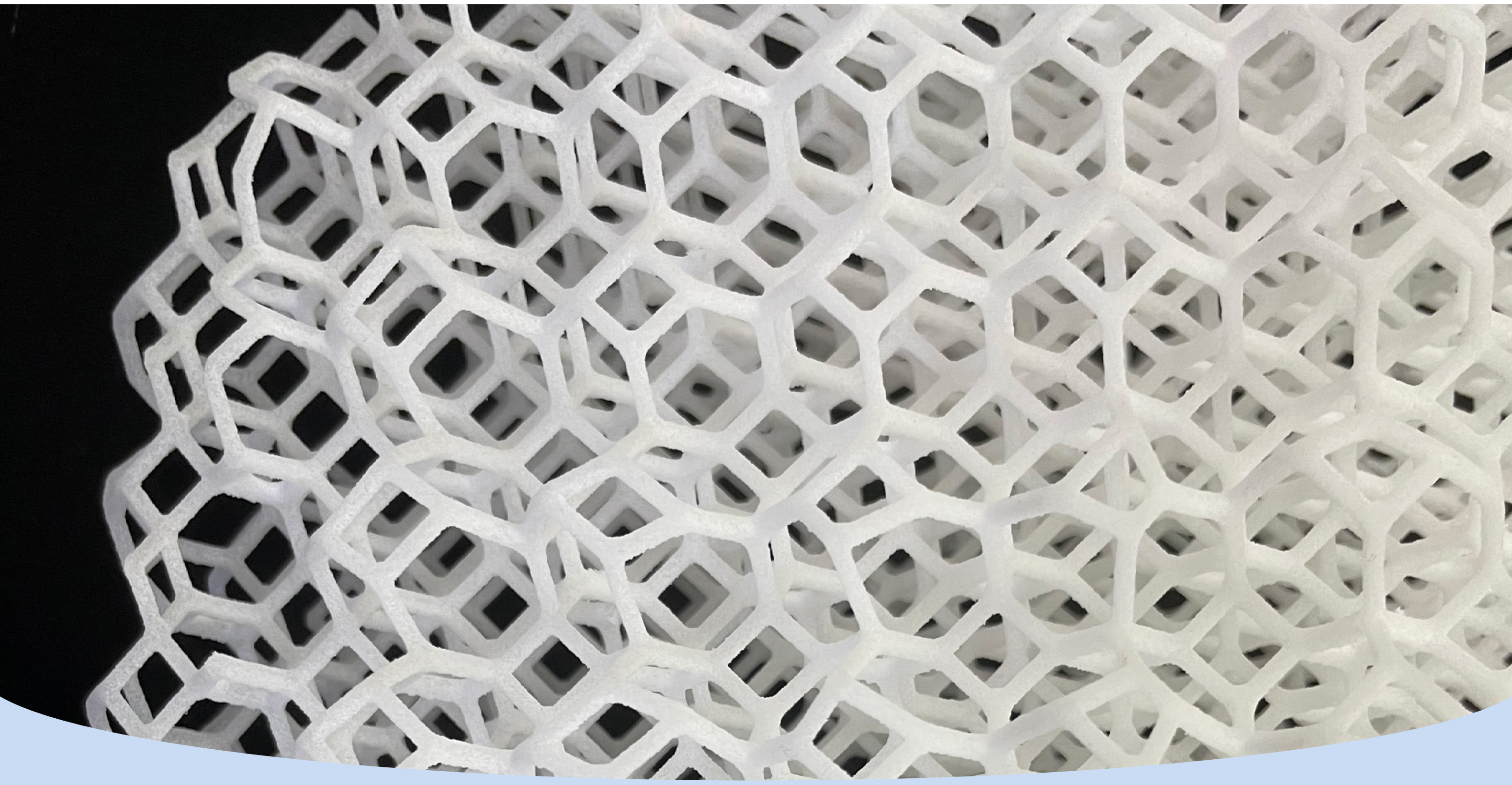
FORWARD AM
Innovating Additive Manufacturing

BASF
We create chemistry

Transforming Product Development with Lattices



Executive Summary

Unleashing the power of lattice design – For centuries, architects and engineers have relied heavily on lattice structures to achieve architectural feats and push the limits of design.

