

Assessment of Sustainable Flood Resilient Housing: A Review

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ABSTRACT

The ever-evolving threats presented by climate change compel urban designers to rethink and restructure the built environment, particularly the design of buildings, to saturate them with resilience and adaptability. In this research, this study has embarked on a review of literature to identify design and construction solutions that can enhance the resilience of housing under unstable climate circumstances, particularly flooding results from unexpected heavy rains. The study reviewed two case studies; one from Vietnam and the other from United Kingdom, where experiences of unprecedented rains and flooding had occurred, elucidating the unique obstacles and environmental variances across these regions. From the two case studies analyzed, the study reveals coping strategy by adapting buildings to changing water levels. Key performance parameters such as building materials, raised platforms, floating solutions, services, and structure employed to adapt buildings to live with water in flooding were identified. The findings highlight commonalities and differences in performance parameters between the two cases. Both cases excel in achieving resilient architecture. The research aims to contribute valuable insights and practical recommendations for sustainable and resilient solutions, aiding in the reconstruction of communities affected by flash floods and new constructions in flood-prone areas. The suggested pragmatic guidelines, rooted in utilizing sustainable flood-resistant materials and the employment of resilient design and construction methods offer a tangible roadmap for efficient and sustainable solutions to buildings along the coastal lines and flood-prone areas. Embracing these insights enables policymakers, communities, and professionals to actively participate in the revitalization of regions impacted by flash floods, nurturing resilience and sustainable growth in the aftermath of natural disasters. This research stands as a valuable resource for propelling practices that harmonize with the environment and empower communities to not only build against water but to live with water and also thrive.

Keywords: Climate Change; Flooding; Flood Resilience; Sustainability, Resilient Building

INTRODUCTION

In an age marked by escalating climate uncertainty and severe weather occurrences, the role of innovative architectural design is vital in tackling one of the most catastrophic natural disasters: flooding. This phenomenon can inflict considerable harm on homes, infrastructure, and entire communities, leading to dire social, economic, health and environmental consequences. Floods, arising from heavy rainfall, storm surges, or river overflows, present a serious risk to communities globally.

In Southeast Asia, climate change and global warming are increasing the rate of flooding and sea-level rise (Mohamad et al., 2012). Nations have become more vulnerable due to population growth and environmental degradation due to urbanization (Nekooie et al., 2017). The devastating 2011 Thailand flood raised awareness of the need for village adaptation to brace for future floods (Saengpanya and Kintarak, 2019). Similarly, the 2013 Uttarakhand floods, 2017 China floods, 2018 Kerala floods, 2019 Pakistan floods and

storms, and 2020 Nepal floods were as severe and deadly to the affected regions. The situation in Bangladesh is no different because of its position on the Ganges Delta and the existence of distributaries that flow into the Bay of Bengal. Bangladesh is prone to flooding. Floods strike the country almost every year, wreaking havoc on lives, crops, infrastructure, and the economy (Bhattacharjee and Mukherjee, 2017). One of the most important affords of the human race is the ability to battle and defend against flood vulnerability. The devastation caused by floods as a natural disaster has increased at an unprecedented pace globally. Flooding is a significant issue for many countries around the world, affecting millions of people each year. Historically, many countries have had severe flooding issues: for instance, Bangladesh with its low-lying geography and numerous rivers, more than 58% of its population is estimated to be at risk of flooding. India, China, Vietnam, Pakistan, Netherlands, Egypt, and Nigeria are among many other nations that have suffered varying degrees of severe flooding experiences. In 2024, over one Million people were displaced in Maiduguri, the Borno state capital, where almost 200 lives were lost due to flooding related issues.

Floods have a wide range of interconnected effects on people in flood-prone areas, including loss of livelihood, poor health, and mortality, lack of access to water and sanitation, food and nutrition, lack of safe places during floods, loss of education, and infrastructure damage (Bhattacharjee and Mukherjee, 2017). Each time flood happens, thousands of households across the world are displaced, as many are evacuated upland while several thousands are temporarily accommodated at Internally Displaced Persons, (IDPs) camps. The 2022 flooding in Nigeria impacted the country negatively, as almost all the states of the federation were affected. Data from the federal government indicates that the floods displaced over 1.4 million people, killed over 603, and injured more than 2,400 others. About 82,035 houses were damaged, and 332,327 hectares of land were also affected. A similar disaster in 2012 displaced more people than in 2022. Statistics reveal that the disaster, which began in early July of that year, displaced over 2.1 million people as of November 5, 2012. It killed 363 people, while data from the National Emergency Management Agency (NEMA) indicates that 30 out of the 36 states were affected by the floods. The flooding in Nigeria this year has been particularly devastating. Heavy rainfall has caused severe floods, especially in the northern regions, resulting in the loss of nearly 200 lives and significant damage to homes and farmlands. Over 208,000 people have been displaced across 28 states (NEMA 2024).

