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Cognitive Infrastructure - A Modern Concept for Resilient Performance under Extreme Events

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1.0 ABSTRACT

The increasing frequency and intensity of natural disasters, as well as escalation of manmade threats, are posing significant threats to built environment. Further, much of civil infrastructure in developed countries, built after World War II, is experiencing age-related deterioration and thus are vulnerable to damage under extreme loading conditions. This vulnerability of infrastructure under severe loading conditions can be assessed through a coupled sensing-structural framework that extends principles of the recently developed "Internet of Things" (IoT) technology into civil infrastructure. This concept aims at monitoring key response parameters (i.e. temperature, strain, deformation, vibration levels etc.) by incorporating cognitive abilities into a structure through interaction of various sensing devices and socio-environmental factors. These response parameters can be utilized to trace performance of critical infrastructure during the course of a disaster so as to predict signs of imminent failure and to provide first responders and occupants with much needed situational awareness. The practicality of the proposed concept in enhancing resilience of new and existing infrastructure is illustrated through two case studies.

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Keywords: Cognitive Structures, Extreme Events, Disaster Management, Resiliency, Internet of Things (IoT)

2.0 INTRODUCTION

Civil infrastructure primarily constitutes built-in facilities, such as high-rise buildings, highways, airports, dams, and power plants etc. In general, 10-15% of civil infrastructure is considered to be critical and vital to the functionality of the society. As such, their destruction or incapacitation, in the aftermath of a disaster, would disrupt welfare of the public and overall safety, security, and economy of the country [1-4]. Critical infrastructure is designed to last for 50+ years, and recent surveys have indicated that existing infrastructure continue to operate for more than their intended service life [1, 2]. During this long service life, infrastructure is often subjected to numerous hazards and environmental conditions (i.e. disasters) making them highly vulnerable to damage [3, 4].

A disaster is defined as an event or incident that causes loss of human life, socio-economic damage, ecological disruption, deterioration of health and health services on a large scale to warrant an extraordinary response from outside the affected zone. The impact of natural, manmade and NATECH (Natural Hazard triggering TECHnological disasters) disasters from earthquakes, tsunamis, terrorist attacks, nuclear meltdowns etc. affecting more than 4.4 billion people over the past few decades. For example, the reported losses arising from natural disasters occurring in the US, in 2016 alone, was estimated at $175 Billion [5]. Unfortunately, these losses are growing from year to year due to increasing population pressure on urban infrastructure, as well as lack of measures for upkeeping of infrastructure to withstand these disasters [6]. With the expected increase in likelihood of more intense disasters, losses in the aftermath of any disaster are likely to

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increase as well. In order to minimize adverse effects of disasters, recent studies have highlighted the need for integrating resiliency into design of critical infrastructure [7, 8].

Resiliency is a multidimensional concept that was introduced by Holling to describe ecological systems and since then been adopted by several engineering disciplines [9]. For instance, resiliency in structural engineering is defined by the ability of a structure to maintain acceptable levels of functionality during and after breakout of a disaster (see Fig. 1). Resilient structures, due to their superior performance, can perform satisfactory before undergoing high level of damage and even prevent collapse of structures. This facilitates evacuation of occupants and provides first responders with enough time to tackle (fight) the adverse effects of disaster.

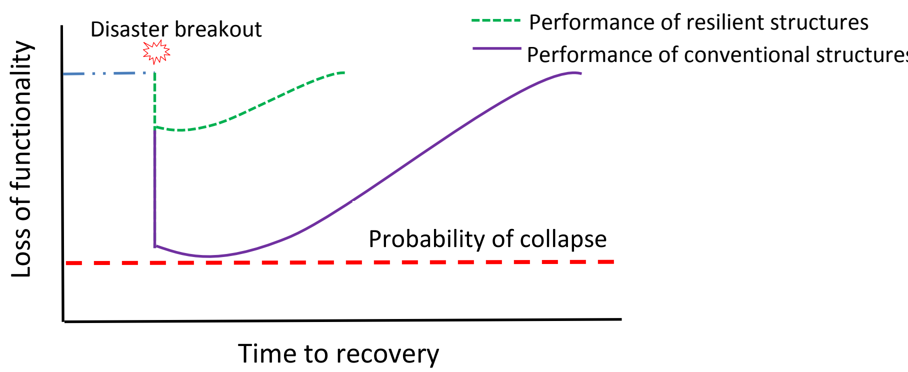

Fig. 1 Concept of resiliency during a disruptive event

In current practice, structural resilience can be achieved through number of design strategies such as applying proper detailing to ensure ductile response in seismically active areas, installing adequate fire protection measures in buildings to enhance fire safety etc. Implementation of such strategies can meet resiliency requirements and can enhance performance under low-to-medium sized disasters. However, these conventional strategies may not be sufficient to achieve satisfying performance under extreme loading events (resulting from earthquake, blast, fire) or a combination of loading events (ex: impact followed by fire or tsunami followed by earthquake) as seen during the collapse of twin towers, Fukushima Daiichi nuclear accident etc. [10, 11]. Further, due to unique characteristics (i.e. structural system, service requirement, environmental exposure etc.) in some critical infrastructure such as bridges and tunnels, implementation of conventional systems may not be practical nor economical [3, 12]. Thus, in order to achieve high level of resiliency, designers are encouraged to seek other innovative and effective solutions that can complement currently used conventional strategies.

The recent technological advancements in sensing and communication technologies, such as RFID (Radio Frequency IDentification) and WSAN (Wireless Sensor and Actor Networks), that enabled development of "Internet of Things" (IoT) can be utilized to monitor structural performance under extreme disaster events. The IoT technology provides a global platform to collect and exchange data between sensing devices, physical objects, and environment. Unfortunately, most of the research-to-date with regard to IoT has focused on developing advanced sensing devices [13], communication systems [14], and processing technologies [15] that enable integration of IoT into micro applications i.e. computing services etc., whilst the implementation of IoT into large-scale applications such as monitoring of infrastructure, from structural point of view, is still not fully explored yet [16, 17].

This paper hypothesizes that an intelligent adoption of IoT technology can institute a platform to enable more resilient design of new and existing critical infrastructure. Unlike conventional health monitoring systems, which are limited in application and targets passively monitoring conventional factors i.e. carbon emission, corrosion in reinforcement etc., a cognitive design is dynamic in nature with the ability to continually assess "in real time" structural response of infrastructure taking into account baseline and dynamic conditions of users (i.e. occupants, first responders behavior), infrastructure (system-level structural behavior), and environment (severity of disaster) all of which continuously interact in a typical built environment. Based on such assessment, cognitive infrastructure can estimate magnitude of damage, predict signs of imminent collapse, and notify occupants and first responders with locations (zones) of imminent damage etc. Further, cognitive structures can be tailored to perform series of pro-active actions i.e. shut down fire doors to prevent fire spread, scan facilities for trapped users, direct evacuee to safest/quickest egress paths etc. as to improve structural resilience, facilitate evacuation and aid disaster response operations. The applicability of the proposed concept is illustrated through two case studies.

3.0 HISTORY, EVOLUTION, AND LIMITATIONS OF INTERNET OF THINGS (IoT)

The "Internet of Things" (IoT), was popularized through the work of carried out at the Auto-ID Center at the Massachusetts Institute of Technology (MIT), which started to design radio frequency identification (RFID) infrastructure [18]. IoT is described as a self-configured dynamic global network with interoperable communication protocols between physical and virtual "things" [18]. The concept of "things" in a typical IoT network refers to any real or virtual participating actors such as human beings, objects, data etc. Since IoT provides the ability for real-time monitoring of any tagged actor within an environment, IoT is often used to create an environment in which the basic information from any of its actors can be efficiently shared with others.

