

Design of a Depth Triggered Mechanical Fuse

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Abstract

AUVs are typically deployed with redundant abort systems to ensure safe recovery even after system failure, but these systems take power to operate (either when triggering the emergency system, or when containing a dead-man trigger). This work presents a passive mechanical pressure fuse which uses a lattice structure known to fail at a specific pressure, allowing emergency ballast to be dropped before more critical systems reach crushing depths. This permits recovery of high-value assets even after total power failure, and enables other passive sampling systems. The parametric design process is described, and in-simulation validation tests are performed. Future works and additional applications are discussed.

I. INTRODUCTION

Deep-sea AUVs and other vehicles are frequently equipped with redundant systems designed to prevent pressure hulls from exceeding their rated limits. These systems typically rely on electromechanical sensors to measure external pressure and compare it against maximum safe limits: should these limits be exceeded, emergency ballast can be dropped, enabling a rapid ascent to safety even during system failure.

While effective, these systems can become complex and present their own challenges for reliability. They must constantly monitor sensor inputs and should be designed with isolated power systems to avoid retaining ballast after major power failure. Alternatively, they can employ a fail-open approach which constantly draws power. Employing an electromechanical system here introduces a layer of complexity that we propose can be resolved passively, improving the odds of triggering safety mechanisms in a catastrophic failure event.

This paper describes a mechanical failsafe system which drops emergency ballast by failing at a pre-computed depth. This concept is inspired by electrical fuses, which are added to systems to prevent excessive current from damaging sensitive components. The proposed component would be installed to hold the ballast system for a vehicle, where the ballast is maintained throughout the designed depth rating of the vehicle, and fail if the vehicle starts to sink below this point. The failure of the component would lead to the buoyancy of the vehicle increasing and cause the vehicle to return to the surface.

The digital design nature of Additive Manufactured components lends itself to simulation as a method of predicting component behavior. Finite Element Analysis (FEA) was used to confirm that the design work satisfied the determined conditions. SolidWorks was used to simulate behavior under hydrostatic pressure. FEA was used in this work due to the limitations present in developing components for additive manufacturing, specifically the cost of the equipment and tuning that is usually required during the development process. FEA allowed for multiple revisions on a rapid time scale.

We propose a design framework to specify operational requirements, computationally model, and fabricate components optimized for fail-safe applications for underwater vehicles. To meet this framework, We describe generally-applicable methodology

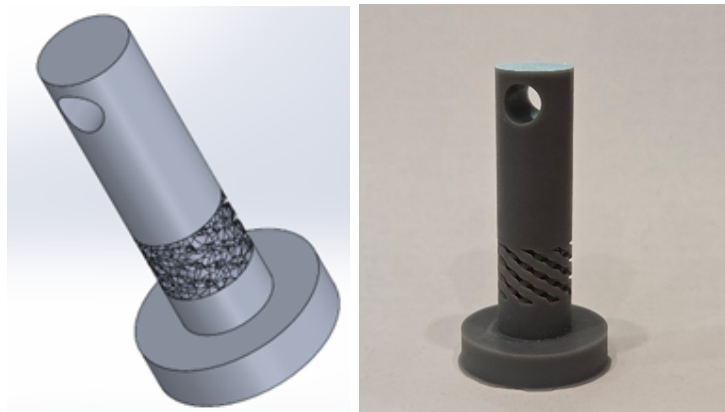


Fig. 1. Rendering of Mechanical Fuse (left) and 3D printed prototype (right).

for creating mechanical fuses which trigger at specific undersea conditions. We begin by describing the current state-of-the art in emergency recovery systems and mechanical fuses, before then introducing our novel approach. The method for designing manufacturable lattices which fail at known depths is described, and in-simulation results are presented. We conclude with future work and potential applications.

