Rethinking Seismic Protection in Areas of Substandard Construction

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ABSTRACT

Earthquakes are destructive and unpredictable disasters which may cause extensive damage and mass casualties. There has been major investment into seismic resistant buildings, but much less into devices built to protect lives from substandard construction that is prevalent in the developing world. The Shaker Shield is the first technology of its kind designed primarily to protect the inhabitants of a structure rather than the structure itself. The shield is composed of laminated urethane fabric and is rapidly inflated using existing aircraft evacuation slide technology. Its computer designed arch has been optimized for strength and integrity and the base mat's rapid latch system provides additional support to resist compression and lateral deformation. The Shield is designed to be deployed over a mattress with the base mat on the floor underneath. It may also be used on the floor alone in open spaces, office buildings and high rises where people may need to seek protection from debris due to failure of curtain walls or glass facades.

Keywords: seismic shield, urethane fabric, earthquake, flood, protection

1 INTRODUCTION

There are more than 500,000 earthquakes that occur annually throughout the world. Most of these earthquakes are low magnitude events with little to no impact on building structures or people. Approximately 3,000 earthquakes are perceptible by humans annually with approximately 4.7 million people impacted each year from these earthquakes [1]. In 2015, there were over 1,500 earthquakes with a magnitude of 5.0 or greater resulting in almost 10,000 deaths [2]. On average there are seven to eleven earthquakes annually that result in significant loss of life. Also, there are approximately 20 earthquakes a year that result in more than ten deaths, more than 100 people affected, a request for international assistance, or a declaration of a state of emergency [3]. In addition to the loss of life and injuries that can occur, the economic impact of earthquakes can be devastating. Earthquakes in the United States alone are estimated to result in building damages of over $6 billion annually [4].

Building construction and the propensity for buildings to collapse significantly contribute to mortality during earthquakes. For example, in the 1976 Guatemalan earthquake that resulted in approximately 23,000 fatalities and over 75,000 injuries, almost all casualties resulted from the failure of concrete and brick structures [4]. Due to the significant risk of mortality and morbidity caused by structural collapse or blunt force trauma from falling objects, there is a market need for inexpensive and portable solutions to protect individuals that live in earthquake-prone areas.

Several inventions for individual protections in earthquakes have been made recently. The LifeGuard desks are designed with an internal steel structure engineered and demonstrated to support over one million pounds. The desks provide protection against falling debris, blasts and high-velocity hazards. Inside/underneath the desk is outfitted with heavy padding and handles to provide individuals with space to lie down and stretch out. In addition, the steel floor of the desk prevents penetration from below [5]. The LifeGuard desks are expensive, with the basic model for corporate environments retailing at approximately $5,000 with custom models retailing at over $10,000. The company also offers a school desk for approximately $500 [6].

An individual inventor, Wang Wenxi, in China has developed an earthquake-resistant bed. The structure is comprised of a bed body, a bedside cabinet storage component, and a protective cover. In the event of an earthquake, the bed body (and mattress) are dropped into the bedside cabinet storage component using a hinged mechanism. The protective cover closes on top of the cabinet storage component sealing the occupant inside to protect from falling debris [7]. The bed has not been commercialized to date. In addition, another individual inventor has developed a sleep structure designed to protect against earthquakes. The structure includes an arched roof extending to a rectangular base supported by a number of truss panels. A canopy layer comprised of fiber-reinforced plastics forms a solid material that covers the arched roof. The canopy layer prevents debris from falling through the arched roof infrastructure. The bed also contains guardrails to properly position the user on the mattress in the protective area and a storage area below the bed to hold earthquake emergency equipment [8]. Again, this system has not been commercialized to date.

In this study, the proposed Shaker Shield could have competitive advantages if commercialized. Unlike engineered retrofit building solutions that are capital intensive, technically complex, and take years to implement, the described Shaker Shield is portable, inexpensive, and can be widely distributed. The Shaker Shield rapidly inflates via a mechanism that is based upon a combination of an initiator mechanism that relies upon a boost from a compressed nitrogen device and then outside air being drawn in through aspirators via the venturi principle [9]. Aircraft evacuation slides are required to inflate in seven seconds and this technology is well established and employed by several leading manufacturers including Goodrich.

Such rafts and slides can stay inflated for extended periods of time. The Shaker Shield is also planned to include additional functionality such as handles for easy maneuvering and use during a flood, and a meter for the compressed nitrogen to ensure it is ready for deployment after extended storage. Since the system is cost-effective, broad adoption of the system for use in earthquake and flood prone areas could lead to improved survival rates in such natural disasters.

2 METHODOLOGY

2.1 Geometry

Based on the expected protection capacity and the preliminary study of the potential loading impact, the research team designed several different types of geometries. The geometry should satisfy the requirement that enough space is available beneath the shield for people to hide and the strength of the shield is able to sustain a significant amount of impact on top.