Hence, IoT possesses the ability to provide comprehensive data about the surrounding environment by tracing its users and/or other objects through number of technologies, such as RFID sensor networks, Global Positioning System (GPS), or infrared sensor detection etc. As a result, IoT has been applied in limited disaster mitigation applications; for example, Zambrano et al. [18] applied Sensor Web Enablement Framework (SWE) and Message Queue Telemetry Transport (MQTT) to develop an early warning system. This framework collects data through wireless IoT communication platform, i.e. smartphones, to anticipate outbreak of an earthquake event. In a recent study, Zelenkauskaite et al. [19] proposed a network-based framework of IoT for disaster management using social network analysis. The developed framework, which dynamically links objects, uses a combination of graph theory and social networking tools to analyze collected data. Although the developed framework was only tailored towards the use of social media networks to aid in crisis management, this framework can also be applicable in other IoT enabled smart environments. Similar platforms have been proposed in other applications such as transportation [20], marketing [21], logistics [22] etc.

Although findings from few recent applications have been promising, it is generally accepted that IoT technologies and applications are still in their infancy [23] as these technologies are facing number of implementation challenges in real life applications, specifically under extreme disaster-type events. For example, most of the proposed frameworks relies on internet as a medium to collect, analyze and transfer data. As a result, successful implementation of IoT is tied to the availability of internet which may not be accessible during extreme disaster conditions as in fire (collapse of twin towers on 9/11), earthquake (failure of oversea cables breakage during Japan earthquake in 2011), severe snow storms (failure of the internet infrastructure in Italy blackout in 2003).

Vermesan et al. [24] stated that some of the major limitations of realizing IoT technology potential relate to lack of Service oriented Architecture (SoA), scalability issues and associated high cost. Other limitations such as reliability of context awareness, inter-machine communication, integration of memory and processing power, and the ability to withstand harsh environments are also identified. According to Vermesan et al. [24], availability of low-power consumption wireless sensors, low cost object monitoring and networking, are fundamental for successful integration of IoT in large scale infrastructure. In a separate study, Hu et al. discussed number of challenges associated with applicability of IoT technology to civil infrastructure (i.e. bridges) [23]. Some of these challenges include data transfer, processing, and management as well as complexity in developing efficient wireless sensor networks, data transmission for long distances and limited transmission band width. Hu et al. noted that data processing and identification, in terms of automated detection of localized damage out of the large amount of collected data on a daily basis, are other key challenges to integrating IoT technology in large structures.

Issues related to energy storage, especially those associated with integrating IoT for large infrastructure applications, has become a key obstacle. Current technologies such as Wireless Sensor Networks and Active RFID suffer from bulky battery packaging and short life times, and hence require recharging or replacement of the integrated batteries. Lack of available and reliable hardware systems such as data acquisition and synchronization, compatibility between sensors and communication devices, privacy and security, as well as software issues (i.e. distributed Commutating) are other pressing challenges. All of the above limitations hinder computing, storage and analysis of collected data [13]. It can be inferred from above discussion that the potential of IoT technology in design of structures has not matured yet [16, 17, 25, 26].

4.0 FRAMEWORK ARCHITECTURE FOR REALIZING COGNITIVE STRUCTURES

The proposed framework comprises of addition of a cognitive component to critical structures to monitor their performance under severe loading conditions as encountered in a disaster. This coupled sensing-structural framework extends principles of IoT technology into design and construction of critical infrastructure including buildings, bridges etc. which enables robust and continuous interaction between various components including embedded sensors, disaster effects and humans (occupants, first responders). The proposed framework allows a newly designed (or upgraded) critical infrastructure to be able to collect distinct data from surrounding environment (throughout its service life, specifically during break out of disasters (i.e. fire, earthquake, flooding etc.)), and to locally analyze this data in order to predict performance of the cognitive structure, in real time basis.

In the proposed framework, key response parameters such as temperature, deformation, strain, vibration, heat signals, chemical (toxic gases) etc. are traced and collected via embedded sensors distributed within the cognitive structure and interconnected using a common network. In case of disaster break out, analysis on these collected parameters is carried out to evaluate overall response in terms of available load carrying capacity, degree of damage, occupant behavior/movement etc. This analysis can be carried out onsite (within structure) or through cloud computing technology. In either scenario, the outcome of such analysis is directly accessible to authorities and first responders (and in some cases to occupants), so that authorities can track performance of the structure, throughout any point in disaster timeframe, to identify critical regions in a structure (i.e. those severely damaged or have high probability of collapse) etc. This additional information can significantly improve disaster response and management operations and enhance what is commonly referred to as "situational awareness". High level of situational awareness can guarantee safety of first responders and occupants, ensure optimum resource allocation, and aid in critical decisions making etc.

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Similar to an IoT model, the proposed framework comprises of three layers namely perception, network, and processing layers as shown in Fig. 2. The perception layer consists of number of physical objects including the structure, sensing devices, and humans (occupants, authorities and first responders). This layer also comprises of environmental factors (i.e. disasters); which, from a structural engineering point of view, translates to load actions. For instance, thermal loads can develop due to breakout of fire, seismic loads arise from earthquake etc. Since the interaction between physical objects and environmental factors constitute structural response during a disaster, monitoring such interaction is key to predicting performance and signs of collapse mechanism in a structure. The "physio-environmental" interaction also dictates human (occupants, first responders, authorities etc.) response and, when properly accounted for, can reduce causalities and significantly improve decision making process. Hence, the main objective of perception layer is to monitor such interaction through various sensing devices (i.e. strain gauges, thermocouples, biosensors etc.) and to collect specific data throughout disaster timeframe.

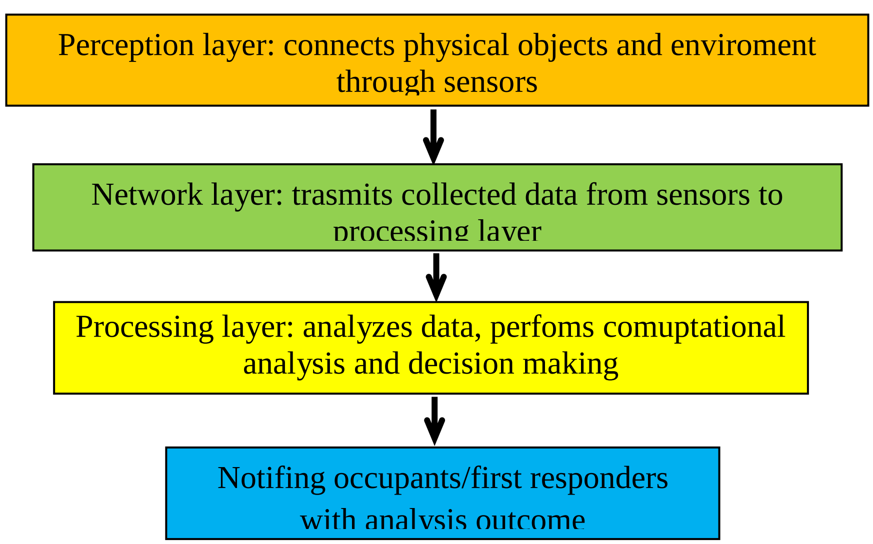

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Fig. 2 Different layers needed in the proposed framework for realizing a cognitive structure

In order to apply the coupled sensing-structural framework, Fig. 3 shows a typical structure divided into a grid that consists of number of nodes where each node hosts number of sensors embedded to main structural members (i.e. beams, columns, joints etc.). Depending on the type of sensor, data in terms of displacement, temperature, vibration, air density (smoke) etc. is collected and stored either in that particular sensor or in nearby nodes with sufficient storage capacity. The embedded sensors (and associated storage nodes) are connected through an infrastructural network that runs through the "skeletal" system of the structure. This network allows transmission of data from perception layer to the processing layer which can take place via wired and/or wireless technology.

