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Please cite this paper as:
Naser M.Z. (2019). "Autonomous and resilient infrastructure with cognitive and self-deployable load-bearing structural components." Automation in Construction. Vol. 99, pp. 59-67.
(https://doi.org/10.1016/j.autcon.2018.11.032).

Autonomous and Resilient Infrastructure with Cognitive and Self-deployable Load-bearing Structural Components

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1.0 ABSTRACT

This paper explores concepts and pilot studies for realizing autonomous and disaster-resistant infrastructures through integrating cognitive and self-deployable load-bearing structural components. These components act as secondary, and independent structural systems, that allow civil construction to autonomously reconfigure their internal structure to adapt to severe loading conditions in real-time. As a result, an autonomous infrastructure can achieve higher levels of structural resilience under extreme events (i.e. fire, earthquake etc.). This improved performance mitigates premature failure (collapse), thus providing occupants with sufficient time to evacuate, and allowing first responders to tackle the adverse effects of disasters. The practicality of the proposed concepts is illustrated through a comprehensive case study that covers fundamental aspects of structural performance and human evacuation in a super-tall 80-storey high-rise building undergoing an extreme event.

Keywords: Autonomous infrastructure; Resilient structures; Extreme events; Foldable structural components; Progressive collapse mitigation.

2.0 INTRODUCTION

Critical infrastructures primarily comprise of facilities that constitute 10-15% of civil construction. These facilities are vital to the functionality of the society as their incapacitation would severely affect safety, security, and economy of the public [1, 2]. Critical infrastructures are

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often designed to last for 25-50 years [3]. During this long service life, it is likely for an infrastructure to undergo a number of natural and/or manmade hazards (i.e. extreme events). An extreme event is defined as an incident, such as an earthquake etc., which can lead to loss of life, and may trigger serious damage/collapse [3, 4]. The vulnerability to extreme loading events can be minimized through implementing resiliency principles into design of new infrastructures or through proper upgrading of existing structures [2, 5].

Resilience is often used to describe balance in ecological systems [6]. However, from a structural engineering point of view, resilience refers to the ability of an infrastructure to maintain adequate levels of functionality during and after a breakout of an extreme event. The integration of resilience into the design (or construction) of a structural system ensures superior performance during harsh conditions. This improved performance not only mitigates possible partial and/or complete structural failure (i.e. progressive collapse), but also limits magnitude of damage and minimize "down time" for repairs (e.g. business interruption etc.) in the aftermath of an incident. Most importantly, a resilient infrastructure facilitates occupants' evacuation while allowing first responders to safely perform rescue operations.

Structural resilience can be achieved through adopting a number of strategies such as proper design and detailing of load-bearing members to ensure adequate performance in high risk areas. For example, installation of dampers, can improve seismic response and ensure ductile behavior in seismically (and Tsunami) active areas. In the case of fire, installing fire suppression measures (i.e. sprinklers) can control fire growth (and spread), enhance structural fire safety, as well as allow timely evacuation of occupants. While integration of such strategies is shown to meet resiliency requirements under low-to-medium sized incidents [7], these conventional strategies

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may not lead to satisfactory performance under an extreme loading event, or a combination of events (ex: fire breakout after impact, or tsunami triggered by earthquake) as noted in the collapse of WTC towers, and meltdown of Fukushima Daiichi nuclear facility (reactor) etc.

On a similar note, the implementation of traditional strategies may not be economical (or even practical) in infrastructures with unique characteristics such as bridges, metro-stations, and tunnels. Many of the features in such infrastructures are distinct and "tailored to fit" specific needs (i.e. facilitate large number of commuters etc.). These infrastructures have challenging service requirements to meet and therefore are built with complex structural systems. Thus, in order to achieve high levels of resilience, designers have been encouraged to seek innovative and effective solutions that complement currently used traditional strategies.

One solution is to introduce higher levels of redundancy to civil infrastructures such that once a structural member (i.e. beam or column); or a sub-system (frame), undergoes significant levels of damage, an impacted infrastructure can still be able to redistribute internal forces in damaged regions, through built-in, secondary, and self-deployable (autonomous) structural components, as to mitigate failure. These structural components can be designed to be independent of the main structural system, and to only operate (activate) during harsh conditions. Hence, once an infrastructure experiences an extreme event, the secondary self-deployable structural component activates and dynamically engages in resisting effects of external (event-induced) forces. To assess structural behavior during extreme conditions, such components need also to incorporate cognitive abilities and maintain real-time interaction with surrounding environment [2]. These components are thought of as a "fail-safe" mechanism and thus is to be only integrated in highly critical infrastructures.

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This paper hypothesizes that an intelligent adoption of autonomous structural components (ASCs) can institute a platform to enable resilient performance in critical infrastructures. An ASC system entails folding a continuum component into a specific arrangement that allows self-deployment mechanism when triggered by external actions. Deployment of an ASC component is defined as the process of transforming a compact and foldable arrangement into a relatively stiff (and workable) configuration with specific structural-based load-bearing capabilities. Unfolding, of a foldable structural component, can be carried out by a number of mechanisms such as inflation, dynamic sliding and use of kinetic or potential energy stored in the folded component(s) [8, 9].

While traditional foldable structural systems have received a considerable amount of attention in recent years [8-10], much of this research is applied towards developing easy-to-deploy robots and refugee camps [11, 12]. The use of foldable structural components/systems to enhance structural resiliency has not been fully investigated yet. This paper explores the integration of ASCs that can respond and adapt to various loading conditions into critical infrastructures. The concepts presented herein aim at realizing improved and resilient performance under extreme events which could eventually lead to development of autonomous and disaster-resistant infrastructures. The practicality of the proposed concepts is illustrated through a comprehensive case study. Results from this study are utilized to show merits of integrating ASC systems into realizing resilient performance of infrastructures in case of fire breaking out in a super-tall high-rise building (of 80-storey with a total height of 320 m). The outcome of this study also infers that integrating ASCs systems to civil constructions can improve societal adaptation to extreme events and ensure sustainable performance of infrastructures.

3.0 A DISCUSSION ON SELF-FOLDING STRUCTURAL COMPONENTS AND AUTONOMOUS INFRASTRUCTURES

Structures can be fabricated (or manufactured) through three possible techniques [13]. The first, often referred to as "subtractive manufacturing" (i.e. sculpting), in which extraneous materials are carved away until arriving at the final form. The second technique that can be used to manufacture (or build) a structure is "additive manufacturing"; where a structure is built one component at a time. The third technique is known as self-folding. Self-folding is the autonomous process of transforming two-dimensional flat shapes into three-dimensional forms; whether manually or in response to an external stimulus (i.e. temperature, pressure etc.). This technique is of main interest to this study.

