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Resilience and Performance of Prefabricated Modular Buildings Against Natural Disasters

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Abstract

Earliest global movement towards modular construction originated as a solution to the sudden housing demand which occurred during events such as British colonization, the California gold rush, the world wars and post war settlement. Present day, modular construction is explored by researchers aiming to maximize from the benefits of Industry 4.0 technology. Buildings of the 21st century frequently face natural disasters such as earthquakes, pandemics, floods, cyclones, and bushfires. This review is developed around recent episodes such as the Covid-19 pandemic which demands design resilience and the intraplate earthquake of Australia, which stresses on the necessity of improved structural performance of modular buildings. To understand the performance of modular buildings against natural disasters, this paper critically reviews recent developments in modular construction research and applications. Through the extensive analysis of literature, this paper identifies future research domains of modular construction that are required to confront natural disasters. The outcomes of this review facilitate timely and sustainable research directives towards resilient modular buildings. The paper concludes that while the overall research in prefabricated modular buildings has evolved in many areas of structural engineering, more research is needed in their performance in natural disaster resilience.

Keywords

Resilience, Modular Buildings, Natural Disasters, Pandemics, Earthquakes, Cyclones

1. Evolution of Modular Buildings

The global construction industry has moved through four phases of industrialization. The first industrial revolution, which is identified as Industry 1.0, rendered new building materials for construction enhancing the form, design, and functionality of structures (Wahlster, 2012). Industry 2.0 enabled the construction industry with mass production and prefabrication of building components and materials (Nam & Tatum, 1997). Previous studies on the evolution of modular buildings report that despite several individual structures, the first global movement in modular construction was enabled by events such as British Colonization, the California Gold Rush in 1848 (Peterson, 1965), first and second world wars (Ovando-Vacarezza, Lauret-Aguirregabiria, Lirola-Pérez, & Castañeda-Vergara, 2014) and post war housing construction (Johnson, 2007). Following these events, Industry 3.0, which began in the 1960s shifted mass production into mass customization. Rifkin (2011) reports that, when compared to industries such as textile, transportation and energy, the construction sector did not gain any major improvements during Industry 3.0 (Pries & Janszen, 1995). The world is now at Industry 4.0 and the construction industry is attempting to shift from its development in Construction 2.0 directly to Construction 4.0 (World Economic Forum, 2016).

Industry 4.0 is characterized by Internet of Things (Tzourmakliotou 2021), information sharing through cyber-physical systems, intelligent control of manufacturing processes, machinery, factories, and warehousing (Bathon, Bletz et al. 2006). In view of absolving the industry 4.0 technology into construction, many modular building researches and applications focus on digital design, design for manufacturing and assembly (DfMA), use of skilled labor, lighter, stronger, and sustainable materials, construction automation and offsite manufacturing (Oesterreich & Teuteberg, 2016) (Schweitzer & Davis, 1990). The outcomes of these studies aim to positively impact the industry through increased productivity, safety, quality, affordability, resilience, energy efficiency and lower life cycle costs.

2. Resilience and Performance against Disasters

The viability of modular construction research depends on longevity, performance and impacts of modular buildings. The performance of modular buildings must have the capacity to confront the threats of manmade and natural disasters such as explosions (ASCE, 2010), bushfires, floods, earthquakes, and pandemics. For instance, the progressive collapse of Ronan Point high-rise precast concrete apartment building, which was in East London, resulted due to a gas explosion on 16th May 1968 (Pearson & Delatte, 2005). The investigations revealed a deficiency in design standards to ensure building safety and integrity. This catastrophe is a classic example in history which triggered research on progressive collapse, structural robustness, and enhanced design guidelines (Russell, Sagaseta, Cormie, & Jones, 2019). Since this event, the world has faced greater catastrophes, especially due to heightened intensity of terrorism and climate change. Disasters such as the 9/11 attack on the World Trade Center in 2001, hurricane Katrina in 2005, 2010 earthquakes in Haiti, the great east Japan earthquake and tsunami in 2011, the Covid 19 pandemic in the latter part of 2019 and the intraplate earthquake of Australia in 2021 have gained the attention of construction industry to enhance resilience and performance of buildings against such disasters (Gardoni & LaFave, 2016).

Providing permanent housing to disaster victims is a critical and time-consuming activity in the post-disaster reconstruction process. As shown in Figs 1 and 2 the Federal Emergency Management Agency (FEMA), the Florida Department of Community Affairs and the Florida Division of Emergency Management predict that permanent housing may take up to five years to realise from the time of the disaster's impact. This is a very long period to restore the normal livelihoods of disaster victims.

Long-term solutions such as permanent housing are as important as the emergency relief provided after a major natural disaster. Prefabricated modular structures can provide a holistic approach to permanent housing reconstruction in disaster-struck areas.

