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The Adverse Impacts of Climate Change on Infrastructure and Proposed Adaptation Framework for Residential Structures: Part 1

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Abstract. With global change in climate patterns, the uncertainty of natural hazards has also gone up significantly in the last few years. Cold countries have been experiencing seasons of extreme heat and drought whereas dry and arid areas have reported seasons of cold weather or torrential rains. In the past, monsoons in the Indian subcontinent have been very reliable in terms of timing and intensity; however in recent times, both their timing and intensity have been uncertain. Elsewhere in the world, tragic incidents have been reported due to freezing, heat waves or flooding most of which have been attributed to climate change caused by human living and industrialization on our planet. In this paper, the authors introduce to the perils of climate changes caused by rampant urbanization, industrialization, and the associated development. The authors present the importance of adapting every phase of infrastructure development such as materials, engineering, design, construction, and maintenance of our residential structures in order to minimize the impacts of human infrastructure development on climate. The various adaptations required to bring these changes are proposed and methods to make these adaptations practical are put forward. This first part of the overall study focuses on geometric, material and design adaptations. A plausible framework for creating sustainable urban residential infrastructure is proposed. Finally, conclusions are made, and a brief introduction is provided about the next part of this study and further adaptations that complement this framework.

Keywords: Climate Change, Structures, Adaptation, Sustainability, Resilience, Engineering, Construction, Infrastructure

Introduction

The impact of human living on planet Earth is not a new discussion. The impacts of senseless infrastructure development, urbanization and rapid industrialization on our climate and our quality of life have been widely researched and discussed subjects. However, the speed at which we are witnessing climate change is alarming. At the beginning of the 21st century, scientists and researchers thought we have decent time before we could see the hazardous effects of climate change. However, we now start to realize that our planet has little time left unless we take actions not just to mitigate or minimize but to reverse climate change. The reasons for this sudden alarm tone are obvious. Unusual weather patterns have been reported in several countries. Places that are dry and warm and that never experienced snow fall have reported extensive snow fall. The Texas snowstorm in the US in February 2021 at the heights of Covid pandemic caused catastrophic damages. With an official loss of about 250 human lives in Texas alone, this storm is the worst in the history of the state because it lead to wide scale power outages and freezing conditions and caused human fatalities. The city of Houston, which rarely records snow, received several inches of snow and chilling subzero temperatures. Likewise, In July of this year, the state of Vermont

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received up to nine inches of rain in 48 hours causing massive flooding in many towns, this precipitation is the largest ever since 1927 for the town. Both these disasters are reportedly related to global Climate change. In India, the annual rain pattern well known as 'Monsoon' has been erratic in terms of its timing as well as intensity of rainfall it brings or its path through the country's landscape. Weather patterns have clearly indicated a significant rise in temperatures across the world.

The National Oceanic and Atmospheric Administration (NOAA) in the United States which also monitors the global climate patterns reported that the Indo-Pacific ocean warming is causing changes to Madden-Julian Oscillation, a weather maker that influences weather in India (NOAA, 2023). NOAA research at Pacific Marine Environmental Lab reported that the duration of monsoon clouds lingering over the Indian Ocean has reduced from 19 days to 15 days. This is most likely shrinking the monsoon rainfall in India.

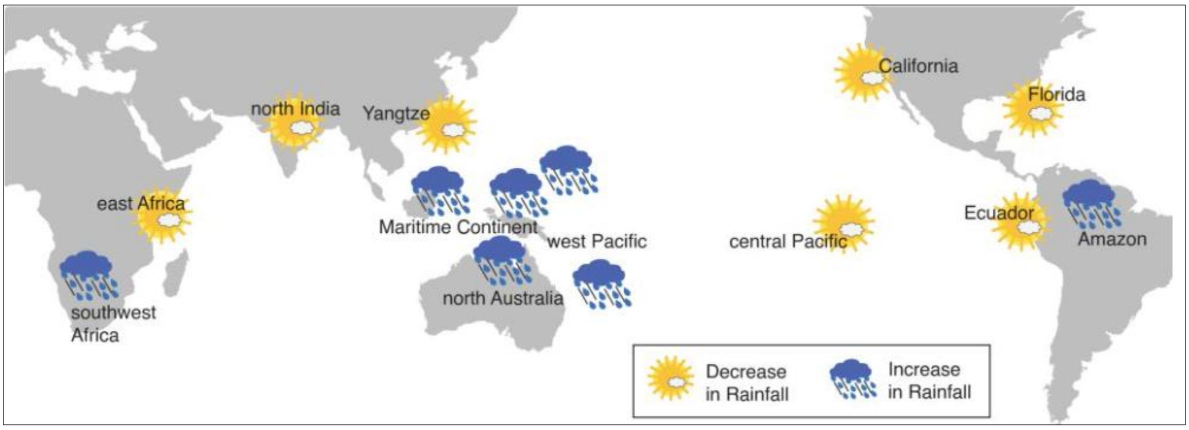

Figure 1: Global rainfall pattern changes due to Indo-Pacific Ocean Warming (NOAA Research, 2019)

Figure 1 above indicates the change in rainfall patterns due to Indo-Pacific ocean warming caused by climate change. Research at Indian Institute of Tropical Metrology (Roxy et al., 2017) estimates that this Indo-Pacific ocean warming will continue and may more intensely affect global rainfall patterns in future. This means that the Indian monsoon will become more and more unpredictable in terms of timing as well as intensity of rainfall it brings to the country over the next few decades. With knowledge of the dependence of Indian economy on the monsoons, it can be inferred that this could have catastrophic consequences on the country of more than 1.5 billion people.

