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Buildings risk assessment towards climate change impacts: A state-of-the-art review within EU CIRCLE

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Abstract

Critical infrastructure protection and management towards the devastating impacts of climate change hazards stands internationally an urgent priority. Climate change – related hazards are a threat multiplier for the urban environment and have the potential to substantially affect the safety, lifespan and the functionality of European buildings. Physical catastrophes to critical infrastructure appraise major social, economic and historical losses. Simultaneously, buildings represent a major part of the critical infrastructure and urban environment with several uses in the energy, transport, information and communication technology and public sector. There is a consistent effort by the European Union to contribute to the standardization process in the examined research field in order to lift the results, in the domain of climate impact assessment and resilience of buildings and defense the societies from natural threatens. In this context, *EU-CIRCLE "A pan-European framework for strengthening Critical Infrastructure resilience to climate change"* project established an innovative framework for supporting the interconnected European Infrastructure's resilience to climate pressures. A review analysis has been conducted and a state of the art has been derived regarding buildings damage and risk assessment towards climate hazards within EU CIRCLE. The undertaken workings steps based on literature study of frameworks for risk assessment, mainly from existing standards, codes and research projects. Common climatic hazards are referred along with their critical parameters and thresholds. A generic methodology for the damage assessment of buildings is described. Buildings uses of critical sectors are referred along with natural hazards thresholds and impacts. Structural design principles for buildings according to Eurocodes and existing damage models are presented for specific climate-related hazards: flood, wind, snow, high temperature, drought and temperature difference.

Keywords: Critical Infrastructure; Vulnerability and Risk Assessment; Climate Change Impacts; EU CIRCLE; Buildings Damage Assessment

1. Introduction

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability. Climate change is a threat multiplier for the urban environment [1]. It is presently acknowledged and scientifically proven than climate related hazards have the potential to substantially affect the lifespan and effectiveness of European Critical Infrastructures (CI) or even destroy them, particularly the energy, transportation sectors, buildings, marine and water management infrastructure with devastating impacts in EU appraising social and economic losses.

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The targeted strategic objective of recent research is to move towards infrastructure network(s) that is resilient to today's natural hazards and prepared for the future changing climate. There is the need for enrichment of the existing applied methodologies of specific vulnerability assessment and impacts of *multi hazards* in critical sectors and the urban environment.

Buildings represent a major part of critical infrastructure with several uses in the energy, transport, information and communication technology (ICT) and public sector: Public transport stations, traffic control/ data centres, military buildings, police stations, jails, public buildings, hospitals etc. The disaster risk protection and preservation of buildings towards natural hazards developing monitoring-decision support tools with best practices, adaptation strategies, action plans and enhancement of the capacity to apply that knowledge in practice by engineers and the buildings managers is more than urgent. For this purpose it is needed the: **1.** Establishment of collaboration among researchers, engineers, governmental and EU authorities, local actors, civil protection and public agencies, civil society, buildings managers, economic/ technical/ environmental sector leading to better natural threatens governance. **2.** Elaboration of concrete frameworks for the vulnerability and risk assessment, adaptation and resilience strategies that are suitable to being replicated and transferred across other exposed building stock with similar characteristics.

The comprehensive enrichment of the existing damage and risk assessment models uncertainties on the building environment regarding climatic hazards and the implementation of concrete adaptation and resilience plans could:

- Tackle the assessment of building sector exposure, structural vulnerability, adaptation and resilience;
- Assess impacts in different time scales (scenario analysis) and multi natural hazards which may be applicable in different spatial scales (European/National, regional and local) with similar building stock;
- Mainstream an improved set of adaptation and resilience indicators amalgamating researchers, engineers, climate change and building managers, civil protection, governmental/ municipal/ social/ economic/ environmental/ technical sector synergies;
- Develop a holistic monitoring decision-support tool for buildings natural catastrophes risk management, adaptation and resilience suitable to being replicated, transferred and mainstream across other sites engaging communities to preserve safe the existing and the future building stock.

Investments in buildings are at risk by changing climatic conditions and related extreme weather events. Due to the long lifespan of many buildings and their great economic value, their preparedness and resilience to future impacts of climate change are critical [2]. Major threats to buildings include:

- *Extreme precipitation*, e.g. leading to water intrusion, damage to foundations and basements, destruction of buildings and infrastructure, overflowing sewers, land- and mud- slides, flooding, etc.;
- *Extreme summer heat events*, especially but not only in South Europe, e.g. leading to material fatigue and accelerated aging, decreased comfort and potentially severe health implications, high energy use for cooling, et cetera;
- Exposure of constructions to *heavy snowfall*;
- *Rising sea levels* that increase the risk of flooding;
- *Soil subsidence risks* [3] are likely to increase, depending on the stability of building structures and their foundations;
- Buildings could be vulnerable to climate change because of their *design* (loads may change due to climate change from the initially design loads) or location (e.g. in flood-prone areas, landslides, avalanches);
- *Flooding* is (after earthquakes) one of the most costly kinds of disasters and this is mainly due to floods in built-up areas. Many European cities have been built along a river; and these rivers will respond to extreme rainfall or snowmelt events with extreme discharges, threatening the cities with floods;
- *Overheating* of the built environment being exposed to rising temperatures and *extreme heat* is also a big problem, which is not only an issue for the construction material but also affects the occupant's comfort and health;
- In coastal areas, *coastal protection* (e.g. sea walls) may require increasing maintenance costs and higher frequency of readjustments.

