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Prototyping and Testing of 3D Printed Quake Proof Structure in Indian Subcontinent

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***Abstract*—The Indian Subcontinent has a history of devastating earthquakes. In the wake of the Indian plate shifting towards Asia approximately 47mm/year, the frequency of earthquakes is continually increasing. According to studies by the World Bank and the United Nations, it is estimated that by 2050 around 200 million city dwellers will be exposed to a high frequency of earthquakes. This paper focuses on the level 5 seismic zones, which expect the highest amount Manuscript File (For Revision, please upload clean version of revised paper) Click here to view linked References 2 of seismicity. This problem has led to creating a 3D printed marvel called Quake column created by Emerging objects to develop seismically resistant structures to encounter problems faced in seismic zones like California. This paper holistically discusses the difficulties these seismic zones face and aspires to bring the technology to the Indian Subcontinent to help deal with such devastating natural calamities with optimized engineering solutions.**

Keywords*—Additive manufacturing; Quake proof structure; Response Spectrum Displacement; Selective Laser Sintering printing; Fused Deposition Modeling printing

I. INTRODUCTION

Developing countries like India experience significant damage when a natural disaster like an earthquake hits the cities. The majority of the earthquake disasters in developed countries provide valuable feedback and results on optimizing the design. In contrast, in a developing country, a lack of resources creates havoc. There have been various natural (earthquakes) and artificial (terrorist attacks) in recent years. Assam's earthquake 1985 (figure 1(a)), Gujarat, India's earthquake in 2001 (figure 1(b)), Kashmir, India's earthquake in 2005 (figure 1(c)) are just some examples of the catastrophes.

(a) 8.5 Magnitude earthquake in Assam, 1985

(b) 7.7 Magnitude earthquake in Gujarat, India, 2001

(c) 7.6 Magnitude earthquake in Kashmir, India, 2005

Fig 1: Destruction caused by an earthquake in recent years.

In India, a basic concrete house of 400 sq feet requires 26 to 36 weeks and costs approximately $20,000, which is destroyed instantly by an earthquake. Using additive manufacturing technology, a concrete house can be constructed in just $10,000 and within three days. The Indian State of Assam is the easternmost projection of the Indian plate where the plate is thrusting underneath the Eurasian plate, creating a subduction zone in the Himalayas. This has led to the state come under the level 5 seismic zone category, i.e., it experiences moderate to a very high frequency of earthquakes. The most recent devastating earthquakes were 8.5 and 8.7 on the Richter scales, respectively. The added danger is prevalent because of the population density and the ill infrastructure in the area. This poses a threat to many lives across the region. Urban Infrastructure in India is often constructed without giving due consideration to minimum safety standards. This 3D printing technique is not yet fully established in the construction industry as it is not long time reliable (a house is

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expected to have a lifetime of 50 years to 100 years). However, some recent developments have shown the potential of 3D printing in the construction industry. Preventing a natural calamity is not in our hands. These effects can indeed be mitigated with efficient engineering to a level where it does not pose an undue danger to flora and fauna. This paper will use additive manufacturing technology, build a quake-proof structure, and optimize it accordingly to suit the Indian Subcontinent, especially the north-eastern region.

II. DESIGN

A. Geometry

The Quake Column, created by Emerging Objects, is a 3D-printed design developed from Inca Architecture, renowned for its work with the Incan Citadel, Machu Picchu. It 4 is a building made from an ashlar technique in which stone blocks are cut to fit together tightly without mortar. There is a lot we do not know about the Incan ashlar techniques. Knowledge of it from the 13th to 16th century has been chiefly unknown, and the Incan people were indeed master builders; they could probably teach us a lot about construction even today. The Inca developers intentionally chose cross-tectonic faults to build their cities. Like Assam, Peru is highly seismic, where the Incas had their Architecture fine-tuned to work with seismic events rather than against, avoiding the mortar and instead of creating dry stone walls with interlocking pieces, inclining inwards by 3° to 5°, with rounded corners which contributes to their stability.

