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The Resilience of Structures in Times of Climate Change

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Abstract. The paper should examine the structural interrelationships and resilient solutions commonly encountered in building construction projects during hazardous situations. The content of the paper will address design fundamentals and interrelationships of resilient building components. Further, the paper will provide insight into a module order, structural design, robustness, and building technology of the resilient structures. The final point of the paper will show the implications of resilient concepts, risk management and determination of the hazards on human safety in times of climate change.

Key Words. Resilience of Constructions, Adaptability to Climate Change, Extreme engineering.

The Concept of Resilience

Introduction

Resilience is the ability of systems to withstand disruptions. Resilient constructions remain fundamentally functional in crises. They are resistant to technical, environmental, and economic partial failures or disruptions through flexibility or redundancy of their systems, thus providing robust conditions for a long-term use. [1]

Mutability of structures is understood as the ability of a system to adapt its construction actively and rapidly to temporally and unpredictably changing tasks from its own substance (adaptability) in conjunction with the ability to evolutionarily develop the structures in the face of temporally constant or longer-term predictably changing requirements from its own substance. [2]

There are many definitions and concepts of resilience of building structures and component connections. What all these different concepts have in common however, is that resilience is the ability or capacity of a system to maintain its functionality, or at least to regain it in the short term, even while facing unusual or unexpected stress situations. Resilience can refer to natural as well as to technical systems. [2]

In the following research approach, the resilience of a structure is to determine how susceptible to damage or resistant this structure is, when exposed to a natural event. It is largely determined by object characteristics for example, the construction method, materials used, protective devices, etc. The risk can be reduced by improving the resistance of a structure to the effects of these natural hazards by regular maintenance (servicing, condition assessment, refurbishment), and by protective and damage mitigation measures before, during and after the event.

Building structures and component connections are exposed to a wide variety of environmental effects. As a rule, these environmental effects on the building are adequately considered in the legal regulations. In addition to this, the approach of this paper should consider the extreme events, the intensities of which significantly exceed the already regulated impacts. The extreme events considered regarding wind, heavy rain, hail, snow and floods are associated with greater hazards to people health and risks of damage to property, from which higher requirements can be derived for the resistance of building structures. [3] The relevance of this topic is increasing due to the climate change that is already occurring and the associated increase in extreme weather events which, however, varies from region to region. Building structures and component connections must be adapted and prepared in this respect (adaptation).

The objective of this research outline is to improve the resistance of buildings and structures to current and future natural hazards at the site. This is to achieve, among other things

- a protection of persons
- a protection of material assets
- the safeguarding of usability as well as the planned service life
- the limitation of insurance needs
- the compliance with the planned life cycle costs.

The evaluation of the resistance of the building structures and component connections to wind, heavy rain, hail, snow and floods should be carried out taking into account the following:

- the nature and extent of current and future hazards at the site under consideration
- resistance of the building to the concrete hazard. [4]

Fig. 1. Resilience of structures and environmental effects

Resilience in the context of extremes weather events

The concept of "resilience" receives special attention in the context of adaptation strategies to climate change and in particular dealing with extreme weather events and the resulting risks to building constructions and society through disruption or damage. Building resilience is in this context as a holistic response to new challenge, which goes beyond mere hazard prevention. Another characteristic of resilience is, that the view is taken by adapting to future events. Thus, damage, processes and experiences from past must be analyzed and reflected upon. Building resilience refers to both physical structures as well as to systems. In the urban context resilience is an overarching concept, which covers all phases of dealing with an extreme event. In order to create resilient structures, adaptation processes must also be initiated in the built environment. A municipality must be aware of the fact that future events may be milder, but also stronger, than those experienced so far. This variability must be taken into account through a range of different scenarios. These scenarios must not only reflect the increasing frequency of extreme events. Also, other environmental changes that may affect the vulnerability of a city, its population and its built environment in the long term should also be taken into account. Examples include land use changes, infrastructure replanning, and technological and demographic change. [5]

By consciously addressing the topic of extreme events in the context of urban resilience strengthening, the awareness and learning capacity of all actors involved should be increased. The planning view through the resilience enables a comprehensive perspective and a more comprehensive analysis scheme than, for example, in classical extreme event risk management. In summary, a resilient structure is so designed and managed in such a way that the impacts of extreme weather event are as low as possible.