The concept of self-folding is borrowed from nature. In fact, nature has been able to fabricate self-folding and lightweight structures using various bio-based materials and products. Nature-based structures can vary from simple forms (i.e. flower) to more complex arrangements (ex: brain tissues). From an engineering prescriptive, self-folding automates the construction of components (and systems), especially those with arbitrarily complex geometries and features. Overall, self-folding has great practical applications particularly in robotics [11], space applications [14], biosciences [15], and packaging [16] etc.

Self-folding, in some of the aforementioned applications, often involves ideal (thin or near zero-thickness) surfaces. Due to the high difference in energy scale associated with stretching and bending of very thin surfaces, the study of folding in such applications is known as extreme mechanics. However, from civil construction perspective, the thickness of a load-bearing component is relatively large since the stiffness of a structural member is a function of the member

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thickness (i.e. beams, walls/slabs etc.). This feature allows a structural component to physically resist effects of loadings (arising from gravity, wind etc.), as well as loading effects such as heat (thermal energy) or pressure as a result of fire breakout or blast incident.

This study revolves on the notion that if foldable structural components are incorporated with artificial intelligence and Internet of Things (IoT) technologies, then they can be integrated into structural engineering applications and this institutes the first step towards realizing autonomous and resilient infrastructures. By integrating configurable (self-folding) structural components, to act as secondary and independent structural systems, the proposed framework enables a newly designed (or upgraded) critical infrastructure to achieve resilient performance by allowing it to autonomously adapt to the surrounding environment, in real time, and to withstand severe loading conditions during extreme events (i.e. fire, flooding etc.). Thus, infrastructures equipped with autonomous structural components (ASCs) have the ability to reconfigure their internal structure in order to redistribute event-induced forces carried by damaged structural components (i.e. beams, frames) to ASCs as to postpone failure (collapse) of the main structural load bearing components or systems.

The proposed ASCs can be integrated as part of compartment boundaries* and to be aesthetically appealing (i.e. integrated as a partition) as shown in Fig. 1. An ASC component can stack up against compartment boundaries (walls or columns) as to not occupy large spaces or obstruct the interior layout of the structure. Such component may remain inactive at ambient (working) conditions and is only activated once an extreme event breaks out. An ASC system can

* ASCs can be fitted into a specific location or can be designed to be "free of attachment" and travel within the structure when desired.

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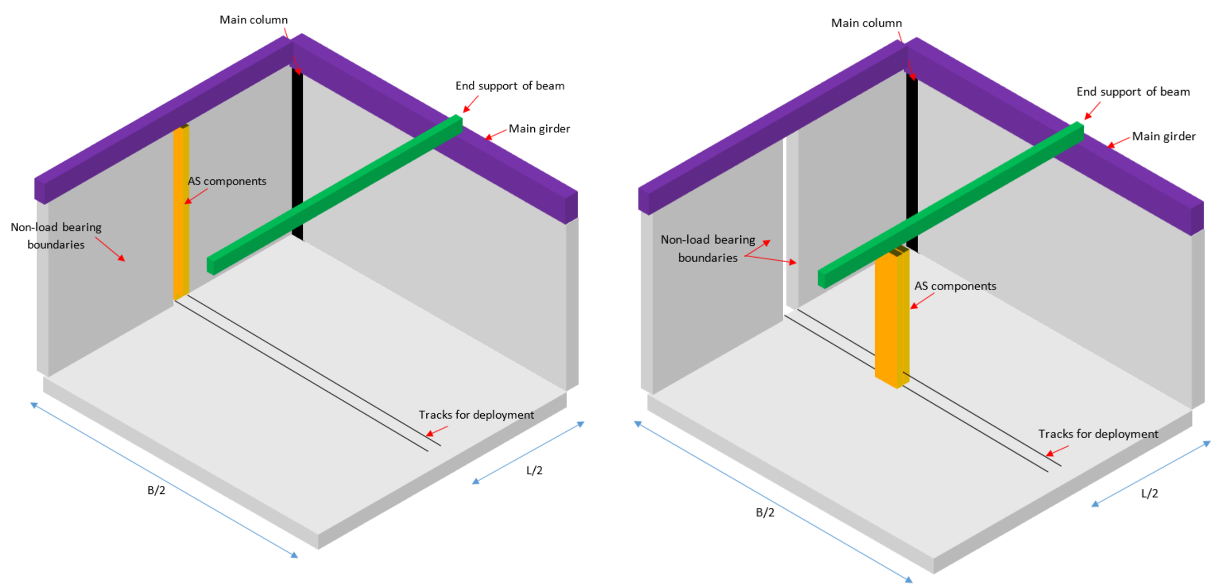
also be activated once pre-determined limits within the surrounding environment, such as load level, deflection, sudden rise in temperature etc., are exceeded beyond a specific limit. The proposed ASC systems can be activated through various mechanisms. For example, the activation of an ASC system can be triggered through human control (i.e. occupants/engineers), sensing devices (or use of motors), or through self-powered mechanisms (i.e. through utilizing specific materials with the ability to respond/react to surrounding environment).



(a) Inactive mode (b) Active mode

Fig. 1 Illustrations of autonomous structural component in a typical compartment (*L* and *B* are length and width of compartment, respectively)

As can be seen in Fig. 2, ASCs may utilize "accordion-like forms" that could be made of structurally-rated construction materials with load bearing abilities and good thermal resistance properties (i.e. light weight concrete, insulated steel shapes etc.). In case concrete is used as a construction material, concrete panels can be incorporated with steel mesh or reinforcement to enhance overall axial and flexural capacity. Steel or polypropylene fibers can also be added to improve tensile strength of concrete and to mitigate possibility of fire-induced spalling during a