More recently, developments in Additive Manufacturing (AM) technology, materials, and especially software have provided a breakthrough for fabricating lattice-based designs, making them much more accessible to product designers across various industries.

Numerous examples of 3D printed applications taking advantage of lattice designs are already being produced in flexible polymeric parts exhibiting superior performance. They include protective gear, bike saddles, shoe midsoles and insoles, motorbike seats and also seating furniture, but this is just the tip of the iceberg. In the past, applications like these had to rely on foam with its limitations as the only solution because subtractive technologies like CNC (Computer Numerical Control) machining and traditional molding techniques are not suitable for creating lattices.

With the evolution of AM, lattice-designed applications offer a long and exciting list of advantages. The most prominent of these is the ability to optimize properties locally. This means that a lattice-based component using a single material can be precisely tuned to control loading conditions like force-displacement behavior, influencing energy absorption, rebound, stiffness, compaction, density, and more. Lattice structures also can provide additional benefits like weight and material reduction, heat transfer and ventilation, and enhanced aesthetics.

Choosing the ideal lattice defines the success of lattice application development. Until now, identifying the appropriate type of lattice for a component required time- and cost-intensive „design-print-test-redesign“ iterations. Because of this, the advantages of using lattice-driven designs for creating new and better-performing products have not been explored to their fullest.

Forward AM has taken on the challenge of pushing lattice innovations forward by offering Ultrasim®, a Virtual Engineering Service, enabling a smart search for the optimal lattice geometry to fulfill a specific component‘s unique mechanical performance requirements. By leveraging digital simulation tools, engineers can digitally generate, simulate, and manufacture finely tuned lattices. Opening up the possibility of significantly enhanced 3D printed parts for various industry verticals, such as automotive, medical, or consumer goods.

This whitepaper provides new insights into how Forward AM leverages their Ultrasim® service to help designers develop lattice structure-based applications with flexible materials by covering the following topics:

- Features and benefits of additively manufactured lattices
- Selecting the ideal lattice for an application
- Lattice Engineering possibilities with Ultrasim®

FEATURES AND BENEFITS OF ADDITIVELY MANUFACTURED LATTICES

„Any material is a structure if you look at it through a sufficiently strong microscope.“

(Bendsøe and Sigmund, 2003)

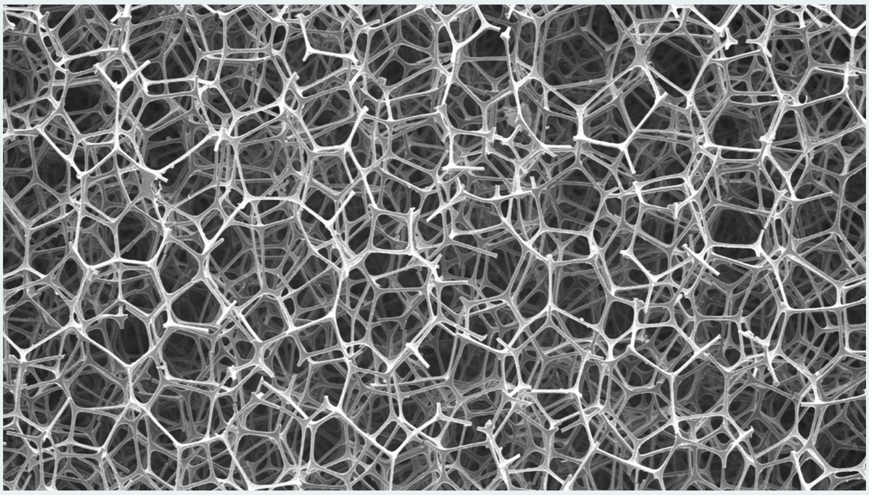


Image 1: Close-Up of Basotect® foam (Source: BASF).