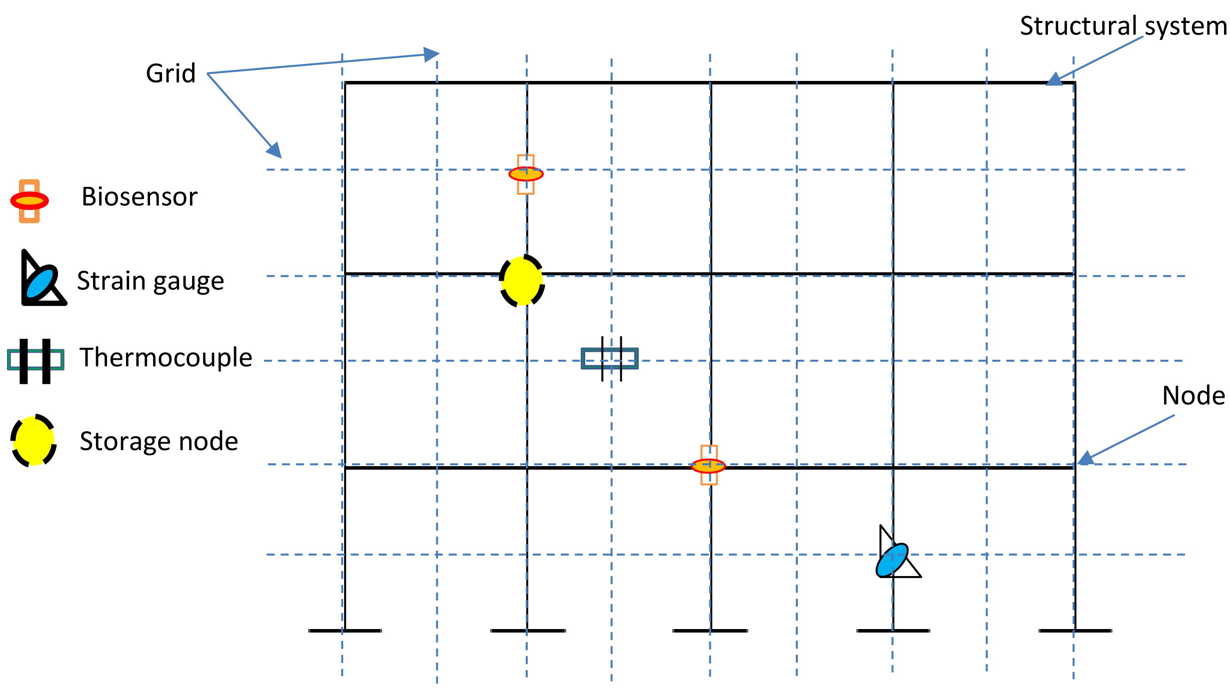

Fig. 3 Skeletal infrastructure (sensors locations are selected for illustration purposes)

Once transmitted data reaches the third layer, further handling and analysis takes place in the processing core "brain" of the cognitive structure. This processing system deals with analyzing

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data feeds and has the ability to identify anomalies (i.e. incidents). Anomalies can occur in one of three different ways; 1) when a disaster breaks out, 2) when sensor readings exceed a pre-determined threshold, and 3) in case of loss of communication between any of these layers. For example, if a fire breaks out in a building compartment such as the one shown in Fig. 4, temperature rises in the compartment and its structural members. Once this temperature reaches a predetermined temperature limit, the brain "processing core" identifies this situation as "fire incident" and starts a chain of actions that include; 1) activation of sprinkler system (or active firefighting measures), 2) notifying authorities and occupants when an incident breakout and, 3) continue monitoring temperature rise and other response parameters in case the incident escalates. In a similar analogy, if the core senses prominent levels of vibration across number of structural members, an "earthquake event" is identified and different set of actions can be carried out.

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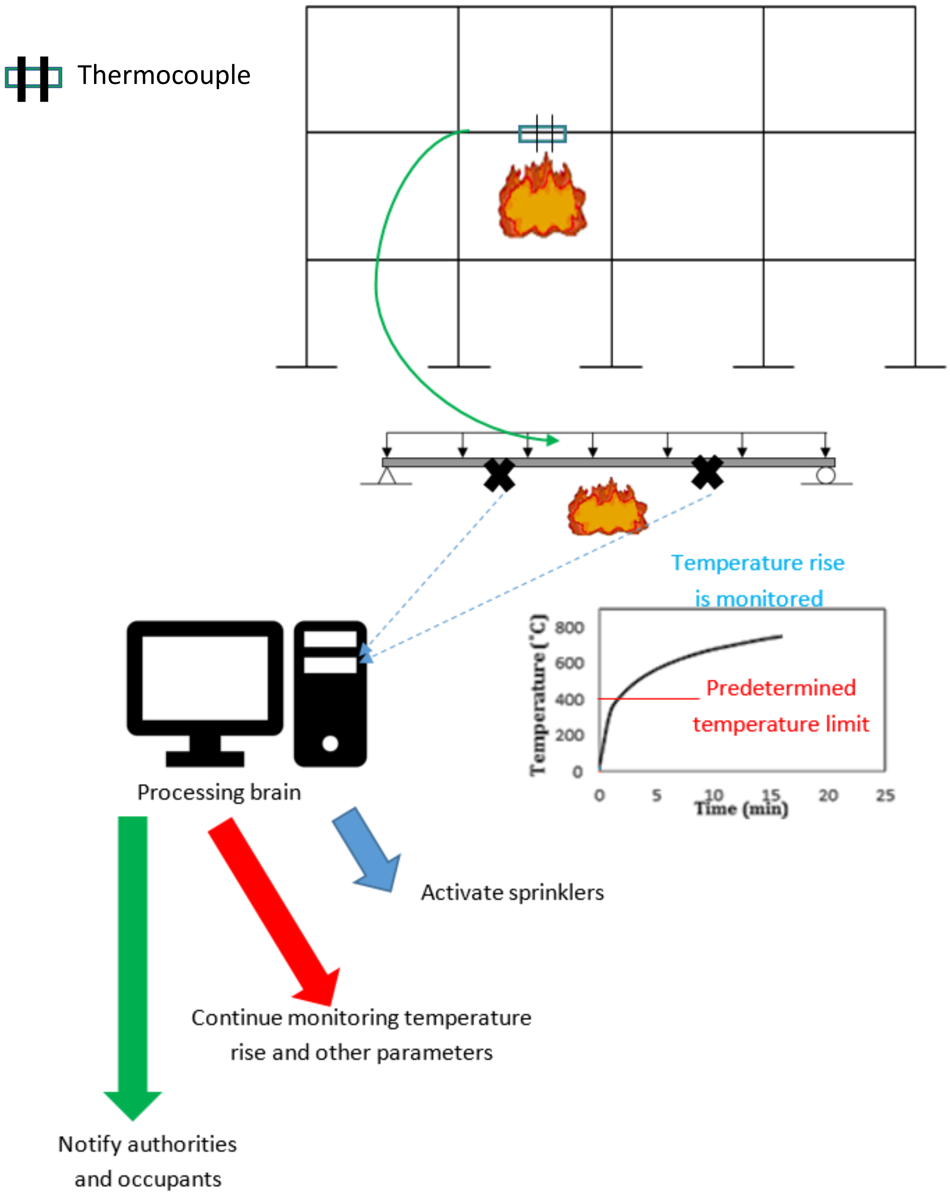

Fig. 4 Identification of fire incident at the processing layer

The processing core is also capable of carrying out complex structural analysis to evaluate available load carrying capacity or extent of deformations in structural members in order to assess level of damage (or safety), and estimate (probability) of imminent failure (collapse) (see Fig. 5). Load carrying capacity and/or stability of a structural cognitive member can be carried out knowing key parameters such as cross-sectional dimensions, material properties etc. which are

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constantly being updated through data feed from embedded sensing devices. The evaluated load carrying capacity is then compared against existing load levels and failure occurs once load bearing capacity falls below that of applied loading. In case a structure undergoes sudden and/or severe damage that lead to disconnecting infrastructural “skeletal” network, the processing system recognizes lost connection and runs diagnostics to check for potential glitches and identify damaged nodes.