To identify the competence of modular buildings to endure such catastrophes and post-disaster situations, this study critically reviews and traces the recent developments of modular buildings against natural disasters. This review aims to identify natural disasters, to map the disasters against recent developments of modular buildings and to determine future research domains of modular construction required to sustain such natural disasters. The outcomes of this review primarily contribute towards identifying opportunities in modular buildings to confront extreme events of the modern world.

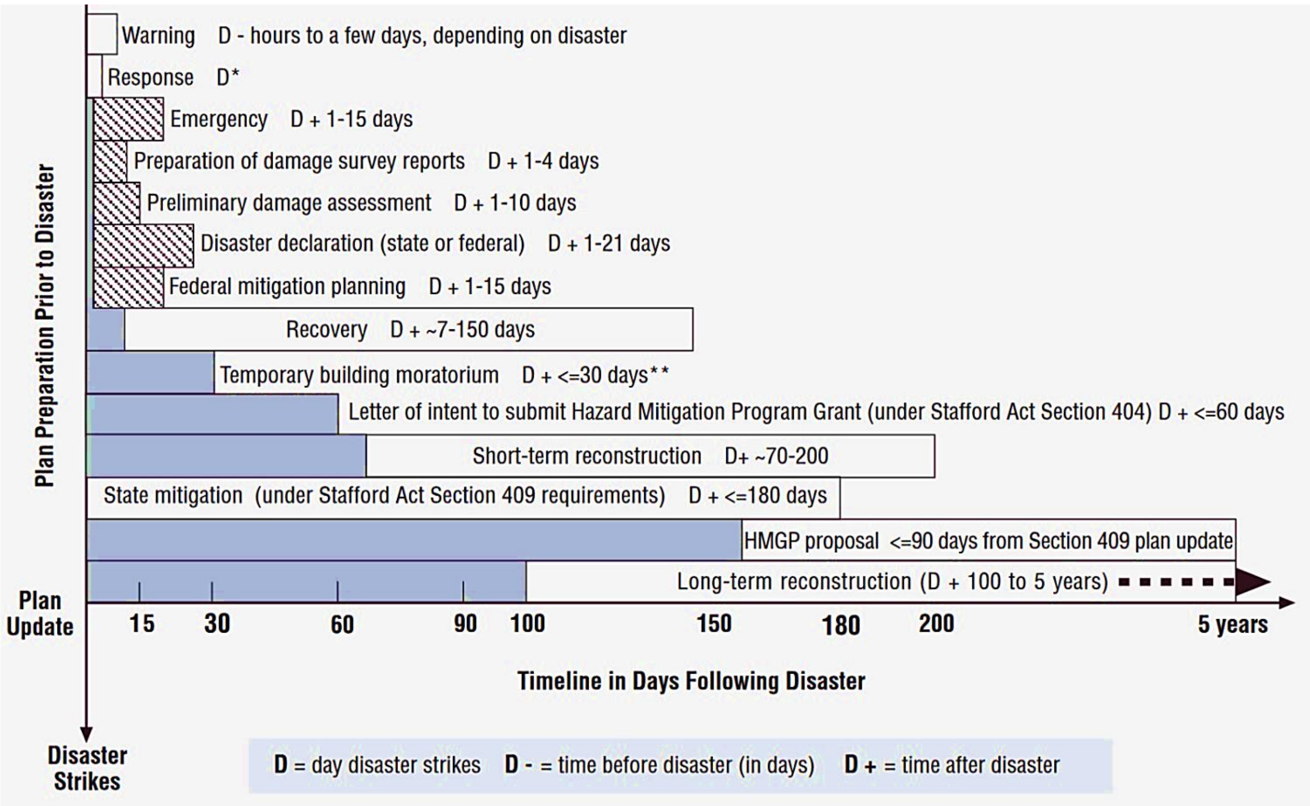

Fig.1 post-disaster recovery and reconstruction timeframes adopted by FEMA (Federal Emergency Management Agency) (Gunawardena, 2014)

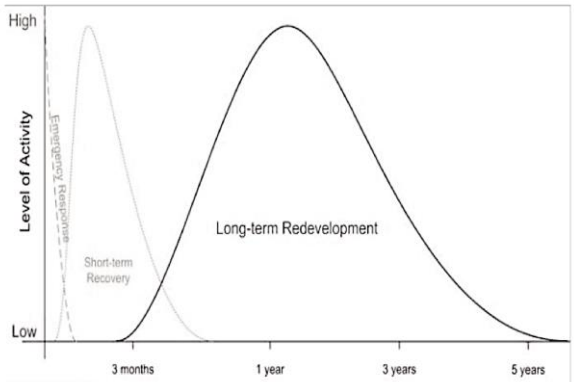

Fig. 2 Probable post-disaster phased activity for a major disaster scenario as adopted by the Florida Department of Community Affairs and Florida Division of Emergency Management (Gunawardena, Ngo et al. 2014) Developments in Modular Construction to Confront Disasters

3. Developments in Modular Construction to Confront Disasters

Disasters can be categorized into three types, namely, technological disasters, manmade disasters, and natural disasters (Gill and Malamud 2014, Gill, and Malamud 2016). Technological disasters of modular construction involve calamities which occur during manufacturing and transportation of modular components which are not reviewed in the scope of this study. However, natural disasters such as earthquakes and cyclones exert extreme loads on buildings while disasters such as pandemics and small-scale floods demand resilient modular designs. Navaratnam et al. (2019) report applications of modular technology (Fig 3a) and volumetric modular buildings (Fig 3b) in Australia and the significance of structural performance of prefabricated building systems against earthquakes, wind loads and bushfires.