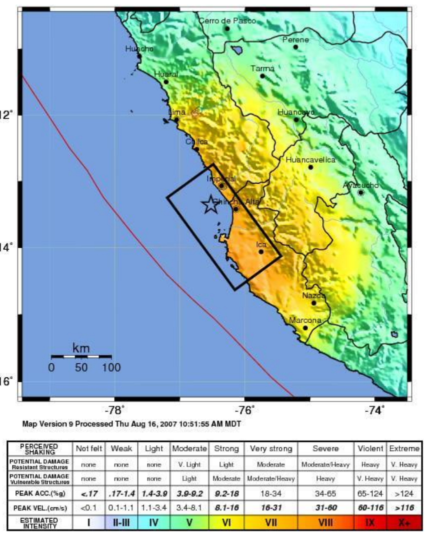

Fig 2: United States Geological Survey Shakemap of the coast of central Peru. ShakeMap is a map of the anticipated severity and extent of ground shaking, based on the measured strength of ground shaking and known characteristics of the affected locality. ShakeMaps provide near real-time maps of ground motion and shaking intensity following significant earthquakes. These maps are used by federal, state, and local organizations, both public and private, for post-earthquake response and 5 recovery, public and scientific information, and preparedness exercises and disaster planning.

B. Materials and Methods

The materials were chosen based on

- Availability
- Compatibility with the printer
- Cost
- Durability

The selection process was started by taking the availability of material and method of printing into consideration, then examining the compatibility of the material with the printer. As it is understood, these two go hand in hand with each other. These factors were taken into account, and further advanced to the following points: cost and durability a requisite for the selection. Selective laser sintering (SLS) is a powder-based layer-additive manufacturing process meant for rapid prototyping and rapid tooling. Predetermined sizes and shapes of layers are printed with the help of Laser beams either in continuous or pulse mode. The Computer aided design model or the Stereolithography(STL) files of the geometry are printed in a top to bottom process. After the initial layer is done canning, a layer of loose powder is deposited over the existing layer. The process is repeated until the entire model is done printing. Compared to the other processes, Selective laser sintering stands out in strong, complex, and intricate designs. Many irregularities may hinder the production process with methods like Fused Deposition Modeling, like supports, non-uniform surface finish, weaker heat and chemical resistance, and dependence on layer orientation. Selective laser sintering does not need all this; because of the powder used, the designs do not 6 need support; hence the surface finish and the strength enhances. Materials used in Fused Deposition Modeling like polylactide, Acrylonitrile Butadiene Styrene, polyethylene terephthalate glycol filament are all susceptible to higher to higher temperatures. In contrast, Selective laser sintering uses a nylon-based powder with a higher strength to weight ratio than the materials mentioned above.

TABLE 1: Comparison between different types of 3D printers

Parameter	Fused deposition Modelling	Stereolithography	Selective Laser Sintering	Selective Laser Melting
Abbreviation	FDM	SLA	SLS	SLM
Principle	Nozzle filament extrusion	UV curing	Laser sintering	Laser melting
Common materials	Filaments like PLA, ABS, PETG, etc.	Resins/photocurable liquid materials	Powdered sinterable polymers (i.e. polyamides, TPU, TPE)	Various metal alloys
Advantages	• low cost • fast printing time	• high print resolution • high process automatization	• no support structures • quality prototyping	• printouts durability
Disadvantages	• need of support structures • thermal shrinkage of filament	• narrow material variety • high maintenance costs	• long printing time	• high cost
Applications	• fast prototyping • low volume production	• complex internal geometry prototypes • dental models	• education • functional prototypes • medical models	• automotive and aviation industry • functional parts
Layer thickness	0.1 - 0.3 mm	0.05 - 0.15 mm	**0.060 - 0.15 mm**	0.02 - 0.1 mm
Printing without support structures	No	not always necessary	**yes**	not always necessary
Printing objects with movable parts	not always achievable (lower precision)	No	**yes**	no

After severe considerations and analyzing much material, finally, a nylon-based fine sand mixture was selected because of its strength and availability. For the testing process, a scaled-down model of the original column was taken because the available testing apparatus can only work for small models; the model was scaled-down to one tenth of the original size. The nylon-based fine sand mixture was selected

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to give the column a coarse finish for better grip between the blocks and better bonding between the particles during the printing. It also decreases the chance of failure of the block under high tensile loading.

