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Design Resilient Building Strategies in Face of Climate Change

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Abstract**—**Climate change confronts the built environment with many new challenges in the form of more severe and frequent hydro-meteorological events. A series of strategies is proposed whereby the various aspects of buildings and their sites can be made more resilient to the effects of such events.

Keywords**—**Design resilience building, resilience strategies, climate change risks, design resilience aspects.

I. INTRODUCTION

RESILIENCE in the context of the built environment means incorporating into the design of a building, aspects and features that allow the building to carry out its intended functions, now and in the foreseeable future. Specifically, here, it refers to the ability of a building to continue to function as intended in the face of environmental stresses imposed by climate change [1]. Building resilience design will be addressed in six categories (Fig. 1).

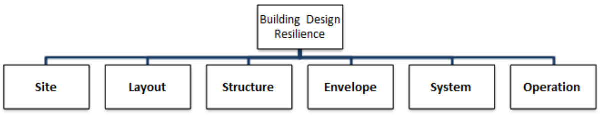

Fig. 1 Classification of design resilience strategies

II. SITE DESIGN RESILIENCE STRATEGIES

Data from the site analysis, together with information on the landscape and site climate, are fed into the design process to evolve a resilient design aimed at addressing the risks of climate change [2]. Central to the success of the design is interoperability between the occupants, the exterior of the building and the building itself, and how this is impacted by hydro-meteorological events associated with climate change.

The amount of sunlight exposure and wind to which a building is subjected, as well as the risk of flooding and erosion, can be managed to some extent through appropriate landscape design [3]. The risk of flooding and erosion may be alleviated by providing adequate runoffs to a catchment system, and taking steps to stabilise any areas of unstable soil [4]. The need for surface water drains can be reduced or eliminated if runoff is allowed to permeate through a porous material. Depending on ground conditions, the water may infiltrate directly into the subsoil or be stored in an underground reservoir [3].

Landscape factors such as trees can be interoperable with the local climate and human aspects of the design to help offset some of the impact of climate change [5]. By suitable positioning of trees and other plants around a building, airflow can be controlled rather than hindered, and incident solar flux moderated [6]. The shading and solar access factors of a site can only be determined through accurate site analysis. Self-shading is another technique that can be used to protect a building from the heat of the sun [7].

Orientation is important in determining how much incident solar energy contributes to thermal gain and to what extent prevailing winds are used for natural ventilation and cooling. A building can maximise the advantages of the natural environment of the site by keeping the largest façade facing south. The opening sizes on the south-facing facade are typically increased as compared to those on the other sides, though solar access may need to be minimised in summer and maximised in winter [8]. As compared to the east and west facing sides, the north and south facing are more suitable for solar gain, as the sun is very low in the former two [9]. Various authors, for example [10], have indicated an optimum orientation to the south of 30°. Warm climates will however have a different situation.

Wind exposure is another factor in optimum orientation. This can be illustrated through the example of the University of Newcastle’s Design Faculty building, which takes full advantage of natural ventilation and prevailing winds for its occupants [11].

Surrounding structures should also be considered when orienting a building. The chances of benefitting from the wind and other natural resources can be increased through an accurate distribution of buildings on the site. On the other hand, building functionality may be affected by obstructions in the form of surrounding buildings, for example in an urban environment [12].

III. LAYOUT DESIGN RESILIENCE STRATEGIES

A good interior layout facilitates many resilience strategies adopted with climate change in mind, particularly as they relate to future use, thermal mass, lighting and ventilation [2]. Discussed risks of dysfunctionality in buildings linked to climate change and how designs should be considered that are sufficiently adaptable and flexible that they allow for different future utilisation [13]. Discussed ways to classify strategies

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aimed at changes of function [14]. The design of the layout should be sufficiently flexible and resilient to allow components or elements of a space to be added or replaced while maintaining functionality of other spaces nearby [15]. Thus, incorporating fixed elements is disadvantageous [13]; rather, elements should be simple to change or reposition, and other spaces should not be interrupted or disturbed when carrying out modifications in a space, such as changing a window. A prevailing theme in this approach is that of neutrality among elements and spaces [16].

Buildings should be adaptable enough to conform to, and remain in harmony with, future regulations or safety procedures [17]. A building designed with good layout resilience, should, for example, allow removal or modification of any part, while at the same time its skeleton can remain untouched [18].

Allowing sufficient floor-to-floor height is another aspect of design that impacts on resilience, enabling modifications to be made to the space to address future needs [19]. For example, environmental changes might imply that the height of a window must be increased or decreased accordingly [20]. The importance of using modular spaces and the manner in which these spaces play an important role in the designing of resilience has been discussed by [18].