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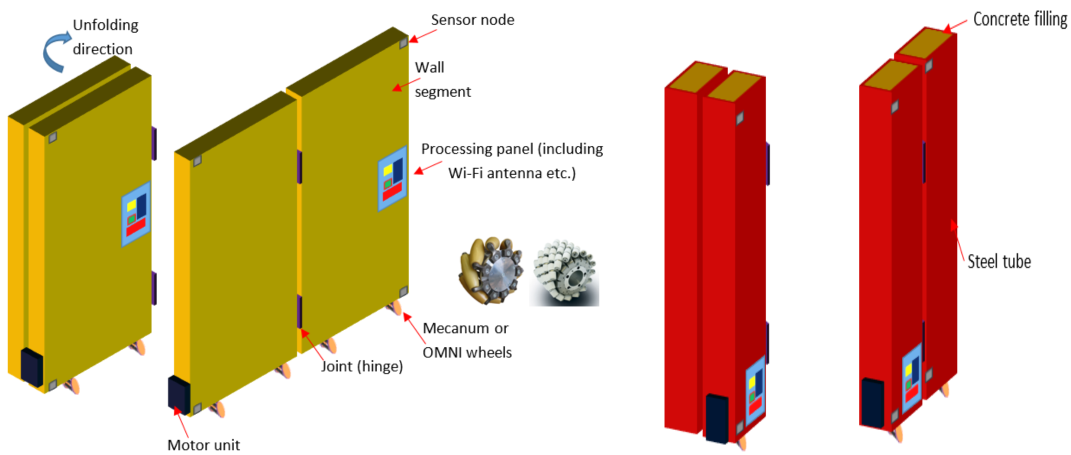
fire incident. ASCs can be made of steel plates or hollow sections, insulated with fire-rated materials (such as gypsum or sprayed with intumescent paint), and hence are able to provide robust performance under various types of loading (i.e. earthquake) as well as under elevated temperatures. The use of composite ASCs, i.e. concrete-filled tubular steel shapes, could be considered if such ASCs are able to satisfy moderate fire rating requirements; among other loading conditions. In all cases, such ASCs can be used as a secondary load bearing system that is dynamic and independent of main structural framing of an infrastructure.



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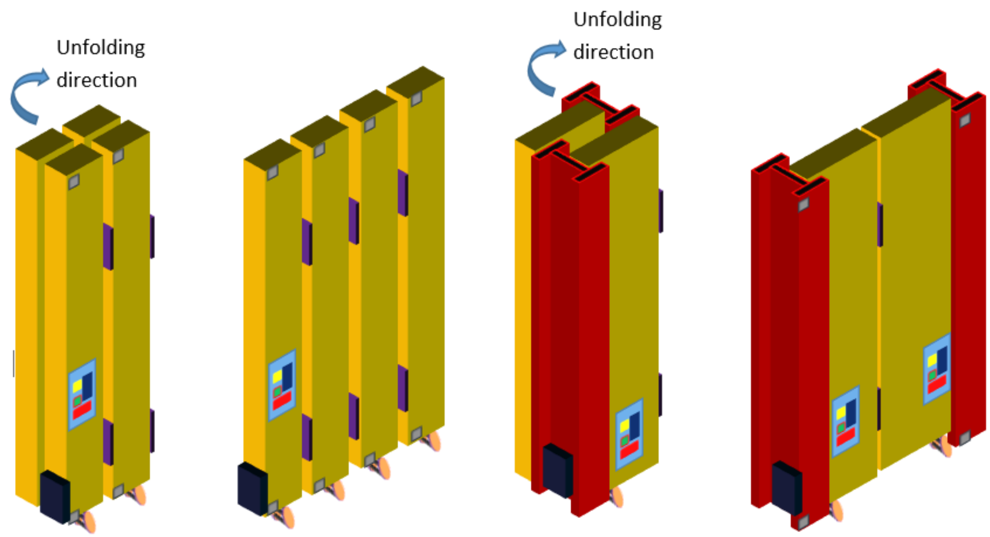

Fig. 2 Illustration of proposed ASCs concepts

Figure 2 also shows that ASCs are equipped with sensors, motor units, and a processing panel (that includes communication antenna etc.). This allows integration of ASCs into the "cognitive framework" of the structure [2]. Buildings, or structures, incorporated with cognitive abilities can monitor key response parameters (i.e. temperature, deformation etc.) through interaction of various sensing devices and socio-environmental factors. These response parameters can be utilized to trace performance of main load bearing structural members during the course of an extreme event so as to evaluate overall structural integrity. This evaluation can be carried out through a processing unit; installed onsite or on a cloud computing service. This processing unit is capable of carrying out complex structural calculations to continuously evaluate available load carrying capacity, together with extent of deformations, in structural systems in order to assess level of damage and estimate probability of failure (collapse) at the local or global level. Once the cognitive framework identifies high level of damage in a certain region, the ASC system at that

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location (i.e. node) is activated to autonomously unfolds to aid in re-distributing the applied loading carried by the weakened components (i.e. beam or slab) of the main structural system.

The successful use of self-folding components, such as ASCs, depends on the complete unfolding of the whole system. By definition, smooth deployment (unfolding) requires mechanisms that are reliable and do not necessitate sophisticated instrumentation. Thus, mechanisms with inherent flexibility are desired. One such mechanism can be similar to segmented panels that integrates hinges into stiff panels (i.e. accordion door). Once an ASC is activated, panels can slide through tracks (or seals) at the floor and ceiling levels (to divide a compartment and partake in carrying some level of applied loading). ASCs may also be designed to navigate throughout a floor plan using Mecanum or Omni wheels.

The deployment process is completed when the ASC attaches to main structural systems through physical contact i.e. when an ASC bearing wall is situated under a deflecting beam/slab. At this stage, the applied loading gets transferred from weakened (heavily-stressed) beams through ASC and directly to the floor slab located within the same compartment; rather than to end supports (i.e. connecting columns) as shown in Fig. 3. This shortens load path, minimizes deflection in damaged beams/slab, as well as releases some of the additional developed stresses in the end connections. This mechanism has been shown to significantly improve structural performance, by preventing excessive deformation, especially under fire conditions [17]. Overall, the ASC system continues to redistribute the applied loading until failure of the ASC, collapse of the structure, or controlling the extreme event (i.e. extinguishing fire). In the former case, the ASC system folds back to its original form and location. Since the ASC systems comprise of lightweight,

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prefabricated components, an ASC could be repaired or replaced in the aftermath of an extreme event