We designed and scaled two durable geometries using AutoCAD as shown in Fig. 1. The finite element model of different geometries is being tested under same loading conditions using ABAQUS. Stress and deformation responses of the models determine the optimum design, which better guide us towards the manufacture of the final geometry. Three dimensional printed models have been tested and the phase will be to test inflated scaled prototypes comprised of laminated, urethane fabric.

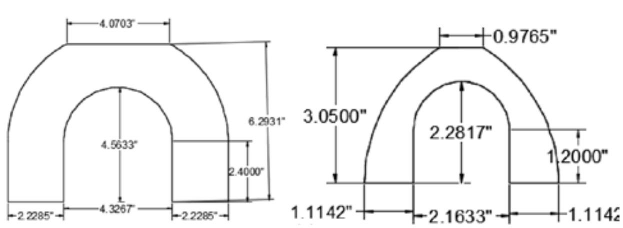

Fig. 1 Tentative scaled shield geometries.

2.2 Material

Inspired from the raft material, the shield will be made of laminated urethane fabric, which provides for rapid inflation with enough flexibility while offering excellent strength and puncture resitance. Prototypes will be used to conduct laboratory stress tests designed to mimic the real case of loading impact from falling structural components.

2.3 Inflation mechanism

After the final choice of geometry and material, the team will look into the most suitable inflation mechanism for the shield. Rapid inert inflation could be inspired from existing aircraft evacuation slide that can be fully inflated with inert nitrogen or gaseous CO_2 in less than seven seconds. The inflation will be triggered by user activtated rip cord. Inflation will be directional just as in an aircraft slide and simple, clear instructions will be printed on the storage bag.

2.4 Integrated design

To secure the integrity of the shield system after inflation, and prevent it from collapsing laterally, the base of the shield will be linked via a quick latch system. The latch system is planned to feature three reinforced eyelets on each side and will be field tested upon the final prototype completion. The base mat may be prepositioned under a bed frame or easily deployed in open space such as might be found in a moder office building.

3 RESULTS AND DISCUSSION

3.1 Finite Element Modeling

Models created in AutoCAD were imported into the commercial Finite Element software ABAQUS. The material follows a linear elastic law. For different model geometries, the same vertical load is applied to account for the weight of a structural element such as collapsed beams, columns or walls during the earthquake. Because each model has different contact areas, the resulting pressure applied will be adjusted accordingly.

Figures 2 and 3 present the simulation results of stress and displacement test for the designs illustrated in figure 1. These simulations were under unconfined compressive loading and the stress contours indicated that strong stress concentration is be observed in the most concave section of the arch structure. Displacement shows a strong movement along the lateral direction. Given the same total vertical load, results indicate that the geometry in figure 2 yielded lower stress concentration with vertical compression loading. Additional testing is being undertaken using printed designs.

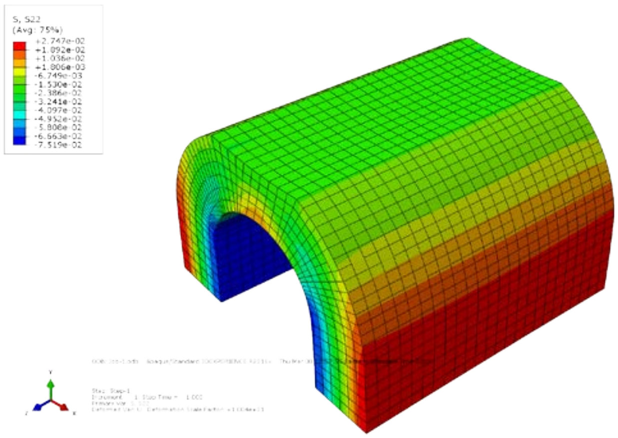

Fig. 2 Vertical stress distribution of geometrical design 1 (the left one in Fig. 1).

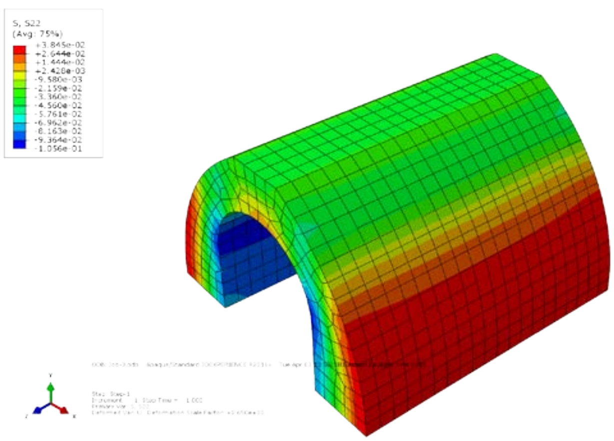

Fig. 3 Vertical stress distribution of geometrical design 2 (the right one in Fig. 1).