Sufficient flexibility is needed in the design to support the full functionality of the building and continuity of access through and between spaces should there be modifications in the spaces and linkages [21]. Resilience to the effects of climate change involves maintaining undisrupted access both within and outside the space in the event of extreme events or an emergency.

TABLE I
SITE DESIGN RESILIENCE STRATEGIES

Resilience Strategy	References
Site stabilisation techniques	[1]
Direct runoff to a catch basin or holding area	[1]
Plant mature trees	[1]
Use water catchment systems/cistern	[1]
Prepare site landscape and landforms for high wind conditions	[1]-[3]
Use optimum building orientation	[4]-[8]
Use permeable surfaces in landscaping	[9]

IV. STRUCTURE DESIGN RESILIENCE STRATEGIES

Structure resilience here means the capability of a building's structural system, materials and foundations to continue to function in the face of internal and external change of climate and to degrade gracefully when it must. Due to the increased threat of flooding in some regions due to climate change, one way to enhance structure resilience is to raise the construction. Flood resilience measures include raising floor levels, electrical fittings and equipment so that they are at a sufficient height above a predicted flood level [22].

Additionally, buildings should use materials and construction methods that are durable when confronted with severe weather events [23]. The ability of buildings to withstand powerful winds can be enhanced by ensuring permeability [24]. This may involve providing void decks at the ground floor, higher floor-to-floor heights and/or void spaces in between buildings to encourage air flow through and around buildings.

TABLE II
LAYOUT DESIGN RESILIENCE STRATEGIES

Resilience Strategy	References
Plan spaces and layout based on future use scenarios to create usage resilience	[10]
Specify multiple access within and between spaces	[11]
Minimise partitions between spaces	[11]
Use appropriate height floor	[12], [13]
Use appropriate floor-to-floor height	[12], [13]
Specify spaces to perform multi-functionality	[14], [15]
Use stack ventilation	[1]
Use cross ventilation	[1]
Oversize space	[16]
Specify generic layout and program spaces for future flexibility of use (use of modularity and standardization)	[17]
Specify for maximum day-lighting	[4]
Specify the layout of rooms, corridors, stairwells etc. in a way that upholds a low resistance airflow path through the building (both in plan and section)	[18]
Provide 'safe places' in the building	[19]
Specify thermal zones, by facing rooms of high energy demand on the south and put rooms such as cellars, stairs, garages and laundry rooms on the north	[20]

When it comes to structure resilience against potential flooding another type of permeability may be incorporated into the design [4]. This involves placing openings in the building envelope to ensure that floodwaters can enter and exit to prevent structural failure. Other measures include overhangs to keep heavy rain away from doors and windows and prevent infiltration, and temporary free-standing barriers to keep floodwater away from buildings.

Permanent flood defences are normally the preferred means of protection but are not always appropriate due to cost, or environmental or other reasons. In these cases, free-standing barriers, such as flood boards or air brick covers, may be fitted temporarily to properties when needed [25].

With regard to soil instability, some approaches to reducing vulnerability to subsidence or landslip may impact on other aspects of a building's resilience, positively or negatively. For example, heavier foundations and infill may help reduce heat risks by acting as a thermal sink. On the other hand, a timber-framed construction, though effective in reducing the risk of subsidence, may reduce a building's structure resilience to overheating and flooding.

The problem of erosion, especially in clay-based areas that are more susceptible to the effects of heavy precipitation that may accompany climate change, can be addressed in various ways. Among these is the use of products that help to reinforce slopes and stabilise the land.

In some cases, the structure of the building itself may not be strong enough, for example where there is a particular risk of landslip. In such cases, the use of retaining walls may be necessary [3].

TABLE III
STRUCTURE DESIGN RESILIENCE STRATEGIES

Resilience Strategy	References
Elevate structure above flood level	[23], [9], [24]
Use of flexible pipes and joints	[24]
Use of appropriate shape and angle of roof	[24]
Oversize roof coverings fixings	[1]
Increase structure bracing	[1], [21]
Oversize walls and roofs	[1]
Provide anchorage between superstructure and substructure	[1]
Use structure materials that are more resistant to pests	[1]
Construct masonry chimneys with continuous reinforced steel bracing	[1]
Use thermal mass on floor/celling/walls	[1]
Specify durable and robust materials and construction methods	[21]
Oversize connections or attachments among building parts	[21]

V. ENVELOPE DESIGN RESILIENCE STRATEGIES

The envelope plays a vital role in regulating such factors as solar access and ventilation, and providing a secure place for the building's occupants in the face of more severe hydro-meteorological conditions. The selection of materials for the envelope is important because this element of the building plays a major role in controlling heat transmission. Insulation in the envelope limits the conduction of heat into and out of the enclosed space thus reducing heat loss during winter months and restricting heat gain during the summer. With climate change resulting in greater temperature extremes, the selection of insulation with low U-values for use in all opaque areas of the building envelope becomes increasingly desirable. Effective roof insulation also has a major impact on reducing the solar heat gain of low-rise buildings [24].