In this context, ***EU-CIRCLE "A pan-European framework for strengthening Critical Infrastructure resilience to climate change"*** project [4] established an innovative framework for supporting the interconnected European Infrastructure's resilience to climate pressures, supported by an end-to-end modelling environment where new analyses can be added anywhere along the analysis workflow including interdependencies, validate results, and present findings in a unified manner providing an efficient "Best of Breeds" solution of integrating into a holistic resilience model existing modelling tools and data in a standardised fashion. It is open and accessible to all interested parties in the infrastructure resilience business, having a confirmed interest in creating customized and innovative solutions. Additionally, it is complemented with a web-based portal wherein the design principles, offering transparency and greater flexibility, allow potential users to introduce fully tailored solutions and infrastructure data, by defining and implementing customised impact assessment models, and use climate / weather data on demand. Several structural types of buildings infrastructure represent the interconnected assets. A wide analysis review has been conducted within the EU CIRCLE project regarding the climate change impacts and risk assessment on buildings. The buildings were discriminated in discrete structural types dependent on the induced natural hazard. The current paper, based on the research results of EU CIRCLE, presents a review analysis and a state of the art regarding buildings damage and risk assessment towards climatic hazards. The study was based on literature review on frameworks for risk assessment, mainly derived from the following sources: European/ national standards, relevant international projects implemented by cities, regions, nations, studies on risk assessment and distillation of most common approaches deployed for risk management.

The most common climatic hazards are referred along with their critical parameters and thresholds. The hazard, associated with a natural phenomenon, is measured using its frequency of occurrence and its severity, the latter being characterized through a parameter of a physical intensity for a specific geographical location. The hazard assessment is based on the historical frequency of occurrence of the phenomenon and its various degrees of intensity. Once the hazard assessment is determined and completed (stemming from climate data and secondary models), the next step is the damage assessment based on a scenario approach. The first step for the sufficient assessment and management of the vulnerabilities induced by the climate change on assets is the identification of the type and the magnitude of the phenomenon itself. The other factor that enters into natural hazards vulnerability assessment is the discrimination of the build exposure in discrete structural types with group of structures where each asset has similar structural performance against the defined levels of the severity of hazard. In addition, during the determination of natural hazards are often classified by several parameters are involved [5], such as:

- *Magnitude* – the size of the event in terms of energy produced (earthquakes, wildfire), volume (flood, volcanic ash), wind speed (storms), or material displaced (landslides, coastal erosion) ;
- *Duration* – the time or time steps that the event will last;
- *Extent* – the geographical area that will potentially be affected;
- *Speed of onset* – if the onset will be a few seconds to a few hours (e.g., earthquakes, local source tsunami, flash floods); a few hours to a few days (e.g., storm winds, storm surge, frosts, river floods) or if the onset will be very slow (e.g., drought).

Thus, changes in climate may have consequences in the design of new structures, as well as the resistance of the existing building stock. Climatic actions on buildings – such as wind, temperature, rain and snow - have intensities that vary in time. Increasing the lifetime of a structure also increases the probability that, in a given time frame, the intensity of one of these actions will exceed the value assumed in the design. The working life increases with the importance of the structure. In building codes, these definitions are given [6]. The European standard for structural safety, EN 1990, uses 50 years for building structures and common structures and 100 years for monumental building structures, bridges and other civil engineering structures. For the impact of climate change on structural safety, the changes in the following climatic actions on buildings are studied following different climate change scenarios. Increasing the loads due to wind, precipitation and temperature, may create a more robust set of building standards with respect to the loads. The translation from climate change scenarios towards loads on buildings now requires very rude assumptions, thus introducing uncertainties. We need more, and more reliable, information on the climate effects, before we can definitively changes building standards or guidelines. There is a consistent effort to contribute to the standardization process in order to lift the results, in the domain of climate impact assessment and resilience of buildings and the existing standards need to be revitalized.

2. Climate hazards and vulnerabilities

The identification of buildings climate vulnerabilities requires a detailed knowledge of climate change hazards and the factors affecting the likelihood of each potential impact (e.g. region, geography, etc.). These potential impacts should then be evaluated in terms of the utility's own building, considering specific locations and other relevant attributes [7]. A basic understanding of the various types of climate hazards can be selected by gaining information from existing resources that provide an inventory of the potential impacts and the relevant vulnerabilities. A screening analysis may be completed for separate climate hazards, but the approach is best used for cases in which there are regional variations either in the climate hazards (e.g. monthly precipitation or high temperature) or in the attributes of a utility's building (e.g. height above sea level or safe operating temperature). Regional variations could affect their vulnerability to potential impacts. The proper identification of a critical threshold for a specific climate parameter is highly important for the screening analysis. These thresholds are simply values above or below which the likelihood of a climate impact is considered sufficient to render the building vulnerable [7]. The following existing design thresholds were found during the literature review process and transformed into a unique design with the aim to safeguard harmony and homogeneity. The aim is to homogeneously characterise the different hazards in order to compare them among each other's. Table 1 presents common climate hazards in connection the above three main characteristics.