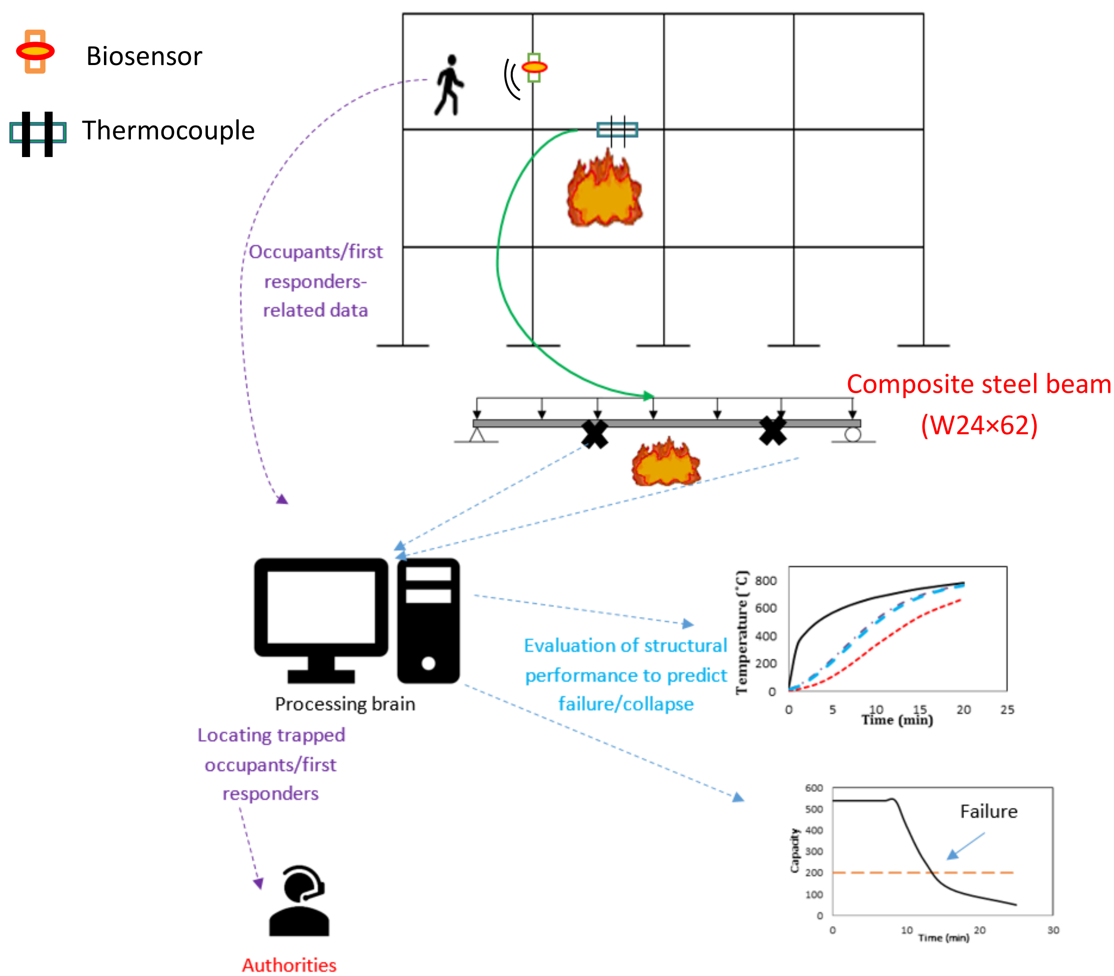

Fig. 5 Framework for cognitive structures

Cognitive structures can also employ pressure and infrared sensors along with other sensing devices. These sensors are to be installed in wall and floor surfaces to detect pressure, heat body signs and/or to track wireless signals (i.e. from cell phones). These sensors can be used to locate occupants and/or facility users in case of incident breakout (see Fig. 5). For example, data collected from embedded sensors and actuators can be processed to scan interior of a structure for occupants. This enables monitoring additional, (more humane) aspect, other than those related to structural performance. Such aspects include tracking progress of evacuation of occupants, looking for trapped occupants, tracing locations of first responders etc.

It can be seen from above discussion that proposed framework is a dense collection of devices that uses a shared network paradigm. Since this paradigm uses both radio (i.e. wireless), as well as hard wiring, communication between devices does not only depend on one medium of transmission, but also has high built-in redundancy. The redundancy of this system can be further improved through using energy harvesting sensors such that nodes are not affected by power black-outs and/or damaged power cables. This means that even with a large loss of nodes, there is a good chance that the network can still operate even under extreme events. Some of the predictive techniques that could be used to process this dense collected data include use of artificial intelligence techniques, deep learning, artificial neural networks etc.

5.0 CASE STUDIES

Io order to demonstrate the applicability of integrating proposed sensing-structural framework to achieve resilient performance in buildings, from structural point of view, two case studies are carried out. In these cases, the applicability of cognitive structural design is demonstrated in case of fire breakout as well as aiding occupants/first responders with situational awareness in case of evacuation from high-rise building.

5.1 Case I – Monitoring Load Carrying Capacity and Prediction of Failure during Fire

In a cognitive structure, if thermal and mechanical response parameters (i.e. temperature, deformation etc.) are tracked during a fire incident, in real-time, then it is possible to monitor and trace actual behavior of structural members so as to predict any signs of imminent failure. To demonstrate this hypothesis, the building shown in Fig. 6a is assumed to experience a fire incident.

5.1.1 Description of fire incident

As the fire grows within a compartment (on second storey), temperatures in structural members (i.e. beams and columns) raise with time. Recent fire incidents such as Grenfell tower in London, UK or Chennai Silk tower in Madras, India, have shown that fire continues to develop and spread to adjacent compartments and floors, in spite of barriers (compartmentation) and firefighting efforts [27, 28]. As a result of fire spread, multiple structural members (i.e. columns and beams) experience temperature rise which in turn lead to degradation in strength and stiffness properties in materials. This leads to rapid degradation in load carrying capacity, development of instabilities etc. throughout number of floors which can trigger partial or complete collapse mechanism. The proposed cognitive framework can trace such mechanisms across multiple floors, predict any signs of imminent failure in structural members, and notify occupants/first responders with structural response as a function of fire timeline.