The impacts of floods on the Nigerian population over the years have been enormous. This is because the associated risks, such as destruction of lives and property, livelihood displacement, and impoverishment of victims arising from increasing flood cases, have constituted a threat to the citizens' survival. As climate change continues to bring more extreme weather events with significant uncertainty within climate change projections, architects and engineers are tasked with finding innovative solutions to protect both existing and new structures from flood damage. To mitigate these impacts, architects and engineers are developing cutting-edge techniques and materials such as floating architecture, flood resistant materials to create flood-resilient buildings.

This study therefore aimed at assessing the phenomenon of flood globally and identifying the sustainable architectural solutions available that have helped buildings become sustainably resilient to flood through the case studies of existing examples.

FLOOD RESILIENCE: CONCEPTS AND DISCOURSES

The concept of flood resilience introduces a new perspective of 'living with floods' (Batika & Gourbesville, 2016). While the term "resilience" was initially introduced by Holing in 1960 within ecological studies, it has since been adopted across various disciplines, including disaster management, spatial planning, psychology, medical sciences, and social sciences (Walker et al., 2004). The planning field began incorporating resilience terminology in the late 1990s, including concepts such as "climate change adaptation", "sustainability", "disaster risk reduction", and disaster management (Sharifi & Yamagata, 2016). Teitelbaum et al. (1991) articulated, resilience is the capacity to absorb a shock while maintaining form or state without significant disruption or damage.

Fundamentally, resilience refers to the ability of a system to resume functioning after a disruption (Haimes, 2009). However, the broad application of resilience across disciplines has led to ambiguity in the ultimate application of the concept. To realize the 100 Resilient Cities framework, Martin-Breen and Anderies (2011) reviewed the resilience research and created a spectrum of the resilience of increasing complexity based on three interdisciplinary frameworks: Engineering or technological resilience, systems resilience, and resilience in complex-adaptive systems. These frameworks align with others in the literature that have different terminology, see for example (figure 1): engineering resilience, ecological resilience, and socio-ecological/revolutionary resilience (Douven et al. 2012). This paper uses Martin-Breen and Anderies (2011) framework as it accounts for over 50 years of interdisciplinary resilience research, therefore providing a robust overview of the concept.

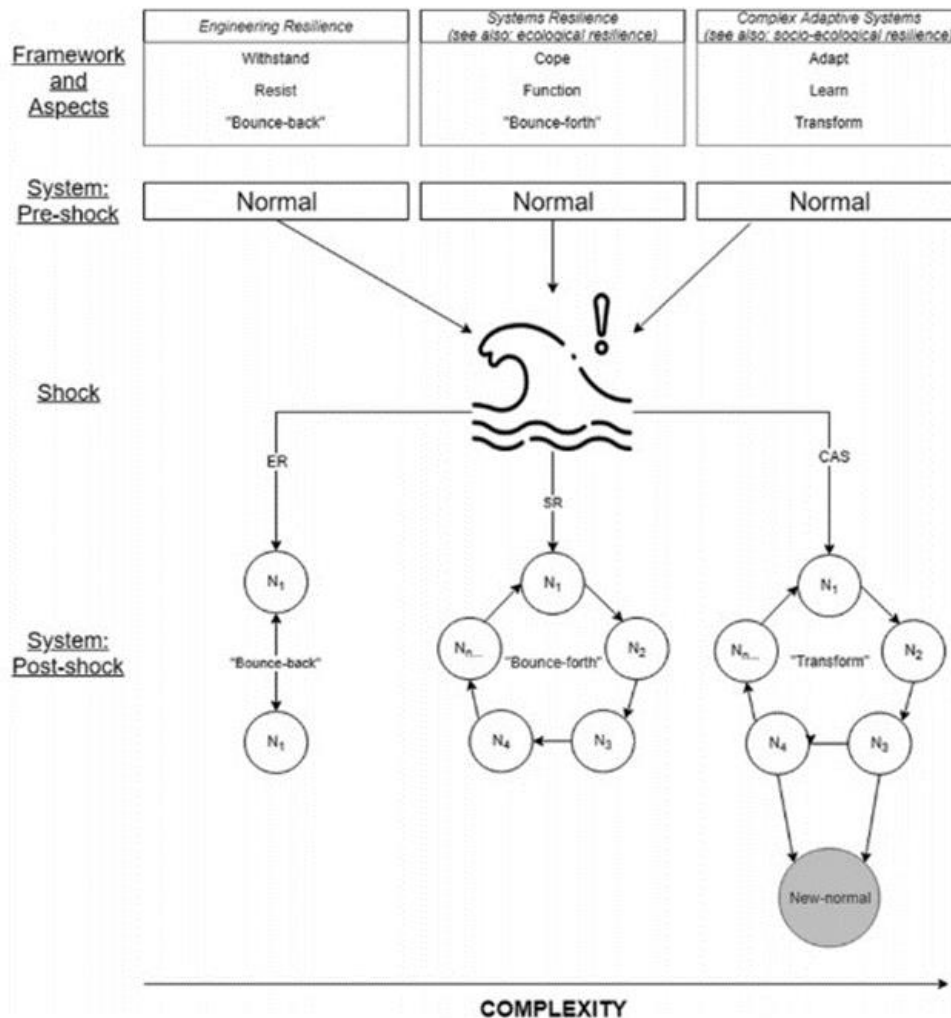


Figure 1. Conceptual model of resilience illustrating examples associated with each framework