Certain disasters such as small-scale floods and pandemics do not impose severe loads or structural damage. However, the performance of buildings against such events depends on the resilient design of the buildings and their Mechanical, Electrical and Plumbing (MEP) services. For instance, events such as the Covid-19 pandemic have stressed the need of changes in the designs of buildings and MEP services to confront such disasters. Following state-of-the-art review, screens the resilience and structural performance of modular buildings and their recent advancements.

(a)

(b)

Fig. 3 (a) "Little Hero" Building in Melbourne, Australia; (b) SOHO Apartments in Darwin, Australia (Gunawardena, Karunaratne, Mendis, & Ngo, 2016).

3.1 Earthquakes

Growth of modular construction has introduced multi storey and high-rise modular buildings (Lawson, Ogden, & Bergin, 2012). The height of the building has a critical impact on the lateral load distribution especially from wind and seismic loads (Gunawardena T., 2016). Fathieh & Mercan (Fathieh & Mercan, 2016) have emphasised the importance of knowledge in the performance of modular buildings against seismic loads as the lack of it may result in unsafe or uneconomically overdesigned buildings. In terms of applications, the Canadian Embassy in Haiti carried out the installation of 46 modular housing units as temporary shelter for 75 individuals following the Haiti earthquake in 2010, as shown in Fig 4 below.

Gunawardena, et al. (2016) introduced and evaluated the seismic performance of an innovative system of prefabricated modules. The lateral load distribution of the proposed system consists of vertically stacked modules, horizontally connected through bolted plates and modules of in-fill concrete walls acting as deep beams (Rajanayagam, et al., 2022). A nonlinear time history analysis and a capacity spectrum analysis were conducted in the study for 10 story building models with and without the in-fill concrete wall component (Gunawardena & Mendis, 2022). The model was tested on six different earthquake scenarios with a maximum moment magnitude scale of 7.6 for a duration of 90 seconds and time steps of 0.005 seconds. The results implied that the structure falls between the 'Immediate Occupancy' to 'Life Safety' ranges of Federal Emergency Management Agency (FEMA) 356 of the United States of America (Federal Emergency Federal Agency, 2000). The study identified the significance of successive column connections and the ductility of corner columns. The authors have established that the column connections must be designed to take the full shear force of the lateral loads. The study emphasizes the vulnerability of the proposed method under severe earthquakes and the immediate requirement to incorporate Structural Health Monitoring (SHM) in buildings to understand the seismic responses.

A series of studies (Annan, Youssef et al. 2007, 2008, Annan, Youssef et al. 2009, Annan, Youssef et al. 2009) evaluated the elastic performance of modular steel braced frames vertically connected by field welding subjected to seismic loads. Factors and components such as ceiling beams, eccentricity at the joints of the braces and provisions on rotation between neighboring columns of the module enabled through semi-rigid welded connections, illustrated remarkable differences in the seismic response between modular and regular steel braced frames. Further, the studies emphasized the design significance of specific detailing in modular steel building braced systems to improve performance under seismic loads. Similar conclusions are drawn in Savoia, et al. (2017) based on the 2012 Emilia earthquake in Italy. In the analysis of a prefabricated modules based flexible structural system, Gunawardena et al. (2016) modeled a 20-story modular building using ETABS software. The model was subjected to nonlinear earthquake time-history analysis allowing for geometric and material nonlinearities, that may occur because of severe dynamic loads. Maximum storey drifts of 0.13% and 1.20% were recorded for static and dynamic analyses respectively. Although the resulting drift values were within the permissible range, the study recomended further investigations into redundency and failure mechanisms.

Fig. 4 Modular housing units installed by the Canadian Embassy in Haiti (Gunawardena, Ngo et al. 2014)

Arslan et al. (2006) argue that economically underdeveloped countries prioritize economic benefits over structural strength of buildings which leads to poor performance of modular buildings during earthquakes. The study analysed causes and effects of failures in modular indusrial structures during the Adapazari and Duzce earthquakes of 1999 in Turkey. The authors argue that the modular buildings which collapsed had been constructed with the aim of maximizing the economic benefits through modular construction and the developers had adopted design guidelines of non-earthquake countries. Liu et al. (2017) propose a combined weld and bolt connection method in which the welding is conducted at the factory and assembled by bolts on site. The proposed joint provides slipping between the cover plate and beam flange. The variable stiffness of the proposed connection performs rigid during minor earthquakes and provides slippage and dissipates energy in larger earthquakes. Lacey et al. (2018) state that the earthqukake design criteria of modular buildings is based on safety of lives and prevention of collapse.