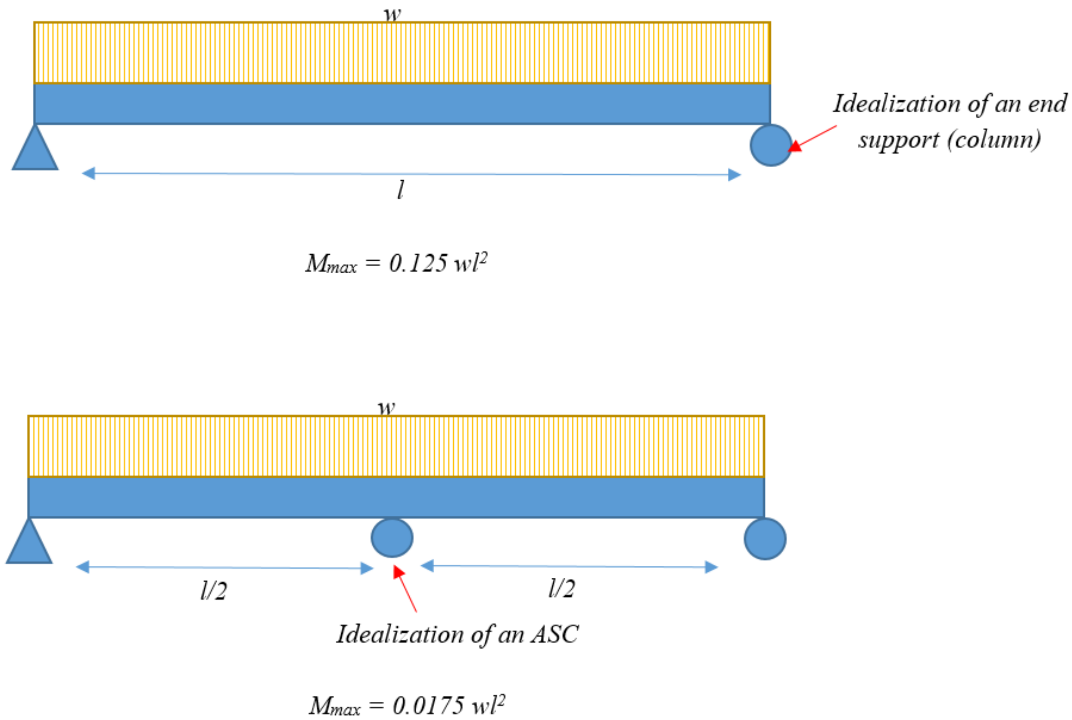

Fig. 3 Illustration of ASC on load distribution

Integrating a unique structural system, such as ASCs, can be a challenging process especially during harsh conditions (i.e. elevated temperature, low visibility, unorderly evacuation etc.) and if not properly designed, may injure occupants, first responders etc. Hence, special attention is needed to allow successful and complete utilization of ASC in order to allow safe deployment along with forming a correct "load path". Hence, various safety features need to be implemented to ensure safe use of ASC systems. Such features may include use of laser and optical sensing devices, ability to identify occupants and debris etc.

It should be noted that an autonomous structural load bearing component needs not be designed to transfer full amount of loading arising from disaster-weakened structural members given that type and intensity of loading can be unpredictable during an extreme event. But rather, these systems are incorporated to help negate occurrence of significant levels of damage and/or immediate collapse (more specifically localized failure in structural system that can trigger progressive collapse). The proposed ASCs are thought of as a faultless mechanism that ensure high built-in redundancy which can improve structural performance as well as facilitates evacuation of occupants and safe continuation of rescue activities carried out by first responders. Figure 4 presents a framework for activation, deployment, and retraction of a typical ASC system.

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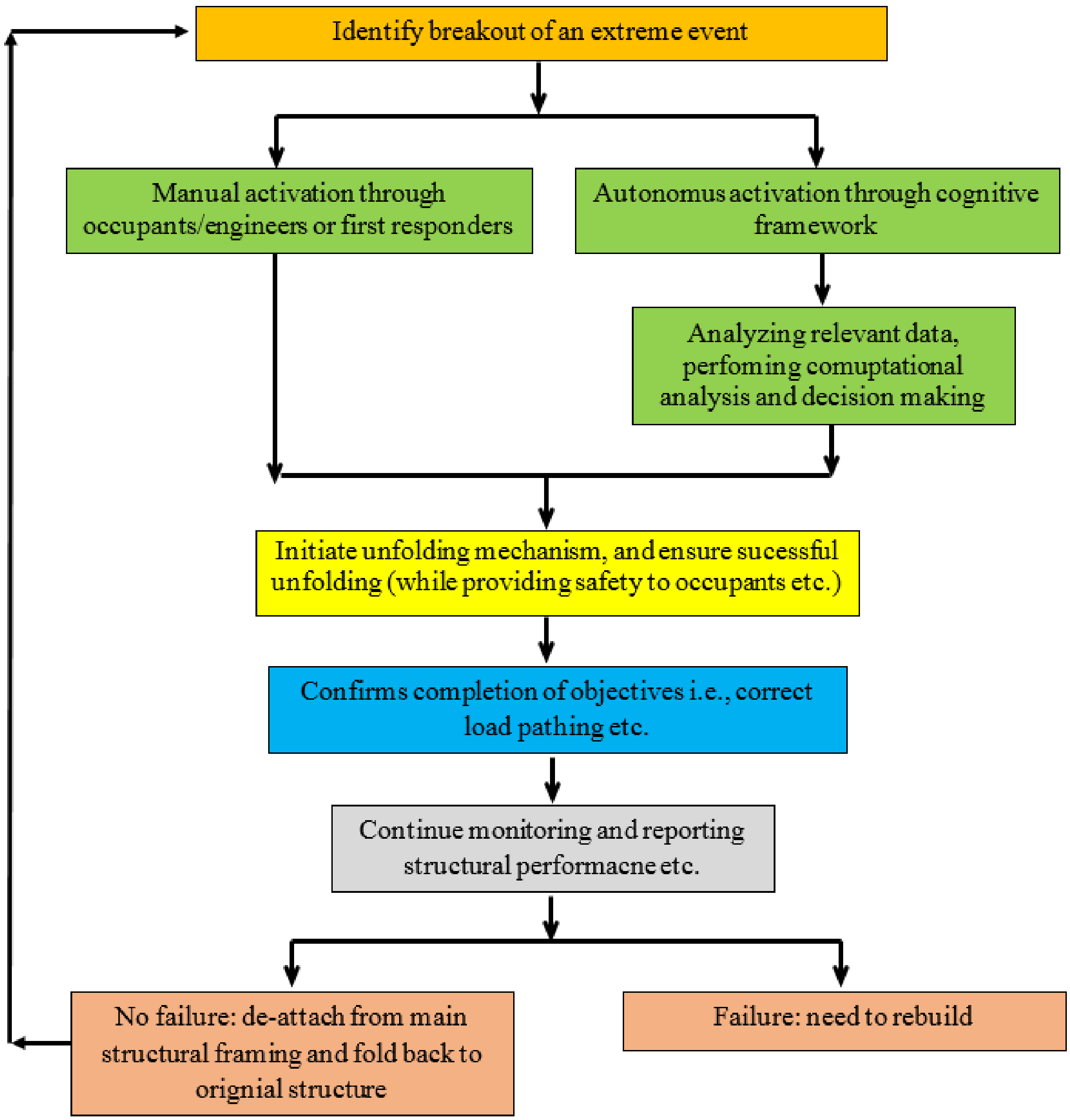

Fig. 4 Flowchart showing different layers needed in the proposed ASC systems

4.0 CASE STUDY

In order to demonstrate the applicability of integrating the proposed ASCs to achieve resilient performance in an infrastructure, from structural and human evacuation points of view, a comprehensive case study is carried out herein. This case study investigates the use of an ASC wall as a load bearing, secondary structural system to, 1) enhance performance during a fire event, and 2) facilitate complete evacuation of occupants. To demonstrate the merits of the proposed system, a super-tall 80-storey high-rise building of composite framing housing 6,400 occupants and subjected to a severe fire is selected for analysis. The floors in this building are of identical layout; each floor has a surface area of 2,000 m^2 and is occupied with 80 randomly distributed occupants (refer to Fig. 5 for occupants’ distribution). It should be noted that actual dimensions of ASC panels, along with their deployment mechanisms, are not fully disclosed herein as this pilot study aims to introduce the concept of autonomous infrastructures. Further details on constructability and fabrication of ASCs is currently undergoing and will be presented in a separate future work.