5.1.2 Selection of cognitive structural member for analysis

Validating the proposed concept at global level (collapse of structure) requires data from full scale fire test on entire building which can be quite expensive. However, it is still possible to

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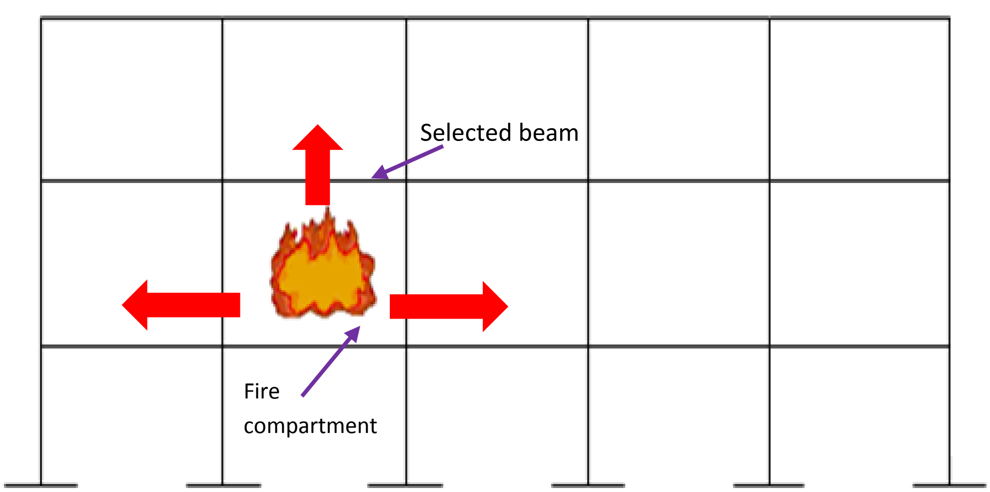
illustrate the applicability of the proposed concept through tracing fire response of a typical structural member (i.e. beam, columns, frame etc.) within a compartment. For the sake of this study, the beam shown in Fig. 6b is assumed to be instrumented with various sensors and thus is selected to carry out a cognitive-structural analysis. This beam shares similar features to that of a recently tested composite beam under fire conditions [29, 30]. This composite girder is fabricated with number of construction materials including, structural steel (for girder), concrete topping (for slab), steel reinforcement (embedded in concrete slab) and high strength steel (for shear studs) and the geometric and material properties of the structure and materials are known. The steel beam is made of W24×62 section (standard hot rolled section) and is fabricated using A572 Grade 345 steel. The concrete slab of 150 mm thickness, cast along the full length of the steel beam, is made of concrete of compressive strength of 45 MPa (see Fig. 6b).



(a) Frame elevation of building (red arrows represent possible fire spread paths)

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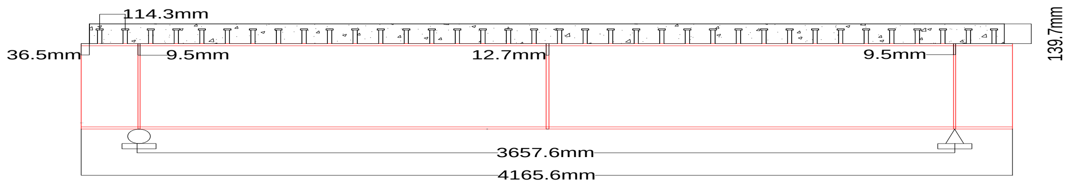
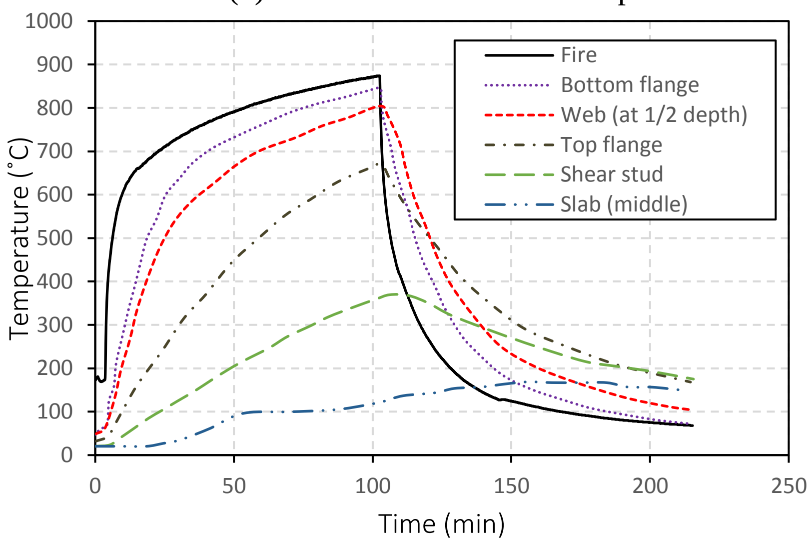
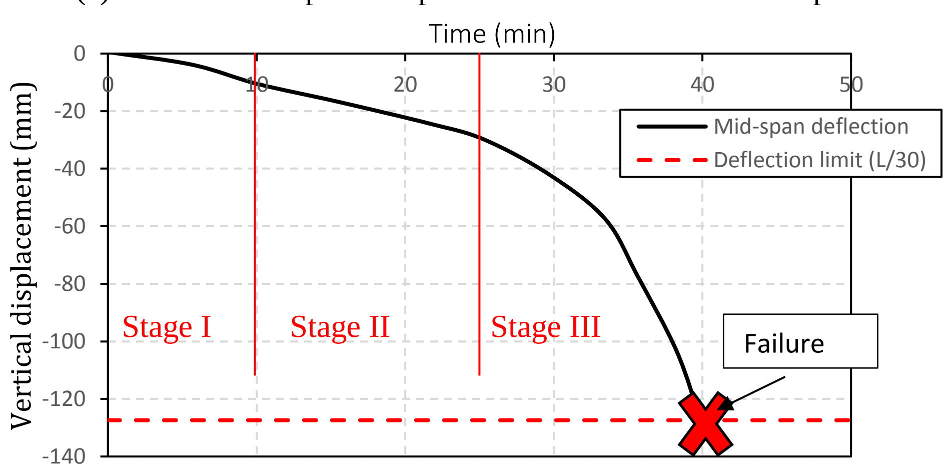


(b) Geometric features of composite beam



(c) Measured temperature profiles as a function of fire exposure time



(d) Vertical displacement in beam

Fig. 6 Cognitive analysis on a building under fire

The selected cognitive beam is instrumented with number of devices (sensors) to monitor its thermal and mechanical response during fire. For example, cross-sectional temperatures were measured through Type-K Chromel-alumel thermocouples, 0.91 mm thick, installed on the lower and upper flanges of steel beam, as well as on four vertical locations along the height of the web. Additional thermocouples were also attached on shear studs, at mid-depth and surface of concrete slab. In order to measure mid-span deflections, vertically and horizontally oriented linear variable displacement transducers (LVDT) with gage length of 375 mm were attached at distinct locations on the beam.

5.1.3 Monitoring response parameters

In order to test the validity of the proposed concept, data generated from the above fire test is utilized to demonstrate how a coupled sensing-structural cognition framework can be incorporated to full-scale critical infrastructure. Since the response of fire-exposed composite steel beam can be traced through above described sensing devices, relative thermal and structural data are monitored at any point during fire. For example, Fig. 6c shows progression of cross-sectional temperatures in web, flanges, shear studs, and concrete slab. It can be seen from plotted thermal response that temperature in steel section increases at a much faster pace than that in concrete slab or shear studs. This can be attributed to the high thermal conductivity and low specific heat of steel as compared to concrete.

The structural response of cognitive beam can also be assessed by tracing progression of vertical deflection as a function of fire exposure time (see Fig. 6d). In general, response of the beam can be grouped under three distinct stages. During the first stage, the mid-span deflection increases linearly up to about 10 min when the temperatures in the bottom flange and web reaches about 200°C. In the second stage of fire exposure, the mid-span deflection starts to increase (between 10 min and 25 min) due to degradation of strength and modulus properties of the steel

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as the bottom flange and web temperatures exceed 400°C. In the final stage of fire exposure (after 30 min), mid-span deflection increases at a rapid pace due to spread of plasticity in the bottom flange, and high temperature creep effects, leading to formation of plastic hinge at the mid-span. As a result, the beam fails after 40 minutes of fire exposure.