Source: McClymont et al.,(2018)

Engineering resilience: conceptualized as maintaining the status quo and defined as the ability to withstand significant disruptions without ultimately changing, decaying, or permanently damaging; in the face of such stress normalcy is quickly restored with less deformation. Engineering resilience does not reflect an engineering discipline, but rather a conceptual framework that can be applied to any field. The framework emphasizes the ability of a system to return to a previous state (bounce back) and is associated with the disaster recovery phase of a shock event.

Systems resilience: defined as maintaining system functionality in the event of a failure or disruption. Although systems resilience and engineering (technical) resilience are related to achieving a normal state

after a disruptive event, the main difference lies in the terminology of ‘bounce-forth (rebound)’ versus ‘bounce-back’ (see Figure 1). This framework emphasizes the interactive parts of systems, which enable them to maintain functionality by metamorphosing into different states in the event of a disruption.

Complex adaptive systems resilience: this framework primarily addresses the ability of a system to adapt and transform in the phase of disruption. Complex adaptive systems are the ability to withstand, recover from, and reorganise in response to a crisis. This framework acknowledges a system's ability to radically transform to a new state in the wake of a disturbance and is therefore focused on longer-term resilience.

Concept of Resilience in Architecture

Resilience in the built environment is the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance. It is the capacity to bounce back after a disturbance or interruption of some sort. Resilient design is the intentional design of buildings, landscapes, communities, and regions in response to these vulnerabilities (The Resilient Design Institute, 2015). Resilience has emerged as a primary subject of academic discourse and a global concern for numerous decades, aligned with the escalating realization and acknowledgment that the world, along with its inhabitants, remains vulnerable to climate and demographic unpredictability (Dupre & Bischeri, 2020). The essence of resilience is often defined as “the capacity of a system to absorb disturbance and reorganize while changing to still retain essentially the same function, structure, and identity” (Walker et al., 2004).

Flood Resilient Architecture: This is the ability of a building to anticipate, withstand, and recover from flood events. Flood-resilient construction has evolved significantly over the centuries. Early examples include levees in ancient China and Egypt, and later, the development of flood control acts and regulations in the United States. The mid-20th century saw a shift towards engineered defense schemes like the Thames Barrier in the UK and the Dutch dyke systems. The early 21st century introduced the "living with water" philosophy, emphasizing the integration of flood resilience at the property level. Flood-resilient architecture is essential to responses to climate change and the increased frequency of extreme weather events. By incorporating innovative techniques and materials, architects and engineers are working to create buildings that can withstand flooding and minimize damage. These advancements protect property and infrastructure and contribute to our communities' overall sustainability and resilience in the face of an uncertain climate future. Embracing flood-resilient architecture represents a step towards a safer, more sustainable world (David & Jessica, 2017).

Historical Evolution of Flood-Resilient Architecture

Traditionally, the management of floods has been centered on engineering strategies aimed at controlling and prevention. Initial approaches involved building levees, dams, and flood barriers. For instance, ancient societies like the Egyptians and Mesopotamians constructed comprehensive levee systems along rivers such as the Tigris, Euphrates, and Nile to shield their agricultural areas and communities from seasonal flooding (Angelakis, et al., 2023; and Smith, 2010). In the medieval and Renaissance eras, cities in Europe advanced their flood defense mechanisms. Notably, the Dutch gained a reputation for their water management skills, creating an intricate system of dams, canals, and windmills to reclaim land from the ocean and safeguard against flooding. A contemporary embodiment of these age-old practices is the Thames Barrier in London, which was completed in the 1980s to defend the city from tidal surges (Johnson, 2015). The 20th century saw significant advances in flood management and a shift towards more holistic and integrated approaches. Large infrastructure projects such as the Hoover Dam in the United States and the Three Gorges Dam in China were built to control river flows, generate electricity, and prevent floods (Brown, 2020). However, these projects also highlighted the limitations and environmental impacts of relying solely on technological solutions.

In recent decades, the paradigm has shifted from purely defensive strategies to resilience-based approaches. This shift recognizes that it is not always possible to completely prevent floods, especially given the growing

impacts of climate change. Instead, the focus has shifted to improving the ability of buildings and communities to cope with and recover from floods (Green, 2018).