II. BACKGROUND

Emergency Buoyancy Based Escape Systems. Systems deployed to the deepest parts of our oceans typically contain several redundant emergency ballasting systems to ensure safe recovery, even after major systems fail. In the case of AUV Sentry, for example, two modes are used in parallel [1]. First, burnwires, where an electrical current passed through a wire of specialized alloy causes the wire to fail in saltwater, will trigger weights to be dropped. This serves as a backup for the more frequently-used manually-actuated motor which also drops ballast. This system contains its own power source, and can be triggered either by the vehicle, by a deadman timeout within the device, or by an external acoustic command. A similar mechanism is reported aboard DSV Matsya in [2], which employs a Frangibolt [3] to trigger dropping of weight through heating of a fixture. Galvanic corrosion devices are also in use, for example, aboard Deepsea Challenger [4] to ensure ballasting is released within a predetermined time frame. Other techniques include electromagnetic weights, where weight is held in place until a power failure, hydraulically actuated systems which drop ballast, or explosive bolts which do the same. Further jettisoning methods are described in [5].

While these systems will (and should) continue to see widespread use, they do require active power draw and active monitoring of depth sensors to ensure maximum depth is not exceeded. In the case of passive systems, like those depending on galvanic corrosion, only a time-based safety mechanism is viable, not a depth triggered one. A fully passive depth-triggered ballast dropping mechanism provides an additional layer of safety.

Mechanical Fuses. Mechanical fuses are components which serve as sacrificial components in a mechanical system. By being designed to fail at predetermined loads, pressures, or torques, these devices ensure that more critical components do not suffer critical damage. A prominent example of a mechanical fuse are shear pins, described in [6], shear pins are used to prevent damage to rotary equipment by preventing rotating components from spinning above their design threshold. This is the common theme among other types of Mechanical fuses, with rupture disks serving a further safety role in gas management as referenced in [7]. These disks are used to prevent overpressure incidents, either in static pressure build up or in dynamic pressure. Relying on the material properties of the component rather than sensor/signal relationship. Mechanical fuses do not have to be passive, however, mentioned previously are Frangibolts. Detailed in [8] failure can be triggered by changing the temperature of the environment around the component, made of a Shape Memory Alloy (SMA). Upon changing the temperature, the material predictably deforms and causes the failure condition. As with many other aspects of engineering, this design ethos has expanded past what would typically be seen as fuses. Automobile design has rapidly progressed in this area, with the concept of a crumple zone being added. This acts much in the way a fuse works, but instead of preventing damage to the vehicle, it prevents damage to the occupants. In designing a Formula SAE car Belingardi [9] researches the ability for composite materials to reduce the impact of crashes. In their work, this team were able to create a simulation model that could predict the complex mechanical system and suggested that the solution would comply with the rules of the competition and provide safe outcomes in case of a crash.

Actively triggered separation devices see frequent use in aerospace (see the review in [10]) among other safety-critical applications. These may include explosive bolts, pyrotechnic triggers, shock separation nuts, and heat knives. These systems are used in a variety of mission critical systems. Explosive bolts are typically used in stage separation operations for launch vehicles to quickly and affirmatively separate two objects. The mentioned systems are similar to the previously mentioned passive systems in respect to their binary nature. The benefit often being rapid and affirmative disconnection. Passively triggered safety systems are widely explored and used in domains outside of oceanography. Burst disks, for example, fail when pressures are exceeded (like the approach described here), preventing damage to more critical components. However, they generally only see use in flow applications, and so additional engineering is required to produce systems that relieve that pressure when the pressure is external rather than contained.

Innovations in Computational Design Approaches. Finite Element Analysis (FEA) has become a widespread tool in engineering, to ‘test’ components before creating the physical component, potentially saving cost, time and highlighting potentially unforeseen failure modes. In [11] two mechanical fuses are examined via an array of physical tests to confirm manufacturer specifications. The components appeared to be in-spec despite the obvious failure. After running an FEA simulation, it was discovered that the component failed in stress concentration and could be corrected with an added radius. In Chen [12] they develop FEA models to create accurate simulation conditions. With these models created, material and structural functions can be evaluated, and changes can be made. FEA has enabled engineers to better understand their mechanical systems before manufacturing components. Building on this understanding is Topology Optimization, a method for producing components designed for a specific set of functional criteria. Cucinotta [13] highlights the ability to redesign components based on their specific criteria. Reducing the weight of a bone screw by 60 percent while maintaining function. The paper uses

