A PRELIMINARY DESIGN OF DISASTER-SURVIVABLE BUILDING BLACKBOX SYSTEM FOR URBAN DISASTER RESPONSE

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SUMMARY: *When natural or human-induced disasters strike an urban area, buildings are always being considered as one of the critical physical infrastructures (CPIs). Information regarding the building and its occupants is critical to disaster response operations, particularly when civil engineers need to make reliable decisions in term of the structural integrity of the building. However, as the experience of the 9/11 terrorist attack showed, access to accurate building information is often limited and inefficient due to the lack of on-site preservation of building documentation and inability to communicate with building systems. To address these issues, this paper presents a conceptual design, initial prototype and preliminary testing results of a building blackbox system to bridge the gap between first responders and building systems and to provide reliable and accurate building information over a mobile ad hoc network (MANET). By maintaining a building information database and incorporating building sensing and control systems, the building blackbox system can provide building information on site as well as monitoring real-time building functional conditions. In order to protect the critical information from disastrous events, the building blackbox system is designed to be disaster-survivable by utilizing state-of-the-art high temperature and high strength geopolymer material and insulation technology. Additionally, sufficient data redundancy mechanisms such as information replication in a decentralized network are also employed to ensure the availability, completeness, and reliability of critical information and its access. To validate the survivability and accessibility of the building blackbox system, a series of required fire tests, strength tests, drop tests, and communication tests were conducted on the prototype according to ASTM, FAA, and EUROCAE standards. The results from the tests confirmed the potential of such building blackbox systems in supporting and improving the disaster response efforts. These preliminary tests also provide insight to the final design of the building blackbox system.*

KEYWORDS: *disaster-survivable, redundancy, disaster response, information systems, geopolymer, mobile ad hoc network, blackbox.*

1. INTRODUCTION

In the past decade, several large-scale natural and human-induced urban disasters have resulted in tremendous catastrophes and enormous casualties. For example, between 1997 and 2006, a total of 7,285 disasters occurred world-wide affecting over 2,265 million people, of which 1,400,831 people died. The average economical cost of damage is $108 million per disaster (CRED 2007). One of the main reasons of these casualties in urban disasters is collapse or structural damage of buildings; for example, the terrorist attack at the World Trade Center complex and the bombing attack at the Murrah Federal Building (Kwan et al. 2005). Hence, building structure damage and collapse has become one of the most important and challenging issues in Urban Search and Rescue (US&R) operations during disasters involving critical physical infrastructures (McGuigan 2002). However, the complex internal structure of the buildings and the lack of real-time, accurate and reliable building information available to both emergency responders and people inside the buildings made it particularly difficult for either rescue operations or quick evacuation in an emergency situation (NIST 2005a, Kwan et al. 2005).

Therefore, civil engineers and constructors are being considered as the “fourth responders” who can provide the rescue team with critical information to support resource allocation, risk assessment and decision-making related to the condition of civil infrastructures in urban areas. Nevertheless, critical building information, such as building design, potential building failure and victim locations, is often missing, hampering rescue efforts. As recommended in the Final Report of the National Construction Safety Team on the Collapses of the WTC Towers (NIST 2005a), a system for “*real-time secure transmission of valuable information from fire alarm and other monitored building systems for use by emergency responders, at any location, to enhance situational awareness and response decisions and maintain safe and efficient operations*” should be developed and implemented.

Thus, to support the rescue operations in large-scale building emergencies, this paper presents a building blackbox system which is designed to be disaster-survivable by utilizing state-of-the-art high temperature and high strength geopolymer material and insulation technology. Equipped with a building information database that employs robust data redundancy, this building blackbox system aims at providing critical building information and facilitating emergency response to disasters on complex building structures in an efficient and effective manner. Furthermore, a communication protocol over a decentralized mobile ad-hoc network (MANET) is also presented and employed to bridge the communications between the building blackbox system and first responders and to ensure the completeness and reliability of the critical information access and dissemination, and improve the efficiency of information transmission.

2. BUILDING BLACKBOX SYSTEM

The main objective of the building blackbox system is to provide first responders and civil engineers with (a) on-site preservation and off-site backup of building critical information; (b) reliable and interoperable communication network; (c) disaster-survivable protection of the system; (d) in-situ structural performance monitoring. Fig. 1 illustrates the components of the building blackbox system. To achieve these goals, several key design challenges will be discussed in the following sections.