Modern flood-resilient architecture incorporates a variety of innovative designs and materials designed to minimize flood damage and ensure rapid recovery. Important examples include elevated structures, which are buildings that are built on stilts or platforms to keep living spaces above flood levels; amphibious homes, which are structures that float on rising water and can return to their original location when the water recedes; and floating buildings, which are entire buildings designed to float on the water, often used in areas where flooding is frequent and severe (White, 2022). The historical development of flood-resilient architecture reflects a growing awareness of the need for adaptive and sustainable solutions. From ancient levees to modern floating buildings, the field has continued to evolve to address the threat of flooding. Today, the focus is on creating resilient communities that can withstand and recover from flooding events, integrating both engineering, Architectural and natural solutions.

Climate change adaptation

Whatever the future holds, we cannot afford to be complacent – especially if these and many other measures can be easily incorporated into current planning processes as part of good new build and adaptation practice. Building adaptation must be designed as an integral part of future city-wide protection measures to enable our cities to meet the challenge of flooding and prevent its threatening consequences of property damage, injury, illness, and even death (DEFRA, 2012). It is important to learn to work with water rather than against it. This includes carrying out flood risk assessments, leaving at least 5% of the space on the site for water storage, and providing effective water flow channels (DCLG, 2006). In addition, green spaces, water sources, and large permeable surfaces are also helpful, as they not only reduce local summer temperatures but also collect rainwater and help drain it away.

At a building scale, considerations must be made for zoning, structural adaptations, and even the use of different typologies, such as sacrificial ground floors, buildings on stilts, or floating and amphibious buildings. Most existing structures can be ‘wet-proofed’, which means they are designed with possible future flooding in mind and result in only minimal damage to the property should this happen. This can be achieved through the use of water-resistant materials for floors, walls, and fixtures (DCLG, 2007).

Sustainability Criteria for Flood-Resilient Buildings

Sustainability in flood-resilient buildings is assessed based on various criteria to ensure that the structures are environmentally friendly, economically viable, and socially acceptable. Sustainable flood-resilient buildings should minimize their ecological footprint by using eco-friendly materials and construction methods. This includes incorporating renewable materials like bamboo, recycled steel, and reclaimed wood. Additionally, designing buildings to reduce energy consumption through passive solar design, natural ventilation, and energy-efficient appliances is crucial. Implementing systems to manage stormwater, such as rain gardens, green roofs, and permeable pavements, also plays a significant role in environmental sustainability.

The cost-effectiveness of flood-resilient designs is essential for their widespread adoption. This involves ensuring that the materials and construction methods are affordable, reducing maintenance and repair costs through durable and resilient building materials, and providing access to affordable insurance and financing options for flood-resilient buildings (Tagg et al., 2016). Community involvement and acceptance are vital for the success of flood-resilient projects. This includes involving local communities in the planning and implementation processes to ensure that the designs meet their needs and preferences. Designing buildings that respect and incorporate local cultural practices and aesthetics, and ensuring that buildings provide a safe and healthy living environment with adequate ventilation, natural light, and protection from flood-related hazards, are also important aspects of social acceptability.

Buildings should be adaptable to changing environmental conditions and future needs. This includes using modular construction techniques that allow for easy expansion or modification and creating structures that can adapt to varying water levels, such as amphibious houses and floating buildings.

Ensuring that buildings can withstand and recover from flood events with minimal damage is crucial. This involves using materials and construction methods that enhance the building's structural integrity and designing buildings to facilitate quick recovery and minimal disruption to occupants' lives after a flood event.

Summary of Literature

Neglecting to future-proof our buildings will only result in a city ill-adapted to the future needs of our society within a changing local and global environment. Buildings will fail to function effectively under extreme weather conditions leading to increased, wasteful energy use, and exacerbating the effects of global warming. At worst, the inability of our built environment to cater to the demands of its inhabitants might simply result in a stock of obsolete, unhealthy buildings unfit for purpose.

Designing for climate change adaptation on the other hand is guaranteed to increase buildings lifespan and help protect occupants from the detrimental effects of global warming, while also reducing the necessity for costly and carbon-intensive interventions in years to come. The effects of climate change are an undeniable reality and to safeguard our cities from extensive damage we need to start designing for these changes right now. With sufficient foresight and planning, we can provide buildings that aid mitigation efforts and, when needed in the future, also support the ongoing adaptation of our cities for years to come.

CASE STUDIES

Two buildings were used as the case studies for this research. The buildings are the Blooming Bamboo Home in Vietnam, and the Amphibious House in United Kingdom. The buildings were selected because of their successes at mitigating the impacts of flooding on the building structure as well as the inhabitants of such buildings.

Blooming Bamboo Home, Vietnam:

The Blooming Bamboo Home is an innovative architectural project designed and constructed in 2013 by H&P Architects in Vietnam (see plates 1, 2 and 3). This prototype aims to provide affordable, flood-resistant housing using sustainable materials and traditional building techniques.