Material	Diameter (mm)	Yield Strength (MPa)	Length between Nodes (mm)	K	Elastic Modulus (GPa)	Area (mm ²)	Failure Crushing Force (Pa)	Failure Buckling Force (Pa)
AlSi10Mg	3	225	0.25	0.5	73.5	7.0686	1.63e9	2.35e8
AlSi10Mg	6	225	0.25	0.5	73.5	28.27	6.50e9	3.76e9
AlSi10Mg	9	225	0.25	0.5	73.5	63.62	1.46e10	1.90e10
316L	3	458.18	0.25	0.5	445.27	7.0686	3.24e9	2.01e9
316L	6	458.18	0.25	0.5	445.27	28.27	1.29e10	3.21e10
316L	9	458.18	0.25	0.5	445.27	63.62	2.91e10	1.63e11

TABLE I
MECHANICAL PROPERTIES AND FAILURE FORCES FOR AlSi10Mg AND 316L MATERIALS.

Additive Manufacturing (AM) to produce the parts. This technology was chosen specifically for its ability to build material only where the model requires (with special consideration for sacrificial support material). This is especially important in the world of medical manufacturing, where each patient is unique. Wong [14] highlights the benefits of AM by producing patient-specific components that fit better and provide better patient outcomes.

Computational design tools have advanced the ability to design components designed for very specific operating conditions. Finite Element Analysis allows for better foreknowledge of an environment and key properties to augment. Augmenting these components have become much easier due to optimization algorithms that preserve material only where needed. Combining all these factors together with the use of Additive Manufacturing results in components that can be precisely tuned.

III. METHODOLOGY

Using a bolt shape that is designed to fail as a specific pressure reduces design needs and complexity. A section of the bolt was removed, and a computationally designed lattice structure was inserted to replace the section of the bolt. This lattice was developed with specific failure modes that allow for operation as a mechanical fuse. The parameters of the lattice geometry were determined using equations for compression and buckling failure.

A. Design Framework

The conceptual design of the failsafe component was inspired by the mechanical behavior of a pressure fuse. Its purpose is to release ballast weights under excessive external pressure, ensuring the safety and operability of underwater vehicles in overpressure scenarios. The proposed design (Figure 1) incorporates a bolt-like structure with an integrated diamond lattice section—selected for its mechanical isotropy, predictable failure behavior, and ability to distribute stress uniformly.

During the ideation phase of this project, several factors that influence the design in this problem were listed. The considered factors are as follows: Lattice diameter, unit cell type, material, production process, and overall bolt diameter. After careful consideration, it was determined that lattice diameter and material would be evaluated through the process of this research. These two parameters were chosen because they were the easiest to simulate and compare across differing parameter sets. Lattices were arbitrarily tested against a depth of 750 feet in saltwater, but the approach remains broadly applicable.

Once the working depth is selected, the design process of the fuse begins. This is broken down into 3 steps:

- 1) **Lattice Generation and Unit Cell Selection.** A lattice or cell unit is constructed such that the diameter can be modified.
- 2) **Computational Validation.** A simulation is created using the parameters of the target failure depth.
- 3) **Parameter Comparison.** The crush and buckling failures of components are evaluated using FEA data.

This iterative process will allow scientists/engineers to specially develop a fuse for their specific scenario. Running the simulation is done first to ensure the failure behavior is as intended, with the failure behavior comparison is used as a check to ensure the FEA provides data that is useful.

B. Lattice Generation

The diamond lattice geometry was tailored through parametric modeling, focusing on lattice cell size, element thickness, and material properties. Table I shows the variation of these parameters based on material and element thickness. During this process the relationship between crushing failure and buckling failure was highlighted. For this system to work, the crushing failure must be higher than buckling. This iterative design process emphasized both manufacturability and structural integrity, leveraging AM to produce geometries unachievable by conventional manufacturing methods. Lattice generation is performed using NTopology (2024), while CAD, rendering, and simulations are performed using Solidworks (2025 EDU edition).