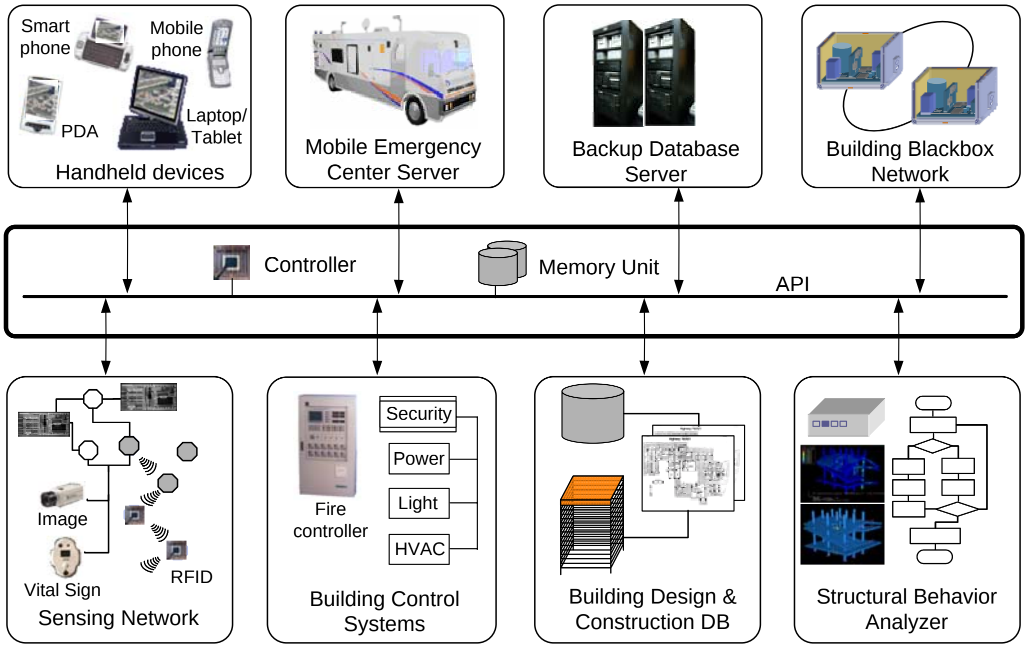


FIG. 1: Key components in the building blackbox system

2.1 Building Information Database Design

The most important functionality of the building blackbox system is the on-site preservation of critical information concerning the building. Real-time access to the critical information will not only empower the first responders but also support the decision-making in rescue operations. Interviews with personnel from Champaign County Emergency Management Agency (CCEMA) and Illinois Fire Service Institute (IFSI) revealed that the information that is critical and valuable to the rescue operations includes, but is not limited to: (a) building design and construction documents; (b) internal structural health of the building (e.g., stress and strain data of structural elements); (c) disaster environment conditions and building performance (e.g., audio/video/image data, temperature, humidity and air level); (d) building systems status (e.g., status of communications and HVAC systems); (e) personnel (e.g., occupants in the buildings, first responders, and civil engineers) information and location.

To store the design, construction, and maintenance records of the building, the blackbox system has a building design and construction database which can be easily and securely accessed by emergency responders during disaster events. Fig. 2 shows the preliminary design of the Entity-Relationship diagram (ERD) of this database. In this database, construction drawings of floor plans and layout, completed structure material specifications (i.e., bill of material reports), deployment of electrical, plumbing and fire protection systems, as well as drawings of emergency exit routes are compiled and indexed for quick search queries.

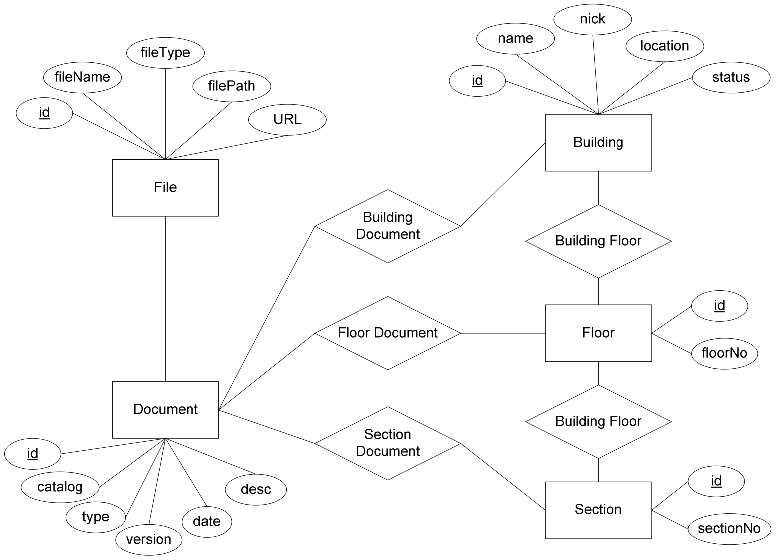


FIG. 2: E-R diagram of building information database

In addition to the documents preloaded in the building information database, the building blackbox system is also integrated with building sensor and control systems to provide real-time measuring and monitoring of the building condition and its occupants status. As recommended in the WTC report (NIST 2005a), this information is particularly helpful in the rescue planning, the engineering assessments, and the evacuation process as it enhances the situational awareness of emergency responders.