The colours, too, of the envelope influence thermal performance; thus white, or other light tones, absorb less heat than darker hues. Breaks in framing systems can also reduce direct heat flow [24].

As it is an essential feature used in facades, openings and doors, the specification of glazing must be accurate. The choice of the ratio of glazed area to non-glazed should be carefully selected in order maximise daylighting and ventilation without giving rise to overheating or cooling [26].

As well as size, the orientation of glazing must be accurate in order, for example, to optimise winter heat [10]. The designer may choose to use different glass on the different facades – that on the south being accurate for balancing of heat gain and heat loss without causing overheating, and that on the west, east and north facades being suitable size to enable high visibility without resulting in too much heat loss [27].

Envelope resilience is optimised through selection of a suitable building form, which is partly determined by the interior and the exterior conditions, and also the building's functions [9]. At the same time, the forms a building can take are influenced by site limitations.

The application of a resilient design is governed by the volume of a building and its surface area. Thermal comfort, ventilation and solar access are all heavily dependent on form [28]. Wind patterns can also affect the optimum building shape and selection of form should involve a detailed wind analysis. Crucial to envelope resilience is the choice of material, which must be able to respond to changes in climate and provide both longevity and durability [29]. One particularly important aspect is to consider the rate of expansion and contraction of materials, which is closely linked to the responses to different environmental agents [30].

In the case of buildings likely to be affected by flooding, the use of materials such as concrete, vinyl and ceramic tiles, pressure-treated timber and others that are flood-resistant is indicated. These can withstand being immersed in water for long periods of time without significant damage.

The material, shape and orientation of roofs are key factors in determining envelope resilience. The roof should be well insulated in order to reduce heat loss from the interior space. Additionally, the shape and slope angle of the roof require accurate design to remove rainwater efficiently, and the orientation should be such as to optimise ventilation [31].

In both cold and hot climates, the green roof has become a significant consideration in building design [32]. "Cool" roofs, made of light-coloured materials, have high solar reflectance and prevent heat gain and reduce the need for mechanical cooling. They can be used effectively when there is a high roof to volume ratio, although they do not offer the climate change adaptation benefits of green roofs and their use must be weighed against the benefits of installing solar voltaic or hot water panels.

Roof overhangs can provide protection for façades against extreme weather conditions, more surface area from which to collect rainwater, and solar shading to reduce excessive solar gain. However, they are also susceptible to high wind loads and therefore more likely to suffer damage, so that some adequate method of restraint must be included in the design [33].

TABLE IV
ENVELOPE DESIGN RESILIENCE STRATEGIES PART 1

Resilience Strategy	References
Appropriate insulation systems to reduce conduction through the thermal envelope	[36], [22]
Expansion joints within materials that are vulnerable to expansion	[37], [38]
High solar reflectance to reflect sunlight and heat away from a building	[9], [1]
Specify roofs' shape and orientation	[21]
Specify roofs sloping upward towards the outlet	[21]
Specify smaller windows for spaces to the north of the building	[20]
Specify glazing ratio 30-50% for vertical surfaces and 20% for rooflights	[20]
Specify buffer spaces such as earth sheltering and conservatories	[20]
Specify forms that follow many future functions	[17]
Use mass construction with suitable insulation to moderate the effects of high external temperatures	[40]
Use materials that can withstand being immersed in water for long periods without significant damage	[24]
Appropriate shape and angle for the roof	[25]
Energy efficient windows and shading devices	[26], [27]
Specify window film	[1]
Advanced wall and framing techniques	[1]

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TABLE V
ENVELOPE DESIGN RESILIENCE STRATEGIES PART 2

Resilience Strategy	References
Windows, doors, and openings that withstand wind loads and windblown debris	[1]
Oversize framing and bracing	[1]
Oversize anchors for roof/wall mounted heating, ventilation, and air conditioning units	[1]
Green roofs	[28]
Appropriate exterior shading	[29]
Use of green roofs	[30]
Openings in the envelope	[1]
Light shelves or specially designed reflective-louvered blinds	[2]
Use of materials that can get wet and dry out without permanent damage	[23]
Airtight junctions and details	[31]
Light paint colours for interior ceilings and walls	[32]
Fenestration high on walls or roofs	[33]
Dry flood-proofing e.g., watertight structure using sealants, flood shields, etc.	[34]
Avoid use of forms and shapes that create wind-suction bag effect during storm	[21]
Avoid use of long rectangular plans with the ratio between the length and width over 2.5	[21]
Avoid use of long roof eaves	[21]
Double façades	[35]

A sunspace is an interoperable element to both the façade and internal space. It serves as a buffer space that naturally heats and cools allowing daytime temperatures to rise higher and nighttime temperatures to fall further than the ‘comfort zone’ temperatures of the adjoining living space [34].

