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R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) Shelter Design

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This research aims to provide the shelter design called R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) in a modularized based-3Dprinting construction method. The R3ER entails an energy-efficient design that showed a lower EUI compared to the benchmark EUI approved by ASHRAE Standards Committee. Additionally, the provided shelter R3ER has multiple uses such as disaster relief shelter, office, and hospital which can justify the environmental justice. Therefore, the R3ER will give stakeholders such as emergency planning commissions, third-party organizations, and construction managers/engineers a resource to maximize the non-monetary and monetary benefits of use of this type of shelter in their community. As a result, the communities would not only (1) be less exposed to disaster damage or less vulnerable to disaster impacts but also (2) ensure maximum utilization of the limited resources to reach out to a larger number of people who might be facing it.

Key Words: Shelter design, Jump into STEM, Energy Efficiency, Modularization, 3D printing

Introduction

There have been fifty-eight tsunamis in the past 100 years, with more than 260,000 casualties (Imamura et all 2019). Since such natural disasters would damage infrastructures, such as houses and buildings, the local people would be exposed in the probability of loss of life, injury or destruction. In addition, lack of readily available, affordable permanent emergency housing is restricting the preparedness and function of communities around the world, impeding monetary and non-monetary attributes of many communities. (Needs)Therefore, disaster relief shelters are very important in large-scale disasters and prevent communities and local peoples from the unexpected treats. (Objectives & Methods)This study proposed a shelter called R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) based on (1) construction method, (2) multiple uses of the shelter design, (3) energy efficiency, and (4) economic analysis: Market readiness. In order to design the optimized shelters, this research identified construction materials that can resist natural disasters. The R3ER have its energy consumption below the targeted energy, which suggested energy consumption of the model is below permissible limit. Therefore, the proposed shelter design provided optimized shelter designs in all aspects of building construction, structure, enclosure, and energy systems. Furthermore, it is expected that the R3ER would help stakeholders and decision makers achieve equity in environmental and energy justice and remediate social, local economic, and health burdens.

"Shelter" indicates a safe and secure place to provide food, water and health care. However, most post-disaster shelters are disposable (tents), and long-term safety is not guaranteed. This research proposes a permanent shelter design. First, this research identifies building materials and structures that have survived different types of natural disasters. Table 1 explains existing disaster resistant buildings. Alma hall, UST main building, The Sand palace were built as concrete buildings. Therefore, it is revealed that concrete, as a structural material and as the building exterior skin, has the ability to withstand nature's normal deteriorating mechanisms as well as natural disasters.

Table 1

Disaster resistant buildings

Authors	Building name	Materials	Disaster faced	Description
(Clem, 2009)	Alma Hall	Concrete, Brick , Wood, Metal Structural Beams	Johnstown Flood (1889)	Built-in 1884, Capable of housing 246 men and women
(Santos, 2008)	UST Main Building	Concrete, Bricks , Wood, Metals, Aggregates	Earthquake (1937, 1968, 1970, & 1990)	Built-in 1927 known as first EQ- resistant building in Asia, 68502ft² and capable to withstand 9 intensity EQ
(Levenson, 2018)	The Sand Palace	Concrete, Rebar, Steel Cables	Hurricane Michael (2018)	Built-in 2017, Can withstand 240-250 mph winds
(Hi-Tech, 2016)	East Pagoda, Yakushiji Temple	Wood, Metal	Different Earthquakes	Built-in 1300 years ago and used core pillar as central column vibration control

The shelters found in Table 2 outlines the current existing emergency shelters provided around the world for refuges and disaster survivors. As shown from the Table 2, WeatherHyde was built within 15 minutes with nylon and polyester wool and Emergency SmartPod was built withing 20 minutes with aluminum panels and steel frame; these shelters are portable, fast to build, and durable. Common shapes among the designs include rectangles, pentagons, and hexagons. Some shelters can be interconnected tents or metal trailers. These shelters provide essential protection from nature while providing privacy to the outside world. Additionally, most of the examples took place in areas with high refuge or places that experience frequent natural disasters like Syria, India, and America.