Table 1 Characterisation of common climate hazards

Hazard	Category[1]	Speed of event	Intensity	Affected area
Temperature	M	Temperature change with time [°C/y]	Temperature [°C; °F] T_{max} above threshold T_{min} below threshold	Area over/below parameter threshold
Precipitation	M	Precipitation rate change with time [mm/y]	Rainfall intensity [mm/h]; Total rainfall [mm] Light, moderate, heavy, extreme threshold exceedance	Flooded area [ha]
Wind	M	Wind speed change with time [m/s]	Wind and gusts speed [m/s]	Area over/below parameter threshold
Snow/ Ice	M	Snow gauge change with time [cm/y]	Ice accumulation index Snow gauge [mm; cm; m]	Covered area [ha]
Solar radiation	M	Change of solar power with time [W/y]	Irradiance [W/m^2]	Area over/below parameter threshold
Sea level rise	M	Rise rate [mm/y; mm/10 y]	Rise rate [mm/y; mm/10 y] Accumulated increasing of sea level [m] Threshold exceedance [m]	Area below sea level [ha]
Lightning activity	M	Seconds / Minutes	CAPE values	Area over threshold
Storm surge	M	Velocity [m/s]	Storm surge height [m]	Inundated area [ha]
Waves	M	Velocity [m/s]	Wave height [m]	Inundated area [ha]
Forest fire	C	Rate of spread [m/min]	Fire line intensity [kW/m]	Burned area [ha]
Flood	H	Rise rate [m/s]	Flood depth [m] Discharge [m^3/s] Flow velocity [m/s]	Inundated area [ha]
Heat wave	M	Change of T_{Min} with time [K/y] Temperature change with time [K/y]	Consecutive days with T_{max} above threshold	Area above parameter threshold
Cold snap	M	Change of T_{Min} with time [K/y] Temperature change with time [K/y]	Consecutive days with Tmin below threshold	Area below parameter threshold
Drought	C	Precipitation rate change with time [mm/y] Temperature change with time [K/y]	Water Exploitation Index [hm^3] Drought indices	Area over parameter threshold

[1] Based on (IRDR, 2014) classification, H:Hydrological, M: Meteorological and C: Climatological

Critical thresholds are mainly linked on the building and operational attributes and concern:

- *Historical operating parameters* associated with damage, accelerated wear, increased costs, or service interruption/disruption;
- *Design parameters* or structured *operating parameters*;
- Measureable *physical characteristics* of buildings.

For some climate hazards, a threshold indicates a clear point at which damage or disruption in the operation of the building could occur (e.g. inundation depth). For other climate hazards, a threshold can be set as a point along an increasing slope of likelihood that the building will suffer a significant cost or impact. In setting thresholds, a planner tries to identify the point above which the risk of impact is great enough to qualify as a vulnerability. In order to describe the different hazard types, three main characteristics can be defined:

2.1. Speed of event

The speed of event characterises the lapse of time from the occurrence of the first precursor to the intensity peak of the hazardous event. It is referred to rapid-onset and slower-acting (slow onset) natural hazards. The speed of onset of a hazard is an important variable since it conditions warning time. Some events (e.g. flash floods) allow no or insufficient time for warning. Events such as hurricanes or floods typically have warning periods of minutes or hours and the likelihood of occurrence is known for several hours or days in advance. Other hazards such as drought, desertification, and subsidence act slowly over a period of months or years.

2.2. Intensity/ Magnitude

The intensity and the magnitude of an extreme event represent an exceptional and harmful condition. Several types of hazards like rainfalls and storms are common atmospheric events but if those phenomena exceed certain thresholds of intensity they become hazardous. Magnitude is related to the amount of energy released during the hazardous event, or refers to the size of the hazard. Magnitude is indicated using a scale, consisting of classes, related to an increase of energy.

2.3. Affected Area

The affected area designates the region that has been struck with a natural hazard and identifies the size and the impact of the hazard risk area.

3. Basic principles for the buildings damage assessment

The generic methodology for the assessment of damage on buildings is described. The term "damage" may include the assessment of the direct consequences caused by the hazard event on the building operation, due to physical and operational damage, the corresponding business disruption and the relative response to hazard. *Primary direct damage* can be differentiated in *physical/ structural* and *functional/ operational* damage whereas *secondary losses* are those that result from a failure of another building in interconnected network. In this paper, only the direct losses are considered. A methodological framework would define a chain of harmful consequences (damages) due to the hazard occurrence regarding different buildings types, different time steps and different types and intensities of hazards. In EU CIRCLE project [4] several damage types have been examined for the damage assessment referring to the different buildings types and time steps – hazards: *physical damage; performance losses; casualties and injuries; evacuation and release of harmful substances.*

Buildings of infrastructure may have different possible uses that belong in critical sectors. Thresholds and impacts on them of natural hazards depend, as already mentioned on the type, intensity and the affected area. The basic principles for the structural design are given in international or national building codes and regarding Europe in Eurocodes and national Annexes. Existing damage models are presented in the current research after the review analysis for specific climate hazards: flood, wind, snow, high temperature, drought and temperature difference.

Structural performance assessment is based on reliability analysis using probabilistic models for both the loads and the building's resistance and strength. All relevant aspects are considered to be stochastic in nature, and are treated stochastically. In structural analysis, the probability densities of the building's resistance R and of the load effect S are predicted. A structure is safe when the probability that R is larger than S, is acceptably small. This can be expressed as follows:

$$Pf = P\ (S > R) < P\ acceptable \qquad \text{.........(Eq. 1)}$$

Since S is depending on climatic actions and R on the material properties, they are both variables with a certain range and S and R can be described using probabilistic distribution functions. Using statistical methods and adequate models it is possible to calculate the probability of failure Pf. Given the above mentioned variability of the loads in time, Pf is always relative to a defined lifetime of the structure. For a structure to be acceptably safe, Pf must be smaller than a predefined value that depends on the importance of the building, the type of loss of performance taken into account, and the potential consequences C of failure. For example, when considering a limit state of static equilibrium of the structure (EQU), it shall be verified that [6]:

$$E_{d,dst} \leq E_{d,stb} \text{………….(Eq. 2)}$$

where :
$E_{d,dst}$ is the design value of the effect of destabilising actions,
$E_{d,stb}$ is the design value of the effect of stabilising actions.