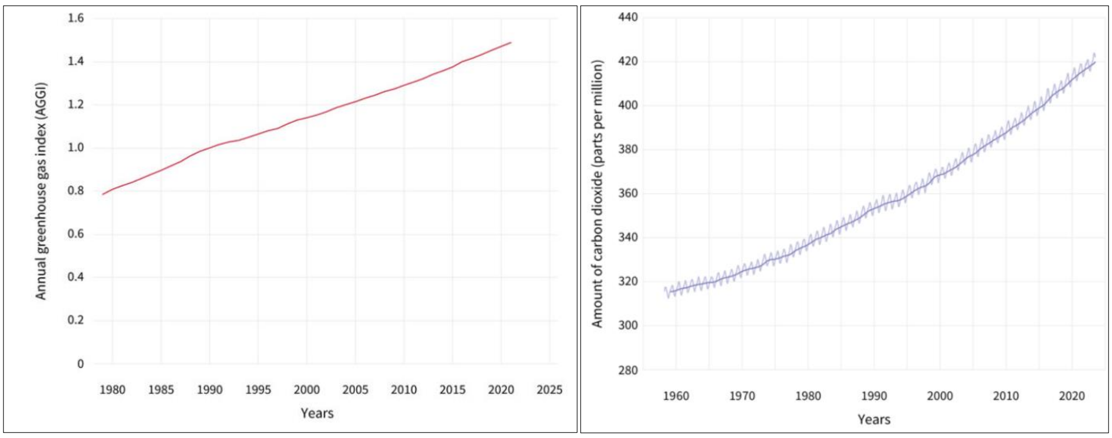

Figure 2: Green House Gas Index & CO2 Content (NOAA, 2023)

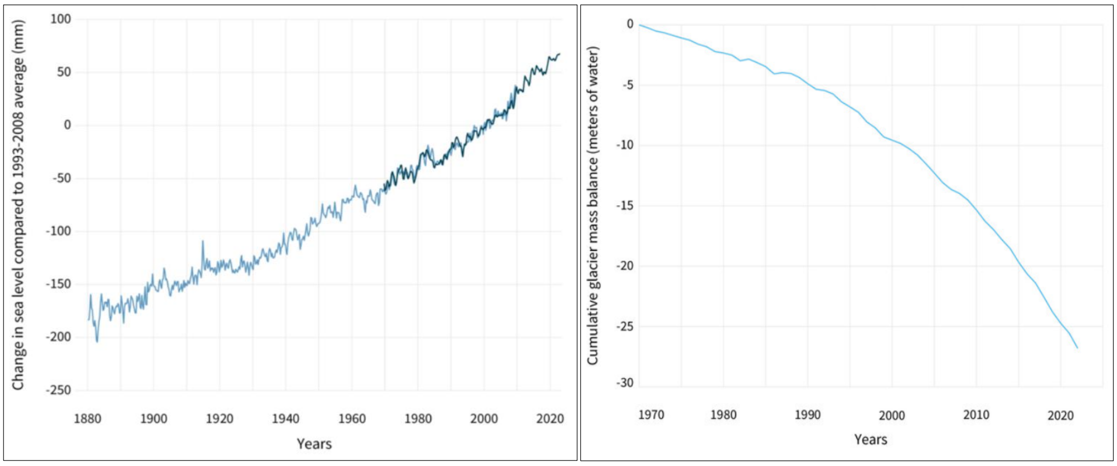

Figure 3: Mean Sea Level Change & Glacier Mass Balance (NOAA, 2023)

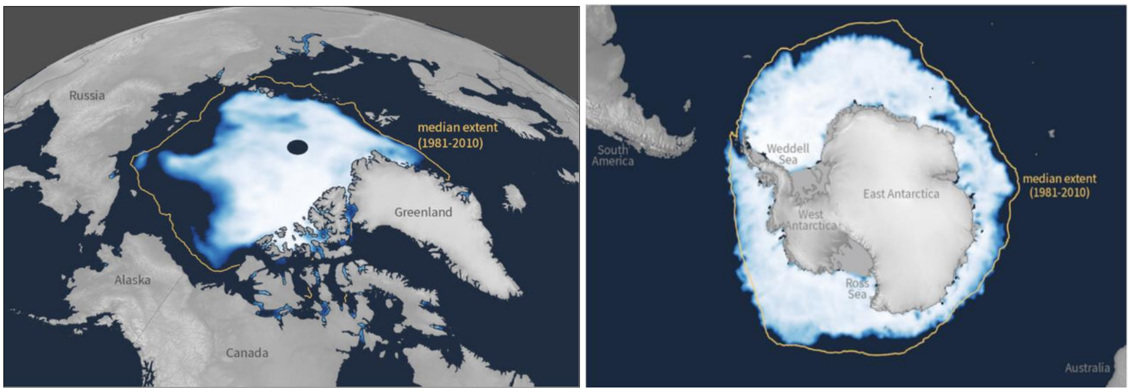

Figure 4: Arctic and Antarctic Ice Cover Shrinkage (NOAA, 2023)

Figures 2 through 4 show the rapid rise in several indicators that deteriorate the world's environment and directly impact the climate patterns across the world. These figures show the change in measure of greenhouse gases, carbon dioxide content in the air, annual mean sea level, glacier mass balance and loss of polar ice covers. These indicators point to the bad news that the earth is warming up, the sea levels are rising, and the polar ice cover is rapidly shrinking. Scientists all over the world are unequivocally warning us about climate change and its impact on weather patterns. The changing patterns make our weather unpredictable; historically dry and moderate areas receive extensive rain and flooding, record rainfall during summer months is seen, regions of tropical weather freeze in subzero temperatures. Many parts of the world can see record high temperatures. Rise in sea levels along coastlines that are already burdened with forest cover loss cause heavy storm surges that inundate coastal towns and make them uninhabitable. Areas that traditionally receive heavy rainfall may not see rain for years thus leading to drought conditions. In the coming decades, India may see several years with no monsoon which could cause catastrophic damage to its human life, plant life, wildlife, agriculture, and economy.