2.2 Disaster-Survivable Design

Designed to be a critical information provider in disaster situations, the building blackbox system must survive various disaster scenarios. Fires, static crushes, penetration impact, crash shocks, vibrations, fluid immersion and any combination of these events are likely to happen to a building and the blackbox systems in natural, accidental or intentional extreme events. Table 1 depicts the design specifications of the survivability requirements for the blackbox systems. Most of these requirements are derived or modified from the NIST, MIL, and ASTM standards (NIST 2005a, DoD 2000, ASTM 2004, ASTM 2007). The other requirements are obtained from other sources such as Federal Aviation Administration (FAA) aircraft recorder specifications (Thompson 1999, EUROCAE 1990, EUROCAE 1993) and rail and locomotive recorder specifications (Hogan et al. 1994; Thomas et al. 1999) in the absence of definitive information. The source of each specification used is shown in Table 1. These requirements serve as initial design parameters for designing a prototype for the building blackbox system.

TABLE 1: Survivability requirement for the building blackbox system

Situation	**Survivability Requirement**	**Referred Specification**
Fire (High temperature)	1,200˚C (RC Structure) for 60 minutes	ASTM E119-07 / E1623-04
Fire (Low temperature)	260˚C for 10 hours	EUROCAE ED-55 / ED-56A, NSTB Standard (Rail Event Recorder)
Static Crush Pressure	25,000 lbf for 5 minutes (faces and diagonals)	EUROCAE ED-55 / ED-56A, FAA TSO-C123a / C124a, NSTB Standard (Rail Event Recorder)
Drop	Free drop from 48 in height (corners and faces)	MIL-STD-810F (Method 516.5)
Shock	23 g's / 250ms or energy equivalent	NSTB Standard (Rail Event Recorder)
Penetration	500 lbs / 0.05 in^2 steel pin drop from 10 ft height	EUROCAE ED-55 / ED-56A
Immersion (Fire extinguisher fluid)	8 Hours	EUROCAE ED-55 / ED-56A
Immersion (Corrosive fluids)	48 Hours	EUROCAE ED-55 / ED-56A

Among these requirements, emphasis was placed on temperature, static crush pressure and free drop requirements in the preliminary design tests since they are the most likely combinations to be encountered in building disasters. To ensure the survivability of the building blackbox system for these requirements, three state-of-the-art technologies including high temperature and high strength geopolymer material, insulation technology and solid-state memory unit were explored. The following sections describe these technologies and their utilization in the building blackbox system.

2.2.1 Ruggedized Geopolymer Coating Protection

Geopolymer, or “man-made rock”, is a noncombustible, heat/fire/acid resistant material synthesized by raw materials (e.g., fly ash), inactive filler (e.g., metakaolinite) and geopolymer liquor (e.g., potassium silicate solution) (Davidovits 1994). Due to its excellent durability performance and high bond strength with steel, concrete and wood, geopolymer has been widely used as a protective coating material (Balaguru 1998). In particular, Kevlar-fabric reinforced geopolymer composites have two excellent properties: high thermal stability (up to 1528˚C) and high compressive strength (up to 100 MPa) (Duxson et al. 2005). These two rugged properties meet the survivability requirements for the blackbox system as tested in our experiments (refer to Section 3 for details). In addition, another critical advantage of using geopolymer composites as the coating material for the building blackbox is that it could avoid shielding wireless signals, which metal housing might encounter. These properties make the Kevlar-fabric reinforced geopolymer composites excellent material for the ruggedized protection in building disaster environments.

In the coating process, as shown in Fig 3, a potassium silicate solution with molar ratios of ($SiO_2:K_2O = 2$) and ($H_2O:K_2O = 13$) was prepared by dissolving potassium hydroxide (KOH) pellets in KASIL 6 potassium silicate solution from PQ Corp. (Fig. 3a) The solution was allowed to mature under stirring for 4 hours. Class F fly ash and metakaolin was then mixed with the potassium silicate solution using a high-shear mixer with a weight ratio of 3.54:7.95:1 (solution: fly ash: metakaolin) to initiate polymerization (Fig. 3b, Fig. 3c). This ratio was chosen based on optimum fly ash/metakaolin reactivity and strength of the resulting geopolymer adhesive (Bell et al. 2005). After mixing, Kevlar-fabric segments were immersed into the geopolymer (Fig. 3d) and applied to the respective sample (Fig. 3e). Finally, the sample was cured in the furnace for 24 hours at 40˚C (Fig. 3f).