A lattice is a porous structure formed by a network of unit cells (comprised of nodes and beams) arranged in patterns that influence the overall entity‘s mechanical performance, resulting in a lightweight structural design with high strength. Lattice structures are visible everywhere if one look close enough. From ancient to modern times, they have been utilized in construction and architecture, are common in nature, and can also be found in technical foam structures (see image 1). The microscopic geometrical structure of the underlying lattice unit cells and their material control the macroscopic behavior and properties of the lattice part. This means that each individual lattice structure exhibits unique thermal and mechanical properties like stiffness, energy absorption, rebound or heat transfer.

A lattice structure is a repeating set of unit cells in XYZ directions. Each unit cell consists of beams and nodes which make the basic structure of cell – see image 2.

Different lattices can be used in many ways to create conformal and nonconformal lattices – see image 3.

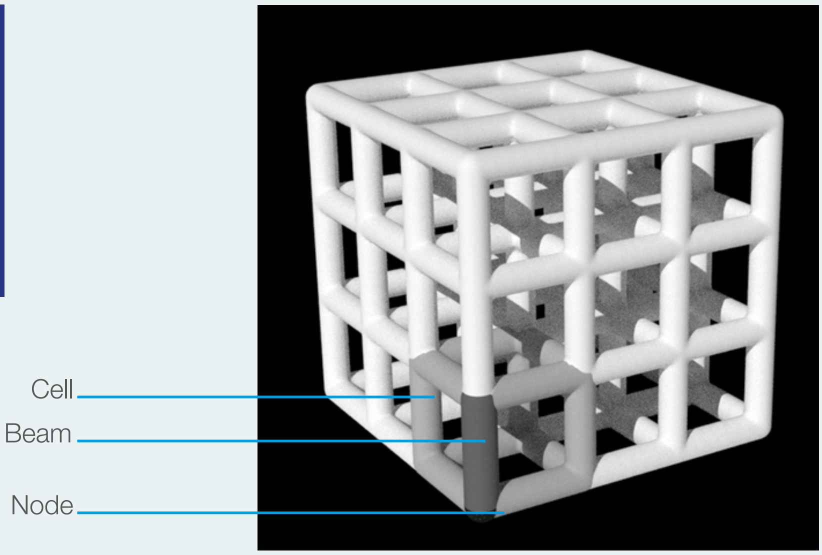


Image 2: Lattice block highlighting the different elements of lattice (Source: Forward AM).

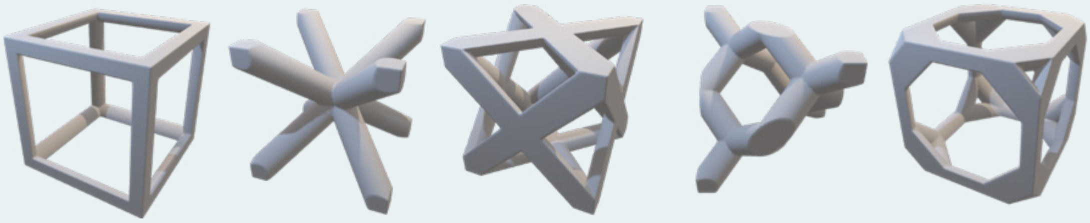


Image 3: Examples of common lattice unit cell types (Source: Forward AM).

Features of lattice structures

Design dictates function – One of the most poignant features of lattice structures is that the design (more so than the material) steers the control of the mechanical properties. Individual lattice unit cell types exhibit dramatically different thermo-mechanical properties and behaviors, and these can be combined and tuned using AM. This means that a lattice-based component using a single material can be designed to control multiple mechanical properties affording the designer boundless opportunities that would not be achievable with other manufacturing methods.