Figure 5 tags the various weather anomalies and hardships the different countries and regions across the world have faced in the past year or two as per global report published by National Centers for Environmental information (NCEI, 2023). Similarly Figure 6 points all the natural disasters in the United States in the year 2023 so far that caused more than a billion dollars of damage to economy.

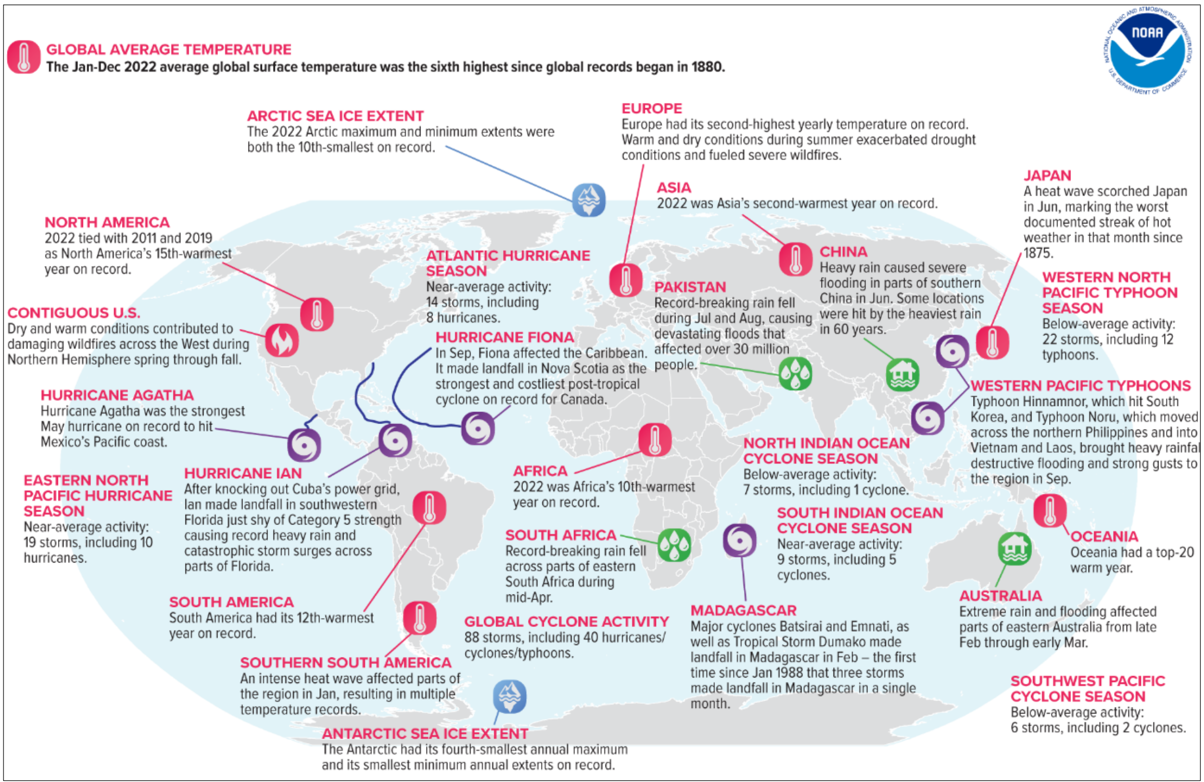

Figure 5: Global Weather Anomalies and Events in 2022 (NCEI, 2022)