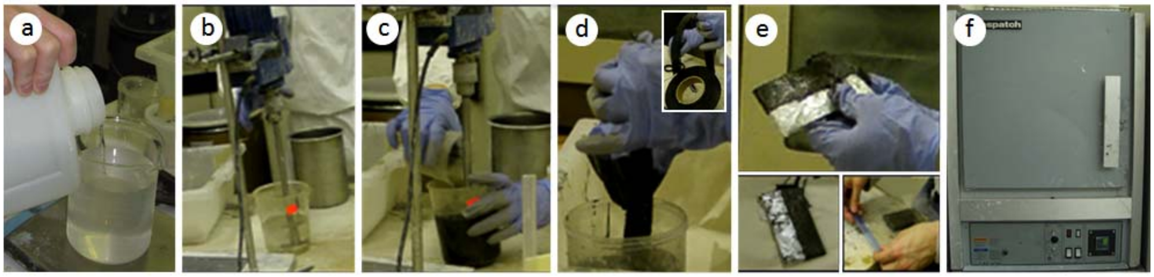


FIG. 3: Kevlar-fabric reinforced geopolymer coating process

2.2.2 Thermal Insulation

To maintain the interior environment of the building blackbox system at an operating temperature range and to prevent the damage of electronic components from overheating, the disaster-survivable design of the building blackbox system is internally insulated with dry-silica based thermal insulation. Like those in aircraft blackboxes and space shuttle thermal protection systems (TPS) (NASA 1988), the high performance insulation material to be used in the building blackbox system has a service temperature up to 1,260˚C while its low thermal conductivity (0.3W/m·k@1,100˚C) would reduce flow of heat transmitted into the interior to a temperature that a computer could operate (around 15˚C to 75˚C), even when the outside temperature is over 1,000˚C.

2.2.3 Solid-State Memory Unit

Another state-of-the-art technology used as part of the disaster-survivable design is a solid-state memory unit. A solid-state memory unit is a highly reliable flash-memory based replacement for conventional hard-disk drives; it has very complex modules of internal NAND non-volatile memory chip and controllers instead of magnetic, spinning disks. Everything in the memory unit is electronic instead of mechanical. As a result, there are no moving parts to break, thus providing better shock and vibration resistance than hard-disk drives. The additional advantages over hard-disk drives are faster data access time (<0.1ms), lower power consumption (0.5W in operational mode and 0.01W in standby mode) and less heat dissipation, which are crucial to the operating environment of the building blackbox system (Samsung 2006). Fig. 4 illustrates the design of the blackbox system with the disaster-survivable protections.

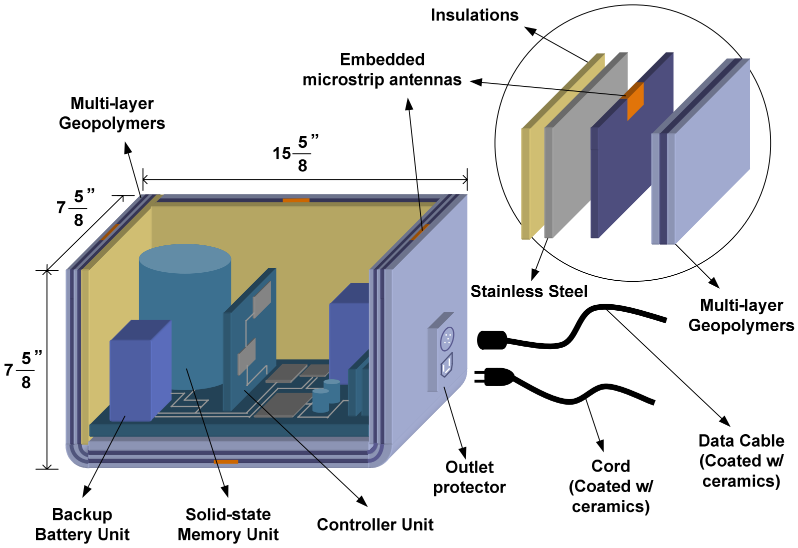


FIG. 4: Disaster-survivable protection of prototyping building blackbox system

2.3 Redundancy Design

Due to the dynamic nature of ad-hoc network and disasters, the functioning of the building blackbox system is enhanced through redundancy design to ensure high availability of reliable and accurate information. There will be two types of redundancy mechanisms employed in the proposed system, i.e., data redundancy and system redundancy.

2.3.1 Data Redundancy

Through Internet Protocol (IP) mirroring technology, all the information in the building blackbox database will be replicated and transmitted to other storage facilities during realtime. The replication is chosen to be at byte level rather than file level or directory level to save the network bandwidth by avoiding transmitting the entire file or directory. The replication process is in a mixed mode in terms of synchronization, i.e., the replication engine will use both synchronous and asynchronous mirroring, depending on the network condition. The default mode of the replication process would be synchronous mirroring as it guarantees high performance of the system and complete data integrity at any point of time (Kosacek and Vasudevan 2002). However, when the available bandwidth is low, it will be switched to asynchronous IP mirroring (AIM) mode to save the network bandwidth, though AIM will introduce some performance lags.