The goal of building resilience is to be able to respond to challenges in an adaptive and anticipatory manner and, at the same time, to be able to derive learning and stabilization processes and thus adaptation options from past crises. Resilient construction can anticipate crises, absorb them, recover from them, and successfully adapt to the new circumstances in order to shape the structure in the future in a way that minimizes damage in the extreme event. In this context, resilience does not represent a desirable end-state. Rather, resilience can be understood as a dynamic process in which the reflection of past events and continuous learning processes by all actors lead to a transformation of built structures - accompanied by dynamic behavioral changes on the part of the actors, for example through improved preparedness and crisis management. [6]

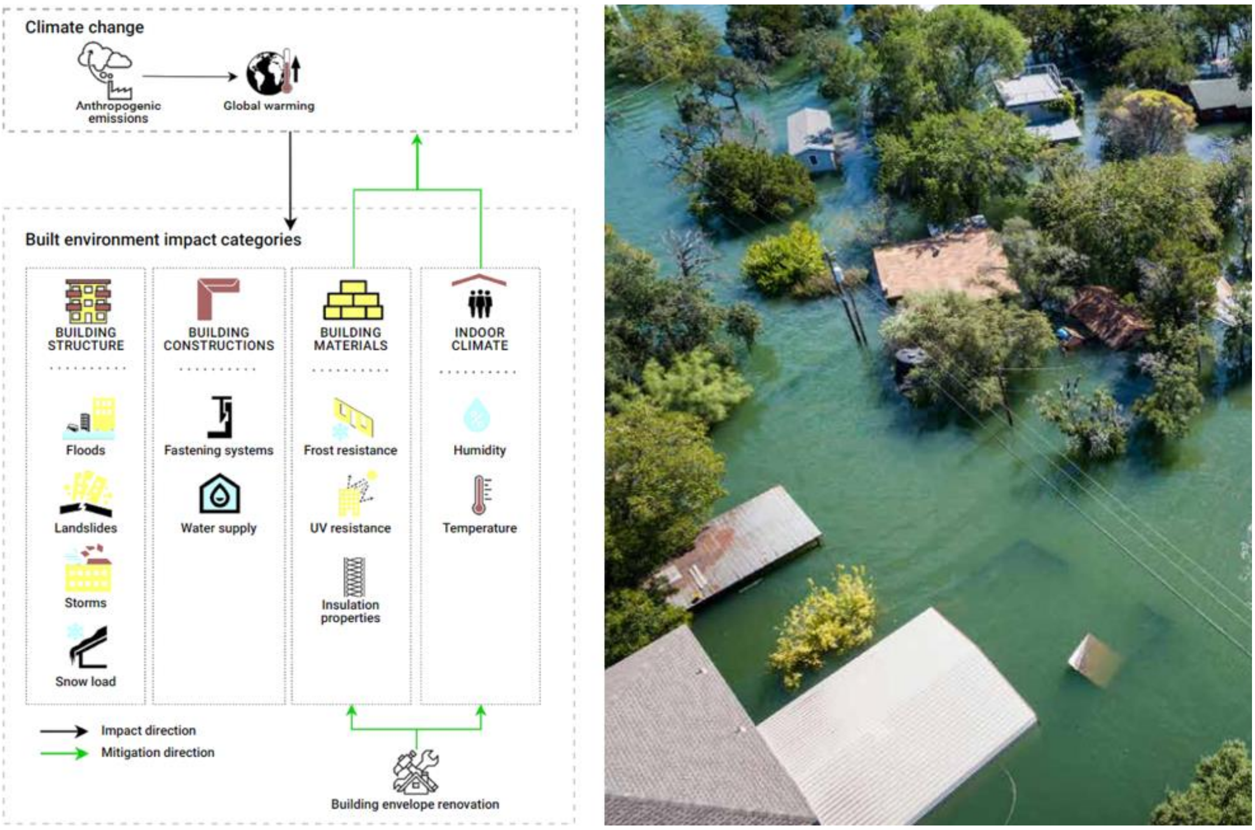

Fig. 2. Resilience, climate change and built environment impact categories

Main principles of resilience

Starting from a cyclical view (from one extreme event to the next), it remains that four main features are essential for the characterization of a resilient structure:

Ability to learn: In the aftermath of an event, it is important to learn from the crisis. This requires reflection with regard to patterns of damage and functional failures, among other things. Even communities that have not yet been affected by natural hazards can (and should) learn from the experience of other cities. The ability to learn in the sense of resilience also means, that actors recognize whether their objects/facilities are resilient or not. The ability to learn therefore also has a lot in common with raising awareness and with the development of institutional knowledge.

Adaptability: A resilient structure is characterized by its ability to adapt, e.g., by integrating knowledge gained from reflection of past (extreme) events into its planning and processes or in the participation/networking of the relevant actors among each other, in order to strengthen the protection and crisis management for the next event. [7]

Robustness: previous heavy precipitation events have produced enormous damage. Protecting people and critical facilities (and buildings as a whole) is therefore a central aspect of resilience. A resilient construction is able to withstand extreme events in such a way that damage is minimized.

Coping capacity: The analysis of risks and past damages makes it possible to take precautions. Due to the ubiquity of natural disaster and the many other uncertainties that are associated with, a total hundred percent protection against hazards is not possible. Therefore, not just resistance, but also to cope with the event accordingly that there are less serious failures and deformations. In order of this achievement, good organization and good crisis management are necessary, which includes both the local government (if necessary the district administration), the communal departments as well as the citizens and professionals. [8]

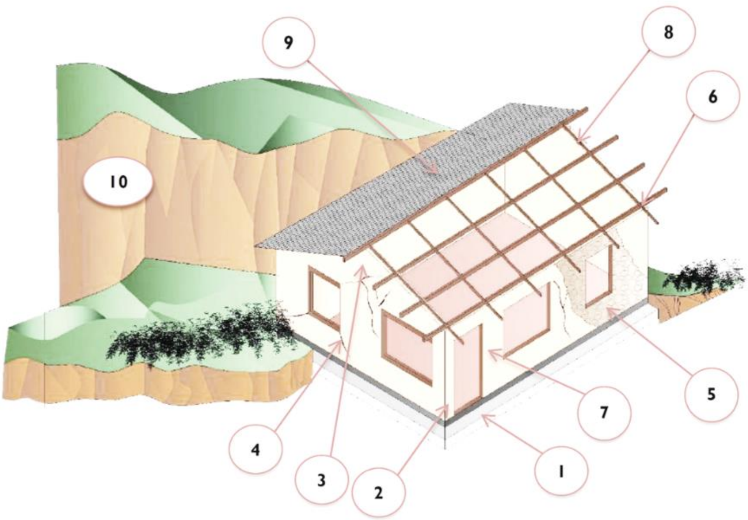

Fig. 3. Weaknesses of a non-engineered house

1. Insufficient depth of foundation and soil located below the flood level.
2. Insufficient connection between the walls or absence of a frame structure to increase the stiffness.
3. Unsupported gable wall and exterior walls.
4. Diagonal cracking at the corners of the openings due to lack of sill and lintel beams.
5. Building material of inferior quality, lacking in required strength and performance.
6. Inadequate connection of the roof truss to the structure.
7. Inadequate anchorage of door and window frames frame to the structure.
8. Inadequate connection of gable to structure and the roof covering to the gable.
9. Inadequate anchorage of roof panels and/or roofing tiles to the roof framing.
10. Deterioration of existing soil conditions.