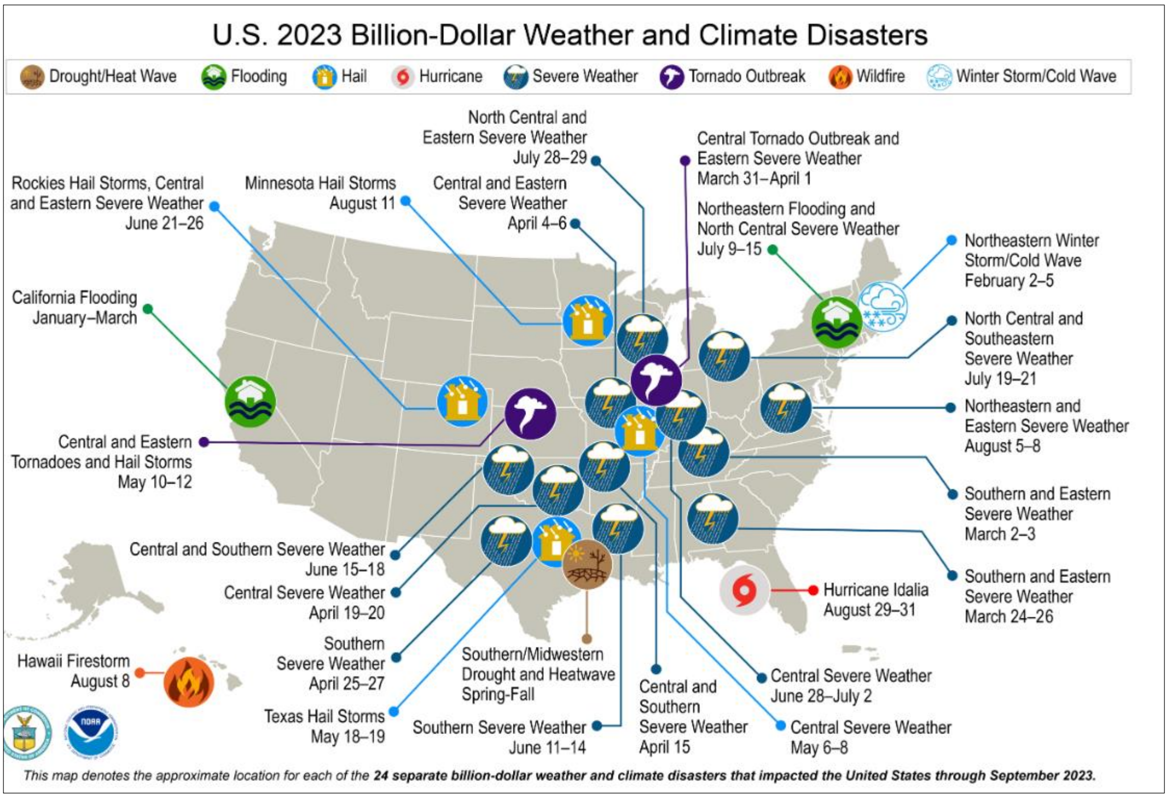

Figure 6: Major US Weather Anomalies and Events Until September 2023 (NCEI, 2023)

All of the above anomalies point to unpredictable weather conditions and resulting natural disasters shaking their countries. These natural disasters destroy our landscapes, as well as the infrastructures on which our economies depend on. Hurricanes, storm surges, flooding, snow, hail, wind, and wildfires destroy our homes, offices, industries, ports, bridges, highways, airports and cause extensive damage to our towns and cities. Many times it takes decades to rebuild the infrastructure before it waits for the next disaster to strike. Parts of the problem are the engineering and design methods we currently practice building our infrastructure. These engineering and design principles are based on probabilistic methods that rely on predictable weather to arrive at the recurrence intervals of natural disasters and their scale. However, with global climate change causing unpredictable and extreme weather conditions, the authors opine that it is time to rethink the principles of engineering and design of our infrastructure. Engineers and builders need to adapt our methods to scale up our infrastructure to a higher set of standards that can reduce the impacts of natural disasters caused by climate changes.

In this paper, the authors propose the various adaptations that are required by engineers, builders, contractors, owners, and policy makers to redesign our infrastructures in order to make them more aligned with the increased probability of disasters caused by climate change. An effort is made by authors to propose in detail the various types of infrastructure adaptation such as geometry, material, design, construction, and policy making. Due to size limitations on manuscripts and better organization, this study is divided into two parts and this first part of study focuses on geometry, material and design adaptations proposed by authors to achieve sustainable construction goals. Though this paper approaches these adaptation proposals based on residential structures due to their high carbon footprint overall, this framework can be extended to any other areas of infrastructure. While proposing these adaptations, the authors not only consider improved resilience to natural disasters but also weigh-in the need for sustainable practices that reduce human footprint on environment and decelerate the rate of climate change.

Adaptation of Infrastructure

Adaptations are very important for survival. Darwin's theory of '*The survival of the fittest'* states that those species that adapt to changes will sustain and those who do not will perish. Adaptation of infrastructure is essential for the survival of human life on our planet. Traditional infrastructure building is an act of exploiting natural resources which in turn contributes to global warming and triggers climate changes leading to increased likelihood of disasters unpredictable both in time and space. These natural disasters cause widescale destruction of infrastructure. Rebuilding of infrastructure leads to further exploitation of natural resources adding up to climate change causes. This negative causal-loop must be broken in order to reduce the carbon footprint of infrastructure building and reverse climate change effects (Jonnalagadda and Ross, 2017). Adapting the way we are building infrastructure not only improves its resistance to natural disasters but also cuts carbon footprint and improves environmental sustainability of our infrastructure.

Geometric Adaptations

The geometry of a residential building is often decided based on local practices. However, local construction practices are developed over time based on local climate patterns, risk of natural disasters, local materials and labor availability. In areas where snow and rain are expected roofs are built sloped whereas dry and arid areas go for flat roofs. Similarly where hurricanes and flooding are a threat, floor levels of homes are kept high. Tornado prone areas often are built one level or two at the maximum. Areas that are located in seismic zones are built with low weight materials such as wood instead of masonry or concrete. These homes are also designed with framed structures that safely transfer the lateral seismic forces to foundations safely. The size of the home is another aspect of geometry. The size of a residential home is often decided by the owner's choice and affordability. A typical home size may vary anywhere from 1000 to 2000 square foot (sq ft) in developed countries whereas this can be around 800 to 1200 sq ft in Indian cities. Areas with low levels of income often have houses that tend to be smaller at under 500 sq ft. Unfortunately our society often correlates the size of a home with the economic prosperity of a family. However, this needs to change in the bigger interests of our next generations. Sustainable living is no longer a choice, it's a requirement. Simple living is the key.

Several adaptations are required to the geometry of the building to make it more resistant to natural disasters. The following are some of the changes the authors put forward in order to adapt buildings to be resilient to natural disasters but at the same time promote sustainable living.