The data storage facilities can be both on-site and remote backup centers. Examples for on-site storage are the mobile command center and other building blackbox systems in the ad-hoc network (Fig. 5) while examples for remote storage are federal, state, and county emergency/command centers.

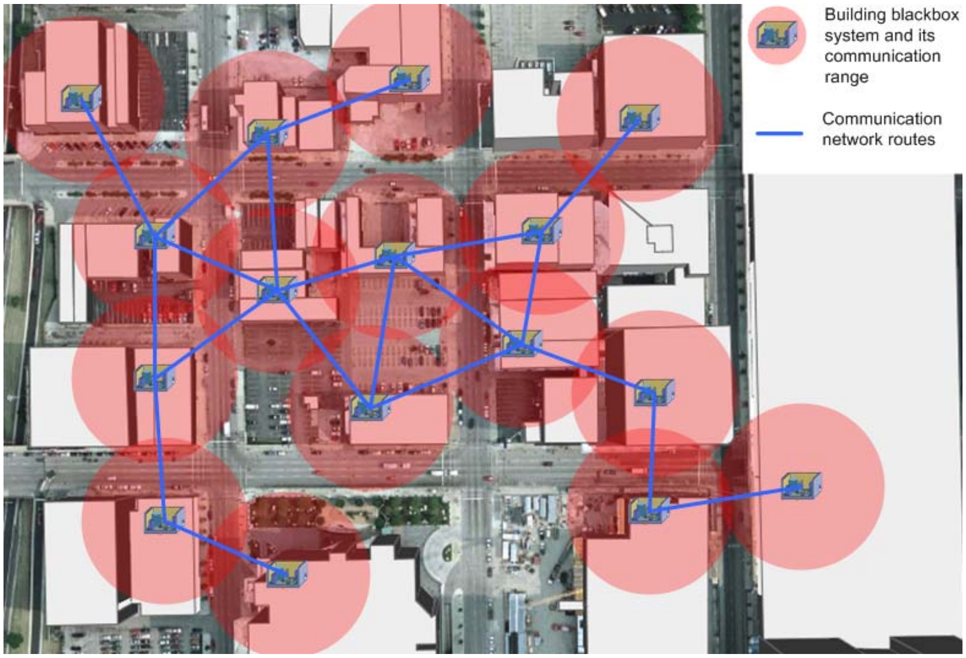


FIG. 5: Building blackbox network for data redundancy purpose

2.3.2 System Redundancy

The second redundancy is system redundancy. More specifically, the building blackbox system would be equipped with redundant key components. For example, multiple antennae will be installed in/around the building to ensure the availability of continuous communication and data transfer channels between the blackbox and sensing and control systems and first responders.

2.4 Communication Design

To cope with the issues related to communication among first responders and the building blackbox system during a disastrous event, an infrastructureless communication platform is needed as the existing communication infrastructure might be damaged or overloaded. In this paper, Mobile Ad-hoc Space for Collaboration (MASC) (Aldunate et al. 2006) was used as the collaborative framework along with IEEE 802.11a/b/g/n specification as the communication standard protocol.

Over the MASC, first responders and on-site mobile emergency centers are able to request critical building information from the building blackbox by exchanging pre-defined XML-format files through various mobile computing devices with wireless communication capability. As a typical communication process illustrates in Fig. 6 and Fig. 7, a first responder uses a GIS-based interface to locate the buildings and other responders and to send requests to the target building. The building blackbox system first authenticates the requests and then retrieves the data either from the building information database or the sensor systems. All the data will be wrapped into XML-format files and transmitted to the requestor through the multi-hop ad-hoc network.