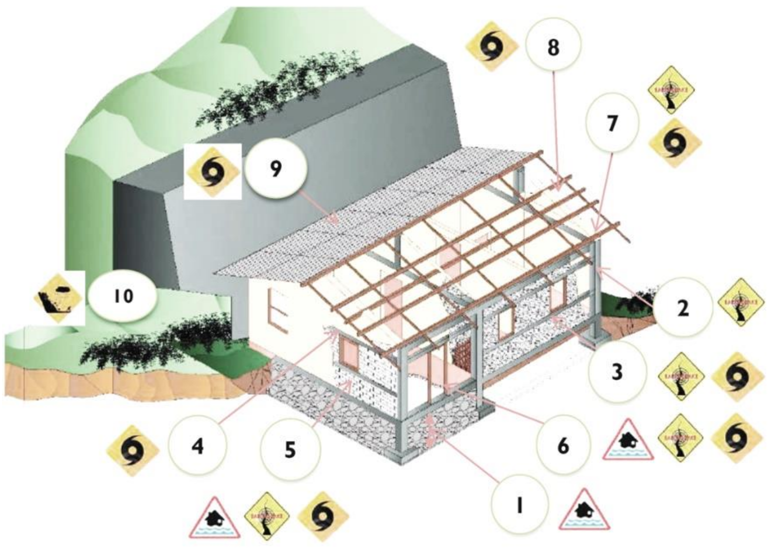

Fig. 4. Features of hazard resilient house

1. Increased depth of the foundation and raised ground level.
2. Truss construction with reinforced concrete columns supports.
3. Walls with adequate framing.
4. Bracing of walls at openings with lintel/threshold beams.
5. Use of good quality building materials in all the components used to provide the required strength and other properties.
6. Properly anchored door and window frames to the structure.
7. Properly erected and connected roof structure to the main structure.
8. Properly connected gable wall to structure and roof covering with gable wall.
9. Proper connection of roof covering to roof structure.
10. Minimal disturbance of the soil and supported cuts to preserve slopes.

Resilience of Components and Structures

Robustness as the basis for building resilience

In common sense, the word “robust” is used in the context of insensitive or stable. It is assumed that small causes do not produce a large effect on robust persons or things. If this context is applied to construction, society expects robust structures whose damage or failure is limited to an extent that is in reasonable proportion to the cause. This means, for example, that local damage must not lead to failure of the entire structure. If this understanding is transferred to large buildings, they can only be considered robust if the failure of a load-bearing element does not lead to the collapse of the complete building. In this context, columns are the most critical load-bearing elements in building construction. They carry high loads and, due to their slenderness, are particularly vulnerable to impacts such as collision or explosion. Therefore, it is senseful to design large buildings also for the possible failure of a column. Columns occur in most cases in so-called skeleton buildings, the majority of which are made of reinforced concrete. This means, for example, that span widths or slab thicknesses do not occur in arbitrary orders of magnitude, but are limited to certain bandwidths. The failure of a column is a dynamic event, since the structure loses a load-bearing element within a short time. The dynamic load-bearing behavior plays an important role, since the possible failure time of a column is often less than one tenth of the intrinsic period of the structure after failure. In the linear-elastic case, this means that the effects of a dynamic structural analysis can be up to twice as large as those of a static structural analysis. A structure failure is a rare event compared to storms or large snowfalls and can therefore be treated as an exceptional design situation. Similar to other exceptional design situations, e.g. earthquakes, the design values of the bearing resistances must therefore not be used for the verifications, but higher values, in case the characteristic bearing resistances, should be calculated. The correctness of this assumption must not be checked by means of a probabilistic analysis, but it can be assumed that the safety level for this hazard pattern is at an acceptable level. The structural analyses for structure failure could be performed for example using the finite element method, taking into account both geometric and material nonlinearities. In order to obtain realistic results from structural analyses, it is necessary to represent the load-bearing behavior of reinforced concrete as accurately as possible. In addition to the partially linear-elastic behavior of reinforced concrete, phenomena such as the flow of the reinforcing steel and the cracking or breaking of the concrete could also be simulated within the framework of the structural analysis. Shear force failure of the concrete and cracking of the reinforcing steel cannot be simulated directly in the structural analysis and therefore had to be excluded by a downstream design. [9]

To verify the structural models set up, physical tests should be recalculated on three different load-bearing elements: a beam, a line-supported slab and a point-supported slab. All three tests could be simulated with sufficient accuracy. Furthermore, it is important that a static structural analysis underestimates the effects after a column failure and that damping as well as distortion rate dependent material behavior can be neglected. [10]