The risk is often defined as the probability P that failure will occur multiplied by the consequences given that failure occurs, i.e: Risk=P*C. The level of risk which is accepted is determined more or less by our society. The larger the consequences will be, the smaller the accepted probability P of failure will be. These principles have been worked out in the Building Regulations and Codes, both on national (NEN standards) and on European basis (CEN standards; Eurocodes). The reliability of a structure depends on both loading and structural properties. The structural properties are treated in separate, material dependent standards. The loads are given in a series of standards under number EN 1991. In these codes, methods to determine a design load are given. The design load and design resistance must have values which are chosen so to obtain a structure that is safe enough during its lifetime. This implies that the design load has a very small probability of exceedance of about 10^{-4} or 10^{-5}. To establish these design loads, statistical distributions are needed of the extreme loads having very long returns periods. Traditionally, design codes have used past climatic load data to help forecast future loads on buildings. Since this extrapolation to the future is based on historic records of meteorological observations, as fundamental assumption, the possible existence of long term trends with a period of some decades or so is not taken into account. When climate change influences structural risks, the distribution S of the load, from which the design load results, can probably no longer be based only on measurements from the past, since the future development of the load under climate change has to be included.

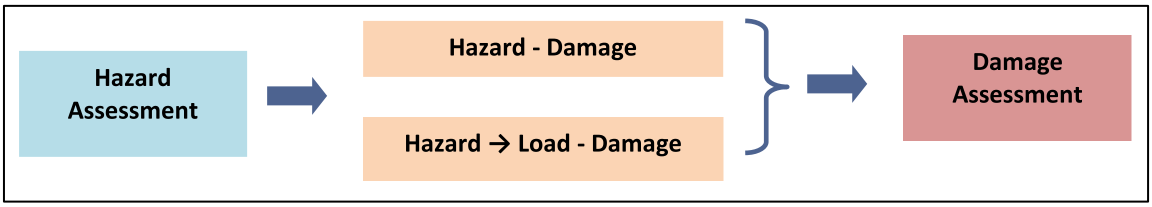

Figure 1 Typical steps for hazard assessment

Physical damages are considered as primary and direct losses to a building or network(s) of Critical Infrastructure [4]. The assessment of physical damage presupposes the accurate hazard characterization interpreted in the imposed load on a building which could potentially cause the direct physical, structural on non-structural, damage (Figure 1). Damage characterization and assessment is usually based on an algorithm with methodological steps and the implication of qualitative or quantitative indicators. Existing damage functions are based either on qualitative or quantitative measures. In both cases, under normal climate conditions and for the design loads the building remains safe preserving its normal physical and operational condition. On the other hand, when the hazard reaches a certain intensity level which leads to an imposed load on a building that exceeds its design load, the physical damage stars to develop on a building from minor damage state to total damage or collapse. In order to consider the different damage states and hence correlate these states with the building's performance capacity, the damage scale must be calibrated according to a measurable structural response parameter or else according to defined performance criteria. The last requires the discrimination of building exposure in groups of buildings with similar attributes and performance under a specific natural hazard. The categorization of buildings/ structures in defined structural types, regarding the materials, structural system, date of construction, period of design standards etc, plays an essential role during the damage assessment procedure. Different damage scales exist for the damage assessment regarding several types of hazards. Predefined performance levels of a specific structural type may declare the severity of damage. The description of damage in every performance level is based on existing damage scales and may be either qualitative or quantitative.

Several damage scales and methodologies exist for the qualitative or quantitative assessment of damage. Once the asset/ network is thoroughly described and the hazard scenario is selected, the analysis is conducted producing a quantifiable information on how different structural types react to different hazards and intensity levels in different time steps. On the other hand, during the structural design, or the structural performance assessment of an existing building, all codes and standards, estimate the imposed loads (concentrated or distributed linear and surface forces) or deformations (displacement, rotation, etc.) based on the available climatic values. The estimated load or deformation is compared to the internal forces or displacements to determine the development of damage for a particular structural system. The structural system transfers loads through interconnected elements or members. The same value of an imposed load would have a different impact on the structural response of different structural systems and materials. In a simplified expression for the safety of the structural design the equation $S \leq R$ has always to be met, where S is the applied load and R is the resistance or strength of the element. If this equation is not met, the ultimate limit state connected with the building's safety or the serviceability limit state connected with the functionality cannot be covered. Complying with the design criteria, the ultimate limit state is considered as the minimum requirement to provide the proper structural safety. To satisfy the serviceability limit state criterion, a structure must remain functional for its intended use.

Deformation demands are specified to determine the performance level (characterization of damage level) attained by the structure in response to the design loads. These values are compared with pertinent capacities associated with predefined performance criteria. Performance-based assessment centers on the ability to identify possible damage localization, where damage is identified by the amount of deformation occurring in the various components of the structure. This procedure enables, through simple calculations, the determination of the envelope of the developed deformations along the structural system of the examined building for a design scenario. Both demand indices and acceptance criteria are geometric variables (drift ratios that quantify the intensity of out of plane differential translation and in plane shear distortion of masonry walls oriented transversally to and along the seismic action, respectively for in plane and out of plane deformation) related through derived expressions with the fundamental response of the building [8].