5.1.4 Validation of proposed concept

The above measured data points can be used to evaluate load-bearing capacity of cognitive member by employing the proposed coupled sensing-structural framework (see Fig. 7). For instance, temperatures monitored at different cross-sections of composite beam are used to generate thermal profile at each time increment. Through these thermal profiles, associated degradation in strength and modulus properties in materials can be evaluated. Using the reduced properties, sectional capacity (ex. moment capacity) of cognitive beam can be evaluated at various "fire exposure" times. This sectional capacity can be evaluated through specific algorithm that extends room temperature design equations to fire conditions, together with accounting for any fire-induced forces and instabilities [31-34]. For example, flexural capacity of steel beam under fire conditions can be evaluated through Eq. (1) as:

$$M_f = min\ of \left\{A_s f_{y,T}, 0.85 f'_{c,T} A_c\ or\ \sum Q_{n,T}\right\} \times y \quad (1)$$

where, $f'_{c,T}$ is the compressive strength of concrete at temperature, T, $f_{y,T}$ is the yield strength of steel section at temperature, T, A_s is the area of steel section, A_c is the area of concrete slab, and y is the moment arm of the couple formed by $A_s f_y$ and $0.85 f_c' A_c Q_{n,T}$ is the shear strength of shear studs at temperature, T.

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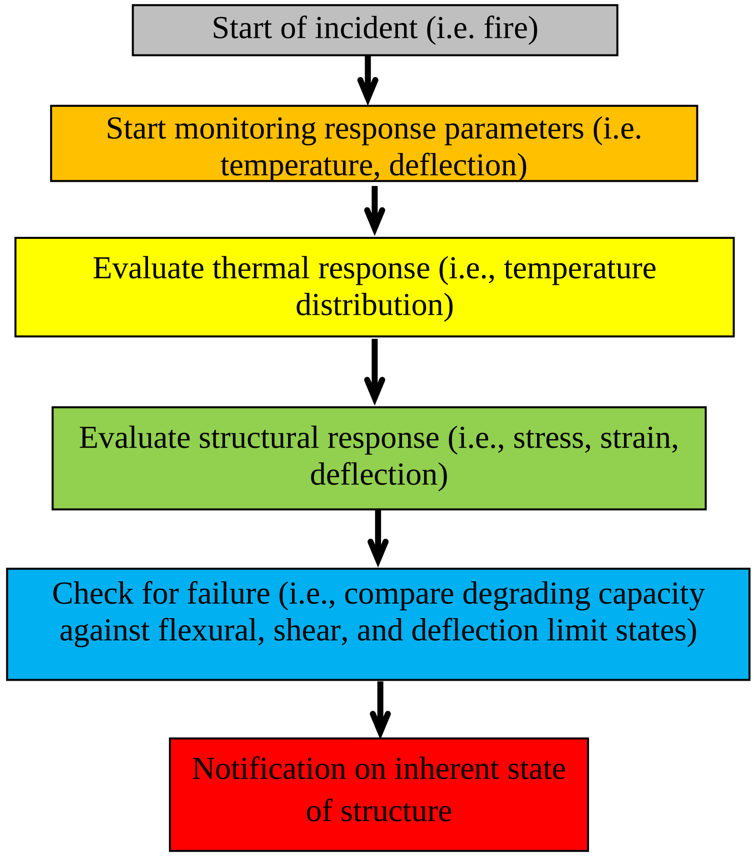

Fig. 7 Evaluation of load-bearing capacity of structural members using a coupled sensing-structural framework

Following above procedure, degradation of moment capacity at critical mid-span section with fire exposure time is plotted in Fig. 8. It can be seen that moment capacity in the beam remains intact for the first 15 minutes due to lower average temperature in flanges (much below 200˚C). Then, once steel temperature in flanges and web rise beyond 400˚C, moment capacity gradually starts to degrade. Degradation of moment capacity at critical section continues until the beam fails at 40 min; when the moment capacity at mid-span drops below the moment due to applied loading (which agrees with failure time from experimental data in Fig. 6d). It can be inferred from this analysis that failure of main structural members can be accurately predicted through adopting sensing-structural framework. It should be noted that this approach can also be extended to

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evaluated shear and axial capacity in other flexurally (i.e. plate girders) or axially loaded members (such as columns) [34-37].

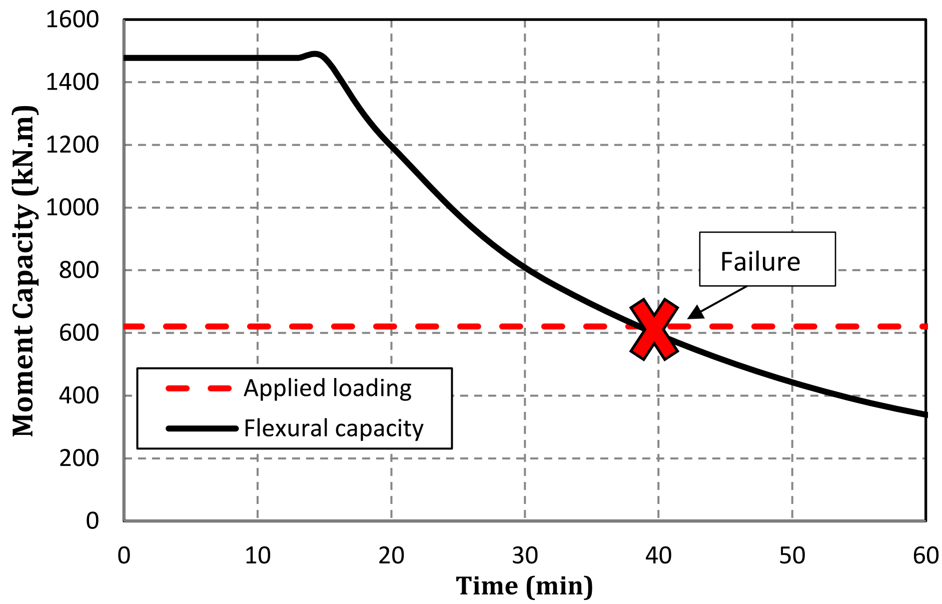

Fig. 8 Degradation of sectional capacity as a function of fire exposure

5.2 *Case II – Evacuation of High-rise Building*

In general, disaster situations are often accompanied with number of uncertainties i.e. cause, extent of damage, critical regions etc. These uncertainties, when combined with low information flow, can significantly hinder evacuation efforts, response and relief operations as well as authorities’ decision-making ability (or what is commonly referred to as situational awareness). Thus, the application of proposed concept during a disaster can be applied to continuously update facility users (occupants) and authorities with accurate representation of disaster scale and development etc. is illustrated through a second case study. Situational awareness has been identified as one of the key factors needed to undertake effective disaster response, especially at early stages of disaster when information flow (and accuracy) is generally poor [38-39].

5.2.1 Role of situational awareness in minimizing disaster impact

Situational awareness is defined as the perception of environmental elements with respect to time and/or space to analyze adverse consequences of the situation under a disaster and to make projections on possible scenarios and alternatives in reacting to the event. Recent studies have examined influence of poor/lack of situational awareness on disaster response and management. For instance, Son et al. [38], Yang et al. [39] and Itoh and Inagaki [40] inferred that first responders' deaths during 9/11 terrorist attacks and the Three Mile Island nuclear crisis were caused by inappropriate decisions made based on lack of situational awareness. For instance, during 9/11 disaster relief operation, the initial response by the New York City Fire Department (FDNY) officials was to rescue and evacuate building occupants. This decision was made despite the fact that first responders did not have adequate information on damage scale, nor overall perspective of conditions in the World Trade Centre (WTC) towers (in terms of which floors are burning or the stability of towers) [41]. During evacuation operation, number of problems with radio communication caused commanders stationed in the command center (outside the towers) to lose contact with firefighters. Even with this loss of communication, FDNY officials continued to instruct firefighters to move up to burning floors in the towers. It was not until the collapse of WTC2 tower that FDNY officials instructed firefighters to come out of WTC1 tower. Unfortunately, due to lost (failure) communication systems, many responders inside WTC1 (who were still climbing stairs to reach trapped occupants in burning floors) were not aware that WTC2 collapsed and could not heed to instruction from the command center [42, 43]. Findings of these studies infer that number of firefighter casualties would have been prevented if they had better situational awareness on the adverse conditions present in the burning floors of WTC towers.