3.2 Mechanical testing of 3D printed specimen

The geometry identified in section 3.1 was printed using a desktop stereolithography (SLA) 3D printer (Formlabs Form 2 resin printer). To mimic the real design of an inflated shield, the specimen was designed to be hollow with a uniform layer thickness. To avoid any residual resin in the hollow shield, two holes were placed on the base to facilitate resin drainage. An unconfined compression test was carried out in the laboratory. The test was displacement-controlled at a constant rate of 0.001 in/min. As shown in figure 4, a uniformly spaced grid was plotted on the side to demonstrate the deformation of the resin specimen under compression.

Fig. 4 Unconfined compression test using the MTS loading machine.

The loading displacement response obtained from the test indicate a strong, brittle behavior of the resin shield. The load increased gently in the beginning stages of the test due to the increasing contact area between the shield and the loading platform. After the contact area stabilized, the load increased rapidly until the generation of the first microcrack, which can be reflected through the lateral movement of one shield column. Figure 5 illustrates the stress strain curve reaching its peak as pressure approached 6,000 psi and showed a fluctuating phenonmenon before ultimate failure was achieved. This is attributed to the intiation and propagation of microcracks located in the most concave part of the specimen, which is consistent with our observation of stress concentration in the FEM simulations.

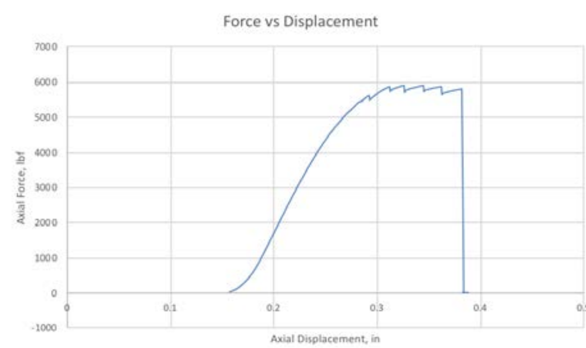

Fig 5. Stress strain response of the 3D printed resin specimen under unconfined compression.

Although the resin material exhibits a different behavior from the urethane fabric, through these tests, we can qualitatively evaluate the influences of geometry on the shield performance, which provides us a better guidance for subsequent designs.

4 MARKET AND OPPORTUNITY

The Shaker Shield's key features include: User activation via a pull/rip cord, rapid inflation via a chemical explosive (sodium azide or similar) that will generate an inert gas, comprised of durable, puncture resistant laminated fabric designed to be secured to a high tensile strength mat and secured with three reinforced eyelets on each side. It will also have EPIRB support through Cospas-Sarsat. The Shield can stay inflated indefinitely. In addition, the system is compatible with existing bedding and is available in multiple sizes. The Shield is augmented underneath by the mattress on the bed thereby distributing impact forces over a wide area. The Shaker Shield combined with the mattress could potentially protect people in situations involving a building collapse. The Shaker Shield also has applicability in other natural disasters and can be used as a flotation device in flood situations.

A relevant market for the described technology is the personal protective equipment market. The global personal protective equipment market was estimated at approximately $40 billion in 2016 and is expected to increase to almost $60 billion by 2022 with annual growth rates of approximately 6.5 percent [10]. Growth in the market is primarily driven by government regulations and increased awareness about the importance of worker safety. Although the market is targeted towards worker safety, it could serve as a comparable for personal protective equipment purchased for natural disasters such as earthquakes.

A better approximation of the market in the United States can be determined based on the target population at-risk of experiencing an earthquake and the potential market penetration of the Shaker Shield. There are approximately 28 million or 9 percent of the population living in areas with a "high potential" for hazardous earthquakes. Assuming a retail price of $300 for the Shaker Shield, the potential market opportunity would be $8.4 billion for the population in areas with a "high potential" for hazardous earthquakes [11].

5 CONCLUSIONS

By joining and repurposing existing technologies a new paradigm of disaster protection can be achieved. While seismically resistant structures are always desirable, they are not always achievable in practice, and cost also becomes an issue. This new technology is multi purpose and can offer benefits for people even in seismically protected structures such as skyscrapers. The Shield's important advantages include: portability, relative inexpensiveness, ease of distribution and deployment in areas prone to seismic activity and the ability to be used as a flotation device in flood situations.

The potential market opportunity for Shaker Shield is significant in the United State alone due to the high populations in high seismic risk areas. Since this technology could also be used as a flotation device in flooding situations, it presents another potential market. Recent extreme flooding events in the southeastern U.S. have demonstrated the usefulness of such an emergency flotation device. The Shield presents an opportunity for leading manufactuers to partner Rowan University, South Jersey's leading research institution, in an exciting and promising endeavor to save lives in major natural disasters.

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