Plate 1. Typical view Blooming Bamboo Home

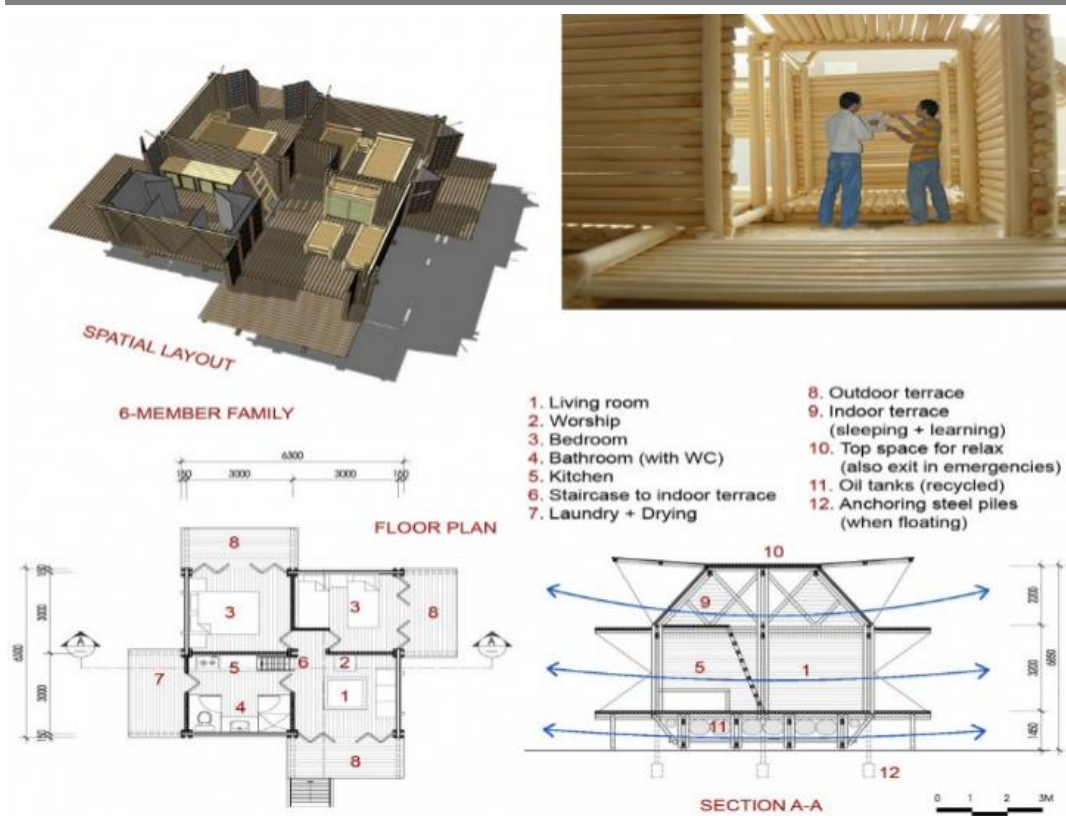


Plate 2. Floor plan, Section and Interior of the structure



Plate 3. Typical view of the Blooming Bamboo Home

Key Features

Design and Structure

The house is constructed primarily from bamboo, along with bamboo wattle, fiberboard, and coconut leaves. These materials are locally sourced, renewable, and eco-friendly. The structure is elevated on stilts, allowing it to withstand floods up to three meters above ground. This design helps protect the living spaces from floodwaters. Its construction follows a modular approach, with bamboo modules that can be easily assembled and disassembled. This makes it adaptable to various local climates and site conditions.

Functionality

The walls of the Blooming Bamboo Home can fold outwards to ventilate the building, and sections of the roof can be propped open or closed depending on the weather. At night, interior lighting shines through the

cracks in the walls, creating a glowing effect. Inside the house features living and sleeping areas on the main floor, with ladders leading up to attic spaces that can be used for study or prayer. The space beneath the house can be used for keeping plants and animals, allowing water to pass through during floods.

Sustainability

The use of bamboo and other natural materials reduces the environmental impact of construction. Bamboo is a fast-growing plant that sequesters carbon, making it a sustainable building material. The house is designed to be affordable and accessible, providing a viable housing solution for communities affected by flooding. It can also be adapted for use as schools, medical facilities, or community centers.

The Blooming Bamboo Home has been recognized for its innovative approach to flood resilience and sustainability. It has been featured in various architectural publications and has won awards for its design. The Blooming Bamboo Home stands as a beacon of hope in the realm of flood-resistant architecture. Its sustainable design, innovative use of bamboo, and adaptability to diverse environments make it a compelling solution for communities facing the challenges of rising water levels.