The damage criteria for earthquake loads outlined in the Australian Standards is based on displacement, ductility ratio and inter story drift (Standards Australia, 2007). However, there is an impending requirement of international scale design guidelines for modular buildings to sustain earthquake induced seismic loads.

3.2 Pandemics

Pandemics have largely reformed the built environment. The Bubonic plague that plagued the 14th century drove the western civilization towards the evacuation of overcrowded cities, development of quarantine facilities and to seek urban renewal. Many infectious diseases such as tuberculosis, typhoid fever, Spanish flu, polio, severe acute respiratory syndrome (SARS), Middle East Respiratory Syndrome (MERS) and Ebola plagued the 20th and the 21st centuries. These diseases influenced urban planning and built environment reforms to a substantial degree, while the spread of Cholera was the key driver towards the sanitary reform (Jones and Saad 2003, Johnson 2007). The esthetic clean modernism with low ornamentation, strict geometries and a higher regard for purity was partly driven by tuberculosis. Modern buildings are hence designed to increase security from infections through improved ventilation and adjustable architecture.

Covid-19 pandemic declared by the World Health Organization (WHO) on 12th March 2020, has plagued the world ever since, driving countries into lockdown, safe distancing, quarantining and work from home schedules. This new normal has greatly confined the modern man to their residencies as lockdowns are imposed. Moreover, hospitals demand additional ward space to house covid patients, deploy quarantining facilities and vaccination drives. Thus, the Indoor Environmental Quality (IEQ) has become a priority concern of modern day. IEQ comprises of Indoor Air Quality (IAQ), thermal comfort, acoustics comfort, ergonomics, lighting, and other related factors (Jayalath, Navaratnam, Gunawardena, Mendis, & Aye, 2021). Both IAQ and thermal -humidity conditions are quint essential factors for the control of pandemics and other infectious disease spread, as polluted air (infested with chemical, biological or physical pollutants) and low temperatures are ideal breeding grounds for pathogens (Kubečková, Kraus, Šenitková, & Vrbová, 2020). Unlike other pandemics Covid-19 has largely affected the current building standards. Hence, offsite sophisticated modular construction of manageable modules with simple assemblies can easily adjust to these evolving building standards than traditional buildings (Samarasinghe, Gunawardena, Mendis, Sofi, & Aye, 2019).

During pandemics, people spend 80-90% of their time in confined spaces. Therefore, effective maintenance of IAQ, temperature and humidity are key elements which can help reduce the transmission of infectious particles such as air borne droplets in the case of SARS-CoV-2 (Sun, et al., 2020). This can be achieved either through natural or mechanical ventilation, which dilutes the accumulated pathogens. Studies show that mechanical ventilation is important in countries that experience seasonal changes as the dry climate and winter are ideal breeding grounds for pathogens due to variation in temperature and relative humidity (Kraus, Michal, & Šenitková, 2017).

Najem et al. (2021) have discussed the importance of prefabricated modules that can adjust living spaces for improved ventilation, reduce sick building syndrome which is a caused due to higher levels of CO2 accumulation in residential spaces and improvements in sanitation units. Based on the functional purpose additional partitions, ventilation units and other components can be easily added to modular units (Generalova, Generalov, & Kuznetsova, 2016).

Following the Great East Japan earthquake in 2011, prefabricated temporary housing was established. The IAQ and thermal comfort analyses of these prefabricated houses demonstrated that dew condensation and fungi was prominently observed on prefabricated panels. It was identified that the dew condensation and fungi growth in prefabricated temporary houses was 58% and 37% higher than conventional houses respectively. These conditions were heightened during the winter period. The key reasons behind this were improper ventilation, negligence of occupants and poor insulation (Lawson, Ogden et al. 2005, Lawson, Ogden et al. 2012). By 2017, advances in engineering have put forth sustainable material and modular HVAC systems designed according to proper guidelines and are installed in prefabricated buildings such as the low-rise apartment building 'Little Hero' in Australia (Gunawardena D., Mendis, Ngo, Aye, & Alfano, 2014).

Respiratory viruses such as SARS-CoV-2 are currently evaluated for their relation to air pollution. Pandemics cause a surge in the amount of occupational capacity in hospitals and other patient housing facilities. Thus, HVAC services must expand to adapt to the increasing occupancy. However, this cannot be achieved with a traditional HVAC system as they require rework and cannot be facilitated in emergency situations while maintaining IAQ, lighting, thermal comfort, and filtration to curb the pathogen transmission. As hospitals have varying cooling and heating loads, standardized systems are not feasible. Hence, modular HVAC systems are highly sought after in such situations (Samarasinghe, Mendis, Aye, Gunawardena, & Karunaratne, 2017).