Application examples: protective gear, bike saddle, shoe midsoles, insoles

Definition of local properties – With lattice structures, engineers define properties precisely where and how they are needed resulting in highly individualized part performance. A prime application example that illustrates this feature is the midsole. Today most sneaker midsoles are composed of foam that offers relatively uniform support from the toe to the heel. The only possibility for varying flexibility is by varying thickness over the sole – while an effective midsole needs to offer alternating degrees of support across different areas of the foot. Uniquely with AM, it‘s possible to tune lattice structural parameters enabling varying levels of structural stiffness and therefore support across the midsole using a single-component design with individual sections conceived with a specific function so that the foot is perfectly supported. The heel is designed to provide shock absorption, the midfoot offers superior support with increased structural stiffness, and the front encourages the foot to roll off with longitudinal flexion and rebound.

Application examples: shoe midsoles, insoles

Lightweight – With legacy subtractive manufacturing techniques, a component‘s weight is reduced by removing material in the non-critical areas that are accessible using complex tooling procedures. Additively manufactured lattices enable selective control over the material density in all areas of the part (including critical areas), which optimizes material usage and significantly improves the strength-to-weight ratio of a given component. The obvious result is a lighter-weight part that maintains its strength and uses less material.

Application example: protective gear

Heat transfer and ventilation – The ability to control the voids in a lattice-designed part greatly facilitates characteristics like heat transfer and ventilation, resulting in improved air circulation for cooling or heating systems. Plus, the fact that lattice structures are porous by nature makes them perfectly suited for applications requiring breathability.

Application examples: motorbike seats, protective gear, bike saddles

Optimized impact – The selection of different lattice types offers the ability to control the level of energy absorption across a part, which results in impact optimization. A designer can easily specify a component with high and/or low energy absorption. More information available in our on-demand webinar here.

Application examples: helmets, protective gear, knee pads

Custom cushioning – It‘s also possible to design a continuous force response over a large displacement with lattice that is tunable for individualized comfort.

Application examples: automotive interior components, motorbike seats, sport/protective glasses, midsoles, insoles

SELECTING THE IDEAL LATTICE-TYPE FOR AN APPLICATION

The distinct advantage of using lattice structures is that it‘s possible to create drastically different mechanical behavior properties with a single material in a single component. The trick is finding the ideal lattice structure out of the countless lattice types there are to choose from.

A typical approach for identifying the best lattice for an application is to translate the requirements of a mechanically loaded part into the desired force-deflection curve. This provides an understanding of the force-displacement behavior and the influence on characteristics like energy absorption, rebound, stiffness, compaction, density, and more.

As illustrated in image 4 below, distinctive deformation behavior is observable for a given structure volume and material mass, leading to varying force-displacement behaviors. Some lattice cells show a high initial stiffness which deteriorates drastically to nearly zero; others show almost linear curves; the onset of compaction is also quite variable.

The beams in the respective unit cells are bent, sheared, or axially loaded. They can show instabilities (buckling) and interact which each other by contact, depending on the geometry of the unit cell. Rebound and dissipation differ from cell to cell. The observed deformation modes can be quite complicated, but they can all be numerically simulated very precisely.

By changing the lattice structure and keeping material and density the same, the force-displacement behavior can be tuned to produce a range of behaviors from low linear stiffness (soft foamlike feel) to high linear stiffness (rebound effect) to low or high energy absorption.