In order to quantitatively calibrate damage, a descriptive information in terms of structural or non-structural indices is needed. Thus, from the extent and the severity (type of the developed damage) of structural and non-structural damage, the entire damage level for the building may be estimated. In addition, the severity of damage is connected with the type of the developed damage of structural and non-structural damage (position, type, width of cracks, drifts, joint damages, bar buckling, failure of infills, failure of beams and columns, partial collapse etc.). The extent and severity of damage are both dependent on the structural type of the building and the type and intensity of hazard. The correlation between the severities of any type of hazard - provoking damage in a building could be expressed with different existing mathematical formulae. Physical damages can be estimated through qualitative or quantitative indicators. For instance in EU CIRCLE the following indicators are taken into consideration:

- *Designated in the x-axis*: Hazard severity
- *Designated in the y-axis:*
    - Percentage of damage varying from none (0%) to total (100%) damage. This refers to a quantitative categorisation of damage. Existing mathematical forms correlate the severity of hazards to the level of the developed damages;
    - Numeric values (a quantity expressed in a unit) ;
    - Logic values (description of damage) ;
    - Categorical values (damage state calibration or damage grading) ;
    - Binary values (Yes/No or 0-1).

4. Buildings of critical infrastructure sector at climate change risk within EU CIRCLE

Buildings represent a major part of critical infrastructure sector and the urban environment. Thus, the preservation of their safety and functionality and additionally the adaptation and resilience strengthening to future provoking climatic risk is considered crucial for the prosperity of the societies. Table 2 presents types of buildings in critical infrastructure sectors and sub-sectors within EUCIRCLE project. Respectively, Table 3 presents the buildings assets and the relative sector that they may derive from.

Table 2 Buildings critical infrastructure within EUCIRCLE project

Sector	Sub-sector
Energy	Electricity/ Renewables/ District Heating
Transport	Road/ Maritime
ICT	Telecommunication/ Information
Public	Fire and rescue services/ Emergency medical services/ Military/ Law enforcement/ Public services/ Health care and public health

Table 3 Buildings assets and connection to the relative sector within EUCIRCLE project

Buildings Assets	Brief description and connection to the relative sector
Buildings (for infrastructure operators)	Buildings and control rooms for several uses of the energy sector
Control room (to be specified: IT services, monitoring equipment, network communication equipment)	
Public transport stations	Buildings used for public transport stations of transport sector
Traffic control centre	Buildings used for traffic control centre of transport sector
Fire dispatch centre operated by private road operators/owners	Buildings used for fire dispatch centre operated by private road operators/owners of transport sector
Warehouses	Buildings used for warehouses of transport sector
Lighthouses	Buildings used for lighthouses of transport sector
Base stations	Buildings used for base stations of ICT sector
Data centers	Buildings used for data centers of ICT sector
Carrier hotels	Buildings used for carrier hotels of ICT sector
Call centers	Buildings used for call centers of ICT/ public sector
Base stations (private com)	Buildings used for base stations of public sector
Dispatch center	Buildings used for dispatch centers of public sector
Military personnel buildings	Buildings used for military personnel buildings of public sector
Police stations	Buildings used for police station of public sector
Detention rooms	Buildings used for detention rooms of public sector
Jails	Buildings used for jails of public sector
Public buildings	Buildings used for public services of public sector
Hospitals (building facilities)	Buildings used for hospitals (building facilities) of public sector

At European level, Eurocodes have been proposed addressing climate resilience in different infrastructure sectors. The Structural Eurocodes are a harmonized set of European Standards (EN) for the structural design of buildings and civil engineering works, produced by the European Committee for Standardisation (CEN) to be used in the European Union over the last 30 years regarding all types of structures made of steel, concrete, timber, masonry and aluminium. They provide for compliance with the requirements for mechanical strength, stability and safety as basis for design and engineering contract specifications. Based on ISO Guide 64, CEN has developed and adopted CEN Guide 4 "Guide for the inclusion of environmental aspects in product standards", which aims to provide a helpful tool for people involved in standardization who are not necessarily environmental experts to take the potential environmental aspects related to their standards into account. Following discussions with the Commission, CEN is currently considering how to amend Guide 4 to take into account climate change in the development and revision of standards. Table 4 presents several types of impacts on buildings due to different climate hazards.

Table 4 Types of different climate hazards impacts on buildings

Climate Hazard	Impacts on buildings
Heat waves, cold snaps	Contraction & expansion of the materials/ structural members causing cracks and deformations.
Floods / costal floods	It may causes damages to structural and non/structural member of a building and its content according to the building height/ structural type/ material/ maintenance level/ location of doors and openings/ existence of basement/ floorspace/ use.
Forest Fires	It can cause partial damage or total failure of a building depending on the material and the burning time.
Droughts	Droughts may lead to building damage due to shrinking and swelling of soil. Thus, a vulnerability curve due to drought correlates the intensity of drought, possibly expressed with a soil subsidence parameter, with the building damage.
Sea level rise	Similar with floods it may causes damages to structural and non/structural member of a building and its content according to the building height/ structural type/ material/ maintenance level/ location of doors and openings/ existence of basement/ floorspace/ use.
Ice, frost, permafrost	The snow mainly affects the roof of structures or/and the upper horizontal surfaces. Ice, frost and permafrost.
Storm surges, waves	It can seriously affect constructional components installed on the roof and/or façade. Storm damage is mainly recorded in the building envelope, windows and peripheral installations.
Lightning / thunderstorm	It may cause severe damage to the roof or the highest parts of the building (chimneys, antennas, etc).
Earth movement caused by climate drivers such as rain (landslide, erosion, avalanches, rock fall, soil subsidence, liquefaction, etc.)	The deformation of the foundation will cause further deformation to structural and non structural members regarding the structural type and the material (eg cracking on beams and columns and/or masonry infills).