MEP systems require several alterations to facilitate infectious disease control, which in turn requires redesigning of building services. The MEP systems are designed prior to construction and imposing any alterations to the installed MEP systems can hinder the building services and comfort of building users. Thus, making alterations or facilitating infection control mechanisms in an already constructed MEP system can result in poor energy efficiency and dysfunctional systems due to heavy load and unoptimized MEP designs. To address this issue modular HVAC systems, which are designed and tested in a factory can be used to replace the existing HVAC systems to suite the emerging demands as a resilient option. However, the constraints in module size and rate of replaceability are still intact (Samarasinghe, Mendis, Aye, Gunawardena, & Karunaratne, 2017).

Elsaid et al. (2021) recommend that portable air purifiers and air cleaners are feasible alternatives to HVAC ventilation when outdoor air exchange is not adequate. Further, portable High Efficiency Particulate Air (HEPA) filters can be used in ventilation in critical situations such as enclosed spaces with poor ventilation. This is critical in the hospital setups to reduce the transmission of pathogens that cannot be effectively addressed through conventional HVAC systems (Luo, Liu et al. 2020, Megahed and Ghoneim 2020). In principle, new modular HVAC systems with HEPA filtering has the functionality to remove 99.97% of the pathogens up to 0.3µm in size. As modern prefabricated contracts are upgraded in lieu of the current standards, effective humidification and temperature controls can be achieved and pre-tested before installation (Ding, Yu, & Cao, 2020). Furthermore, following the highly contagious nature of SARS-CoV-2 virus, patient wards and isolation units require negative pressure HVAC systems. Today, many hospitals comprise of modular theatres and isolation wards designed according to health codes and standards are inclusive of mechanical ventilation, filtration, differential pressure controls, directional airflow control, air curtains, local exhaust ventilation and ultraviolet irradiation (Elsaid, Mohamed, Abdelaziz, & Ahmed, 2021). Prefabrication facilitates effective designs and simulation of the airflow inflow and outflow pathways prior to installation, allowing a higher degree of accuracy in performance than conventional designs that are tested post installation.

As Wuhan was the epi center of the SARS- CoV-2 virus spread, prefabricated negative pressure isolation units were constructed in Shenzhen, China to accommodate SARS- CoV-2 patients and protect the frontline workers of the medical sector (Zhou, et al., 2020). In a traditional hospital building, constructing negative pressure units within a short period of time while adhering to strict guidelines and maintaining occupational safety is an impossible task. However, prefabrication is a resilient option which can facilitate such requirements. The construction of Leishenshan hospital in China was completed within a period of 12 days. This is a significant example which demonstrates how newer time resilient strategies such as Product, Organization and Process modeling (POP) integrated with Building Information Modelling (BIM) can help optimize the building designs (Gunawardena T., Ngo, Mendis, Aye, & Crawford, 2014). These designs include optimization of the building services through methodical arrangement of pathways for patients and medical staff for smooth infection-controlled maneuvering. These new approaches employed in modular construction have significantly reduced the potential bottlenecks in latter phases of the building use. Availability of features such as analysis of indoor and outdoor airflow and heat distributions have enabled effective and efficient interior ventilation in critical areas such as isolation wards (Luo, Liu, Li, Chen, & Zhang, 2020).

Beyond the IEQ of buildings, pandemics make significant impacts on the construction industry, which accounts for 13% of the global GDP. Onsite construction demands a high workforce when compared to offsite construction methods. Pandemics and infectious diseases can halt onsite construction activities causing major disruptions such as financial losses and material wastage. However, offsite construction methods can power through such situations as health codes and safe distancing can be practiced within enclosed spaces in factories. The high degree of automation and enhanced ability of regulating the workforce of offsite construction methods significantly reduce the number of workers required for fabrications (Gunawardena T., et al., 2019). Thus, prefabrication is a viable solution where off site designing and construction can still operate and reduce construction costs. Moreover, the construction sector accounts for 30% of the world's annual greenhouse gas emissions. Studies have shown that modern prefabricated construction strategies record low carbon emissions when compared to conventional construction methods. This is an indirect advantage of modular construction, since diminishing carbon emissions facilitate better respiratory health of the population (Tzourmakliotou, 2021).

3.3 Floods

Erosions caused by floods and fast-moving flood waters with debris damage the structure and the engineered connections of buildings (Fenner, Razkenari, Hakim, & Kibert, 2017). The FEMA has outlined building design regulations to withstand the impacts of natural hazards by establishing a minimum recommended floor elevation for residential buildings based on Base Flood Elevations (BFEs). However, the uncertainty in the return periods of floods makes it difficult to design buildings which are floodproof for a long period of time. Therefore, it is essential to find resilient design strategies and building material which can withstand water ingress and impact loads due to the collision water-borne debris (Wingfield, Bell, Bowker, & Wallingford, 2005). Keeffe and McHugh (2014) have drawn similar conclusions by highlighting the reducing certainty of flood risks and the need for current housing standards to evolve to sustain unpredicted flood events.