Size of the building

The size of the building is the single major contributor to its environmental footprint. With exponential increase in material, energy and waste needs per capita, larger homes unfairly damage our environments. The superficial sense of wealth and prosperity that tags along with large buildings is quite attractive to not fall for. Our societies have long associated richer communities with larger homes. As stated in the previous pages of this article, the per capita area of residential houses is much higher than what is required for comfortable living. For instance, a 2000 sq ft home for a family of 3 members can consume the same natural resources as that needed for building 4 to 5 homes that are 400 sq ft in area and supporting 2 family members each. It means the carbon footprint of 8 to 10 people is produced by just 3 members. So the first major adaptation required is in the sizing of our homes. Keeping wealthy flamboyance aside and living simpler is a major contributor to reduction in global warming and minimizing the resulting climate change effects. Currently, the per capita area of high income households in India ranges from 1500 sq ft to 4000 sq ft. This does not include super rich people. If these segments of people can cut their homes to a third of their current sizes, that can have a very significant reduction in resource consumption. Also net zero emissions through energy self-sufficiency is achievable in smaller homes but gets more and more challenging in bigger homes (due to higher energy needs of bigger homes). The authors opine that on an average, under 150 sq ft of per capita area is the target size of residential homes in India that would balance comfortable living with carbon footprint reduction. This number could be slightly higher for younger families and reduced as the average age of the family goes up.

Shape of the building

In the age of unexpected natural disasters striking at odd times and odd intensities, it is no longer practical to shape the house traditionally because traditional knowledge relies on historic occurrence of natural disasters. However, due to climate change, these historic occurrences are not realistic anymore. Most building councils and code governing bodies have based their loads due to wind, rain, snow, flooding, or seismic events on historic data but have not updated them for climate change effects. It is also not easy to do this because climate change effects do not follow predictable patterns. As mentioned in the previous sections of paper, the 2021 snowstorm in Texas caused a wide scale catastrophe because it was least expected. The snow load specified by American Society of Civil Engineers (ASCE-7, 2016) in those parts of the country is zero. These areas currently cannot take random snow loads caused by climate change related disasters. As such it is important to adapt to these kinds of scenarios by adjusting the shape of the buildings preventively. If global warming trends indicate more recent adverse events of snow, rain, and flooding, it makes sense to add some roof slopes to historically flat roofed buildings. Similarly, higher occurrence of hurricanes leading to uncommonly high intensity winds make the case for aerodynamic roof systems such as hip roofs or other shapes (Vemuri & Jonnalagadda, 2023c).

Floor Level and Foundation

Climate change is reported to bring heavy rains and flooding to many parts of the world. Heavy flooding, which is witnessed in big Indian cities of Chenani, Hyderabad, Mumbai, and Bangalore (Krishnakumar, 2023) in the last 5-10 years caused heavy damages by inundating homes that were never prepared for these levels of water. This is indicated in Figure 7. One study showed three-fold increase in extreme rainfall events in central parts of India over the last 65 years (Roxy et al., 2017). Global warming discussed in the previous pages clearly suggests raise in sea levels and associated flooding in these towns. One way to tackle this problem is to elevate the floor level of buildings in cities that do not have a good flood control and storm water drainage system.

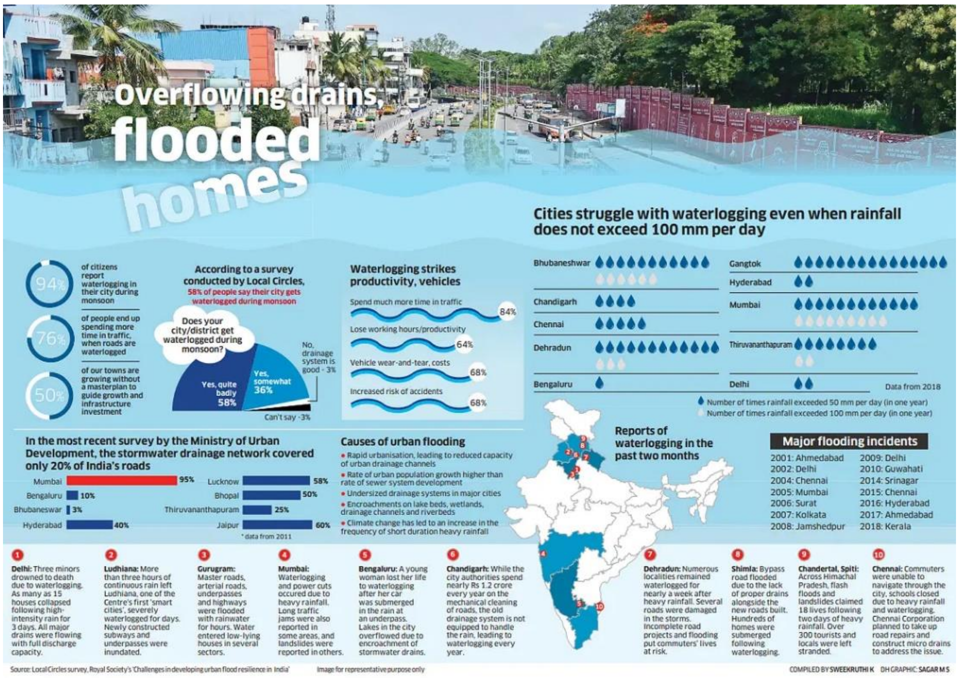

Figure 7: Flooding Incidents In Indian Cities (Krishnakumar, 2023)

This family had to evacuate its ground-floor home in Badlapur in late July when floodwaters reached the ceiling. VAISHNAVI CHANDRASHEKHAR / YALE E360

Figure 8: Flooding of a rural home in India (Chandrashekhar, 2019)

Ideally it makes more sense to fix the bigger issues of improving the storm water drainage systems in these cities and having good flood control plan, but individual building owners need to prepare for flood disaster in the event of institutional failures as happened in the case of big city flooding repeatedly. Many buildings got inundated with flood water (Figure 8) for several days and when help arrived it was too late for some people. Human loss and property loss to a great extent were reported during the flooding of these cities. Many of these buildings were rendered to be unfit for reoccupation when flood water receded. The elevated floor levels will provide additional time for people to evacuate when help is ready. Also, the elevated floor level when combined with a good foundation system can have the potential for reoccupation of the building when flood water recedes. Both the property damage and human loss can be minimized with this adaptation.