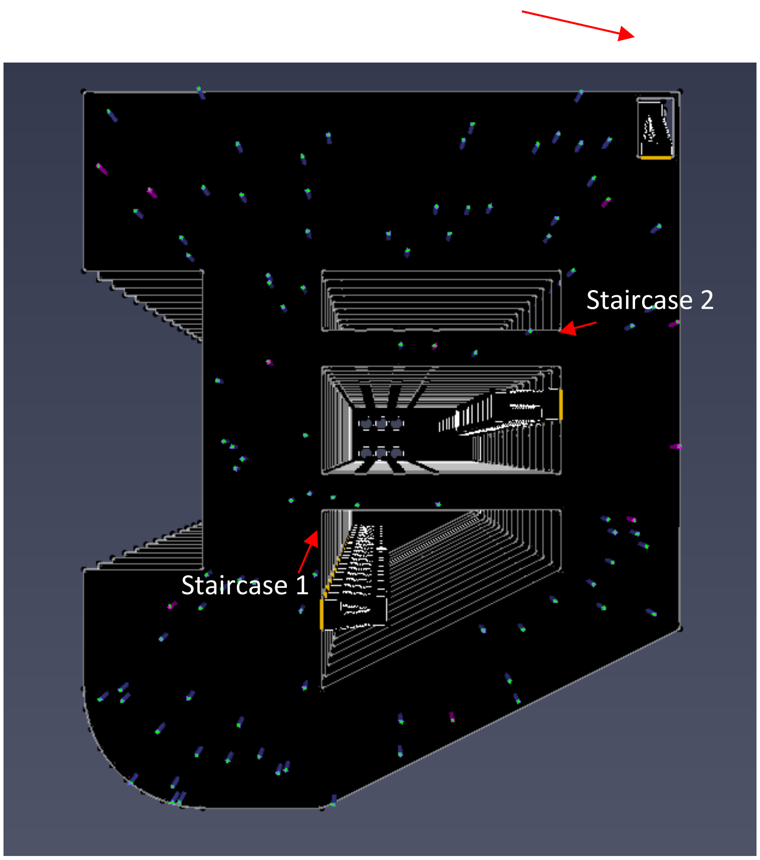

Fig. 5 Plan view of the 80-storey high-rise building selected for analysis

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4.1 Description of fire incident

A severe fire is assumed to break out and to grow within a compartment in the 55th floor of the super-tall high-rise building shown in Fig. 5. While fire severity in a high-rise building is often of a lesser intensity than that of a standard fire, fire breakout in this building is assumed to follow ASTM E119 standard temperature-time curve to; 1) comply with availability of experimental data, and 2) better demonstrate the effectiveness of the proposed ASCs under harsh conditions. As a result of this fire breakout, temperature rises in a composite beam located at mid-span of the room (in the long direction). This composite beam comprises of a steel beam (W24×62 section fabricated using A572 Grade 345 structural steel with tensile strength of 345 MPa) attached to a concrete slab cast along the full length of the steel beam (see Fig. 6a). The concrete slab has a depth and width of 140 and 815 mm, respectively, and was made of concrete of compressive strength of 45 MPa. The concrete slab is also reinforced with two layers of no. 4 steel reinforcement. This composite beam is experimentally tested and numerically analyzed under gravity loading (of magnitude of 150 kN) as well as fire exposure (ASTM E119) earlier [18, 19].

4.2 Investigation into thermal and structural response

The composite beam was exposed to fire from the bottom and sides and this led to rapid temperature rise in the uninsulated beam. Results from fire tests, plotted in Fig. 6b, shows progression of cross-sectional temperatures across the height of the beam. It can be seen that temperatures at different points on steel girder increase at a much faster pace than that in concrete slab. This can be attributed to the high thermal conductivity and low specific heat of steel (as compared to concrete). Figure 6b also shows that the measured temperatures in top flange of steel beam are much lower than that in the bottom flange due to the insulating properties (i.e. heat sink effect) of the concrete slab.