The Diamond lattice's unit cell, a continuous triply periodic minimal surface (TPMS), was chosen for its isotropic mechanical properties, which ensure multidirectional load response. This is a critical feature for components subjected to hydrostatic pressure. The curved surfaces of the diamond lattice enables uniform stress distribution, reducing the risk of localized failure and enhancing overall mechanical resilience. This is critical to ensure that failure occurs only when the system is expected to

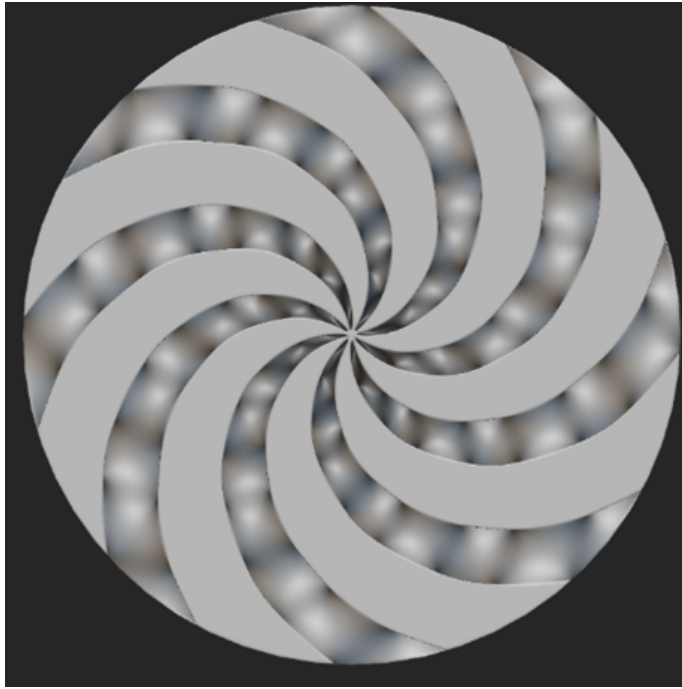


Fig. 2. Lattice cross-section view.

trigger. A cylindrical unit cell volume was used to ensure that the stresses were distributed evenly. A cross section of the final part can be seen in (Figure 2)

Finite Element Analysis (FEA) was used to validate the design techniques used to produce the component. A variety of simulations were run to assess the mechanical properties of the lattice and its inclusion in the larger component.

FEA simulations targeted three modes.

- **Stress Distribution.** FEA was run on the lattice structure alone to ensure that there were no stress concentrations built into the part during design. This validated the reasoning for choosing a TPMS lattice, highlighting the distributed forces along the swept edges.
- **Deformation behavior.** Crushing behavior was simulated to confirm that the lattice failed when expected, and not under other loading conditions. Combination compression and tension failure is important for operation of the component.
- **Failure Mode.** The expected failure mode is shearing for this part. Other failure modes, such as bending, would not allow for the component to function.

C. Simulation Setup

The FEA simulation was set up with 2 external loads which model the conditions under which the mechanical fuse should trigger. We assume the bolt is part of a larger mechanism which suspends ballast weights¹ and that it experiences pressure due to pressure at depth². The bulk of the component was at a diameter where the compressive factor was negligible compared to the compression resistance.

IV. RESULTS

A. Stress Distribution

Simulations conducted using FEA revealed that stresses were dispersed uniformly across the lattice's curved surfaces. The heat map (Figure 5) illustrates how regions of peak stress were localized at junctions where lattice elements converge, while the remainder of the structure experienced lower stress magnitudes.

The critical function of the designed component is a rapid failure mode, ensuring that once a single segment of the lattice fails, then the entire lattice fails. Any other mode, such as partial shearing could pose risks to the vehicle. As such the uniformity of stress response for the lattice was critical. To check the uniformity, a simulation was run on just the lattice, without the downward force (Figure 5). The results seen in (Figure 4) are the deformation of the lattice from the simulation that was run with downward force being applied

¹We have chosen 50 pounds, producing a force of 222 newtons.

²We have chosen approximately 750 feet, producing approximately 2.23Mpa in saltwater.