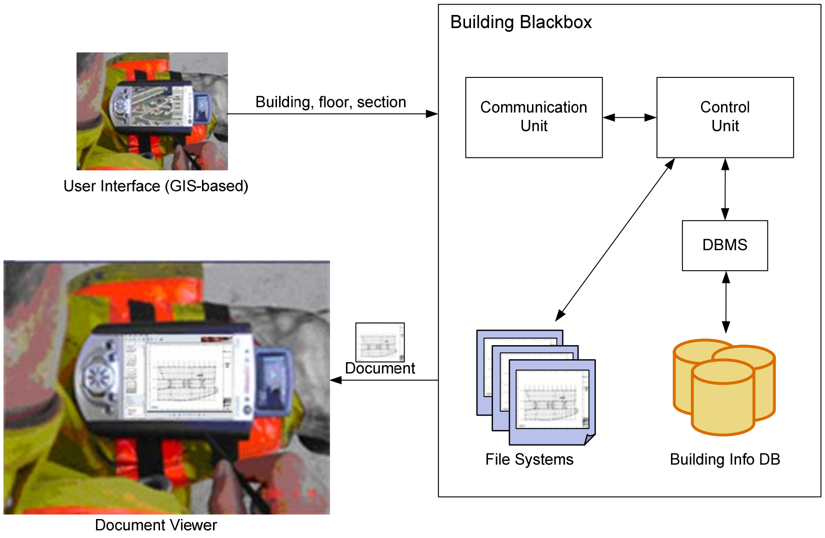


FIG. 6: Information request by building blackbox system over MASC

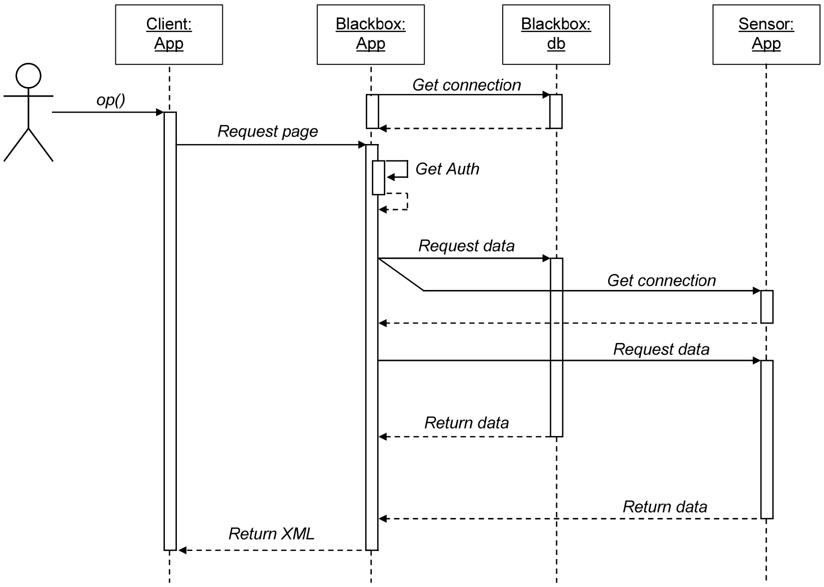


FIG. 7: Sequence diagram of communication with Building blackbox system

2.5 Security Design

While the information shared by the system is critical to support rescue planning and operations, the shared information could also be used to inflict more damage in case of intentional and human-induced disasters. Therefore, preventing unauthorized access to the system has been critically considered for the design of building blackbox system. The security system can be roughly catalogued into three layers: network, user and physical layers. The top concern would be network security, especially for wireless communication networks. Therefore, in the preliminary design of the system, the government-grade wireless security technologies, WPA2 (Wi-Fi Protected Access 2) standards, will be employed to secure the wireless network. Based on the security enhancements introduced in the IEEE 802.11i amendment (IEEE 2004), WPA2 can protect the system communication by making use of sophisticated data encryption algorithms such as Advance Encryption Standard (AES) along with authentication mechanisms such as Remote Authentication Dial In User Service (RADIUS) which also enhances the access security of the user layer (Frankel 2006).

3. SURVIVABILITY TESTS

To ensure that the building blackbox system can survive under the various disastrous events, we used small-scaled preliminary test specimen (PTS) with the same protective structure to validate the disaster-survivable design. Fig. 8 illustrates the structure and the dimensions of the specimen.

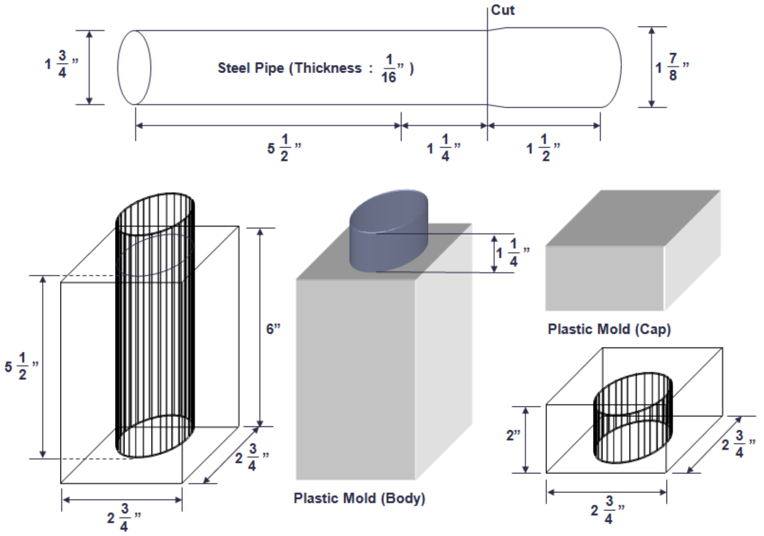


FIG. 8: *The dimensions of the preliminary test specimen (PTS)*

3.1 Simulated Disaster Scenario

The tests were conducted on six preliminary test specimens (PTSs) in the way that each specimen was tested under a sequence of disastrous scenarios, but in different orders, including communication testing, drop testing, static crush testing, and fire testing. Fig. 9 shows the sequence of the testing being conducted.