Comparative calculations should be performed between a dynamic, twofold nonlinear structural analysis and a simplified static, linear-elastic structural analysis. A static, linear-elastic structural analysis is only permissible if shear force failure of the slab can be excluded. In addition, the design after such a structural analysis must always be carried out using the design values of the load-bearing resistances. Although this type of structural analysis is less time-consuming than a dynamic, nonlinear structural analysis, the latter can still be more economical because significantly less reinforcement results from the design. [11]

Overall, the load-bearing behavior of reinforced concrete skeletal structures after a building failure can be described as robust. Such structures can also withstand hazards without changing their geometry, but this requires an additional reinforcement of 5 to 20%. It is therefore reasonable to assume that structures of this type also exhibit similarly good load-bearing behavior under other extreme hazard conditions. [11]

Strategies for the resilience of the structure

This section discusses five strategies, that can be used to improve the resilience of structures. Not every strategy is evenly good for every structure. Therefore, it is the responsibility of the engineer and architect to decide which strategy or combination of strategies is appropriate to the building.

The first requirement serves to ensure sufficient deformation capacity of the structure. This means that even though the effects have been calculated using linear elasticity theory, for example, and the structure has been designed for these effects, it should not suddenly fail even if these effects occurred. In such a case, the structure should first deform strongly before it fails, in order that the upcoming danger can be recognized in time by the users. Therefore this is a strategy that increases the resilience of the structure without having a direct influence on the verification of the safety. [12]

The strategy of continuity is not useful in all cases. A continuous beam may serve as an example. After the failure of one of its supports, the continuity of the bearing element can lead to the fact that even the double span can be bridged or that the entire bearing element fails. Consequently, this is not a good prescriptive rule, since the utility of this rule must always be verified by a structural engineer. Although the application of prescriptive rules is often easy for the planner, there are few rules that are beneficial for every structure. Therefore, there is a risk that the stubborn application of such rules may actually degrade the resilience of a structure. For this reason, engineers should always re-examine prescriptive rules to see if they make sense for each structure and, if necessary, see them only as ideas for forming an alternative load path.

The second strategy is the alternate load path (direct design). In the application of this strategy, it is assumed that one or more load-bearing elements suddenly fail. The reason for this failure is irrelevant and it is assumed that other parts of the structure are not damaged by the cause of this failure. The objective of the subsequent structural analysis and design is to show that the loads of the failed load-bearing element can be taken over by other parts of the structure. In other words, the structure is able to find another alternative load path after the failure of one of its elements without failing. Examples of such requirements are the hazard cases of a column failure in buildings with 5 to 15 stories or the failure of a cable in certain bridge structures. A disadvantage of this strategy is, that the structural analysis is often quite costly, since the dynamic and nonlinear structural behavior often cannot be neglected for such hazard patterns. [13]

The third strategy is event control. The idea of this strategy is to keep an action away from a structure that would cause disproportionate damage. The aim is to mitigate the effect or prevent it from hitting the structure in the first place.

The fourth strategy is local reinforcement (direct design - local resistance). In this strategy, individual load-bearing elements are designed for increased actions. These effects can be determined, for example, for an assumed explosion or impact. When using this strategy, it is difficult to determine the necessary design level of the action. The reason for this is that any kind of impacts cannot be predicted using statistical data. Furthermore, local reinforcements can also worsen the aesthetics of the structure. The advantages of this strategy compared to the alternative load path strategy are the lower design and construction costs, since both are limited to a local area of the structure.

The fifth strategy is compartmentalization. In this strategy, the structure is divided into individual sections. This is to prevent a local failure from spreading to the entire structure as a result of a chain reaction. The sections can be formed within the structure by joints or articulations. When joints are used however, it must be borne in mind that large forces can act on the joint during the failure of a section, but these must not lead to a failure of the intact sections. Overall, the strategy of sectioning can be considered to be easily implemented and cost-effective. But it should be emphasized at this point, that loss of life due to failure of a section of the structure must be accepted as a risk.

