3-D Printed Smart Designs for Disaster Prone Regions and Disaster Relief Applications

Author: Vallabh Ramesh

DuPont Manual High School, Louisville KY

Email: rvallabh2026@gmail.com

Academic Advisor: Prof. Kunal Kate, University of Louisville, KY

Email: kunal.kate@louisville.edu

Executive Summary

Conventional construction of habitable structures such as buildings, housing, stadiums, etc. is accomplished using traditional construction methods. The construction industry happens to be one of the oldest and has not modernized in decades. Cement is the most commonly used material and cement-based structures are designed for mass production in many countries around the world.

However, there is a need for unique structures for areas prone to disasters such as earthquakes, tornadoes, and floods. Developed countries such as Japan use advanced construction technology and materials, but these solutions are typically expensive.

The issue is further complicated when these structures need to be assembled on site to provide emergency disaster relief and constructed with maximum speed and efficiency. Generally, the durability of these structures is low to medium quality at best with a limited lifetime.

In this submission, a 3-D printable low cost, novel design was developed that uses smart and lattice features that are highly resistant to vibration, impact, and highly durable. The structures developed can be custom infilled with bio-based and sustainably produced resin matrix systems. They can be printed on site, or packed/transported very quickly, and deployed with precision in disaster relief areas.

The use of sustainable resin in the design provides greener solutions from a raw material perspective. The use of recycled materials as fillers has the dual purpose of improving the environment and providing habitable solutions for a community that is in dire need of housing solutions.

Industry Overview

Conventionally, concrete is made as a mixture of Portland cement, aggregates, and water. This process takes up to two weeks to develop full strength. Instead, additive manufacturing through the 3-D printing of polymers significantly expedites the time to construct high-strength panels. Published industry reports, academic research and review articles show the use of various technologies, substrates, and materials for the construction of habitable structures in disaster prone zones and for disaster relief applications.

For habitable areas that are prone to natural disasters such as earthquake and tornadoes, special construction materials that are light weight, durable and resistance to these shocks are needed. Although major advancements have happened in this field, especially in the last two decades, there is still a gap in terms of speed of construction, efficiency, and durability. Also, custom designing the housing needs based on the available space and topographical conditions of the area is limited.

The two areas that need improvements are a) Building structures for Disaster Prone Areas and b) Rapid deployment of structures for Disaster Relief applications.

a) For disaster-prone areas, improvement in weather resistant buildings (from earthquakes, tornadoes) is always a necessity. Most buildings are currently based on concrete and were not designed to withstand strong external forces and vibrations.

Concrete is also an unsustainable building material for disaster zones. Research on the use of concrete shows that 4.1 billion tons of concrete in general were manufactured around the world in 2023. Cement manufacturers use a huge amount of coal or natural gas cement is huge and leave a large carbon footprint. According to the Scientific American, "…the chemical reactions involved produce concrete has even more carbon dioxide as a by-product. Making one kilogram of cement sends one kilogram of CO_2 into the atmosphere. Worldwide every year cement and concrete production generates as much as 9 percent of all human CO_2 emissions." In addition, a Princeton University study found that the concrete industry has released "4 billion tons of carbon dioxide annually."

b) For the disaster relief areas, the HUD document recommends structures such as trailers, mobile homes, and temporary/permanent housings. These structures are typically heavy to move and difficult to mobilize quickly. Therefore, light weight, portable structures that can be custom designed, produced and erected at the site will be the best and efficient way to provide immediate relief to the affected communities.

For newer construction, governmental agencies and communities that live in the region prefer environmentally friendly building materials that are cost-effective.

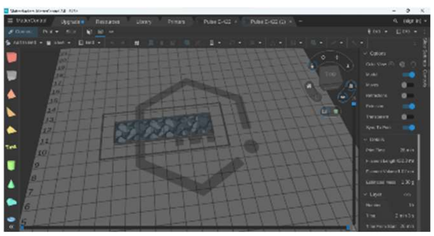
Design, Functionality and Durability:

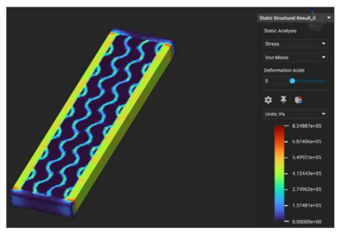
The composite panel design must be able to withstand impact to a higher degree than commercially available concrete.