C. Assembly

The meshing stones of Incan Structures overlook echoing frequencies and stress concentration points. The dynamic process of laying, removing, cutting, and then relaying blocks to make them fit exactly together consumed too much time. Each stone block could weigh tons. These dry-stone walls could move slightly during an earthquake and resettle without the walls collapsing, a passive structural control technique employs both the principle of energy dissipation and suppressing resonant amplifications

Fig 3. Machu Picchu is a 15th century Inca citadel located 7,970 feet above sea level. Constructed around 1450 but was an uninhibited century later in the period of the Spanish Conquest.

Due to the 3D printed materials used, this structure is different from the cyclopean blocks of Incan construction in that it is very lightweight and hollow. The hollow bricks create a high strength-to-weight ratio. Each massive 3D printed block has a provision to be easily maneuvered and placed. The blocks are numbered to assemble in the construction sequence.

During an earthquake, a building is put through the random motion of the ground at its base, which generates displacement-type loading, causing buildings to collapse. Using quake columns eliminated the consequences of displacement-type loading.

Fig 3: Numbered Blocks

III. ANALYSIS

Response spectra are a valuable tool for earthquake engineering to analyze the performance of structures and equipment during earthquakes. Most structures behave as simple oscillators, known as a single degree of freedom systems in engineering terms. Response spectrum is a plot of the maximum response of a single linear degree of freedom oscillator for a given component of earthquake ground motion(excitations).

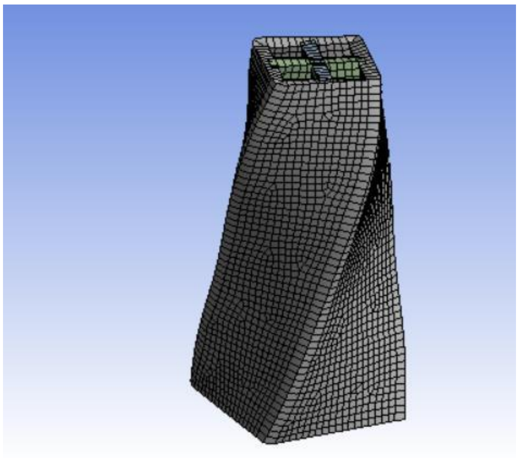

Fig 5: Meshed model of the 3D printed Structure

The X-axis has a natural period and, on the Y-axis, it is the response quantity (maximum displacement, maximum velocity, or maximum acceleration). Whatever the different structure's mass and stiffness be if the natural period is identical, then the maximum response is the same for all the other oscillators making it so that the maximum response of any linear single degree of freedom system to any given component of earthquake motion depends only on the natural frequency. Response quantity was chosen to be displacement. Lateral forces due to earthquakes are usually predominant. These forces can be either in the x or z direction. To evaluate the seismic loads' response, spectrum analysis is used. Modal analysis is the first and vital step in the process as the response spectrum is calculated based on the modal responses.