Material Adaptations

Traditionally, local materials and their availability often mandate construction material for housing. For instance, concrete is one of the most sought after construction materials for housing because its main ingredients such as sand and gravel are readily available locally. For instance, there are more than However, traditional practices too need to adapt overtime (Jonnalagadda & Vemuri, 2023b). Steel and cement used to be many times cheaper than their current costs as per Bureau of Labor Statistics reports. Also, the greenhouse gas emissions in the manufacture of these two materials needs to be considered. As such it is required to not only adapt to new materials but also consider sustainability in the selection of materials so natural resources are not depleted rapidly. Any slightest improvements in design or material efficiency are to be welcomed in order to reduce the environmental footprint of construction industry (Jonnalagadda et al., 2021).

The research in engineering and construction of structures has led to the discovery of new materials. While reinforced concrete and wood are the traditional materials of construction of choice for residential buildings, new innovations such as Carbon, Glass, and

Organic fiber Reinforced Polymers (CFRP/GFRP), High Strength Concrete (HSC), Ultra-High Performance Concrete (UHPC), recycled aggregates, pozzolanic waste materials such as fly-ash, blast furnace slag are promising. Significant research has been conducted on all these materials to confirm their application to building homes. Among these choices, UHPC and CRRP/GFRP are two potential replacement materials for conventional concrete and steel. UHPC are concretes that give an impressive compressive strength of 120 to 150 MPa with a proportionately high tensile strength (ACI239R, 2018). This strength cuts down the need for heavy steel rebar reinforcement that is common in reinforced concrete designs. UHPC has several advantages as building material, it is very durable and tough (Yudenfreund et al., 1972); structures built are slim in size and volume (Fehling et al., 2008), needed minimal to no steel reinforcement or shear reinforcement (Gee et al., 2020) and performed superior as compared to conventional concrete in terms of resistance to corrosion, water ingress, impact, blast and fatigue (Jonnalagadda & Vemuri, 2023c). The reduced concrete and steel consumption by using this material combined with its 100-year design life spans cut down life cycle costs of the structure and its maintenance. UHPC structures with their low self weight provide much higher live load to dead load ratios. The overall efficiency of this material is high as compared to conventional concrete. The improved life span, reduced carbon emissions aid sustainability in the long term and provide a good case for this material (Jonnalagadda & Vemuri, 2023a).

Table 1: Alternate Construction Material Choices

Ingredient Material	**Alternative 1**	**Alternative 2**	**Alternative 3**
Conventional concrete	UHP Concrete	GFRP concrete	CFRP Concrete
Wood	GFRP composite	CFRP composite	Bamboo/Organic fibers
Cement	Low/zero carbon cement	Fly-ash cements	Slag cements
Steel/Strand reinforcement	GFRP bars	CFRP bars	Kevlar aramid ropes
Aggregate	Recycled Stone	Metal/Tire waste	No aggregate mix
River sand	Quarry sand	Sea sand (with FRP bars)	Recycled stone powder
Potable water	Salt water (with FRP rebars)	Admixtures	Recycled water

Glass fiber reinforced polymers (GFRP) are being considered as substitute for steel reinforcement. These composite materials are corrosion free, lighter than steel and offer a good choice as reinforcement bars in concrete members. ACI 440 committee provide design guidelines for the design of structural concrete with GFRP as reinforcement bars (ACI440.1R, 2015). Figure 9 shows GFRP bars and their usage in a seawall in Hawaii in the US.

Figure 9: GFRP bars Used in Seawall in Hawaii, US (ACI 440.1R, 2015)

The Portland cement used in concrete manufacture is the worst contributor to carbon emissions among all building materials. It is found that about 4 to 6 Giga Joules of energy is required to manufacture 1 ton (2000 lb.) of this cement (Derouin, 2023). This is equivalent to the energy required to run an average home for about 2 months. The manufacture of Portland cement is responsible for about 8% of global CO2 emissions. As such it is imperative for us to be socially responsible and replace this cement with other alternatives in concrete production. Adding pozzolanic materials such as fly-ash and furnace slag are some known alternatives. These are waste by-products in electricity generation and steel manufacture respectively.

Another promising alternative is low- carbon to zero-carbon cement. Referred in research by Dr. Savary at Massachusetts Institute of Technology (O'Neill, 2023), this cementitious material known as C-Crete is produced by using locally available binder materials to replace Portland cement as base ingredient in cement manufacture. This cuts carbon content in cement production very significantly. Use of this cement and pozzolanic materials in construction are readily viable for low-rise residential buildings which constitute the majority of construction projects. Table 1 provides guidance on three partial or full alternative adaptations for the most common construction materials in order to cut down carbon emissions and achieve material adaptation in residential infrastructure.

Design Adaptations

In order to make our buildings more resilient and sustainable, the biggest adaptation needed is in the area of design and engineering of these buildings. There are several aspects of engineering that when addressed together can help our structures designed to be capable of taking new challenges related to climate change. Some of these aspects are discussed in the following sections.