The EN Eurocodes are a set of European standards which provide common rules for the design of civil engineering works and construction products. There are ten Eurocodes, each published in a number of separate Parts: 58 Parts in total. Some Parts give general rules and other give rules applicable to one form of construction. When the 58 Eurocodes parts were published in 2007, the implementation of the Eurocodes was extended to all European countries and there were firm steps towards their adoption internationally. They were produced by the European Committee for Standardization (CEN) and embody national experience and research output together with the expertise of international technical and scientific organisations. From March 2010, the Eurocodes were intended to be the only Standards for the design of structures in the countries of the European Union (EU) and the European Free Trade Association (EFTA). The Commission Recommendation of 11 December 2003 stresses the importance of training in the use of the Eurocodes, especially in engineering schools and as part of continuous professional development courses for engineers and technicians, noting that they should be promoted both at national and international level. Although the Eurocodes are harmonized documents that are applicable throughout Europe, certain provisions, such as the setting of partial factors for safety, are chosen by the national standards bodies (such as BSI). The Eurocodes are thus accompanied by National Annexes that set out those national choices.

5. Building damage models towards climate hazards

The review analysis regarding climate change impacts assessment on buildings needed the accurate and in depth research of multiple relative projects (ARMONIA, CIMNE, CIPRnet, CONHAZ, CORFU, CRISMA, DEFRA UK, DRIVER, ENSURE, FLOODsite, FRC, IMPACT, IMPROVER, INFRARISK, INTACT, MATRIX, MOVE, PLACARD, PREDICT, RAIN, RAMSES, REAKT, RESILENS, RESIN, RESISTAND, RESOLUTE, SNOWBALL, STAR-FLOOD, STREST, SYNER-G, WEATHER etc), papers, documents, researches, codes and standards. In the references [9] ÷ [43] are referred only some of them.

A building is a multipurpose entity. Several parameters influence its integrity and response and are those that are taken into consideration through the structural design and assessment. The materials influence building's discrete mechanical characteristics and behaviour. A building can be constructed using reinforced concrete, masonry, metal, timber, glass and combinations of these materials. The structural system is composed of structural and non-structural members and transfers loads through interconnected members classified into tensile, compressive, shear and bending structures and trusses. The height of a building may be low-, mid- or high- rise. The structural (primary) elements are important for maintaining the structural integrity and support of a building (e.g. frames and walls) and are those that mainly transfer the loads from the upper floors to the ground. Their failure will certainly lead to collapse. On the other hand, the non-structural (secondary) elements (e.g. chimneys, infills, building contents) are not essential for the structural integrity. Therefore their failure usually does not lead to collapse. The type of use determines the significance of a building and its necessity for protection (warehouses, dwellings, schools, museums, stadiums, cultural heritage buildings etc). Once a hazard and a hazard scenario are defined, the design load can be estimated. The **damage assessment methodology** usually follows the *algorithm*:

1. Hazard scenario selection
2. Load determination
3. Structural analysis
4. Determination of demands (forces and deformations)
5. Identification of critical structures
6. Structural criteria
7. Determination of structural performance
8. Pass or fail criterion based on the correlation between the imposed demands and the structural capacity.

Figure 2 summarises the process of damage assessment for buildings. The so called performance levels express the permissible amount of damage for specific level of design hazard.

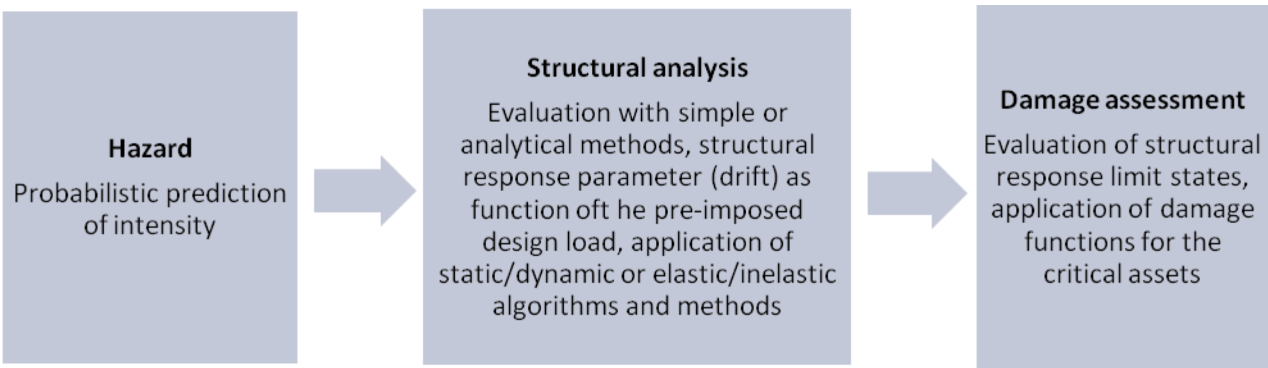

Figure 2 Analyses within the structural response damage assessment framework.