The Amphibious House, UK

An amphibious house is a building that rests on the ground but whenever a flood occurs, the entire building rises in its dock, where it floats, buoyed by the floodwater. Amphibious Construction brings together standard components from the construction and marine industries to create an intelligent solution to flooding. The house itself sits in the ground and the floating base is almost invisible from the outside. Amphibious designs can vary to suit the location and owners' preferences. The amphibious design allows the floor level to be set less than 1m above the ground level instead of 2m, had the house been static. This enables a 225 sq m 3-bed dwelling to be constructed over three floors in place of the existing 1-storey 90 sq m house without significantly increasing the ridge height and therefore achieved full planning. Construction is slightly more expensive than mainstream house building due to the requirement for two foundation systems: the dock and the hull; but overall the costs are comparable to a typical basement extension, or around a 20-25% uplift on a similar size new house. The technology is ideally suited to areas of high flood-risk or if there is uncertainty regarding future flooding levels, as well as in historical or sensitive landscape settings where more heavy-handed solutions would be unacceptable.

Description: Located in Buckinghamshire, UK (see plate 4), the Amphibious House is designed to rise with floodwaters, preventing water from entering the living space.



Plate 4. Front view of the Amphibious House, Uk

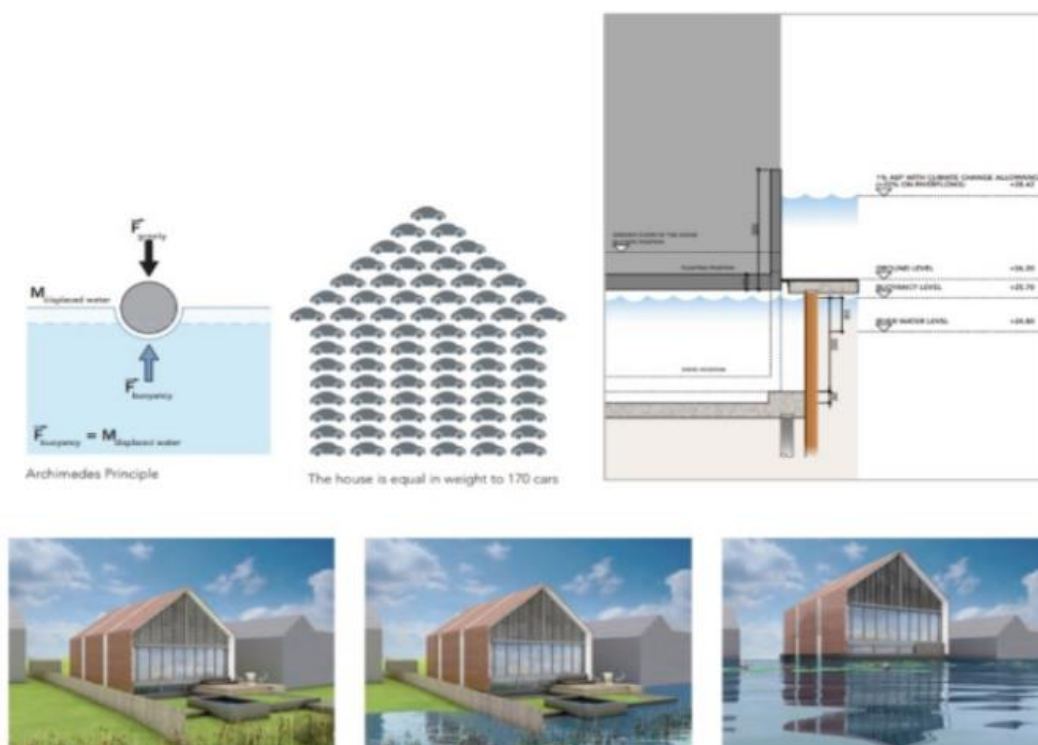


Plate 5. Details of the floating principle of the Amphibious House, Uk

Amphibious Foundation: The house rests on fixed foundations but can float upwards when floodwaters rise. Also the use of water-resistant materials ensures minimal damage during floods.

The house has shown effective flood resilience, successfully rising with floodwaters and preventing interior flooding. Between November 2019 and February 2019, severe winter flooding occurred across the United Kingdom. During this period the River Thames swelled and the owners of the Amphibious House, as featured on Channel 4's Grand Design series reported: "The house continues to rise and fall without intervention".