Probability of Recurrence of Extreme Events and Design Return Periods

Engineers design structures for strength and performance under design basis loads. The most common design methodologies referred to as Limit State Design (LSD) and Allowable Stress Design or Working Stress Design (ASD or WSD) are based on design for maximum loads that a structure can possibly experience during its lifetime. The design philosophies and the design load combinations specified by international code bodies such as ASCE, ACI, AASHTO AISC, EC2, IS456, IS800 and many other international code councils are based on the limit state design philosophy where in design maximum loads due to natural forces such as wind, earthquake, snow, rain, ice and flooding were determined based on a specific probability of recurrence of natural events. After extensive research as part of National Highway Cooperative Research Program [Nowak, 1992], the probability and return periods calibrated for the design maximum loads are specified with a typical 2% probability of exceedance which means once in every 50 years. This research, even though it set a rationale logic for defining target loads for targeted performance of structures has certain limitations in its founding principles. While calibrating the probability of recurrence and return period of extreme events, this research was entirely based on near-historic data of natural events and the maximum forces those events triggered. So it effectively limited itself to normal climate pattern based occurrence of extreme weather events. However, the effects of climate change were never considered nor incorporated into this load calibration process for establishing design methods.

The rate of climate change has been rapidly rising in recent times and its effects on global weather patterns have triggered many extreme weather events across different parts of the world as discussed in the previous sections. The intensity of these extreme weather events and the frequency of their occurrence are drifting away from historic patterns. As such the 2% probability of occurrence of extreme natural events and the corresponding return period of once in 50 years do not hold validity in coming years. A stronger natural event is being triggered more often by abnormal weather patterns caused by climate change. Thus it is reasonable to say that it is required to revise the return periods and the corresponding probability levels specified for the calibration of design maximum loads adopted by the limit state (and LRFD) design methodologies to properly account for extreme event forces due to natural disasters caused by climate change.

Design Loads

The design basis loads for natural forces such as wind, earthquakes, flooding, snow, ice, and rain are specified and set by code bodies based on certain parameters. These parameters include the location of the structure, the importance and risk associated with the collapse of the structure and certain force specific parameters. For instance, the design basis wind forces set for a building are mainly determined based on its location, altitude, and topography even though risk, terrain, and geometry of the building are other minor influencing factors (Vemuri & Jonnalagadda, 2023a).

Snow loads, rain loads, and flood loads are very strongly linked to average annual precipitation, and temperatures in the location. These natural forces which govern the majority of the building designs for strength and serviceability are very strongly coupled with weather in the location of the structure. Because climate change can affect weather patterns that significantly alter rain, snow and flood intensities and duration in a location, these design maximum loads can also vary significantly as a result of climate change. Also, it is difficult to quantify the impact of climate change on weather patterns, so historic data and traditional methods are not always very helpful in coming up with an easy method to recalibrate these loads for climate change related irregularities.

Though it is not clearly established if climate change can affect tectonic plate dynamics, it is intuitive to think so because loss in polar ice cover and glacier melting due to climate change can cause natural imbalance in earth’s mass distribution. The resulting effect on fault lines and plate movement can trigger seismic events that were not previously marked or reported. The design maximum loads due to seismic forces are mainly a function of building location and mass even though other minor factors such as type of soil, type of structure, geometry, dead loads, and dynamic properties of the building influence too. Any changes in tectonic plate shifts due to polar ice cap melting and glacier movement could cause a change in seismic risk mapping of locations. This means seismic spectral accelerations and resulting horizontal and vertical seismic forces will change in both space and time. This will call for remapping of seismic force contours and rezoning of geographic areas based on seismic category. This will be a continuous process unlike in the past where the seismic risk categories remained largely unchanged for many decades.

Design Methods & Life Cycle Designs

In the previous sections we discussed the adaptations required in design philosophies and assessing design basis loads. In this part we will discuss the required adaptations of the methods we are currently using for the design of building structures. Traditionally most of the structural members are designed by either Limit State Design (LSD) or Allowable Stress Design (ASD) methods (Vemuri & Jonnalagadda, 2023b). The first fallacy of these methods is that they do not specify the life span of the structures that we engineer. No wonder most of our structures including public transit structures such as bridges are only good for 30 to 40 years which is the reason our infrastructure is crumbling due to ageing (Jonnalagadda et al., 2016). While the human body which is made of organic matter is performing for 70-100 years, concrete and steels structures have a life span of less than half as much, wooden homes rarely have more than 30 years of useful life after which many of them rebuilt. Our current codes and specifications set the performance requirements of a structure by keeping the stresses or deflections and cracking under control at the time of construction. Long term deflections are talked about other than that there are no real specifications on component material specifications with regards to their performance over 50 or 100 years. For instance, steel reinforcement or structural steel do not have any technical requirements as they age. Material test and quality control requirements by American Society for Testing of Materials (ASTM International) set minimum requirements on immediate performance in laboratory conditions but not during the entire life of the structure in real field conditions. Our designs never talk from the standpoint of the life of a structure. This needs to change. The life of a structure is very important parameter because it controls the life cycle costs.

The life cycle cost of the structure is defined as the cost incurred in all stages of a structure's life since its conception. This means it includes every cost from earthwork until dismantling of the structure after its life. It also includes a cost concession for the recycle value of the structure. This life cycle cost approach is fast gaining acceptance in calculating the real economic impacts of construction projects including carbon footprint and greenhouse gas emissions. As such, life of a structure becomes a very major factor in life cycle costs because the costs are annualized over the life of the structure. Structures with longer design life are very likely to have lower life cycle costs because it takes more time, material, resources, and carbon footprint to construct and deconstruct a project than maintaining it. However, this is contingent on the assumption that a structure is built robust and performs reasonably well over its lifetime with minimal maintenance costs. Poorly built structures incur high maintenance costs. So it makes good sense for code bodies and committees to specify life span of a structure along with its long term performance specifications and preventive maintenance requirements.