Thus, updating situational awareness can improve the ability to perceive and respond to a disaster event. Update on situational awareness provides valuable intelligence for complex decision making, resource allocation, response and management effectiveness. This is due to the fact that as disaster progression, instantaneous changes to both informational and logistical disaster mitigation operations are required [44-46]. This can be demonstrated through further analysis of the first case study. In that case study, temperature readings are collected by embedded sensors and processed to evaluate degrading sectional capacity of cognitive member (fire-weakened beam). Since the command center also monitors all members in a cognitive structure, the overall response and stability of overall structural system can be instantaneously evaluated. As a result of this comprehensive concept, first responders can identify vulnerable compartments and avoid them while performing firefighting activities.

More importantly, situational awareness can aid command center to track extent of damage in the building and advise fire fighters to come out of a fire-weakened building prior to anticipated (or imminent) collapse. This can give firefighters enough time to evacuate fire-damaged building without being trapped or injured. In a more futuristic concept, cognitive structures can be able to automatically shut down fire doors to contain spread of fire and/or direct fire spread (growth) towards a pre-defined "fire resistant" area that is specifically built to contain fire either through advanced firefighting (i.e. pressurized walls) or fire self-containing suppression technologies (auto-extinguishing mechanisms).

The proposed concept can also incorporate other types of smart devices such as cameras, pressure sensors, cell phone readers. These devices can provide first responders with another dimension of situational awareness i.e. directing firefighters to trapped persons in a particular compartment/floor or communicating with evacuees. Thus, shortest paths to safety can be identified and those which are inoperable can be avoided. This can be important in cases where occupants cannot identify location of egress paths due to harsh conditions i.e. smoke, fire etc.

5.2.2 Description of building, fire, and evacuation simulation

In order to further illustrate potential of the proposed concept, evacuation in a typical reinforced concrete high-rise building, that is designed to have two-hour of fire rating as per applicable codes [47], has been carried out using Pathfinder simulation software [48]. Pathfinder is a continuous agent-based model that provides unique trajectory of each evacuee. In Pathfinder, movement of occupants is represented by adopting embedded multi-agent-based approach in which each agent has its own individual properties [49]. Route choice is simulated using a "Steering mode" which is dependent on collision avoidance and occupant interaction of the model in which a quickest path planning approach is used, i.e., routes are ranked hierarchically using information about people location and queuing times at exits. The evacuation model also uses mathematical distributions to reproduce actual aspects of human behavior during evacuation, e.g., delay time distributions, unimpeded walking speed distributions, etc. Pathfinder model has been validated against field evacuation studies and is used in number of evacuation studies [49-51].

The concept introduced in Section 4 is applied to a hypothetical evacuation scenario in a twenty storey building exposed to fire. The floors in this building are identical and each floor has a surface area of 2000 m^2 and are occupied with 100 randomly distributed persons, with 2000

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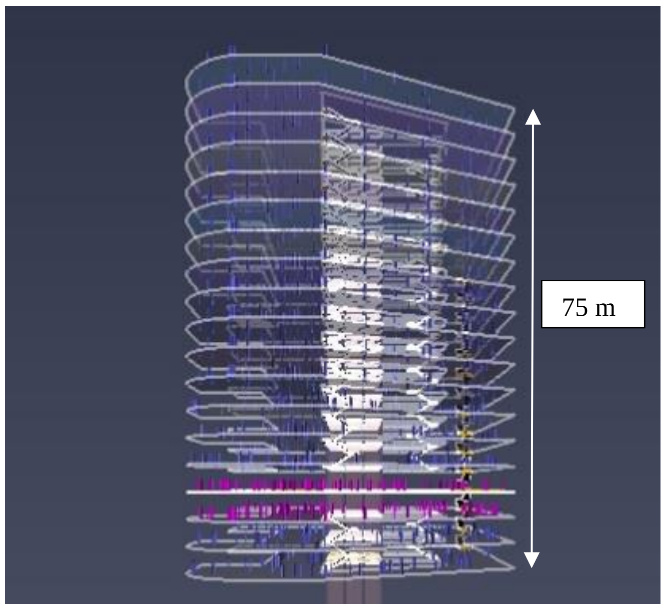
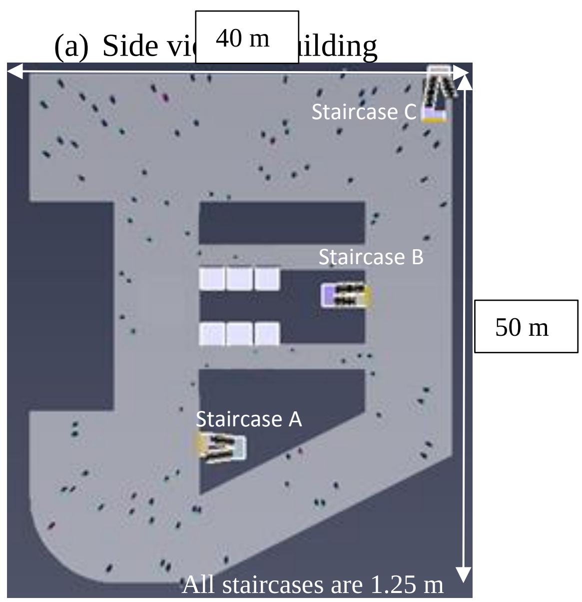
people overall in the building (see Fig. 9). Further, this building has three staircases (two near middle section of each floor (staircase A and B), one at the corner (staircase C)) and six elevators located near mid-section of floor. In order to quantify the positive effect of situational awareness on evacuation strategy (i.e. time to evacuate), a case study under three scenarios was carried out.



(a) Side vi ilding



(b) Plan view of a typical floor and distribution of occupants

Fig. 9 Details of building and occupants used in evacuation case study

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5.2.3 Monitoring response parameters

In the first scenario, time to evacuation for all occupants leaving the building at normal conditions (to simulate an evacuation drill) is undertaken. In this scenario, occupants were only allowed to use stairs (and not elevators) to evacuate the building. As can be seen in the evacuation time-history plotted in Fig. 10, it took 26 minutes for all occupants to evacuate the 20 storey building. In order to investigate evacuation time in case of breakout of a disaster, a second scenario was carried out. A fire is assumed to break out at the second floor between staircases A and B then vertically spreads across to the third floor within five minutes. As a result of this fire spread, staircases A and B in the second and third floor were filled with smoke and became inoperable (i.e. dangerous to use) after few minutes of fire.