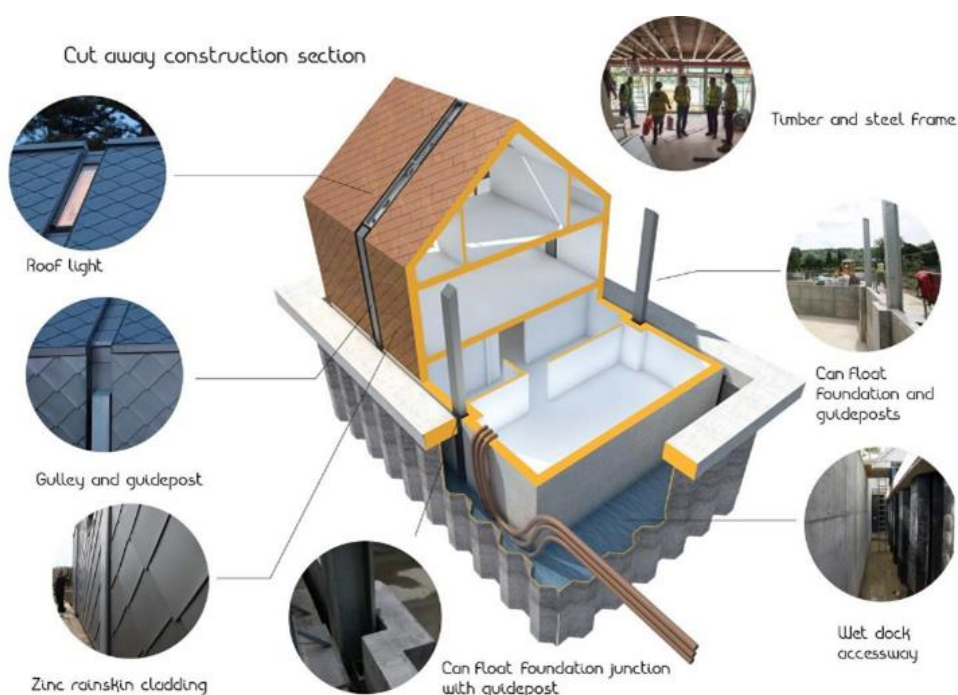


Plate 6. Details of Amphibious House Construction

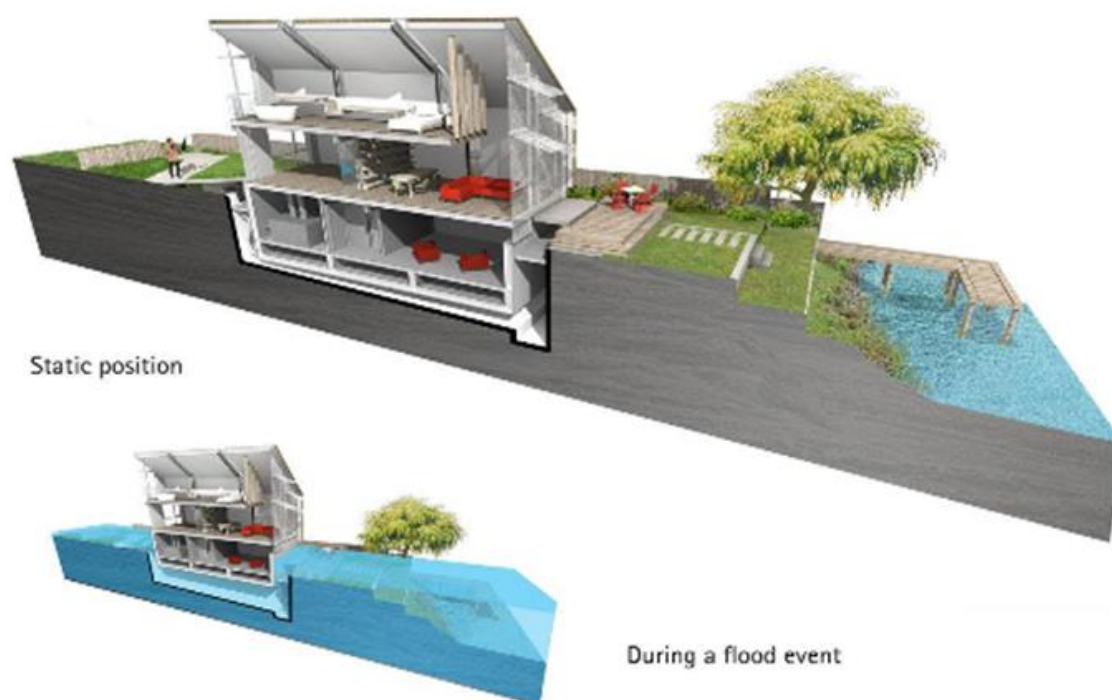


Plate 7. Section of amphibious house before and during flooding

How it Works

River and groundwater are hydrologically linked, so during flooding, as the River Thames rises, the dock fills gradually from the ground, gently raising the building, as the river level rises. When the water is just below the ground level the house becomes buoyant. The house is designed to rise to 2.7m to cope with a 1 in 100 flood event, however, the guide posts extend almost 4 m above the ground level such that the house would still be retained between the posts in the event of an even bigger flood. The flexible service pipes are designed to extend up to 3m allowing all of the services to remain clean and operational during any flood event and crucially to allow the occupants to return to the property immediately after a flood, maximizing the continuity of their daily lives.