All five strategies aim to limit potential failure of a structure to a point where it is reasonably proportionate to its cause. The goal of limiting a possible failure of the structure even further, in order that the serviceability is not limited, is only reasonable in a few cases. The reason is that serviceability can often only be achieved at great financial expense and with aesthetic restrictions. [14]

Risk Management and Determination of the Hazard

Resilience as a result of the risk management

Vulnerabilities and risk management focuses on managing the potential risks posed by natural hazards. These risks can vary enormously depending on which building structure, population or even study areas are considered. In order to be able to develop a successful hazard risk management, two levels of risk perception have to be distinguished: risk analysis and risk assessment. These two processes deal with different information. [15]

In the risk analysis, the available information is analyzed exclusively objectively, aggregated or summarized and classified among each other by means of fixed threshold values. Risk analysis is followed by risk assessment. This process is to be separated clearly from the analysis and contains a subjective evaluation based on the target system and planers decisions.

The most important prerequisite for strengthening the resilience of the structure is to identify potential hazard areas and vulnerabilities (especially critical infrastructures) during severe weather events in the neighborhood in order to subsequently determine the risk in the respective area under consideration by intersecting these data. [16]

For example, heavy rainfall events can very quickly lead to rising water levels in water bodies, backups in the sewage system due to the sudden influx of water masses, as well as to flooding and/or flash floods and thus to considerable hazards. In addition, there are influencing factors such as the topography, the degree of sealing or the building density, which can affect the runoff dynamics and impoundment. They influence not only the flow velocity, but also the amount of runoff water, which results in greater impoundments both in extent and depth. In cities and urban areas, vulnerability to heavy rainfall is particularly high as many people, goods and material assets, sensitive facilities and building and infrastructure are found in a confined space.

A large number of buildings and infrastructures also exhibit a high degree of systemic criticality due to their enormous importance for the functionality of the entire urban system. Criticality can be seen here as the relative measure of the importance of an infrastructure in terms of the consequences that a disruption or functional failure has for the security of society's supply with important goods and services.

In a next step the risk analysis is followed by the risk assessment as an independent component, which includes in particular an evaluation of the various potentially affected objects of protection. This is a normative process in which the results of the risk analysis are evaluated by the municipality. Finally, the risk assessment serves as a basis for the formulation of priorities for action as well as for the prioritization of flood prevention and protection measures. [17]