Table 2

Current existing shelters

Authors	Shelter name	Material used	Cost	Construction durations	Total area
(Cooke, 2017)	WeatherHyde, 2013	Nylon, Polyester wool, Fiber reinforced mylar	\$199	15Minutes	29ft²
(Better Shelter, 2021)	Better Shelter, 2015	Polyolefin panels & galvanized steel, woven high-density polyethylene fibers	\$1260	4-6Hours	188ft²
(Gupta, 2012)	Hexyurt, 2011	Cloth, Wood, Plastic, Polyiso insulation, OSB, Sandwich panels, Cardboard	\$229.7 1	4Hours	41-276 ft²
(Baylor College of Medicine, 2021)	Emergency SmartPod, 2015	Aluminum panels and steel frame	\$195K - \$485K	20Minutes	398ft²
(Domo, 2021)	MTS DOMO Systems, 2014	Aluminum, Polyester PVC tarpaulin, Cotton	\$4625	25Minutes	252ft²

3D printing is new construction-technique which is gaining popularity in the construction sector. before it was used only for prototyping. Because of its duration of construction, capability to construct complex structures, and cost of construction, 3D printing in the construction sector has proven to be beneficial than the conventional method. Different types of materials can be used for printing structures. The structures can either be printed onsite or offsite. The structures printed offsite can be transported later to the site for installation. Among the varied materials, concrete is one of the famous materials used for printing infrastructures. Table 3 indicates representative examples of 3D Printed buildings that are found around the world. 3D printed commercial building (Dubai) is printed offsite, construction cost is \$140K, and total printing durations is 17 days whereas 3D printed home (New York, US) is printed onsite, construction cost is \$299.99K, and printing durations is 2 days for almost similar area. Examples in the table shows onsite printing has a less printing durations whereas offsite printing has comparatively less construction cost.

Table 3

Concrete 3D-printed building around the world

Authors	Building name	Printed onsite/offsite	Construction cost	Printing durations	Total area
(Kira, 2015)	Ten 3D Printed Houses (China)	Offsite	\$4800	1Day	200ft²

(Mohan, 2020)	3D printed Commercial Building (Dubai)	Offsite	$140K	17Days	242ft²
(Carlson, 2020)	3D printed House (Belgium, China)	Onsite	-	3Weeks	90ft²
(Olick, 2021)	3D printed Home (New York, US)	Onsite	$299.99K	2Days	139ft²
(Overbeeke, 2021)	3D printed Home (Netherland)	Offsite	$946/month	2Days	94ft²
(Englefield, 2021)	East 17 Street Residencies (Austin, US)	Onsite	$450K & above	7Days/ home	90-185 ft²

Methodology

To achieve the aims set by the study a methodology was proposed (Figure 2).

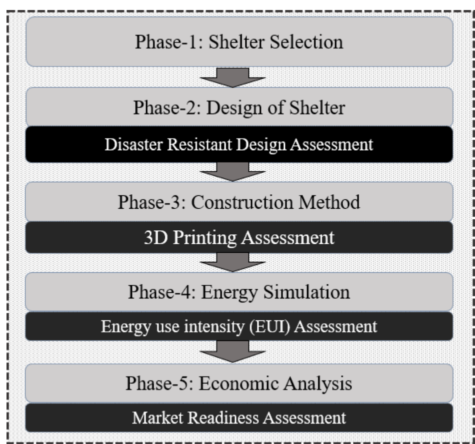


Figure 2: Methods use for the study

Case Study

With the aim to provide environmental and energy justice-based shelter design in the form of construction method, multiple uses of the shelter design, and energy efficiency, we created a holistic real-world scenario "R3ER" ensuring the functions. The "R3ER" is design to build using 3D Printing technique at Stillwater, OK. The population of Stillwater is 50,000 people (Bestplaces, 2021), growth rate present is 28% since 2000 (Bestplaces, 2021), 1.4% average annual rate, and predicted growth rate is 29.4% (Bestplaces, 2021). Figure 1 indicates number of businesses per industry in Stillwater, OK. As can be seen from the figure that education, health, and social services has high industrial capacity in the city. This location was selected due to more diversities including residential district, local business, college town with students at Oklahoma State University.