The IDEAhuas modular house design of UK provides concrete basin type gourd floor with closed cell insulation and doorway protection to repel flood water ingress to a depth of 750mm (Keeffe & McHugh, 2014). In their study Piatek and Wojnowska (2020) show that conventional buildings cannot be constructed in flood prone areas which frequently inundate with fast flowing floodwater and debris, due to the low flood resilience of building material and design. As a solution, amphibious boulevard pavilions are proposed in the study. The proposed structure consists of lightweight modular components which can be demounted within a short period of time and be evacuated from the flood zones. These amphibious flood resistant pavilions are generally designed to be raised by flood waters undergoing vertical movement. During vertical movement they are held by 4 clamps that slide along dolphin piles, which prevent lateral deformations of the structure.

Floating modular architecture is an emerging area of study as a sustainable construction method. For example, the city of Rotterdam developed the floating pavilion in 2009 to study self-sufficient architectural models which are less vulnerable to climate change. The floating pavilion is equipped with prefabricated materials. The IBA dock in Hamburg Germany is positioned in a 50 m x 25 m modular concrete pontoon superstructure which allows the building to be disassembled for transportation. The pontoon is fastened on to dolphins which extend above the water, allowing the building to move vertically up to 3.5 meters above water daily (Moon, 2012).

The flood resilient studies discussed thus far provide sound evidence on innovative efforts that have been made through modular applications to provide resilience against floods. However, the studies show the significance of strong and durable construction material which can withstand the impact loads caused by water-borne debris and water ingress.

3.4 Cyclones

Cyclones are meteorological events that take place at the atmospheric level causing heavy rains and high winds. Cyclones are defined by meteorologists as rotating organized cloud formations generated above water bodies. The high ocean water temperature in the latter part of summer and low atmospheric pressure causes warm water vapor and air to elevate towards the atmosphere. This further decreases the air pressure above the warm water body and as a result, surrounding air travels at high speeds towards these low-pressure zones causing cyclones. Cyclones travel at high speeds and upon reaching a cooler water body or land, the cyclones dissipate due to higher air pressure in the environment. However, before dispelling, cyclones induce major damage to people and infrastructure resulting in loss of human lives, injuries and damage to roads, bridges, and buildings. Lacey et al. (2018) classifies the major impacts of cyclones on buildings as extreme wind loads and collision of debris and water damages. Modular buildings resist and transfer wind loads through elements such as braces, wall sheathing or both (Nam and Tatum 1997, Navaratnam, Ngo et al. 2019).

In terms of applications, a design by Architect Marianne Cusato inspired a modular house named the 'Katrina Cottage' (see Fig 5) was used to cater to the large housing demand which followed the Hurricane Katrina disaster in 2005. It was designed to be installed with a floor area of 27.8 square metres. However, this had been improved to incorporate a more permanent housing solution with 20 different cottage models that allowed for future extensions (McIntosh 2013).

Typical design criteria for wind loads on conventional buildings are governed by deflection and vibration through key parameters such as the stability, strength, and serviceability of the structure (Mendis, et al., 2007). Previous studies (Pearson and Delatte 2005, Ovando-Vacarezza, Lauret-Aguirregabiria et al. 2014, Oesterreich and Teuteberg 2016) present that a structure is generally considered as wind sensitive when the slenderness ratio is greater than five and the fundamental wind frequency is less than 1Hz. Based on such design criteria and supporting parameters, Mendis et al. (2007) recommend static analyses for conventional buildings of less than 50 m height. Contrastingly, based on lateral wind load and deflection analysis of a 10-storey modular building, Gunawardena (2016) recommends static analyses for modular buildings up to 10 stories (30 m in height) and dynamic analyses for modular building of height beyond 10 stories.

Bathon et al. (2006) present findings on the structural response of a modular building fabricated by timber-concrete-composite panels (Fig 6). Hurricane wind forces up to 400 km/h were induced on the developed structure and the results highlight the significance connections between modular components used in the building. The floor level lateral load of the building was 429 kN/m, and the stability of the structure was facilitated through the wood-concrete-composite panels. Moreover, in comparison with conventional buildings, it is identified that the proposed panel system design is cost effective. The composite panel design of the modular structure delivers enhanced resilience against lateral loads induced by winds and earthquakes when compared to typical building structures (Abu-Zidan, Mendis, Gunawardena, Mohotti, & Fernando, 2022).