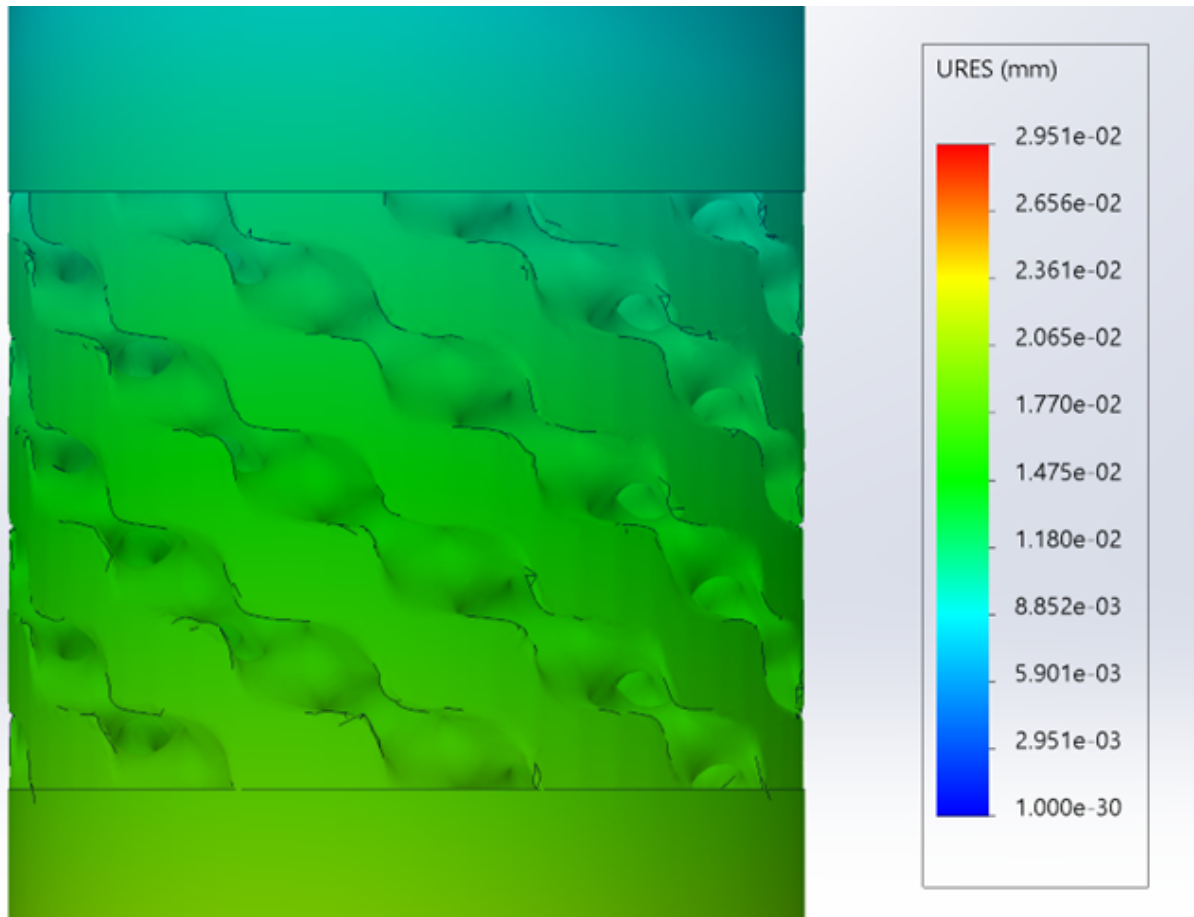


Fig. 3. FEA showing Uniform Downward Stress

B. Deformation Behavior

Deformation analysis provided key insights into the diamond lattice's failure mechanism under increasing pressure. As simulated hydrostatic pressures approached the target crush threshold, the lattice exhibited predictable and controlled buckling behavior across its elements. The strain measurements confirmed uniform deformation patterns prior to complete collapse, reinforcing the design's role as a mechanical failsafe.

The deformation behavior of the lattice section is visible in (Figure 5). The results from the simulation show an even amount of deformation around the diameter of the lattice, with deformation pulled towards the loaded section (Figure 3). The gradient visible above the lattice highlights the intended effect of the component. To have a combined failure mode wherein the downwards load causes the failure due to the weakened lattice.

C. Failure Modes

The failure mode analysis identified specific weak points within the diamond lattice where material yielding occurred during overpressure scenarios. The regions most susceptible to localized failure were at junctions between lattice elements, where the combination of compressive and tensile forces exceeded material limits. The progressive buckling and collapse of these critical regions under increasing pressures is visible in (Figure 4). This simulation result highlights the overall goal of the paper, a component designed to fail at a specific pressure.