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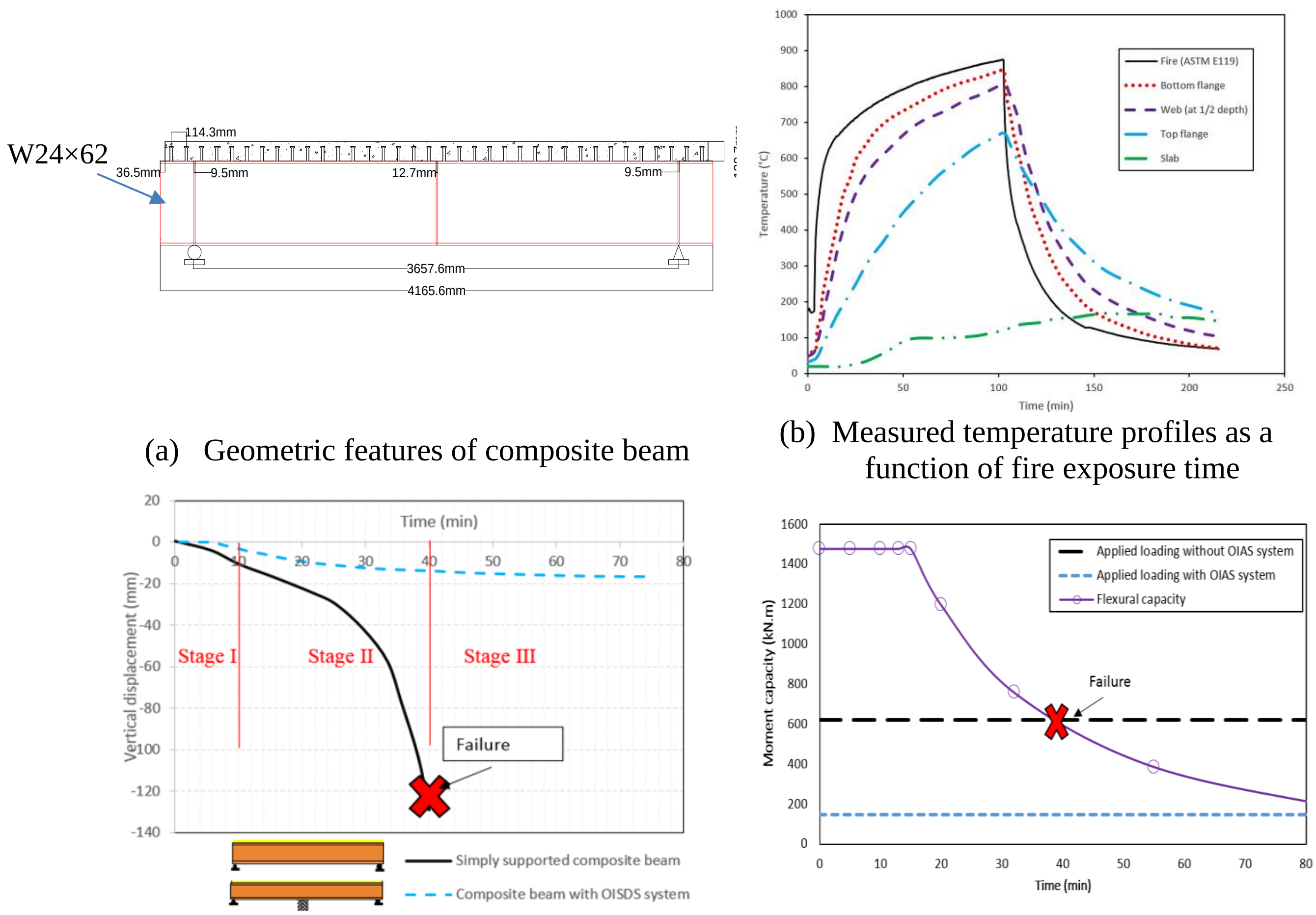

(a) Geometric features of composite beam

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

(c) Vertical displacement in beams

(d) Degradation of sectional capacity as a function of fire exposure

Fig. 6 Thermal and structural response of the selected composite beam under gravity and fire loading

The structural response of the tested beam can also be assessed by tracing progression of vertical deflection and temperature-induced degradation in moment capacity as a function of fire exposure time. It can be seen from Figs. 6c and 6d that the structural response of this beam can be grouped under three distinct stages. During the first stage, mid-span deflection starts to slowly increase once temperatures in the bottom flange and web reaches 200˚C. At this temperature range, the moment capacity in the beam remains intact due to the moderately low rise in temperature. In

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the second stage of fire, steel temperature in flanges and web rises beyond 400˚C and this leads to rapid degradation of strength and modulus properties of steel. This degradation in constituent properties translates into losses in moment (and shear) capacity accompanied with accelerating rise in mid-span deflection. In the third and final stage of fire exposure, mid-span deflection in the composite beam increases at a rapid pace due to further degradation in steel mechanical properties together with development of high temperature creep effects. These effects lead to formation of plastic hinge at the mid-span and triggers a collapse mechanism. As a result, the beam fails after 40 minutes of fire exposure once steel section yields and concrete slab crushes at mid-span. Further details on the thermal and structural response of this beam can be found elsewhere [17, 20]

4.3 Investigation into evacuation process

Extreme events, such as building fires, are often accompanied with a number of uncertainties i.e. fire cause, magnitude of damage, possibility of collapse etc. These uncertainties can significantly hinder evacuees' decision making process. In order to shed light onto the evacuation process in this 80-storey building, evacuation simulations have been carried out using Pathfinder program [21]. This software uses a three-dimensional (3D) triangulated mesh to model complex geometry as well as to facilitate continuous movement of occupants (evacuees) throughout the building and hence can provide exclusive trajectory of each evacuee within the simulation environment [21]. It is worth noting that Pathfinder has been developed and validated based on actual evacuation incidents and has also been used in number of evacuation studies [22].

The evacuation model in Pathfinder also uses mathematical distribution functions to reproduce actual aspects of human behavior during an evacuation scenario (i.e. unimpeded walking speed etc.). Thus, occupants can be assigned specific features (and behaviors) that allow

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them to interact with fellow occupants as well as surrounding environment (i.e. building boundaries). In this study, occupants' behavior (including decision making) was modeled through steering mode. In this mode, each occupant has a unique behavior that dictates a series of goals to achieve, i.e. egress out of a room. In order to complete such goals, each occupant must plan the best path for moving toward his/her destination. Thus, route choice selection is derived to promote quickest path planning depending on evacuees' interaction and avoidance of collision (against other evacuees or boundaries). Further, occupants can attempt to steer around obstacles to avoid being pressed against boundaries (walls) or other occupants. Overall, occupants have an average collision response time of 1.5 sec, and acceleration time of 1.1 sec. The population of occupants was divided such that 90.75% with normal speed (of 1.2 ± 0.2 m/sec) and 9.25% with slow speed (of 0.6 ± 0.2 m/sec) to represent similar distribution to that of an actual building as implemented in Pathfinder.

As discussed earlier, the floors in this building are identical and are occupied with 80 randomly distributed persons (i.e. 6,400 occupants in total). Further, this building has three staircases (two near middle section of each floor (staircase "1" and "2"), one at the corner (staircase "3")), and six elevators located near the center of each floor. In order to establish a benchmark trend, where the time it takes all occupants to evacuate the building under normal conditions is monitored, a simulation of an evacuation drill was carried out. In this benchmark scenario, occupants were only allowed to use staircases to evacuate the building (to simulate an actual drill scenario). As can be seen in the evacuation time-history plotted in Fig. 7, it took 56 minutes for all occupants to evacuate the 80-storey building. It is clear that the time taken to complete this evacuation drill is much longer than failure time in the tested composite beam (which fails at 40 minutes as shown in Fig. 6c). As the failure of this beam could trigger a partial and/or complete progressive collapse, the outcome of such failure would cause at least 710 casualties (i.e. evacuees who did not manage to successfully evacuate before 40 minutes (see Fig. 7)).