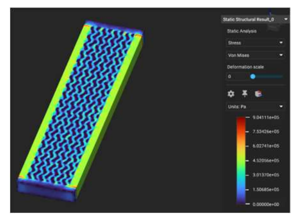
The proposed solution utilizes 3-D printable lattice panel with gyroid infill for building panels of strength, impact resistance and stability.

There are little health considerations for the design itself, mainly the quality of the structure is always dependent on the raw materials used to build the structure, panels and infills. Although the durability of these structures on composite lamp poles etc. are studied for some time, long term durability of these structures for 30, 50 years and beyond still need follow up and study.

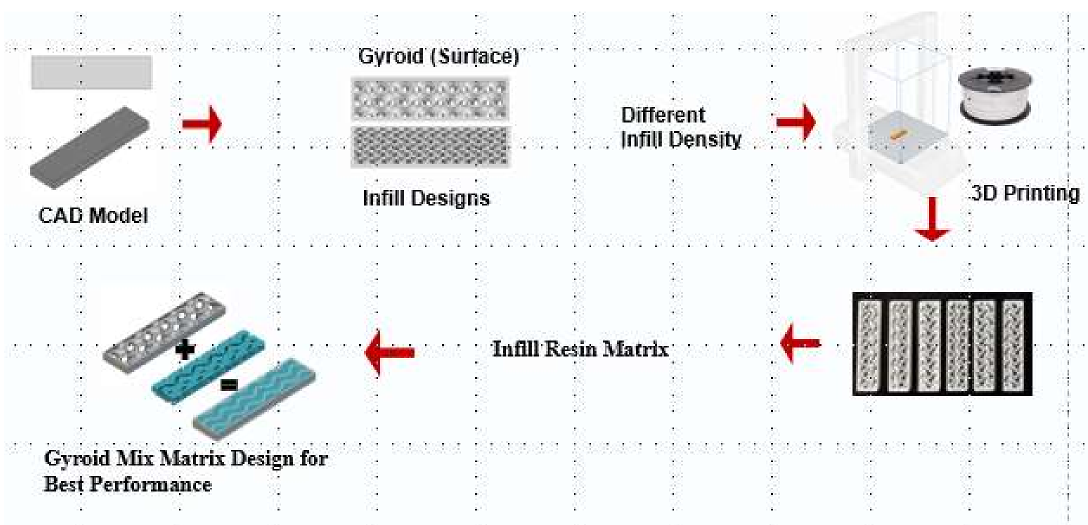
The pictures of the designs are shown below.



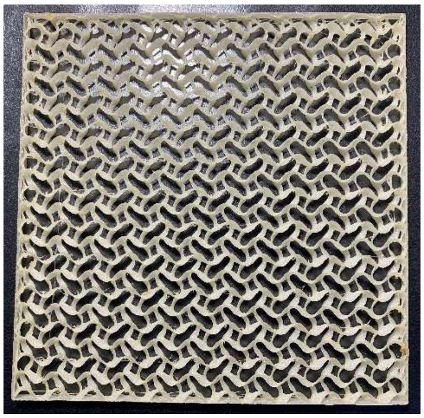




The schematic way to produce this design using 3D printing technique is shown below.