The International Code Council (2001) distinguishes four performance groups for buildings (Table 5). The structural design of buildings establishes performance levels on how a building will tolerate the various actions and loads. For each magnitude of load the design will provide the maximum tolerated damage for the specific performance group. The International Code Council (2001) distinguishes four design performance levels (Table 6). The performance-based engineering uses scientifically defined loads, direct design approaches and defined outcomes with associated probabilities of achieving them. It can provide multiple limit states or performance targets (e.g. the ability to resist collapse). The damage assessment needs to calculate the amount of yielding, buckling, cracking and permanent deformation of the structure. The stakeholders need to know the repair cost, the time for repair and whether the building is safe for use after the event. The Department of Homeland Security FEMA defines discrete structural performance levels referred to percentage of damage or loss (Table 7).

Table 5 Performance group classification for buildings and facilities (International Code Council, 2001)

Performance Group	Description	Examples
I	Low hazard to humans	Agricultural facilities, temporary facilities, minor storage facilities
II	Regular buildings	All buildings except for those referred in group I, III and IV
III	Hazardous contents	Buildings with > 300 people, elementary and secondary schools, colleges with > 500 people, jails, health care facilities with > 50 residents with no surgery or emergency treatment, any occupancy with > 5000 occupants, power generating facilities for water treatment and potable water
IV	Essential facilities	Hospitals, fire, rescue and police stations, emergency shelters, power generating stations, aviation control towers, buildings with national critical defence functions

Table 6 Maximum level of damage to be tolerated based on performance groups and design event magnitudes (International Code Council, 2001)

Hazard magnitude	Performance Group I	Performance Group II	Performance Group III	Performance Group IV
Very large (very rare)	Severe	Severe	High	Moderate
Large (rare)	Severe	High	Moderate	Mild
Medium	High	Moderate	Mild	Mild
Small (frequent)	Moderate	Mild	Mild	Mild

Table 7 Discrete structural performance levels, adapted from Department of Homeland Security FEMA

Performance levels	Damage	Damage range
Operational	• negligible structural and non-structural damage • occupants safe during event • utilities available • facility available for immediate re-use (clean-up required)	< 5 %
Immediate occupancy	• negligible structural damage • occupants safe during event • minor non-structural damage • building safe to occupy but may not function • limited interruption of operations	< 15 %
Life safety	• significant structural damage • some injuries may occur • extensive non-structural damage • building not safe for occupancy until repaired	< 30 %
Collapse prevention	• extensive structural and non-structural damage • potential for injury but not wide scale loss of life • extended loss of use • repair may not be practical	> 30 %

5.1. Flood damage models

The consequence of flooding is often described as a combination of depth [m], velocity [m/s], discharge [cms], extent [ha], duration [hr;day;week], and quality [-]. These characteristerics are associated with different vulnerability, fragility, and socio-economic factors to determine the damage or impact of flood events. For pluvial events, the intensity or accumulation of precipitation are utilised to describe the main driver that leads to flooding, which are also used for the standards for designing drainage networks. The combined sewer overflows often pollute the environment such that the concentration of contamination is also considered. The occurrence of fluvial events depends on the conveyance capacity of river channels and the protection level of embankments. Therefore, the discharge and water level of flow are the critical parameters to describe such events. Coastal flooding may occur due to sea level rise or storm surge. For the former, it is a long term process and the water level is the major factor leading to flooding. For the latter, the moving speed and height of waves are the main drivers.

For determining these parameters in flood modelling, either historical observations or statistical analyses can be used as the inputs of initial and/or boundary conditions. The modelling results normally include the above-mentioned critical parameters that can be used to determine the impact to critical infrastructures. For simulations using historical records, these information can be used to calibrate and validate the flood models, while the results using statistical analyses can be used to estimate the likelihood of hazard impacts. Table 8 presents an overview of design values for various CI assets according to Eurocodes. Each type of CI has been designed to withstand inundation levels specific for each installation site.

Table 8 Flooding – critical structural and operational thresholds

Asset	Design thresholds	Impacts
Transport		
Roads	floods with Annual Exceedance Probability of 2% (≈ Average Recurrence Interval (ARI) of 50 years)[2]	Insufficient drainage, slippery surfaces, aquaplaning, damage to superstructure
Bridges[3]	minimum hydraulic force on bridge pier = 75 kN/pier minimum stream velocity = 2.0 m/s. *force on superstructure*: depth of debris mat: the greater of 3.0 m or structural depth of superstructure in elevation + 1.5 m *force on substructure*: minimum depth of debris mat = 3.0 m resilient to 0.6 m inundation[4]	Loss of stability of bridge piers, bridge collapse
Tunnels[5]	probable maximum precipitation event + 300 mm 100 year ARI flood 100 year ARI storm tide	Insufficient drainage, aquaplaning, structural damage

[2] State of Queensland (Department of Transport and Main Roads) 2015: Road Drainage Manual
[3] State of Queensland (Department of Transport and Main Roads) 2018: Design Criteria for Bridges and Other Structures, http://creativecommons.org/licenses/by/3.0/au/
[4] New Mexico Department of Transportation 2007: Drainage Design Criteria – Revision of 06/07
[5] State of Queensland (Department of Transport and Main Roads) 2018: Design Criteria for Bridges and Other Structures, http://creativecommons.org/licenses/by/3.0/au/