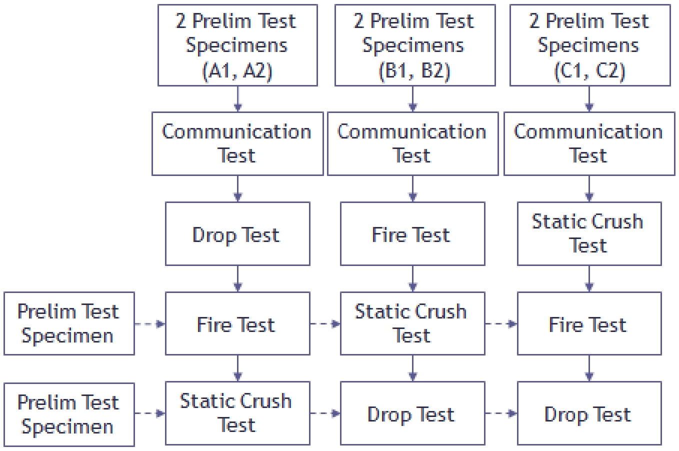
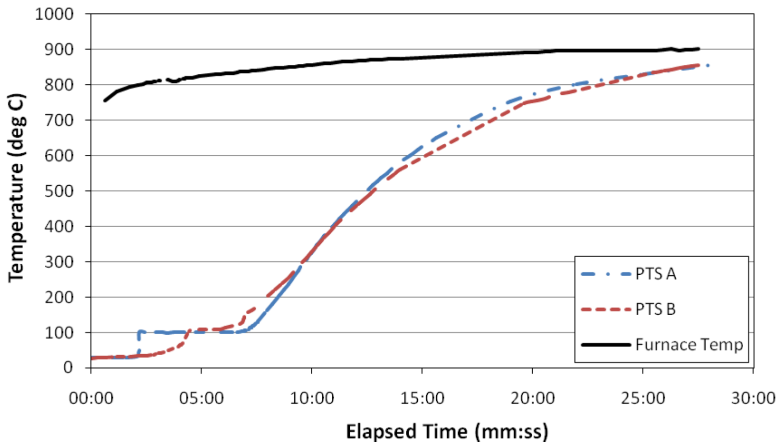


FIG. 9: The sequence of tests conducted

3.1.1 High Temperature Fire

The fire survivability requirements of the building blackbox system are similar to those of the aircraft blackbox. According to the WTC investigation report, the temperature of the full floor burnout fire scenario is assumed to be 1,100˚C (2,000˚F). Generally, the peak fire temperature of a building fire is slightly lower than that of an aircraft-crash fire because the latter has the effect of jet fuel combustion (NIST 2005b). Therefore, an oven with 900˚C interior temperature was used in the fire test on the preliminary test specimen (PTS). As shown in Fig. 10, the DSP provides good thermal shock protections and keeps the blackbox system in workable conditions for the first seven minutes, which is good enough for the blackbox system to respond to the disastrous events and to complete the emergency data backup and replication processes.



(a) Fire test results on PTS A1 & B1

(b) Minor cracks in PTS B1 after test

FIG. 10: Test Rusults on Fire Tests

3.1.2 Static Crush Pressure

In order to prevent the building blackbox system from static crush as a result of building collapses or structural element damages, it is required to withstand high static crush pressure. In the concern of the heavy weight of structural elements, the building blackbox system is designed to sustain a 25,000 lbf (111.12 kN) loading for five minutes, which is five times higher than that of aircraft blackbox. Due to the reduced size of the PTS, this static crush pressure requirement is rescaled by the surface ratios, which is shown in Table 2. The force-displacement curves of the test results are illustrated in Fig. 11. The maximum loads in X-direction and Z-direction are 6,500 lbf and 2,400 lbf, respectively. This indicates the design of PTS can fulfill this static crush requirement well.

TABLE 2: Static crush requirement for reduced-size PTS

	Blackbox System (Dim: 8" × 8" × 16")	Preliminary Test Specimen (Dim: 2.75" × 2.75" × 8")
X – direction	25,000 lbf (Surface area: 128 in^2)	4,000 lbf (Surface area: 22 in^2)
Z – direction	25,000 lbf (Surface area: 64 in^2)	2,500 lbf (Surface area: 7.56 in^2)