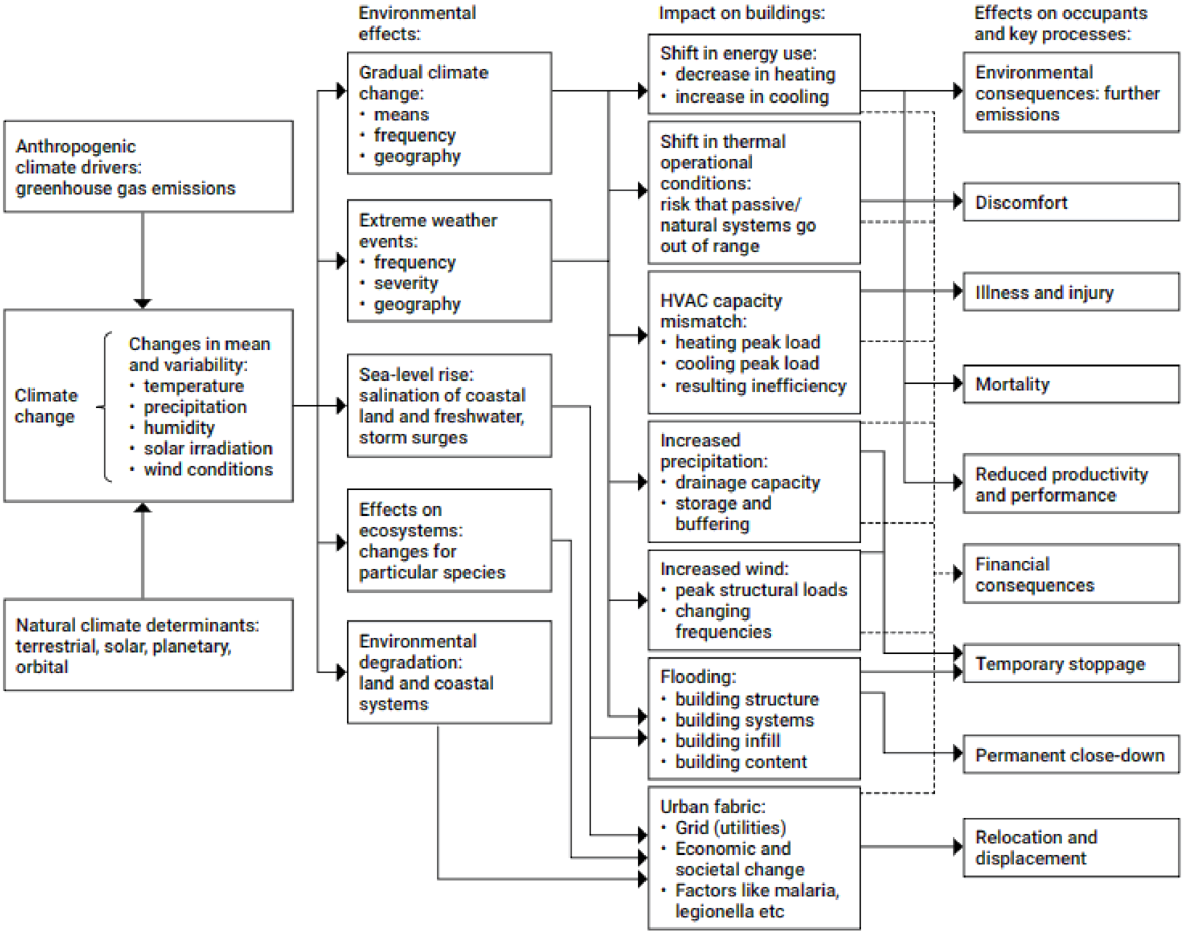

Fig. 5. Challenging and impacts of a changing climate on the built environment

Determination of the hazard

In order to determine a hazard or risk, analysis for the effects of extreme events in the urban context must be first drawn up in hazard maps. Hazard maps can be used to identify the areas of a municipality that could be for example flooded during a heavy rain event. They usually contain information on flood extension, flood depth and/or flow paths and velocities for a specific design. The necessary modeling is usually contracted out to specialized engineering firms by cities with a less specialized administration and often a lack of human resources. Based on the determined flow paths, it is easy to show where the water flows into and through the settlement area on the surface. Depending on the flow velocity and the topographical conditions, these so-called runoff paths can also be used to assess a possible erosive hazard.

For a city-wide investigation of areas, structures and infrastructures that are particularly affected by a hazard, meaningful threshold values are required to classify the risk. This is because it is often underestimated that even for example small flood depths of surface water can penetrate into ground-level or low-lying building openings, such as cellar shafts. In common practice, very different approaches and corresponding threshold values can already be found. The setting of these threshold values is influenced by various dimensions. For example, curbs usually have a height of 10-30 cm, multifunctional housings for power distribution and telecommunications technology usually have a height of 20-30 cm and conventional cars usually have a fording depth of approx. 40-50 cm. However, it is certain that from a water depth of 50 cm, significant material damage and, from 1 m, danger to human life must be expected. These examples can be used as an aid to approach these threshold values. [18]