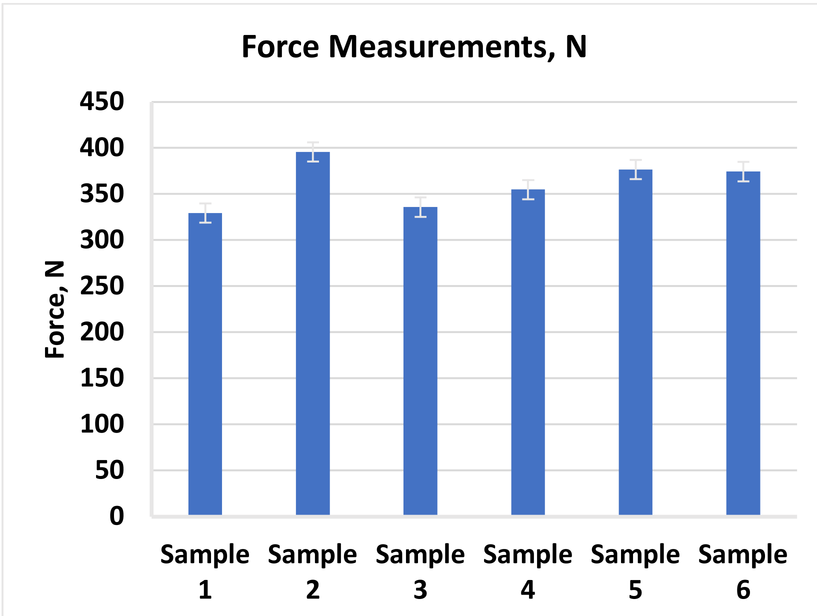


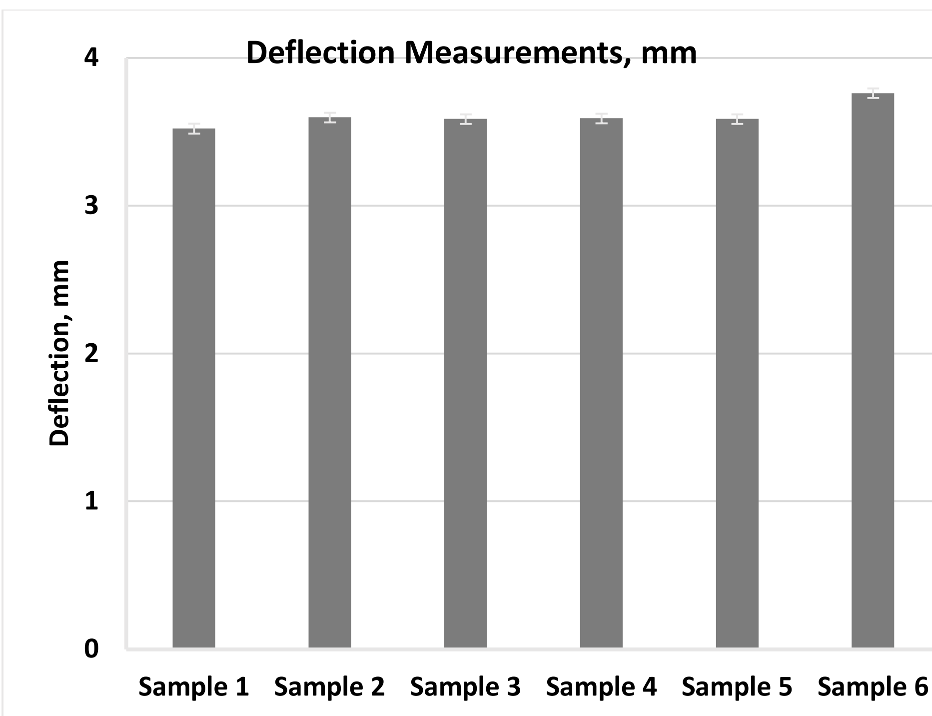
Model structures were printed using Thermoplastic Polyurethane Gyroid structure with infill epoxy resin as shown below.



Model structures were printed using Thermoplastic Nylon (polyamide) Gyroid structure with infill epoxy resin as shown below.

3-point bend test were performed on various 3-D printed gyroid composite panels are shown below

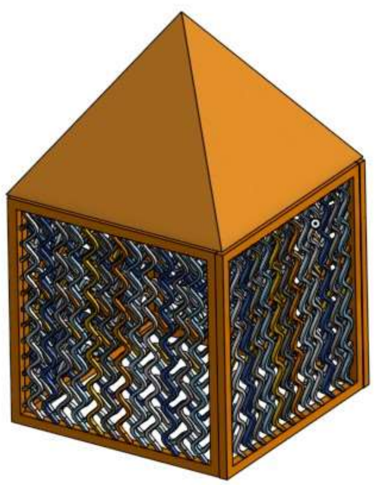




The results show that the composite design that have good hardness as well as good flexibility can be custom designed by the choice of the right thermoplastic resin and the matching infill resin.   Here is an example of a design that has good flexibility and toughness.