In short, we need design methods and code specifications that include life span, long term and life time material and design performance and associated preventive maintenance minimum specifications in one single bucket as opposed to the current practice of only specifying material and performance requirements at the time of commissioning of the structure for public use. This might bring an important question of functional obsolescence of structures (Jonnalagadda, 2016). What happens if the structure that is designed for 100 years may not be required for that term. These kinds of situations are not common in the past but given the routine uncertainty in financial markets worldwide in recent times, the question of functional obsolescence may not be as uncommon in future as it was in the past. However, obsolescence can be addressed in several ways. Dr. Jonnalagadda (2016) discussed in detail about functional obsolescence, what makes structure functionally obsolete and what are the mechanisms to tackle obsolescence and how to minimize the life cycle cost of structures. Dr. Jonnalagadda (2016) suggests in his doctoral thesis that functional adaptation of structures is a viable solution for buildings and structures to overcome functional obsolescence. Reduced obsolescence reduces waste, removes the need for demolition and rebuilding thus reducing the life cycle cost of structures. To summarize, structural plan approvers would insist owners to provide a functional adaptation plan and contingent design adaptation at the time of their construction so that the structures can be modified with minimal changes to transform into their new function in long term future without need for demolition and rebuilding. This is especially important for designs with service life of over 100 years.

Drawing Media & Paper reduction

Anyone who had worked in the construction industry would see the tremendous amount of paper wasted in this industry. Civil engineers' workspaces are often littered with drawings. Even though a lot of industries moved towards electronic documentation in the form of emails or pdf documents, our industry has changed little in this aspect. Structural, architectural, electrical, plumbing, drainage, fire plan, HVAC and every plan document is printed somewhere by someone involved in the project. This adds to a huge burden on our green environment by cutting trees and heating up the earth. The reason civil engineering and construction industry is slow in cutting on paper drawings is twofold. First of all most of the construction work is executed at the job site where only carrying paper drawings was feasible for field engineers and construction contractors. The second reason is the slow adaptation of this industry in general as compared to others. Now a days, the cost of a 10" tablet is probably a lot less expensive than the large number of printouts of the several construction drawings printed during the course of multiple projects. The life of a tablet computer is around 4 to 5 years, assuming that at construction job site it is half as much, it still is 2 or 3 times less expensive than all the printout costs of paper and ink in multiple projects completed over a span of 2 to 2.5 years.

However, a tablet computer is not big enough to read large construction drawings that contain several minute details. The authors propose that a light weight, large screen, and handheld monitor which is big in size to provide large views for construction engineers and workers but at the same time light enough to be hand-held provides a very good solution to this problem. These handheld electronic drawings should be able to roll into a paper like fabric that can be easily carried around. Already, many states department of transportation agencies provide tablet computer such as Apple® i-pads to field engineers who inspect bridges during routine and special inspections in order to collect bridge condition and performance data so this data can be analyzed to assess bridge condition ratings every two or three years. This process became seamless and the electronic data that these inspectors collect directly feeds the artificial intelligence based deep learning algorithms that constantly learn from this data and provide valuable insights into bridge condition and deterioration patterns. Dr. Jonnalagadda (Jonnalagadda et al., 2016) in his work demonstrated in detail the advantages of AI based deep learning methods to evaluate bridge network performance and forecast bridge condition into future that is of great importance to state bridge agencies in prioritizing bridge maintenance treatments. Moving towards electronic drawings also has the huge advantage of preserving drawings long term into multiple centuries when 100 year life span designs become a norm.

Conclusions

It is important to understand that climate change is real, and it is happening at an alarming rate. The natural disasters and the extreme weather events caused by climate change in many parts of the world cannot be ignored. The carbon footprint and the greenhouse gas emissions from construction industry are dangerously impacting the sustainability and resilience of our infrastructure. The changing weather patterns are causing extreme events such as heat, rains, snow, flooding and other extreme events more often and more randomly leading to loss of human lives and infrastructure damage. As such it is paramount importance for structures to adapt to these changing climatic conditions across the world. Infrastructure engineering and construction are very closely linked to weather. Changing frequency of extreme events questions principles of design and engineering of our structures.

In this article, the authors stress the need for adapting engineering and design methods followed by civil engineers and builders. Several types of adaptations are mandatory to not only provide a rational for the selected design loads and parameters but also to improve resilience of our structures. It is required to update our engineering loads and revise designs to build resilience to higher and erratic natural forces such as wind, snow, rain, hurricane, and seismic forces triggered by climate change. The authors also outline the various adaptations required to cut down carbon footprint of construction industry and make sustainable infrastructure construction possible. Needless to mention it is time to adapt every aspect of infrastructure development starting from design till construction and maintenance. The authors advocate for longer life span designs with revisions and recalibration of structural design loads for changed probability of natural and extreme events in the face of changing weather patterns triggered by climate change on planet. In addition to this, recommendations have been made to adapt geometry, material, and design of structures to enable life cycle designs and reduce carbon footprint of this industry. This first part of the study included in this paper is limited to geometry, material and design adaptations required in this industry; the second part of this study will focus on construction and policy adaptations required for improving infrastructure resilience and sustainability.

Disclaimer

The opinions and views expressed in this paper are purely those of the authors' and do not in any way represent the views or opinions of the affiliate organizations or institutes.

Contributions

The second and third authors contributed to the section about Introduction to climate change and infrastructure. The other sections were contributed by the first author.

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