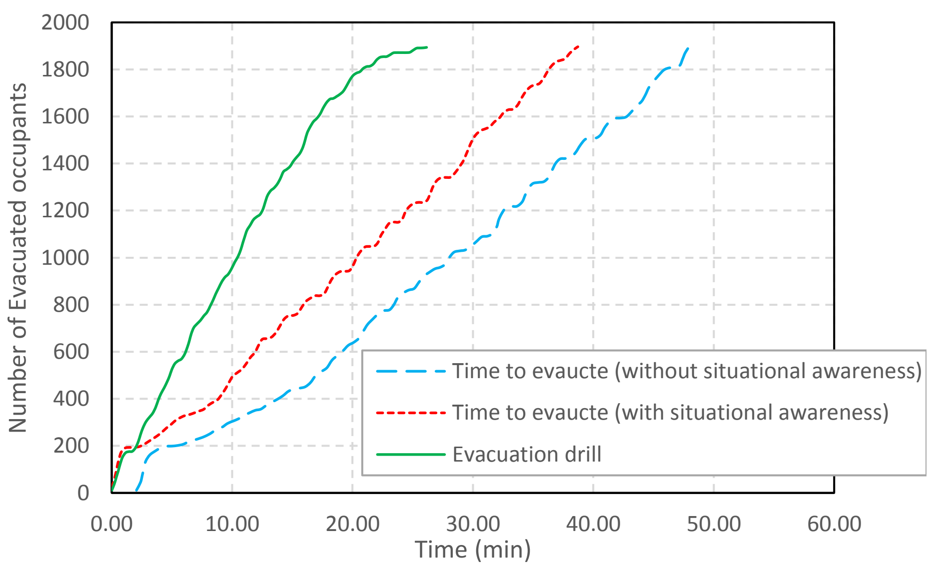

Fig. 10 Evacuation time of occupants

Simulation to capture effect of fire on evacuation of occupants was carried out and occupants were instructed to continue using the closest egress path to evacuate. For instance, occupants in upper floors close to the staircases A and B continue to use these staircases until they

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reach the third floor. Once they reach the third floor, occupants proceed to try to continue to use staircases A and B because evacuees are not fully aware of fire location/intensity and the fact that staircases A and B in the third floor are inoperable. Once evacuees reach the third floor, they try to continue to use stairs A and B only to realize that staircases A and B are inoperable. Evacuees then evaluate this situation, and change direction to proceed towards the only operable staircase, staircase C. As can be seen from Fig. 10, this behavior causes delays, which negatively impacts throughout evacuation process. Due to the fire and associated time delay, it took 48 min to evacuate all occupants (refer to Table 1).

Table 1 Comparison of evacuation time under three scenarios

Evacuation scenario	**Evacuate time (min)**
Evacuation drill	26
Evacuation without situational awareness	48
Evacuation with situational awareness	37

Figure 10 shows time history occupants took to evacuate the building. It can be seen that the associated time-history response with the second scenario starts few minutes late into start of fire because occupants were not aware of fire breakout. Once occupants realize the breakout fire, evacuation process starts. It can be also seen that time history of the second scenario becomes quite different than that of the first scenario after the first 200-225 occupants leave the building. This is because occupants in the first three floors could evacuate using all available three staircases and before staircases A and B become inoperable. After this point in time, disruption to occupants take place which causes large delays. This is mainly attributed to lack of situational awareness and the fact that occupants were unaware of incident breakout or smoke development in staircases A and B.

5.2.4 *Quantifying positive effect of situational awareness*

In order to quantify effect of situational awareness, a third scenario was looked at. This investigation is similar to that of the second scenario except that it utilizes the proposed sensing and cognitive concept such that fire growth/spread is continuously updated through sensors installed in the building. Hence, the building is assumed to be equipped with number of sensors installed in skeletal structural system as well as staircases. Once fire occurs, the "processing core" identifies breakout of fire and immediately notifies occupants in all floors using building communication system. This facilitates quick evacuation of occupants residing in first few floors. Once onsite sensors in the second and third floors (installed in staircases) recognize high smoke levels and harsh environment in staircases A and B, this feedback is processed, and the "processing core" notifies occupants to directly use staircase C and avoid using middle stairs (in 2nd and 3rd floor). Since such feedback is also shared with authorities and firefighters, high situational awareness can be achieved across multiple actors. As expected, this reduces delays in occupants evacuation time (by trying to attempt to use staircases A and B, travelling across dangerous floors as well as injuries between evacuees). Due to this situational awareness, total evacuation time of occupants was estimated at 37 min (which is 22% improvement over case 2). The time history response for this scenario is plotted in Fig. 10.

6.0 RESEARCH NEEDS, LIMITATIONS, AND CHALLENGES

It can be inferred from above case studies that although proposed coupled sensing-structural approach has substantial potential to improve performance of critical infrastructure, still

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number of issues remain a challenge. The areas where further research is needed to overcome some of the current drawbacks in realizing cognitive infrastructure are related to sensing efficiency, durability and power consumption requirements, data mining capabilities and standardization of cognitive structural design.

6.1 Sensing efficiency and durability

In order to apply cognitive concepts to large civil infrastructure, installed sensors not only need to be able to monitor specific aspects of structural, human and environmental factors but also need to be highly durable and versatile. These sensors need to be designed and built from durable materials in order to effectively operate for full service life of the infrastructure (i.e. 50-100 years). As such, they need to be capable of collecting accurate measurements in spite of harsh environmental conditions. Such conditions may include extreme temperature, pressure, shock, radiation, and the presence of chemically corrosive liquids and gases. Sensors also need to have versatile sensing abilities in order to monitor numerous parameters including temperature, strain, vibrations, biological/chemical parameters etc. Other critical considerations include the materials which the sensor is made from, the range of operability i.e. range of temperature, strain, pressure etc. that sensors can measure. When compared with sensors used in more "normal" conditions, sensors installed in cognitive structures represent high potential costs with regard to replacement, maintenance, and system downtime. Hence, sensors need to be cost effective and highly reliable and sustainable to minimize disruption potential and maintenance requirements.

6.2 System power consumption

In order to ensure optimal energy consumption of the proposed framework, sensors need to have low power consumption when operating and especially while being inactive (i.e. sleep

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mode). These sensors need to have wireless charging abilities as well as ability to harvest energy from surrounding environment such as light, vibration and temperature [53-55]. These technologies can substantially extend battery life or even the need to replace battery in sensing devices. Thus, when compared to traditional sensors, sensors with energy harvesting abilities can "theoretically" operate for an unlimited amount of time. The emergence of such technologies can allow energy constraints, associated with sensing devices, to be overcome which promote "green" cognitive infrastructure design.

6.3 Data mining capabilities

One of the fundamental challenges that arises in complex sensing environments at a large scale, similar to that proposed in this study, is how to characterize representation of events and activities with multiple dimensionality [56, 57]. Such challenge can be overcome through developing efficient data mining tools (i.e. algorithms). These algorithms need to extract damage-sensitive features from sensor measurements and to be able to intelligently preprocess collected data rather than analyzing all collected "raw" data points. This is due to the fact that not all raw data (response parameters) are needed but rather analysis of some values of response parameters is only required to identify critical (disastrous) events. As a result, "fewer" and more "critical" data points are processed in order to optimize consumption of energy and computational resources of "processing core".

6.4 Standardization of cognitive structural design

In general, standardization can become the blueprint for adopting new technologies and concepts. Standardization efforts can promote innovation so as to improve widespread, cost effectivity and efficient use of modern technologies at both corporate and user levels. The popularity of sensing networks has increased over the few years and integration of these embedded devices into skeleton system of various infrastructure require a common platform that can be easily and efficiently adopted. Thus, developments and coordination of standards can promote efficient implementation of cognitive design. Such standards should have provisions regarding type of needed skeletal architecture, sensor requirements, protocol, appropriate locations for installing sensors etc. Thus, there is a need for developing appropriate practice guides that address cognitive structural design to be incorporated into relevant building codes and standards. Such guidelines can be developed by professional societies or trade organizations.

7.0 CONCLUSIONS

Based on the results of the analysis presented herein, the following conclusions can be drawn:

1. Critical infrastructure can be highly vulnerable to damage or even collapse under a severe hazard. This vulnerability can be monitored in real-time basis through a coupled sensing-structural approach that extends principles of the recently developed IoT technology into the design of resilient structures.
2. The proposed concept for cognitive infrastructure aims at monitoring key response parameters to trace adverse consequences of a disaster and update situational awareness to occupants and first responders during the course of the disaster.
3. The applicability and beneficial effects of adopting cognitive design into critical infrastructure is illustrated through cases studies where in situational awareness developed through cognitive abilities is shown to significantly enhances disaster response and evacuation of process.

4. Integration of proposed concept into disaster management can be more effective through addressing current challenges and limitations associated with cognitive technology.

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