VI. SYSTEM DESIGN RESILIENCE STRATEGIES

Building system resilience is concerned with designs that incorporate the resources and flexibility within the overall system to withstand shocks and disruption. With regard to building heating and cooling, incorporating natural and passive principles into the design increases system resilience and decreases reliance on external power supplies. Passive design principles, which take into account such factors as the building envelope, natural ventilation, shading, and water capture and storage, enable buildings to furnish acceptable levels of comfort even in the absence of outside sources [35].

A specific instance of this strategy is passive ventilation. A key feature of naturally ventilated buildings is effective window design, which allows for ease of use of windows by all building occupants. Stack ventilation can be particularly effective for passive cooling. Thermal energy storage is another passive technique that provides backup in the case of hydro-meteteorological events severing connection with the grid [4]. Systems resilience also means ensuring that in the event of climate change related flooding, a building’s mains electric system is protected [33].

Because cogeneration and solar power systems are always in use, they can be more reliable than generators that are only turned on during emergencies. Electrical equipment that will run on backup power should be prioritised so that buildings can remain habitable during extended blackouts [4]. Both solar and wind power generation systems provide the means for building system resilience in the face of mains power outages. Solar collection panels use the sun’s energy to heat hot water and can be used for both residential and commercial buildings. Hot water produced from collectors is stored in insulated storage tanks, and may also be used to drive adsorption/ absorption chillers for cooling [24].

Effective site drainage strategies are an essential part of the design process in areas where climate change is likely to lead to higher levels of precipitation. Among relatively straightforward options available for reducing flood risk are installing one-way valves in drains and sewer pipes to prevent backflow into a property. Sustainable drainage systems offer a number of benefits, including natural infiltration and cooling in urban areas.

Rainwater collection and storage is a synergistic approach that simultaneously reduces the risk of localised flooding by buffering runoff before it puts a load on the drainage system, and makes available the captured water for washing, toilets, irrigation, and so forth [25]

Designing buildings so as to make optimum use of daylight in interior spaces reduces dependency on lighting powered by a vulnerable mains supply [36]. A variety of strategies are available to do this, including: the location of spaces to the outside, the use light pipes, and the provision of internal courtyards and atria with curtain glass walls [37]. Increasing the overall surface area of glazing in a building envelope improves daylighting performance but also increases the potential for solar gain or energy loss, depending on circumstances.

TABLE VI
SYSTEM RESILIENCE DESIGN STRATEGIES

Resilience Strategy	References
HVAC system redundancy or overcapacity	[15]
Protection for the main electrical system from flooding	[9]
Cogeneration and solar power capability	[22]
Drainage system able to handle expected levels of precipitation	[19]
Power system separate from the roof and walls	[24]
Use water efficient fittings and devices to ensure the continuity of operation of the building	[9]
Use ductile utility connectors	[1]
Build a permanent water-resistant barrier around HVAC equipment	[1]
Separate electrical circuits, under and above expected flood levels	[1]
Use multi-lighting resources	[41]
Raise electrical service above expected flood levels	[1]
Specify backup power to avoid electricity shutdown	[1]
Provide onsite renewables to protect against power shutdown and create redundant sources of energy	[42]
Specify heat and cold storage in the ground	[43]
Specify spray systems on roofs and terraces	[1]
Specify water features in an atrium	[44]

VII. OPERATION DESIGN RESILIENCE STRATEGIES

Defines operation resilience as: “The capacity to cope with unanticipated dangers after they have become manifest” [38]. As well as other view puts it in these terms: “The ability of a unit to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimise social disruption" [39]. Other sees operation resilience as: "A process linking a set of adaptive capacities to a positive trajectory of functioning after a disturbance" [40]. A common thread among these is the notion of continuity of function in the face of challenging conditions.

Careful consideration should be given to the location of equipment that might be susceptible to damage during severe weather events [4]. In the event of emergency repairs being necessary, elements or components should be easy to remove or replace [41]. The ease of removal, especially in the case of electrical or electronic equipment, demands that the element be readily accessible for diagnosis and testing.

Any control equipment should be easy to use and with controls that are easily located [42]. Operation resilience also requires that thermal comfort be maintained [43], so temperature controls should be well designed for ease of use [42].

TABLE VII
OPERATION DESIGN RESILIENCE STRATEGIES

Resilience Factor	References
Specify early warning systems	[19]
Secure interior furnishings and equipment	[1]
Design for emergency repairs	[1]
Specify temperature control panel	[43]

VIII. CONCLUSION

Events associated with climate change pose significant challenges to designers in the built environment. However, through a series of resilience strategies aimed at countering the effects of such events, it is possible for buildings to continue to function safely and efficiently.

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