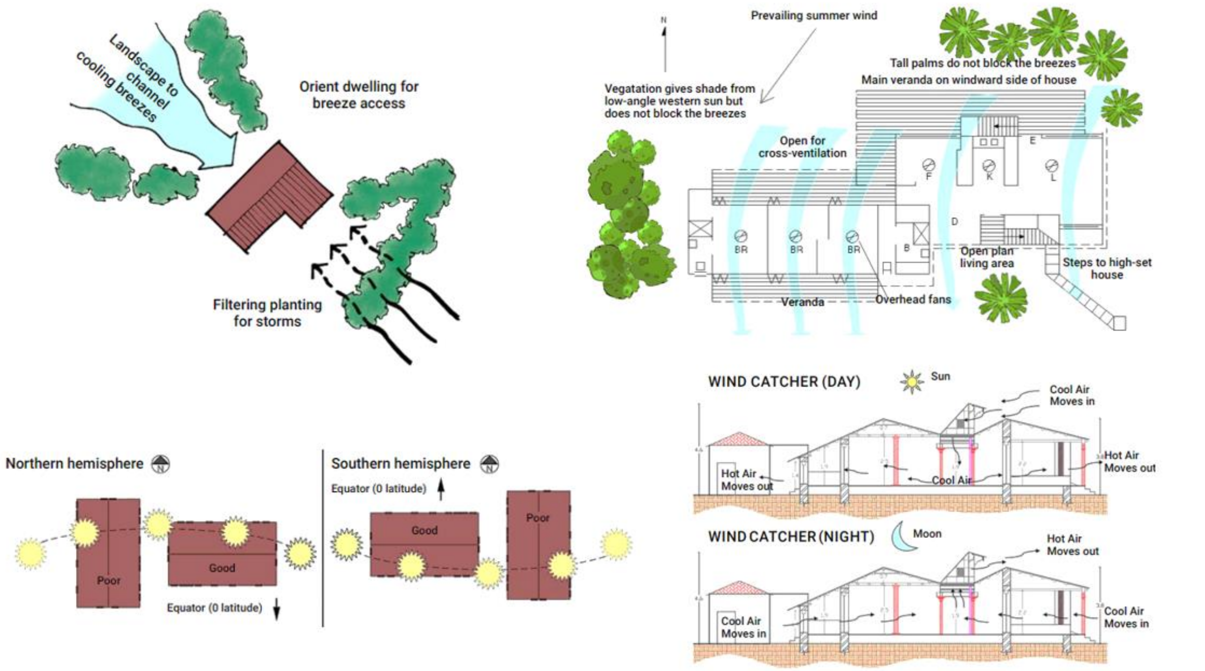

Fig. 6. Nature-based hazards and resilience

Summary

In many cities and municipalities, integrated concepts have been established as planning and control instruments for the entire city, with an integrated and participatory approach. The resilience concepts for areas of development funding, should be supplemented with following aspects regarding to:

- interaction with disaster control, disaster prevention and health,
- socio-spatial monitoring and risk studies as a rule,
- temporary solutions and experimental spaces,
- measures to avoid, reduce and adapt to existing and future risks,
- functional capacity, land reserves for resilience and critical infrastructures.

This planning should be process-oriented, transparent, reversible and open-ended, with goals to be agreed upon and evaluated between the stakeholders involved. To implement resilience strategies, a multidisciplinary body is needed for steering and coordination. In addition, existing processes for increasing resilience can be linked, for example in the context of smart city concepts or climate adaptation measures. [19]

The goals for building resilience can largely be implemented with existing planning law. It is recommended that aspects of resilience and risk management be anchored as planning objectives. It should be examined to what extent further flexibilization and mixing objectives can be anchored in planning and building code law, in harmony with environmental protection and emission control regulations.

In addition to the citywide and regional perspective, this requires greater differentiation at the neighborhood level. According to their function as a steering instrument for the public sector, resilience concepts should also be used as a strategic framework for self-organization in neighborhoods. For this purpose, it is important to communicate desirable visions of the future into which concrete measures can be integrated. These should be developed in collaborative formats with the everyday experiences of all population groups. [20]

Integrated risk and crisis management requires better linkages between prevention, preparedness, response and recovery. This means taking greater account in prevention of the lessons learned from crisis management and thinking about prevention in post-disaster reconstruction.

For the implementation of risk-informed building development, integrated risk and crisis management offers numerous tools and approaches that can contribute significantly to urban resilience. [21] These include:

- Conduct regular risk assessments, including mapping, analysis, and evaluation of local hazards, exposures, and vulnerabilities to increase risk awareness
- Ensure risk-informed planning and appropriate resources, taking into account the different needs and capacities of all population groups
- Learning from past events and rebuilding better
- Make decisions about the acceptability and management of residual risks, in terms of emergency planning, training of leaders and responders, and civic engagement
- Early warning of the population in the event of an incident and, where necessary, adaptation of local crisis management structures in order to be able to act across disciplines or localities
- Strengthening learning networks and exchange formats at the municipal level to optimize structures and processes.

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Figures

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