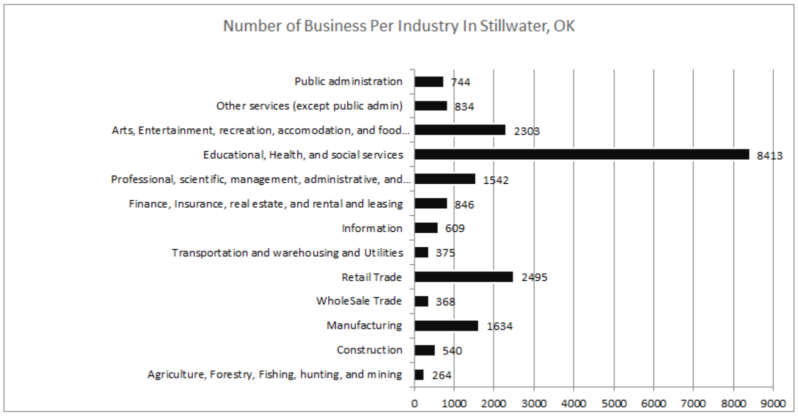


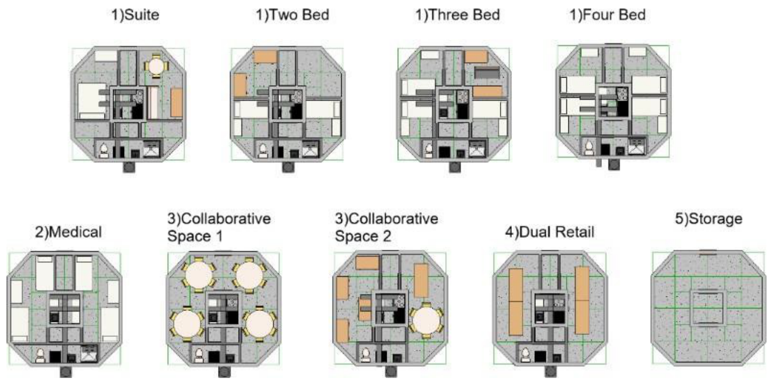
Figure 1: Number of businesses per industry in Stillwater, OK

Phase 1: Location of R3ER

This research found and compared the feasible locations for the disaster relief shelter design. The research selected four feasible locations for the R3ER selected at Stillwater, Oklahoma for 2000 shelters. The land availability for Area 1 is 32,060,160 sf, Area 2 is 20,908,800 sf, Area 3 is 55,756,800 sf, and Area 4 is 62,726,400 sf . The criteria to select the feasible location is (1) accessibility to highway, grocery stores and hospital, (2) accessibility the airport, plenty of open space, (3) Plenty of open space and near the north airport, (4) accessibility to the agricultural station and the southern highway (5) accessibility to the hospital and the western highway also a nature reserve. The scenario of natural disaster assumes that 2000 units with 4000 residents will be found in need of shelter. It will aim to resolve the need for shelter and alternative uses of the shelter after the disaster recovery.

Phase 2: Design of shelter

The designed shelter focused on three primary elements: disaster resistance, speed and cost of construction, and modularity. The shape of the structure was designed to be resistant against elements that could be found in a disaster scenario. This includes the exterior and interior walls utilizing design elements from structure to be seismic, wind, and water resistant. The materials and shapes have also been selected for optimal speed and materials usage in consideration of a 3D printer. Regarding a disaster resistance design of the shelter unit, R3ER adopted the central pillar at the core of the building as an East pagoda, Yakushiji Temple (Nakahara 2000). The central pillar structure has long been thought to be the key to the pagoda's exceptional earthquake resistance. The R3ER design is capable of being stacked and the interior elements can be placed where needed to match the needed function of the structure. Figure 2 shows render images of R3ER design. Figure 2(a) reflect the modularity of a unit, which is designed to be used for multiple purposes such as commercial or residential. And Figure 2(b) displays the ability to stack and link shelter units based on space and desired design.