Fig. 5 The original 'Katrina Cottage' design that was used to cater the housing demand which followed the Hurricane Katrina disaster in 2005 (Gunawardena, Ngo et al. 2014)

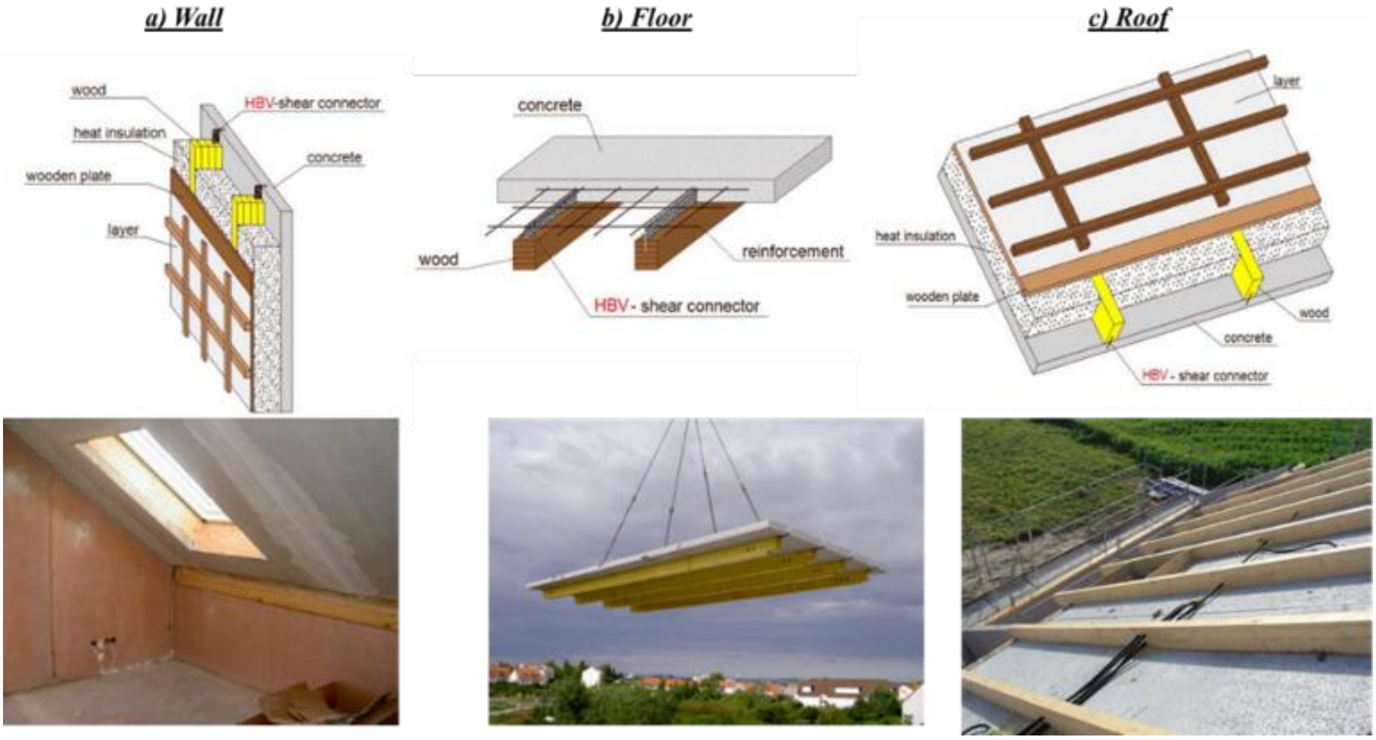

Fig. 6 Timber-concrete-composite panels used in a building (Bathon, Bletz, & Schmidt, 2006)

Reardon (1990) reports test results of a simulated cyclone wind loadings on a steel framed single storey house constructed using prefabricated panels. The lateral and uplift load distribution on the panels were evaluated and the results demonstrate that the structure responded well for a static load simulation up to 50 ms-1 wind force. However, when simulated to the cyclonic condition including cycling and fluctuating wind loads, failure of wall panels was observed. The failure was induced by the fatigue of the rods in the eccentric connections of the building.

Gunawardena et al. (2013) present findings of an investigation on the structural response of a 10-storey modular building. Distinct inter-connection methods were evaluated in the study, and the results demonstrate that the actual structural behavior of the10-storey modular building is between a semi-rigid diaphragm and no diaphragm.

Structural response of the connections in a 11-storey modular building subjected to wind loads was investigated by Styles et al. (Styles, Luo, Bai, & Murray-Parkes, 2016). The results of the study present that the inter-story drift of modular buildings can be minimized through higher stiffness of inter module and intra module horizontal connections. However, the scope of the study is limited to horizontal connections and the study recommends future research into the analysis of vertical inter module joints subjected to lateral wind loads.