Iterative adjustments to lattice thickness and cell dimensions were applied to strengthen these vulnerable areas without compromising the design's predictability as a failsafe. These refinements contributed to an optimized lattice structure that balances robustness and controlled failure necessary trade-off for applications requiring reliable performance in extreme environments.

D. Manufacturing

Feasibility of manufacturing was demonstrated using SLA printing as an analog for the less accessible Laser Powder Bed Fusion (LPBF) method, showing that the complex lattice structure can still be achieved using a similar technology. However,

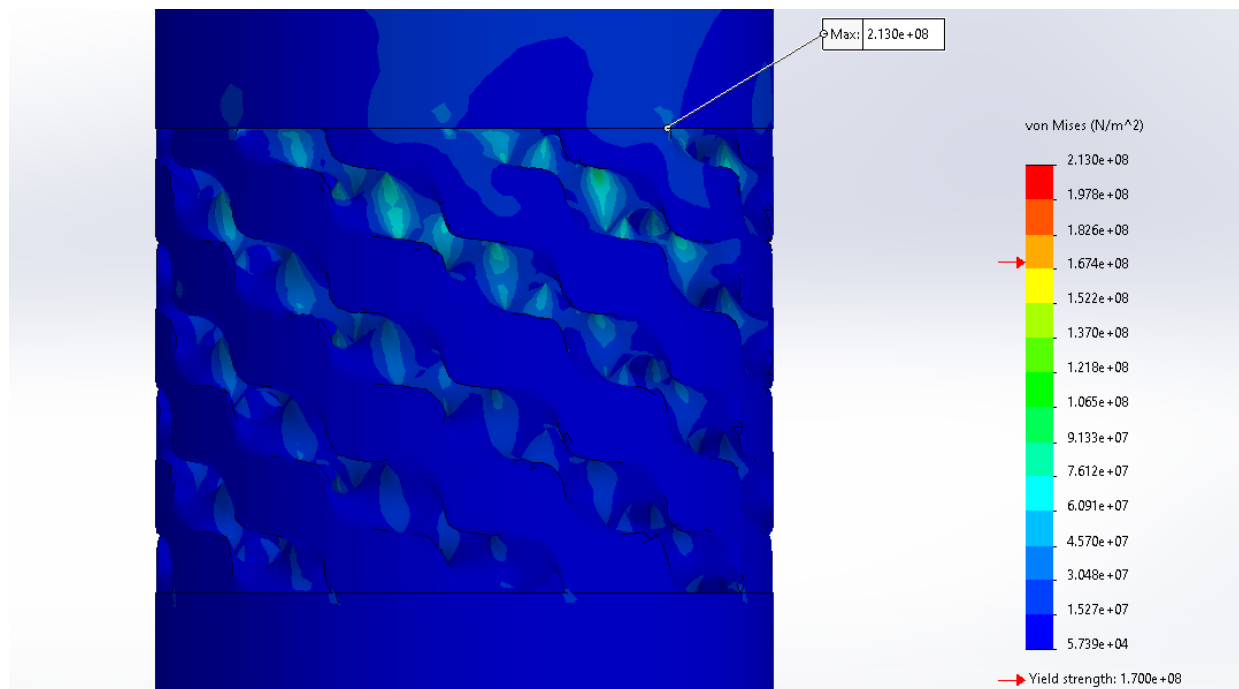


Fig. 4. FEA Results showing Failure start

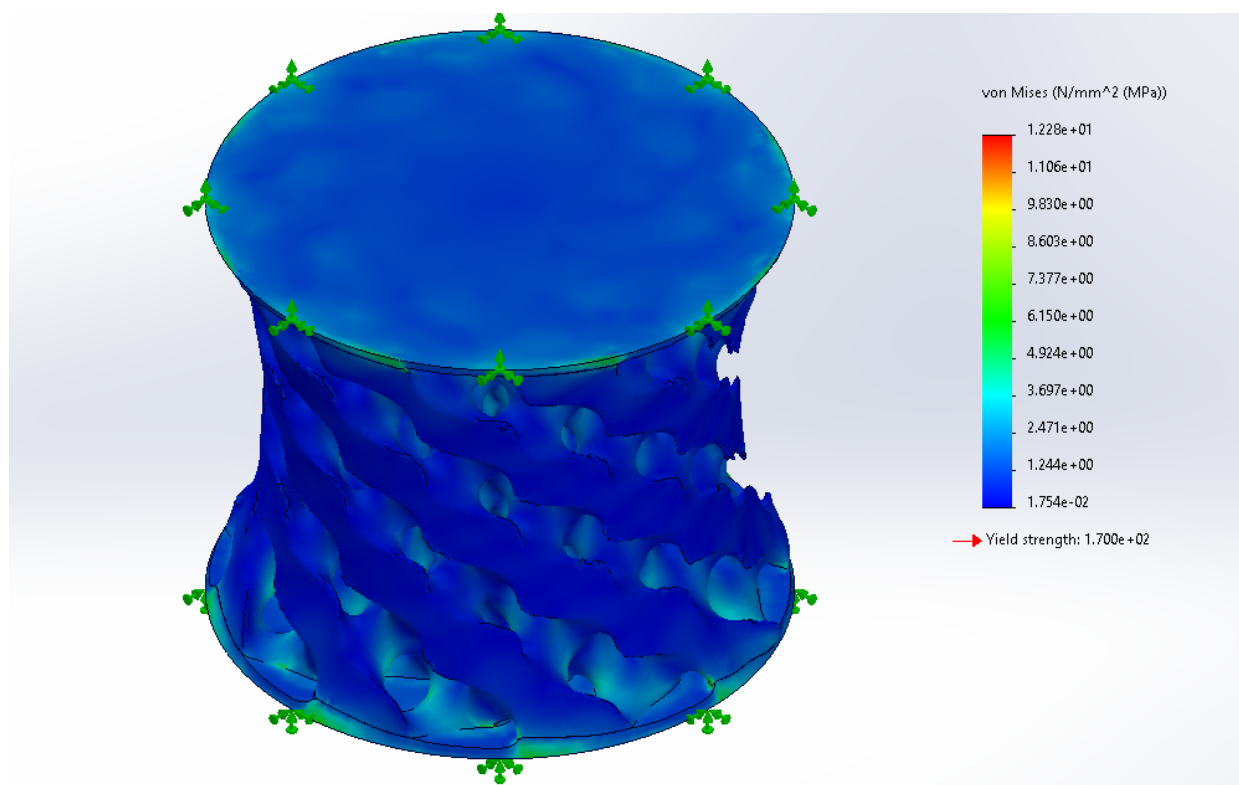


Fig. 5. FEA Results showing Uniform stress distribution

this is no substitute for LPBF manufacturing, which must be examined further (see Section VI for future work). In a limited context, feasibility of LPBF manufacturing was considered using standard manufacturing tooling. Materialise Magics was employed to prepare the diamond lattice design for additive manufacturing using Laser Powder Bed Fusion (LPBF). Two key parameters were considered:

- **Build Orientation.** The component was oriented to minimize overhang regions in the diamond lattice section, reducing the need for support structures and improving dimensional accuracy during fabrication.
- **Support Strategy.** Supports were selectively generated to stabilize vulnerable regions during the build process while ensuring ease of removal in post-processing. This approach preserved the lattice's intricate geometry and reduced post-production labor.

V. DISCUSSION

In summary, these simulations suggest that a diamond lattice structure is capable of producing the desired behavior for a depth-triggered mechanical fuse: that is, it remains fairly robust under standard conditions but fails fully and catastrophically once a known depth is exceeded, enabling emergency ballast to be dropped. In these simulations, 3mm diameter with 316L Stainless Steel (3D printed using powder-bed fusion additive manufacturing) was chosen for its desirable properties within these parameters. These results highlight the potential of additive manufacturing to produce geometries with unique and desirable properties, even for subsea applications.

A. Performance of a Diamond Lattice

The TPMS lattices responded as expected to the simulated hydrostatic pressure. Once the parameters were selected, the generated lattice distributed the stress evenly around the lattice elements. The ability of the lattice to maintain strength at reduced densities is important for this application. As additive manufacturing apparatus become more accurate, these lattices will become a more powerful tool for increasing part performance. Nguejo [15] shows that fine microstructure control over additively manufactured materials can provide a slight boost to performance over wrought.