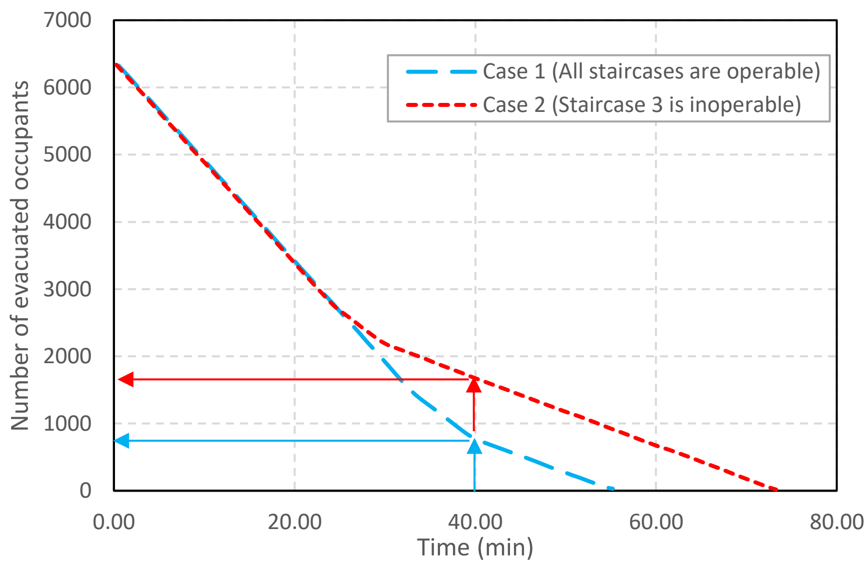

Fig. 7 Evacuation time of occupants

It is worth noting that the above discussed scenario is idealistic, as it assumes all staircases throughout the building to be functional during fire. Thus, a more realistic scenario is also investigated. In this realistic scenario, the fire is assumed to break out at the 55th floor near staircases "3" and then vertically spreads across to the 57th floor. As a result of this fire spread, staircase "3" between the 55th and 57th floors is filled with smoke and becomes inoperable (i.e. dangerous to use).

Thus, to capture the effect of partial closure of one staircase on evacuation of occupants, a second evacuation simulation scenario was carried out. In this scenario, occupants were instructed to use the closest egress path to evacuate. For instance, occupants close to staircases "1" and "2" continue to use these staircases until they reach the ground floor. On the other hand, occupants

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using staircase "3" continue to use the same staircase but once they reach the 55-57 floors, these occupants proceed to use staircases "1" and "2", as staircase "3" in those three floors is inoperable. As expected, limiting egress of occupants through the third staircase in the 55-57 floors causes further delays, which negatively impacts the whole evacuation process. Figure 7 shows that it takes all occupants 73 min to evacuate once staircase "3" in floors 55-57 becomes inoperable. This "time to complete evacuation" also exceeds failure time in the tested composite beam (refer to Figs. 6c and 6d). As a result, evacuation simulation show that 1,650 occupants may not manage to safely evacuate the burning building in this scenario.

4.4 Description of ASC load-bearing wall

The discussion on Sec. 4.2 shows that the fire-exposed composite beam fails within 40 minutes into fire exposure. Hence, in order to enhance the fire resistance of this beam, ASC load bearing walls are assumed to be fitted into the compartment of this building. This autonomous component comprises of self-folding concrete panels attached to room boundaries (walls) and located at middle of the room as shown in Fig. 8. This ASC wall comprises of 40 mm thick joinable concrete panels that extend to full height of the room. These panels are embedded with steel mesh as well as polypropylene fibers (of 0.1% of total volume) to improve fire resistance of concrete and minimize fire-induced spalling. Previous tests carried out by Zielinski et al. [23] showed that well-designed individual concrete panels with similar features to those of the integrated ASC system have an axial capacity of 230 kN which is sufficient to carry applied loading on the composite beam (given that the applied loading on this beam is 150 kN) [20].

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.autcon.2018.11.032

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(https://doi.org/10.1016/j.autcon.2018.11.032).

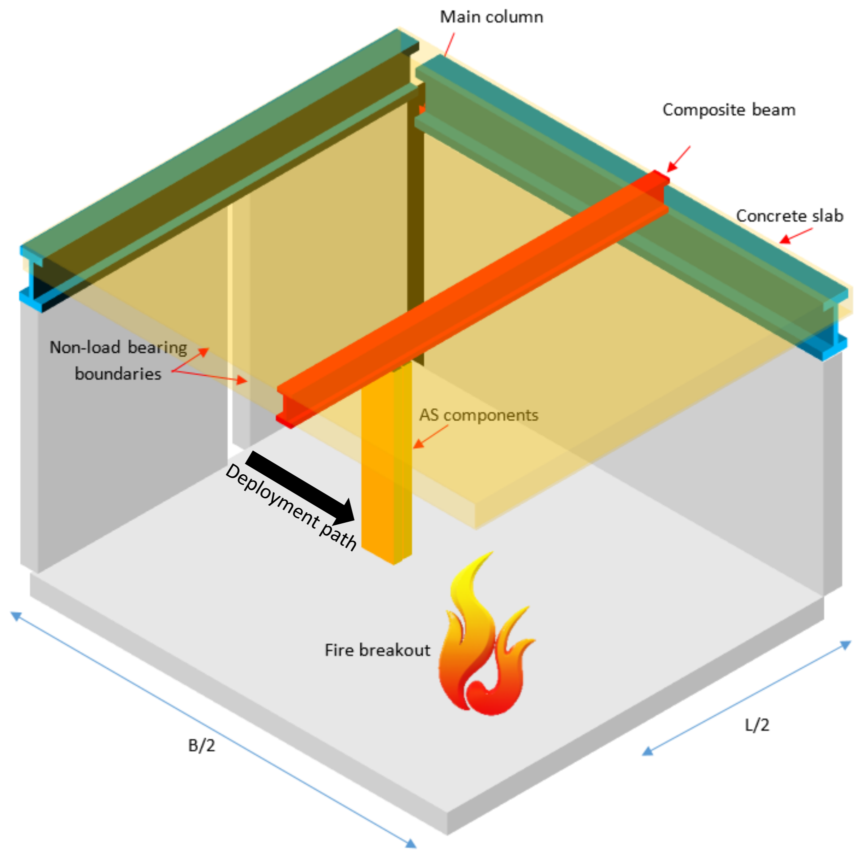

Fig. 8 View of compartment and selected composite beam for analysis

4.5 Contribution of ASC system to structural response and evacuation process

Testing the feasibility of the proposed concept at the global level (entire building) through full scale tests where fire and gravity loading are applied simultaneously is very complex, resource expensive, and perhaps not feasible at the moment. However, it is still possible to illustrate the applicability of the proposed ASC concept through tracing the fire response of a similar composite beam to that shown in Fig. 6a but tested with modified conditions to represent the presence of an ASC.