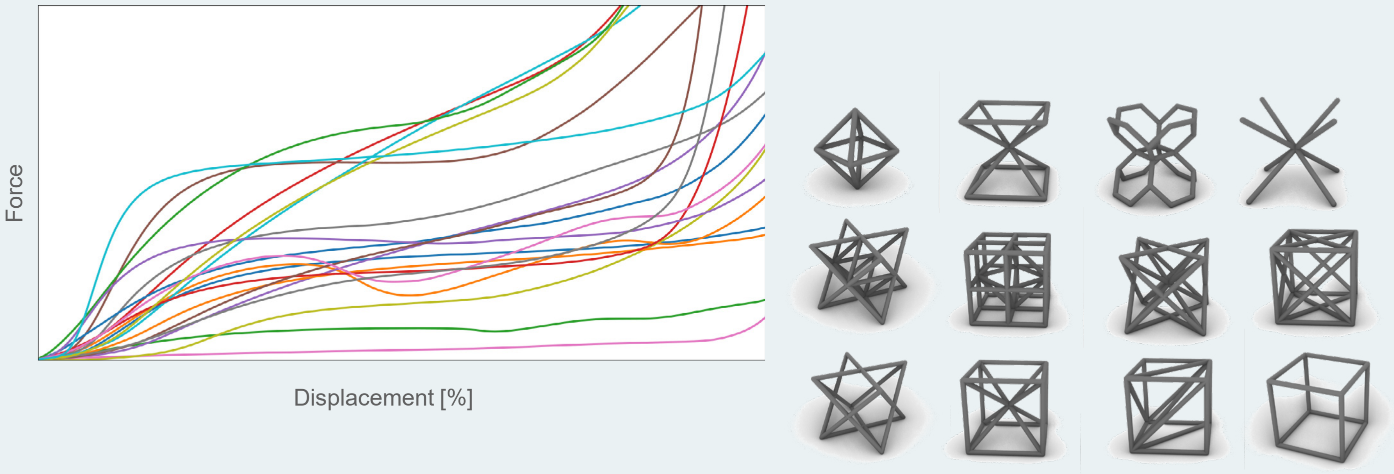


Image 4: Different lattice structures with the same density displaying different performance (Source: Forward AM).

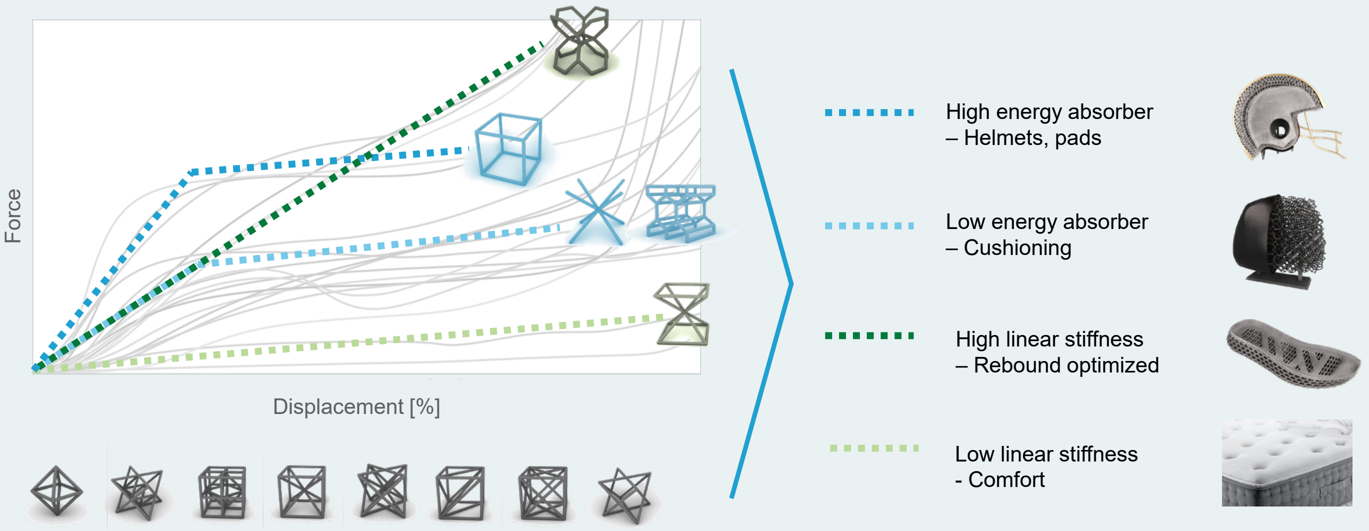
Here are examples of lattice structures and their resulting force-displacement behavior (see image 5):

High energy absorber: A sharp increase of force followed by a plateau to achieve displacement indicates a high energy absorption lattice structure appropriate for helmets and protective pads.

Low energy absorber: A moderate amount of force that starts to plateau represents a low energy absorber that holds the force and results in a cushioning behavior useful in headrests.