Collision of debris on buildings during cyclones is a major concern as the damage to the building envelope may lead to water ingress inside the building. A wide range of studies have investigated the effects of wind-borne debris (Ramaji and Memari 2013, Rajanayagam, Poologanathan et al. 2021, Rajanayagam, Gunawardena et al. 2022). Building design requirements such as AS/NZS 1170.2 (Standards Australia, 2011) specify the use of heavy material such as 4kg timber against the impact loads induced by wind-borne debris. However, modular construction methods include the use of lightweight material building components which facilitate ease of transport and hoisting (Sandeep & Srinivasa, 2020). Therefore, investigations on lightweight structural panels which can sustain high impact loads are significant to enhance performance and resilience of modular buildings against cyclones. A series of studies have adopted a pneumatic canon based experimental investigation and LD-DYNA based numerical investigation into the performance of prefabricated panels against wind-borne debris (Rifkin 2011, Samarasinghe, Mendis et al. 2017, Savoia, Buratti et al. 2017, Russell, Sagaseta et al. 2019, Samarasinghe, Gunawardena et al. 2019).

4. Opportunities & Challenges

Numerous studies have investigated the opportunities and challenges of modular technology and volumetric modular construction. Drawing on the significance of modular construction as the next generation of housing, Ferdous et al. (2019) illustrate the necessity of meeting the increasing residential and commercial buildings demands through offsite construction. Ginigaddara et al. (2019) highlight the future skill requirements for modular construction and the significance of skill transition from conventional construction to modular construction. However, understanding these opportunities and challenges for modular construction in terms of natural disasters is essential to gain performance and resilience in modular buildings of the future.

The covid-19 global pandemic has become the principal challenge for all industries since late 2019. On the other hand, researchers have discussed and proposed numerous modular solutions to gain resilience against the pandemic. The work presented by Abu-Zidan (2021) is a noteworthy example of modular solutions for the pandemic. The study proposes a modular and portable sanitizing chamber with enhanced performance in uniform distribution of the sanitizing spray. The module is equipped with a simple plain orifice misting nozzle which delivered a flow rate of 4.4 L/hour on average at a 900-spray angle. Numerical analysis results of the module propose an optimum design consisting of three nozzle layers at different elevations in the module.

The lateral stability of tall structures has been a key concern for structural engineers for many years in the past, unlike the recent challenges such as the pandemic. Discussing high-rise modular buildings of the future, Giorgio, and Katerina (2019) argue that lateral stability is a major concern for modular tall building designs. Existing lateral stability systems of modular buildings significantly influence net-to-gross area ratio as well as the architectural design of space. Conventionally, there are numerous lateral stability designs for high-rise buildings such as the central core systems and external tube systems. In the modular context, the structural designers' choice of lateral stability is affected by additional challenges concerning factors such as the wind-induced acceleration, constructability, and axial shortening.

Several high-rise modular buildings around the world have addressed the challenge of lateral stability through different design approaches. The 35-story modular apartment building at 461 Dean Street in Brooklyn, New York has provided lateral stability through independent steel braced frames in few elevations of the structure (Generalova, Generalov, & Kuznetsova, 2016). However, these large steel braced frames have affected the freedom of architectural design. The steel braced frames are lighter than a concrete core. However, the use of lighter material for lateral stability has increased the vulnerability of the building for wind induced acceleration. A concrete core system has been employed by the 44-storeid 101 modular building at George Street in London (Bayliss & Bergin, 2020). The construction activities of the building have gained the advantage of having access for module installation through the initially built concrete core which comprises the staircases and elevators (Rajanayagam, et al., 2021).

It is evident that researchers have successfully gained ground in modular applications in the face of severe challenges such as the pandemic and lateral load stability of high-rise modular buildings. The applications and growing knowledge on modular construction show promise on successful transition towards Construction 4.0.

5. Concluding Remarks and Future Research Domains

The review of previous studies conducted in this study demonstrate significant findings on individual mechanical properties and performance criteria of modular components such as in-fill concrete walls, steel braced frames, connections, HVAC systems and timber-concrete-composite panels. It was observed that only a handful of holistic research has been done on the performance of modular buildings and even less investigations on full scale testing of modular buildings. Resilience against disasters is governed by disaster management which includes three key elements namely, preparedness, response, and recovery (Alexander, 2015). A holistic approach to disaster resilience and performance of modular buildings is needed to identify how modular technology can facilitate resilience through the three key elements of disaster management.

Moreover, a significant lack in full scale studies on fire performance of modular buildings was identified through this review. Existing studies on fire performance of modular buildings cover a wide scope but are limited to the analysis of individual components. However, many catastrophes such as the 9/11 attack in New York provide evidence on how a full-scale building may collapse under extreme fire regardless of the use of flame-retardant materials. Similar conclusions have been drawn by recent research as discussed in this article highlighting possible variations in structural response that may take place when both modular elements and connections are subjected to fire.

Therefore, it can be concluded that, while the overall research in prefabricated modular buildings has evolved in many areas of structural engineering, much more attention is needed in their performance in natural disaster resilience.

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