The structures and parts made of these composite panel designs can last for minimum of 50+ years, making it a durable product. The performance indicators would include resistance to high force, stability in earthquake-like scenarios, and ability to be rapidly deployed into structures.

A representative structure designed is shown below.



Design Integration and utilization of DDM materials and processes:

3D printing of high strength thermoset polymers significantly expedites the time to construct high-strength panels. The panels that constitute the basic building structure can be erected immediately (in site printing scenario) or assembled if the structures can be shipped quickly. This 3D printed structure will be completed (patched or infilled) by conventional polymer thermoset systems. These systems can be urethanes or epoxies, combined with the right fillers such as glass fibers, recycled materials like PET etc. depending on strength, impact resistance, weather resistance needed.

Ultimately, resin and hardener will be applied to the porous regions of the design, then left to cure in standard conditions for 15 minutes to 6 hours depending on chemistry of the infill. The cured structure is available to be transported in approximately 24 hours. Depending on the software used to manufacture the structure, there may be minor resin support material on the walls of the columns, but this is not a major concern and can be easily removed.

This is the unique advantage of mix matrix design which combines the speed of additive manufacturing with conventional thermoset cure together.

Depending on the software used to manufacture the structure, there may be minor resin support materials on the walls of the columns, but this is not a major concern and can be easily removed. The simplest example will be applying a urethane foam in the lattice structure that sets within a few minutes and the structure is ready for use.

The process using the polymer is very adaptable to needs and can be applied beyond the filament wire FDM printers. The design can be easily adapted for other Additive manufacturing processes such as pellet extruders, dual extrusion composite extruders etc.

All materials used for the design qualify for the fire-rating and protection by the addition of the right level of fire-retardants in the formulations.

The polymer is based primarily on high density thermoplastic polymers like Nylon, Polyethylene, Polypropylene, ABS etc. They can be recycled at the end of its life. The infills proposed will be biobased resin with low carbon footprint and will have fillers derived from recycled materials like PET plastics etc.

Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

The design can be implemented widely, as it is a pattern that can be customized according to needs. The gyroid mesh pattern can be altered for porosity and flexibility depending on the infill, with waveform patterns.

Typically, agencies such as FEMA will have to adapt this technology and move quickly to implement it in disaster prone areas. The equipment like FDM printers and filaments are now available in larger size and quantities, with the price also dropping exponentially as technology develops. The infill formulations are standard paint/adhesive/composite resin system providers who will package these in larger quantities for easy deployment.

The adhesives/sealants/composite resin manufacturing companies have good after service and production support and so their supply chain is robust in terms of necessity to scale up during emergency or disaster times.

Conclusions:

The key aspect of the design is the novel thermoplastic – thermoset mix matrix lattice structure. The thermoplastic polymer brings the designed structural integrity of the structure, and the thermoset polymer system provides the flexibility to develop hard and tough panels to withstand harsh environmental conditions of the disaster areas.

The lattice design has the flexibility of bringing the performance of both most commonly used thermoplastic resins such as HDPE, HDPP, Nylon, ABS, and high strength thermoset infill such as urethanes or epoxies. For areas where skilled labor is a shortage, simple airdry/sunshine cure or moisture cure 1-pack system can be applied to make it error proof.

The mixed matrix combination allows various custom designing abilities so that it can be tailored or adapted on the conditions to be deployed. The gyroid pattern with customizable infill levels help design modular structures where the right amount of UV light (from sun) can be used to cure the infillings. These structures are extremely lightweight when compared to conventional cement-based structures. They can be assembled easily on site and can be deployed in a very fast turnaround time for disaster relief applications.

Conventional low cost FDM printers were used to print the lattice design, so the raw materials used for these FDM printers can be packed and shipped in filament spools with very minimal space required. The design allows the use of fibers like glass fiber, and even carbon fibers for specialized, high impact, blast resistant applications.

Cost Benefit/Value Analysis:

The average price of concrete is about $ 6 to 12 per square feet per installation. Similarly, the average price of raw materials used in the thermoplastic resins like HDPE, HDPP, Nylon and TPU is in the range of $2.50 to $6.00 per Kg and the infill resins are also in the similar price range. Depending on the thickness of the panels used, the 3-D printed design cost can placed in the same price range. This shows the unique design can compete really well with the commercial standard in the market.

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