High linear stiffness – Rebound: A moderately high amount of consistent force needed to cause displacement indicates a stiffer material that returns to its original shape after removing an applied load.

Low linear stiffness – Comfort: A low amount of consistent force needed to cause displacement signals low linear stiffness or a comfortable material like a mattress.



*holds for equal volume density

Image 5: Classification of a few lattice structure types and their force-displacement behavior (Source: Forward AM).

LATTICE ENGINEERING POSSIBILITIES WITH ULTRASIM®

Now that we‘ve covered how to select the ideal lattice for an application let‘s look at how Forward AM enables users to design a finely tuned lattice-based component in a more automated and cost-effective manner.

The process described in the section above can be effective, but without applying numerical methods, it relies mainly on the experience from impact or actual part resilience tests. Identifying the correct type of lattice in a trial-and-error approach like this requires time- and cost-intensive „design-print-test-redesign“ iterations. This tedious approach makes the design phase long and cumbersome and dramatically diminishes the feasibility of bringing a part into production.

To solve this issue, BASF has optimized and enhanced Ultrasim®, their Virtual Engineering service that enables a smart search for the optimal lattice geometry to fulfill a specific component‘s unique mechanical performance requirements. Ultrasim® applies precise digital simulation methods coupled with 3D design-optimization tools to identify the best-possible lattice structure much faster by automatically varying the topology and geometry parameters of the individual lattice cell. Ultrasim® is rapid, precise, and reliable, accelerating design and test iterations, shortening concept-to-component time, and thus achieving significant cost savings. All this while delivering groundbreaking design possibilities and diverse mechanical properties in a single component with one material.

Ultrasim® benefits for lattice engineering at a glance:

- Cuts development time and cost by minimizing design and test iterations
- Quickly identifies the optimal lattice structure for your new component design, fulfilling a specific norm, e.g. ISO. A detailed case showing this ability can be found here.
- Determines the optimal balance of component performance and weight

Setting up an automated numerical workflow

With Ultrasim®, it is possible to compute overly complex lattice structures with a defined load case and set up an automated numerical optimization process to predict the optimal configuration for the application.

A key success factor for this process is taking a parametric approach with the design so that it’s possible to choose and modify the parameters judged to be the most influential in achieving the desired result.

The process starts with a computer-aided design (CAD) and the input of specific requirements that the structure must fulfill – design constraints like the size, shape, and density; material properties such as energy to be absorbed at impact, required rebound, required stiffness at certain compression levels, and compaction grade; and the desired mechanical responses like force-displacement behavior.

Lattice types deemed to be a good fit based on the defined requirements are selected, and parameters like cell shape, size beam diameter, and even orientation are adjusted as necessary.

Finally, simulation tests like standard compression, shore hardness, rebound, impact or even tests according to a norm (e.g ISO 1621) are defined based on the application's performance requirements.

Once this is set up, the various simulations are run and rerun continuously on the different lattice types and parameters until a landscape of properties is generated.

Here's the workflow broken down into five sequential steps, which run in an iterative loop:

1. Generate the data driven lattice design corresponding to a given parameter set
2. Mesh the generated lattice per the FEM (Finite Element Method) quality requirements
3. Set up the simulation using predefined templates (e.g., specific norm tests)
4. Run the simulation
5. Extract results automatically

This automated workflow (see image 6) enables the use of mathematical optimizers directly on digital twins of actual mechanical tests without the approximation of homogenization-based approaches, reducing manual iterations:

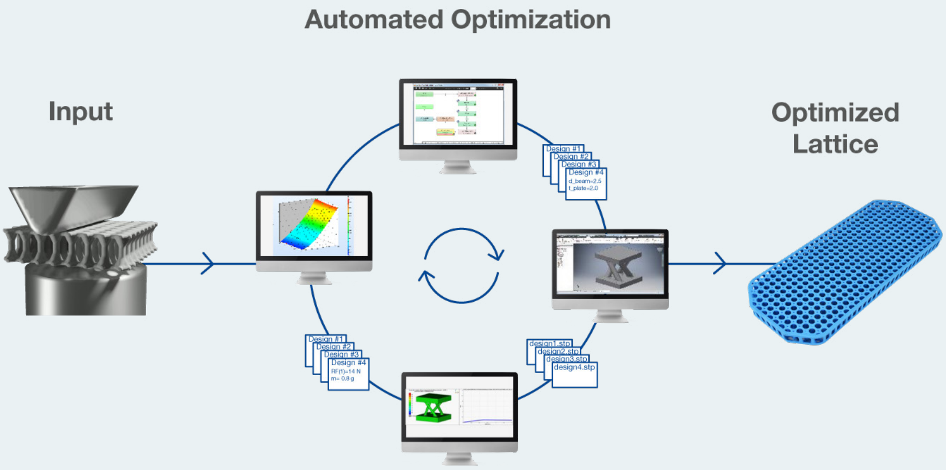


Image 6: How to virtually engineer the ideal lattice: After identifying an application's requirements and functional demands, the ideal match is generated in Ultrasim® (Source: Forward AM).

The output of this workflow is an optimized lattice design with precisely tuned properties as well as an extensive library of lattice options that can be used for fast individualization of parts (e.g., to use in combination with pressure mapping for insoles bike seats, etc.). Image 7 is an example of a digital lattice library developed with Materialise, a 3D Printing software, and services provider.

Name	Stiffness	Density	Shore Hardness	Beam Radius	Dimensions
1.3_D1.4-[3, 3, 1]-BCX	1.37	0.35	10.68	1.4 mm	5*5*5.0
1.4_D1.6-[3, 3, 1]-BCX	2.22	0.44	20.94	1.6 mm	5*5*5.0
1.14_D1.6-[3, 3, 1]-BCX	2.43	0.36	23.33	1.6 mm	5*5*7.5
1.15_D1.8-[3, 3, 1]-BCX	3.93	0.44	38.82	1.8 mm	5*5*7.5
1.23_D2-[3, 3, 1]-BCX	5.98	0.47	55.37	2 mm	5*5*10.0
1.66_D2-[3, 3, 1]-BCX	1.65	0.41	14.08	2 mm	7.5*7.5*5.0
1.74_D2.2-[3, 3, 1]-BCX	1.48	0.38	12.01	2.2 mm	7.5*7.5*7.5
1.79_D2.2-[3, 3, 1]-BCX	1.57	0.33	13.16	2.2 mm	7.5*7.5*10.0
1.80_D2.4-[3, 3, 1]-BCX	2.37	0.38	22.63	2.4 mm	7.5*7.5*10.0
1.81_D2.6-[3, 3, 1]-BCX	3.26	0.43	32.27	2.6 mm	7.5*7.5*10.0
1.87_D2.2-[3, 3, 1]-BCX	1.73	0.3	15.14	2.2 mm	7.5*7.5*12.5
1.88_D2.6-[3, 3, 1]-BCX	3.51	0.39	34.77	2.6 mm	7.5*7.5*12.5
1.92_D2.6-[3, 3, 1]-BCX	3.65	0.37	36.14	2.6 mm	7.5*7.5*15.0
1.119_D2.4-[3, 3, 1]-BCX	1.9	0.42	17.08	2.4 mm	10*10*5.0
1.131_D2.8-[3, 3, 1]-BCX	1.35	0.41	10.41	2.8 mm	10*10*7.5
1.132_D3-[3, 3, 1]-BCX	2.19	0.46	20.59	3 mm	10*10*7.5
1.135_D3-[3, 3, 1]-BCX	1.52	0.39	12.49	3 mm	10*10*10.0
1.143_D3-[3, 3, 1]-BCX	1.7	0.35	14.69	3 mm	10*10*12.5
1.148_D3-[3, 3, 1]-BCX	1.78	0.32	15.74	3 mm	10*10*15.0
1.156_D2.8-[3, 3, 1]-BCX	1.42	0.27	11.24	2.8 mm	10*10*17.5
1.157_D3-[3, 3, 1]-BCX	1.9	0.31	17.11	3 mm	10*10*17.5
1_D1-[3, 3, 1]-Ventile	3.77	0.32	37.37	1 mm	5*5*5.0
2_D1.2-[3, 3, 1]-Ventile	6.23	0.42	56.95	1.2 mm	5*5*5.0
12_D1-[3, 3, 1]-Ventile	3.89	0.28	38.49	1 mm	5*5*7.5