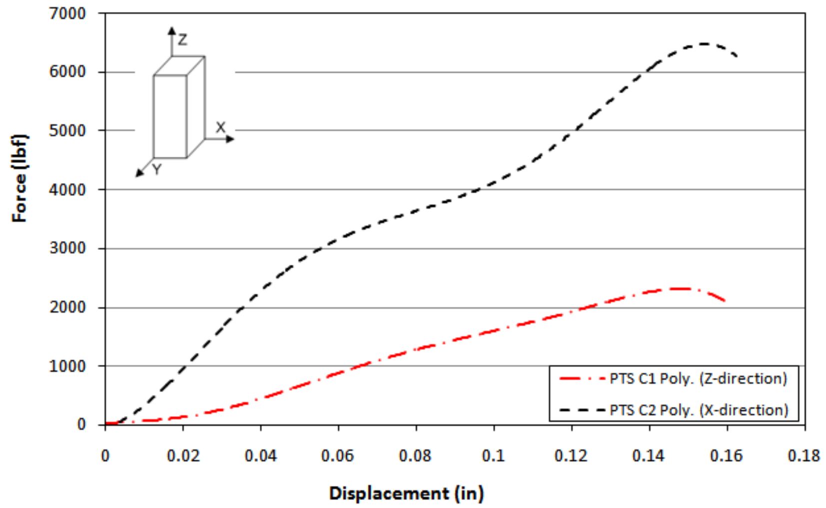
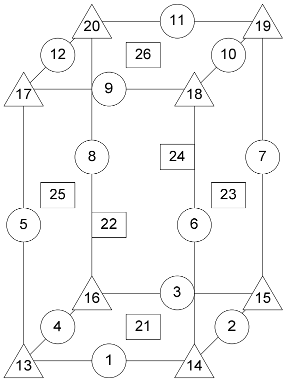


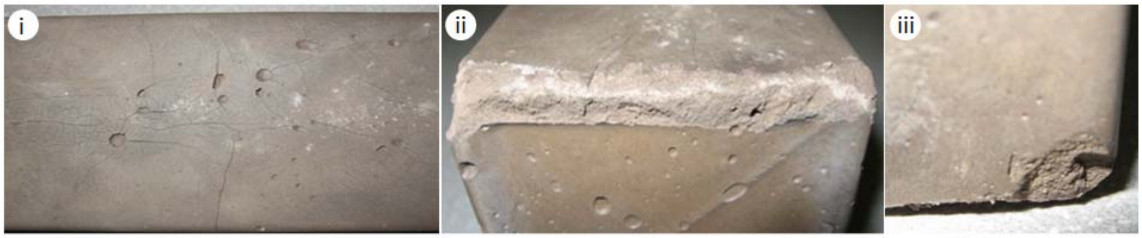
FIG. 11: Fitted force-displacement curves on compression tests

3.1.3 Free Drop

The drop test confirms the survivability when the blackbox system falls down to the concrete floor from forty-eight-inch height. The test was applied on every face, edge and corner, thus the drop test on a single specimen was performed twenty-six times, as shown in Fig. 12a. After each drop, photos and description of exterior conditions were recorded. Some photos of the test results on PTS A1 are provided in Fig. 12b, which shows that only minor cracks and collapses on the corners and edges were recorded after twenty-six free drops. This is also the case that applied to the other five tested PTSs.



(a) Test sequence (O: edges, Δ: corners, □: faces)



(b) Photos of test results on PTS A1 (i: face 23, ii: edge 1, iii: corner15)

FIG. 12: Tests sequence and results of free drop test

3.2 Summary on survivability tests

The results from simulated disaster scenario tests, including fire tests, free drop tests, and static crush tests, show that the preliminary test specimens meet each scaled requirement well. From these tests, we not only confirmed the survivability of the preliminary design on the building blackbox system, but also had better idea on the limitations of the materials and the current design. For example, with the geopolymer and thermal insulation design, it would provide thermal protection for only seven minutes. Therefore, in the next generation design, we have to either increase the survivability by using new material and design or put more emphases on the redundancies of the data and systems.

4. CONCLUSIONS

Building information provides pivotal information for urban disaster response and relief efforts. The building blackbox system described in the paper presents a new concept to instrument critical physical infrastructures with data storage and communications devices. These devices can provide important building layout and exit routes to guide emergency responders to save time and lives. Furthermore, when integrated with building sensors, the building blackbox system can actively monitor building conditions (such as fire zones, smoke, temperature, and stresses/strains of structural members), track personnel locations (from active RFID signals on personnel's ID cards) during rescue operations, and provide life-cycle performance data for building systems (such as energy consumption, maintenance, and repair records). The authors envision that in the near future all critical infrastructures will all contain some kind of blackbox devices which continuously collect pertinent data throughout the life of the infrastructures. These kinds of active devices will allow facility managers to actively maintain structures more efficiently and cost effectively. For example, it is not too far fetched to imagine that one day a facility may receive an e-mail from a post-tension cable, reporting that the strength has lost 25% due to cap failures. This ability makes possible proactive maintenance and saves costs in sending inspectors to the field. We may one day conduct infrastructure inspections similar to the way auto mechanics diagnose problems from the system databox in the car. The preliminary functional tests on the prototype presented in the paper allow the researchers to explore critical parameters that lead to the final design the building blackbox system which will support not only emergency rescue and response, but also life-long monitoring and controls of infrastructures.

5. ACKNOWLEDGEMENTS

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