B. Integration of Computational Modeling

nTopology was used heavily to design the lattice structure, allowing for a precisely generated lattice using the parameters calculated during the preliminary phase of the work. The implicit modeling approach favored by nTopology allowed for rapid iteration to account for changes in calculated lattice diameter. If required, to design the lattices by hand this would have expanded the timetable of the research. SolidWorks was an accessible method for generating simple geometry, and for running simple simulations.

FEA was used due to the high barriers to entry for undersea testing and for Laser Powder Bed Fusion (LPBF). Hydrostatic testing is highly complex and either requires specialized equipment to simulate undersea pressure, or a research vessel capable of running tests at sea. Previously, complexity was a roadblock for applied mechanical research, however simulation technology has enabled innovative studies. Applications such as subsea engineering will continue to benefit from simulated testing before producing parts designed to operate at depth.

C. Applications for Underwater Engineering

A potential application for these mechanical fuses could be to augment Niskin bottles. The bottles are used to collect salinity data and temperature at various planned depths underwater. Historically, a heavy brass messenger activates spring latches at the top bottle to signal its closing [16]. In more modern systems, acoustic triggers are used, requiring specialized hardware both subsea and on-ship. A future proposal to further augment these measurement devices would be to use the fuses to breach the bottom of the bottle and allow the sample to be captured. A further mechanism would be designed to seal the bottle following the filling of the bottle. This could take the form of a lever that actuates upon weight from the water filling the bottle and replacing the air. Once the bottles had been filled, they would be removed in the same fashion as historical bottles. Further benefit from simplifying the design of the bottles by removing any electronic sensors could enable the bottles to be dropped even deeper than standard. Reducing the need to access the exterior of the bottle makes the bottle design easier, requiring no pass through for signals, and a more uniform exterior that reduces pressure concentrations. A final potential benefit is reducing the barrier to entry for this measurement. No electrical calibrations are required and the design can be simplified, reducing the need for experts deploying the bottles, and could potentially even become accessible to fisherman or other citizen scientists that venture into waters of interest.

VI. LIMITATIONS AND FUTURE WORK

Advancements in FEA have enabled high fidelity simulations that enable engineers and researchers to have a degree of confidence when designing new components. Despite the high-fidelity simulations, there are invariably factors that are not possible to simulate and will need further testing. The nature of additive manufacturing means that there is a possibility of inclusions or discontinuities between the model and the produced part. Various methodologies exist that can be applied when certifying a process/part for usage. These methods include Computed Topography scans (CT), X-ray, acoustic testing, and destructive testing. For rated components, it will be required to perform a litany of Non-destructive and destructive testing.

While this research shows the potential for a singularly designed component, the potential to expand this work to further applications is enticing. Additive manufacturing offers the potential for multi-material production; opportunities exist to design lattices with dissimilar materials. Stainless steel was chosen for this project based on its pervasive use in subsea applications owing to its balance of durable material properties and corrosion resistance. Further research into different base material could reduce costs or increase performance.

With the promising data collected via the simulations, the next step for the research will be to produce samples via the selected production method. Based on a combination of accuracy and material properties laser powder bed fusion is recommended to be used to produce the samples. The lattice geometry is complex and will require high accuracy methods of manufacturing. Once the samples are produced a CT scan would be beneficial to understand the internal structure of the parts. Ensuring that all the lattice has uniform radius is important to ensure static pressure does not create stress concentrations. Once the parts are verified to the model, physical testing can begin. Using a pressure tank to evaluate the components will provide the best opportunity to measure the performance. Completing this testing and ensuring that the parts function as normal will advance the components to be further trialed in undersea conditions. Evaluating a variety of conditions, salinity, pressure, and temperature will be important to ensure functionality across the breadth of oceanographic conditions.

VII. CONCLUSION

This research outlines a practical approach for designing, modeling, and validating failsafe components specifically tailored for the demands of high-pressure underwater environments. By combining additive manufacturing (AM) techniques with advanced computational tools, the diamond lattice structure achieved the desired balance of mechanical resilience and controlled failure modes. Utilizing simulation workflows, we find preliminary results suggesting that an additively-manufactured diamond lattice structure can be designed to fail at known pressures, and that this property can be exploited for use in critical subsea applications. To close the gap between simulation and real-world application, future work is required for experimental validation.

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