Image 7: Digital lattice library generated with Ultrasim®‘s Automated Workflow (Source: Forward AM).

Example:

Use Case Motorcycle Back Armor Protective Pads

Always on the lookout for demanding applications that benefit significantly from the implementation of 3D printed lattices and where the Ultrasim® platform can really shine, Forward AM has identified motorcycle back armor as a prime candidate for a lattice-based redesign. The protective pads used in this application are a critical safety component for motorcyclists.

The main challenge was to find a suitable lattice unit cell and the respective parameters for the given mechanical requirements—superb structural integrity, outstanding strength-to-weight ratio, local control of impact absorption, and a lightweight open design enabling excellent passive climate control. In addition to these requirements, there is also a European Standard (ISO 1621-2) that specifies the minimum coverage necessary to ensure the safety of motorcyclists driving in normal traffic conditions.

The Forward AM Virtual Engineering team tackled this challenge and initiated a smart search and automated workflow to identify the optimal lattice geometry tailored to the unique mechanical performance requirements of the back armor protective pads.

The result was a virtually generated lattice-based 3D printed prototype that was sent to TÜV Süd (a technical testing organization that offers a wide range of services with testing and certification as its primary focus) where it was put to the test to see if it would pass the stringent requirements for ISO 1621-2. After exhaustive testing under real-life conditions, the proof-of-concept protective pad passed on the first attempt.

Image 8 shows the numerical test setup according to ISO 1621-2. The optimization approach based on numerical simulations quickly detects which lattices are useable and which do not fulfill the given requirements. The complete use case, including details of the numerical optimization process, can be found here.

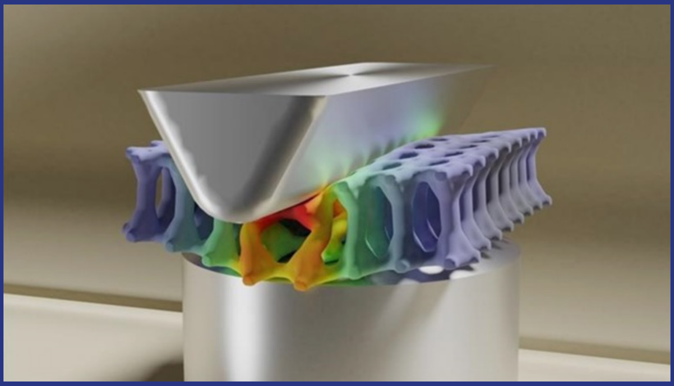


Image 7: Digital lattice library generated with Ultrasim®‘s Automated Workflow (Source: Forward AM).

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CONCLUSION

Until recently, the numerous advantages of utilizing lattice-based designs for creating new and better-performing products have remained largely untapped. The main reason for this is that the software needed to do this cost-effectively was not readily available. Forward AM has addressed this by developing a suite of Virtual Engineering tools and an automated workflow that unlocks these capabilities.

„The Ultrasim® capabilities of Forward AM are second to none – deep knowledge of lattice performance, durability, and design for AM. When provided a design goal, this workflow can be applied to filter the number of design options and converge on a physical product to meet this goal in a very time-efficient manner. This is a game-changer for solving very complex problems with virtually an infinite number of possible solutions!“ Dr. Ron Jadischke, Chief Engineer, Xenith.

Find more information here on how Ultrasim®‘s Lattice Engineering Offer can accelerate the design process and shorten the concept-to-component time, achieving significant cost savings

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