Maintenance

The Amphibious House is designed with minimal moving parts but like traditional houses, it requires maintenance. The house may not float for several years therefore it is important to proactively test and maintain the can-float base and flotation system to ensure that the parts are in good working order, ready for when a flood occurs.

Every five years the dock is expected to be pumped full of water to repeat the flotation test when the house rises to 50 cm to test the integrity and free movement before the water is slowly released and the building is allowed to touch down again.

DISCUSSION

In this section, a comparison is established between the two case studies of sustainable flood-resilient buildings to identify their similarities, differences, strengths, and weaknesses. This comparative analysis will help in understanding the effectiveness of the different design principles, in-terms of materials, and technologies used in these buildings.

Design Principles

Elevated Structures: Blooming Bamboo Home, Vietnam used an elevated foundation on stilts to avoid floodwaters. The Amphibious House, UK uses a Floating house design with buoyant foundations.

Comparison: While the Blooming Bamboo Home uses elevation to avoid floodwaters, the Amphibious House employs a floating design, making it adaptable to varying water levels.

Materials and Technologies

Sustainable Materials:

Blooming Bamboo Home, Vietnam: Uses local bamboo materials.

The Amphibious House, UK: Uses sustainable timber materials.

Comparison: The two buildings use sustainable materials, but the specific materials vary based on local availability and environmental conditions. The Blooming Bamboo Home and The Amphibious House emphasize the use of locally sourced and recycled materials, respectively.

Performance during Flood Events

Blooming Bamboo Home, Vietnam: Successfully withstood multiple flood events.

The Amphibious House, UK: Highly adaptable to varying water levels.

Comparison: Each building has demonstrated resilience during flood events, but their performance varies based on the type of flooding they are designed to withstand.

Sustainability Aspects

Blooming Bamboo Home, Vietnam: Emphasizes the use of local materials and traditional construction techniques.

The Amphibious House, UK: Focuses on low-cost construction and the use of durable materials to ensure long-term resilience.

Generally, Sustainable resilience is a key aspect of both buildings. Successful amphibious foundation systems are functioning in the Netherlands, New Orleans, Sausalito, and Bangladesh, they can provide flood protection that is more reliable and more convenient than the permanent static elevations.

Challenges and Opportunities

Challenges:

Cost: Implementing flood-resilient designs can be expensive, particularly in urban areas.

Accessibility: Ensuring that flood-resilient buildings are accessible to low-income communities.

Maintenance: Regular maintenance is required to ensure the effectiveness of flood-resilient features.

Opportunities:

Innovation: Continued innovation in materials and technologies can enhance flood resilience.

Policy Support: Government policies and incentives can promote the adoption of flood-resilient designs.

Community Engagement: Involving local communities in the design and construction process can improve the effectiveness and acceptability of flood-resilient buildings.

CONCLUSION AND RECOMMENDATIONS

This paper has provided a review of sustainable flood-resilient buildings through a literature review and case studies of two existing buildings. The key findings are discussed below:

Various design principles such as elevated structures, floating structures, and amphibious structures are effective in enhancing flood resilience. The use of sustainable materials like bamboo, wood, recycled materials, and innovative technologies such as flood barriers and water-resistant materials are crucial for building flood resilience. Also, the selected case studies have demonstrated effective performance during flood events, showcasing the practical application of flood-resilient design principles. Furthermore, both case studies emphasize sustainability through the use of local, recycled, and durable materials, ensuring minimal environmental impact which is a positive step towards eco-friendly and sustainable living.

Recommendations

Based on the findings, the following recommendations are proposed for future research and practice in sustainable flood-resilient building design:

1. Encourage the use of locally sourced and sustainable materials in flood-resilient building designs to reduce environmental impact and support local economies.
2. Invest in research and development of advanced technologies such as smart flood barriers, water-resistant materials, and real-time monitoring systems to enhance flood resilience.
3. Governments should implement policies and provide incentives to promote the adoption of flood-resilient building practices. This could include tax breaks, grants, and subsidies for sustainable construction projects.
4. Engage local communities in the design and construction process to ensure that flood-resilient buildings meet their needs and are culturally appropriate. Educational programs can raise awareness about the importance of flood resilience and sustainable practices.
5. Foster collaboration between architects, engineers, urban planners, and environmental scientists to develop holistic and innovative solutions for flood resilience.
6. Establish adequate policies for the regular maintenance and monitoring of flood-resilient buildings to ensure their long-term effectiveness and performance.
7. Document and share successful case studies of flood-resilient buildings to provide valuable insights and best practices for future projects.

By implementing these recommendations, we can enhance the resilience of buildings to floods, reduce the impact of flood events, and promote sustainable construction practices. Further future researches should continue to explore innovative materials, technologies, and design principles to further advance the field of sustainable flood-resilient architecture.

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