Analysis of data plotted in Figs. 6b-d, shows that it is most effective to deploy the ASC once the composite beam enters the second stage i.e. steel temperature reaches 300-400°C. Deploying the ASC at this stage can be beneficial on number of fronts. For example, deformation

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of steel beam at this stage is small which allows full deployment of the ASC system. Further, it is during the second stage of fire that temperature rise in steel reaches critical levels and causes serious degradation to strength and modulus properties of steel. From evacuation point of view, it is unlikely for large number of people to be around a burning compartment as most fire suppression systems have been activated within few minutes of fire breakout. Such activation alerts occupants to evacuate. In any case, and as discussed in Sec. 3, since the ASC is fitted with number of sensors, this system can identify presence of injured or trapped occupants and is programed to avoid them (i.e. by not fully deploy or to deploy at a further location away from occupants etc.).

In order to examine and quantify the positive contribution of the proposed ASC concept, results of a newly conducted fire test are utilized herein [18]. In this test, an identical composite beam to that shown in Fig. 6a is tested under similar fire conditions. However, the mid-span of this newly tested beam was vertically restrained through addition of a vertical support in terms of a concrete column [18]. This vertical support simulates the presence of an ASC. Despite experiencing similar fire conditions as that of the first tested beam, the newly tested composite beam (with vertical restraint at mid-span) does not rapidly deflect as opposed to the simply supported beam as shown in Fig. 6c.

In fact, once the ASC attaches to the deflecting beam, much of the applied loading experienced by the beam is directly transferred to the ASC system rather than to the far end supports of the beam. In this particular case, the addition of the vertical restraint shortens the effective span of the fire-weakened beam which is been shown to be beneficial in fire conditions [18, 19]. Due to the presence of interior support, resembling an ASC, the composite beam fails at 75 minutes (an 87% increase over the first tested beam which failed in 40 minutes). Hence, the

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addition of a vertical restraint located at mid-span of the beam facilitates load transfer mechanism thereby significantly enhancing fire resistance of the composite beam and delaying failure time. This additional allowance in time delays failure of the composite beam and also ensures proper evacuation of occupants (in both case 1 and 2 scenarios which took 56 and 73 minutes, respectively). It should be noted that 60-120 minutes of fire resistance in this beam can significantly lower the risk of collapse/damage since steel girders fail within 20-40 of fire [24-26]. This is of highest importance since average response time for firefighters can take up to 8-20 min to arrive at fire incident location and start firefighting activities [24].

It should be noted that the above discussed case study is primarily selected due to non-availability of actual fire test data needed to validate and demonstrate the merit of the proposed ASCs. It is due to limitations and expenses associated with fabrication ASCs and full-scale fire tests that the applicability of the proposed concept was not investigated through full size experiments. It is believed that the aforementioned case study illustrates the merit of developing and integrating autonomous structural components (and systems), not only to enable buildings to adapt to extreme loading conditions, but also to autonomously reconfigure their internal structure to redistribute applied loading, in real-time basis.

5.0 PRACTICAL IMPLICATIONS

While this study draws an optimistic view of concepts, with substantial potential to improve performance and resiliency under extreme events, that may enable realizing autonomous and resilient infrastructures, it can be inferred from above discussion and outcome of presented case study that the proposed concepts require overcoming a number of limitations and technological challenges. The areas where further research is needed to overcome some of the

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current drawbacks in realizing disaster-resilient infrastructures are related to developing autonomous folding/unfolding technologies that allow construction of load-bearing structural components. While the proposed autonomous structural components (ASCs) can, in theory act as load bearing structural members in fire conditions as well as different loading effects i.e. seismic, wind etc., optimizing these members for adaptability and flexibility and to overcome size and cost limitations, is of utmost importance to realize feasible construction and performance [27-29].

Other pressing challenges that need to be overcome may include, advancements in arriving at self-deployment mechanisms, as well as standardization of design and detailing of ASCs etc. Challenges related to integration of artificial intelligence, machine learning, and ensuring continuous power supply and communication, along with synergy between ASCs and a cognitive framework in infrastructures, are other research areas that require immediate attention [30]. Perhaps, items related to appropriate selection of construction materials, homogeneity of integrating ASCs into main structural framing, their safety and functionality (i.e. reliability) under various harsh conditions warrants further research. Finally, a comparison between proposed ASCs and similar technologies in terms of structural performance, deployment mechanisms, autonomy, associated cost, maintenance requirements and human interaction is worthy of investigation.

Though the presented case study was tailored towards one type of an extreme event i.e. fire in a super-tall high-rise building of height exceeding 320 m, results of this case study infer that the proposed concepts of ASCs may also be extended towards other types of extreme events (ex: earthquake, blast). The performance of ASCs in different extreme events, specifically in the case of an earthquake, blast and flooding is currently being investigated as part of two future studies.

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The author invites his colleagues in the engineering community to improve the proposed concepts and to investigate their merit through numerical and experimental studies.

6.0 CONCLUSIONS

The past few years have witnessed an ongoing inertia towards seeking smart and connected infrastructures. Realizing such infrastructures seems to be a natural transition to this modern era. While announcements of plans for smart buildings continues to breakout much more often, it is only a matter of time before buildings start to get serious upgrades in terms of autonomous and cognitive abilities. Autonomous infrastructures are expected not only to function just like their traditional counterparts, but also to achieve higher level of resilience, especially under extreme events. This study proposes concepts for autonomous and cognitive infrastructures, from structural engineering and disaster management points of view. Based on the potential of proposed concepts and results of the carried out case study presented herein, the following conclusions can be drawn:

1. Infrastructures, when undergoing an extreme event, can be highly vulnerable to damage or even collapse. This vulnerability can be minimized through integrating self-deployable and autonomous structural components to act as secondary, and independent structural systems.
2. The proposed concepts for autonomous structural components (ASCs) allow infrastructures to respond to extreme events and to autonomously re-configure their internal structure to redistribute applied loading from damaged members to ASCs.
3. Integrating ASCs into an infrastructure can improve its structural response under harsh loading conditions and ensure its sustainable performance throughout its service-life. This study shows how installing an ASC can improve response of a main load bearing structural element by 87%, thus mitigating premature collapse and minimizing human loss.

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4. In order to realize autonomous and cognitive infrastructures, challenges encompassing development of structural-based self-folding mechanisms, ensuring reliability, robust communication, and machine intelligence, together with proper optimization under extreme conditions, are research venues that need to be explored.

7.0 ACKNOWLEDGMENT

The author would also like to acknowledge the reviewers of this manuscript for their constructive guidance. The author would also like to thank Prof. Venkatesh K. Kodur as well as Prof. Miroslaw J. Skibniewski for their support.

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