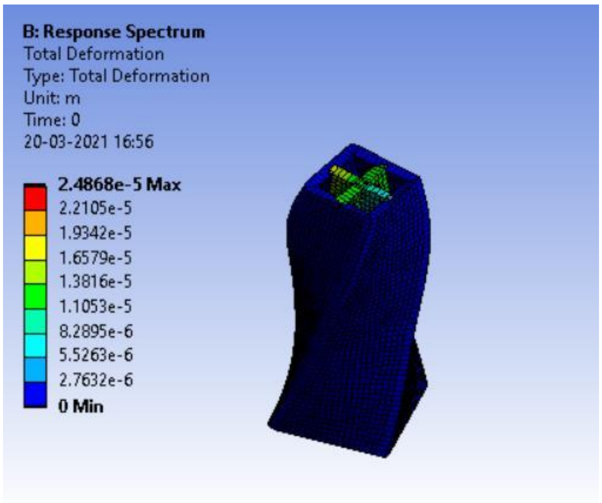

Fig 6: response spectrum analysis solution

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The excitations occurring in an earthquake are applied in the form of a response spectrum. There can be n number of spectrum values; for each of the spectrum values, there is a corresponding frequency. The excitations applied must be with at least one fixed support of the model, i.e., at fixed degrees of freedom. Response Spectrum displacement table was chosen from harmonic analysis, which has frequency with its corresponding displacements.

These values are given as input to find the displacement due to excitations. A 2D model of the quake column was designed and imported for analysis. Fixed support is added at the bottom of the column. The model is meshed with quadratic element order of 1mm size.

As we apply for one fixed support, we use a single-point spectrum type, and the modes are combined by the Square-Root-of-Sum of-Squares method. Total deformation is solved with boundary conditions as fixed support and the direction of excitations in the x-axis. The final result came out to be 0.0025 mm of deformation, which justifies that the column will withhold the displacement load applied by the earthquake excitation. The column will come back to the 0 mm deformation stage because of its intrinsic interlocking technique.

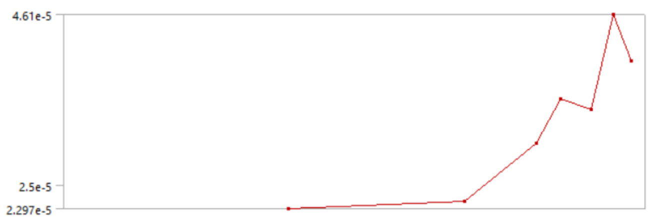

Fig 7: R-S displacement curve

IV. TESTING

The apparatus used for testing was a horizontal shaking table. In general, horizontal shaking tables are used to test the response of structures and soil or rock slopes to verify their seismic performance. These modern shaking tables typically consist of servo-hydraulic or other types of actuators driven in up to six degrees of freedom, which emulates the simulated ground motions that give us any information about the strength of the geometry. Earthquake shaking tables are used widely in seismic studies, as they provide the means to stimulate structures so that they are exposed to conditions typical of accurate earthquake ground motions.

Fig 8: Horizontal shake table

As mentioned earlier in our college, we had access to the apparatus in the earthquake testing laboratory. The machined needed an input of frequency, time period, and the 12 corresponding amplitude. The prototype to be tested require a rigid base for proper constraining, so a 10mm plywood base was cut into the machine's required cross-section, and holes were drilled at desired locations.

Fig 9: Experimental procedure

The 3D printed scaled-down prototype was stuck to the 10mm plywood base with Araldite and left to cure 24 hours. The entire assembly was fixed to the base plate of the shaking table with M15 bolts. Testing was done for a constant 6hz frequency and varying amplitudes for a specific period of 1 minute for each testing iteration. The amplitudes ranged from 4 to 8 units. Upon testing for all values, it was found that our Scaled prototype could handle all the simulated lateral ground motions, thus proving to be a practical geometry for achieving optimum performance.

V. CONCLUSION

A numerical model of the test setup, i.e., the structure, is defined and subjected to the recorded Response Spectrum analysis through the ANSYS software. The structure is designed as a 1 Degrees of Freedom system.

The total displacement is well within the limits of The Bureau of Indian Standards. To investigate the seismic behavior of the structure, shaking table tests are carried out by the horizontal shake table apparatus available at the laboratory of our University. 13

The structure is accurately designed to test the effects of an earthquake on a general building story. The test is executed by shaking the table simultaneously in both horizontal directions. Research conducted through a horizontal shake table provides valuable information on the behavior of composite connections and design. These data and the resulting seismic design guidelines help additive manufacturing as cost-effective and reliable alternatives to conventional steel and reinforced concrete construction in different parts of India, especially in Assam.

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