(A)

(B)

Figure 2: Renders of Design (R3ER): (a) modularity of the unit; (b) stack ability of the shelter

Phase 3: 3D printing-based construction cost

The investigation was done for current 3D Printer Specifications. Gantry printers is considered for printing the shelters along using x, y, and z coordinates. The gantries inside these printers are moved by stepper motors which use digital pulses (Whiteclouds, 2021). To construct 2000 shelters three printers is assumed to be used with the average printing speed of 9.22 inches per second for the three of them. The average length, height, and width dimensions is 30.73' x 38.64' x 12.21'. Table 4 displays the total construction cost for the R3ER for one unit which would be $14,349.54. The total cost includes cost of interior walls, doors, and appliances i.e., $8840.97 along with cost of constructing the exterior walls and HVAC i.e., 5508.57. The average price for a 3D concrete printer range from$350,000-550,000 (COBOD, 2021). Additionally, the expected duration for one unit based on the literature review would be 2 days, with the addition of cure time based on environmental conditions. Table 5 shows the average unit cost per square foot and average durations for existing shelter, shelter printed either using offsite or onsite technique. The construction cost for existing shelter, shelter printed offsite, and shelter printed onsite is $348.38/ft² , $249.62/ft², and $2397.19/ft² respectively. The average construction durations are shorter for existing shelters than shelter printed offsite or onsite as per Table 5. Both construction cost and durations of the offsite 3D printed shelter is comparatively less than onsite 3D printed shelter.

Table 4

Unit cost of design (RS Means, 2021; HomeDepot PC, 2021)

Type	Count	Total

Slab	19.703 cy	$2,620.50
Structural Walls	18.913 cy	$2,515.43
HVAC	1	$1,089.00
Windows	4	$227.04
Door	1	$139.00
Labor	50 hrs.	$2,250.00
Total		$8,840.97
Optional:		
Interior Walls	310 sf	$2,170.00
Doors	4	$556.00
Appliances	7	$2,782.57
Total		$14,349.54

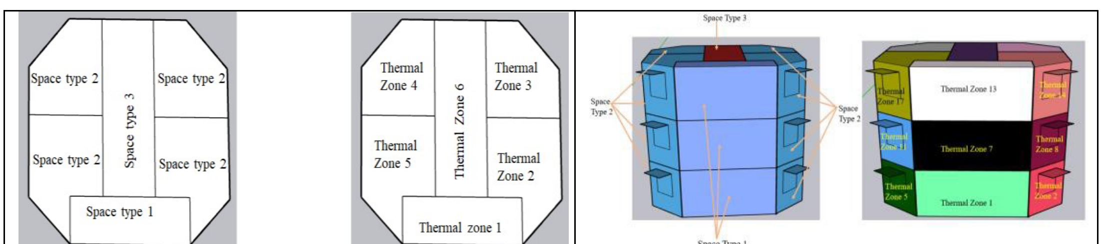
Table 5

Average unit cost per square foot

	Existing shelters	3DP (Offsite)	3DP (Onsite)
Unit cost($/ft²)	348.38	249.62	2397.19
Average Construction Durations	2.2Hours	6.67Days	18.75Days

Phase 4: Energy simulation

The energy simulation was conducted to determine energy consumption of the R3ER shelter with the help of software Sketchup and Openstudio. A few considerations are set for the simulation such as : Large Hotel building type, ANSI/ASHRAE/IES standard 90.1-2010 template, and ASHARE 169-2006-3A climate zone. Figure 3(a) shows three different space types and six thermal zones allocated to each unit whereas Figure 3(b) represents different space types which is 3 and thermal zones which is 18 for shelter when 3 units are stack. For HVAC system Packaged Rooftop Heat Pump was used.



a b

Figure 3: Space types & Thermal Zones : (a) single unit with single floor ; (b) single unit with three floors

Energy Use Intensity (EUI) is the energy consumption of building per total floor area of the building per year which is calculated in the EnergyPlus report from Openstudio software. Then, the EUI of shelter is compared with the benchmark EUI approved by ASHRAE Standards Committee. We took benchmark EUI of Hotel from ASHARE 169-2006-3A climate zone as shelter model is considered as large hotel building type. Table 6 illustrates EUI of Cowboy Cover and benchmark. It is observed that the energy consumption of R3ER Shelter (i.e., Site EUI 47.50 kBtu/ft² and Source EUI 150.55 kBtu/ft²) is comparatively low than the targeted energy (i.e., Site EUI 51 kBtu/ft² and Source EUI 161 kBtu/ft²) for such building type which suggested energy consumption of R3ER is below permissible limit. Therefore, the R3ER are confirmed to be energy efficient shelters provided for natural disasters relief.

Table 6

Energy Use Intensity of shelter and benchmark

	Site EUI (kBtu/ft²)	Source EUI (kBtu/ft²)	Reference
R3ER Shelter	47.50	150.55	From EnergyPlus report
Benchmark (Hotel)	51	161	(Addendum, 2017)

Economic Analysis: Market Readiness

The R3ER is expected to substantially contribute to the local economy and business continuity by playing roles of local landmarks and reflecting the resilience of the local economy in disaster situations. Table 7 presents the markets readiness analysis of the R3ER. The R3ER provide 2000 shelter unites in the designated feasible areas. It is assumed that 50% of shelter units are kept vacant for using the space as an emergency shelter post disaster and 50% of shelter units are used for commercial purpose such as hotel, business space, hospital room, and storage unit as shown in Table 7. This 50% vacant and 50% occupied with commercial purpose would provide both monetary and non-monetary attributes to the R3ER. As per the table 7, is clear that when 1000 units are used as a hotel, office, hospital room, and storage unit in Stillwater, OK it is expected to earn S3000K/month, \$624K/month, \$47,910K/month, and \$75K/month of financial profit respectively. Furthermore, the R3ER will not only save 4,000 lives but also allow business continuity under the disaster when considering the economic added value and brand value. Therefore, such an economic and social ripple effect will lead Stillwater to reach out twice (2.8%) higher than the current growth rate at 1.4%.

Table 7

Market readiness analysis

Assumption: 2000 units with 400 SF/unit				Occupancy: 1000 units	
Benefit	Shelter	Hotel	Business Space	Hospital room	Storage Unit
Monetary		Between \$80 and \$125/night (Tripadvisor, 2021)	Business space: \$1.56/sf (CREXI, 2021)	\$1597/ night (Hanley, 2021)	Between \$50 to \$100 /month (StorageArea, 2021)
		3,000,000 \$/Month	624,000 \$/Month	47,910,000 \$/Month	75,000 \$/Month

(Hi-Tech, 2016)	Saved 1000 units x 4 people =4000 people	Attracting economic growth	Attracts new businesses	Adds medical location	Additional storage

Conclusion & Impact

R3ER the holistic solution was aimed to provide environment-friendly shelter design (1) 3D printing-based construction method, (2) multiple uses of the shelter design, (3) energy efficiency, and (4) economic analysis. The literature review revealed that concrete housing has been resistant to several disasters in world history, which led us to use concrete as the construction material for the shelter. 3D printing on-site construction method is adopted as it allows faster and more accurate construction of R3ER as well as lowering labor costs and producing less waste. The central pillar at the core of the building as of East Pagoda at Yakushiji Temple (Hi-Tech, 2016) is applied to shelter design. The central pillar structure has long been thought to be the key to the pagoda's exceptional earthquake resistance. R3ER has a multi-use purpose including a shelter, hotel, office, or hospital pre or post disaster along with disaster resistant shelter. Additionally, energy consumption of R3ER is calculated with help of Openstudio. The EUI of the R3ER is compared with the benchmark EUI approved by ASHRAE Standards Committee. Therefore, the R3ER could facilitate the transition from pre-disaster life to post-disaster life for people and community. As a result, the R3ER is built in locations that can be easily accessed without external help and a permanent solution to the housing demand after a disaster, and it will have a major impact on the local economic recovery.

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