A summary on building characteristics that are important for determining the damage due to flooding has been presented by van Westen et al. [17]. Further important characteristics for the damage estimation are the building use, the maintenance level, the location of doors and openings where flood water can enter and the distance to flowing waters, which may determine the damages due to erosion [17]. In order to evaluate flood damage, several parameters that characterise the severity of a flood can be used. The most frequently applied parameter is the inundation depth. Analyses of empirical damage data showed that the variability of damages can only be explained to a rather small extent by the depth of flooding experienced, but other flood characteristics are usually not recorded, so that it is difficult to quantify their influence [18]. The emerging damage is dependent on the type of flood event (coastal, fluvial and pluvial flooding). Further, the flood duration needs to be regarded especially for the assessment of productivity losses. The velocity of flowing flood water can impact the structure and lead to severe damages, especially when the water carries debris. Transported sediment and water contamination can cause serious damage to the building materials and contents and may produce large clean - up costs. The flood depth and duration determine how much load the structure needs to bear and may lead to weakening of the structural system. The rise rate of a flood may also be considered, since a fast water level rise reduces time for warning and evacuation. Flood water performs different actions on buildings which are described by Sterna [19].

Differences in the water level inside and outside the building cause lateral pressure and lead to damage of the structural elements. The capillary rise enables water to affect building components located above the flood gauge. The water flow causes dynamic pressure which fluctuates depending on how the water is flowing (turbulences, narrow profiles). In case of coastal flooding, the waves, whether breaking or not, can decrease the pressure applied to the building. Flood water can lead to buoyancy. When the buoyant forces exceed the weight of the building components and the connections to the foundation, the structure may float from its foundation [19]. Buildings are the most comprehensively determined assets in recent damage research. A majority of damage functions is existent. Examples for flood loss models and publications comprising building damage functions are the HAZUS flood model (Department of Homeland Security FEMA, 2013a), Penning-Rowsell et al.[20], Genovese (2006) [21], Hammond et al.[22] ÷[23], van der Veen and Logtmeijer [24], Custer and Nishijima [25], Dutta et al.[26], Kok et al.[28], Schwarz and Maiwald [29], Kreibich and Seifert-Dähn [30] and Nikolowski et al.[31]. Jongman et al. [32] conducted a comparative investigation for well-known flood damage models. The most prominent flood models are [33]:

- The FLEMO - flemops for the private sector and flemocs for the commercial sector,
- The Damage Scanner,
- The Flemish Model,
- The HAZUS flood model,
- The Multi – coloured manual,
- The Rhine Atlas,
- The JRC model and
- The HEC – FIA model.

Schwarz and Maiwald [29] introduced damage grades which link the flood impact with the hazard. A minimum damage grade D1 (without the occurrence of structural damage) has to be assigned due to humidity penetration effects. The generalised damage definitions are related to the quality of structural damage and non-structural damage as well as to the required extent of rehabilitation or other repair measures. Five flood vulnerability classes are distinguished by definition covering the range from low flood resistance/higher vulnerability (A - very sensitive; B - sensitive), to normal (C) and increased flood resistance (D).

5.2. Wind damage models

In the case of the wind risk assessment several critical climatic parameters are taken into account both during the design of new critical infrastructure or during the assessment of the existing ones. Specific variables are considered for the risk estimation of the wind impact on the structural environment. The most common among them is the wind velocity or wind pressure, which is used during the assessment of the wind load along with additional parameters such as turbulence intensity, terrain category, reference height z_e, orography, upstream slope, neighbouring buildings, and the special characteristics of the building (shape, dynamic characteristics, natural frequencies, modal shapes, equivalent masses, logarithmic decrements of damping, slenderness, roughness, structural factors, solidity, reference area, etc). Specifications of the local wind loads are given nationally based on metereological measurements and may characterize specific regions and be demonstrated in maps [42].

Similarly with the snow actions, critical design thresholds for the wind load are applied for different regions. Once the design load is exceeded, damage will start to be developed on structure depending on the local situations. The severity of damage will belong either in Serviceability Limit State with minor damages or in Ultimate Limit State with major and most severe damages. Storm damage is mainly recorded in the building envelope: roof, windows or peripheral installations.

Eurocodes documents are related to the structural design of construction works and products involving several climatic hazards that are imposed on structures in the form of loads [34] ÷ [37]. In case of wind hazard, as building structures are designed for a certain design wind load they may fail when the actual wind exceeds the design load (Table 9). Table 10 presents critical climatic parameters and thresholds of wind for bridges. EN 1991-1-4 [36] refers to natural wind actions for the structural design of building and civil engineering works. The field application of EN 1991-1-4 considers buildings with a maximum height of 200 m and bridges with a maximum span of 200 m. This includes the whole structure or parts of the structure or elements attached to the structure, e.g. components, cladding units and their fixings, safety and noise barriers. Wind vulnerability can seriously affect construction components which are installed on the roof or the façade (e.g. antenna, chimneys, solar panel, scaffolding). Buildings that are situated in a prominent position, high altitudes (hills, mountains), slopes and locations on lakes or in open areas, in wind corridor etc. are especially vulnerable to wind actions. Moreover, buildings that stand out from their environment (high warehouses), with irregular shapes (strongly texturer exterior wall or roof surfaces), with critical forms causing aerodynamic stresses or with critical operating conditions (open building gates) have also an increased risk on storm hazards. Strong winds can seriously affect constructional components which are installed on the roof or the frontage. Storm damage is mainly recorded in the building envelope, windows and peripheral installations. Local wind loads exist, based on meteorological measurements, for the structural wind design and may be summarised in wind load zones. Since building structures are designed for a certain design wind load, they may fail when the actual wind load exceeds the design load. Specific variables are considered for the risk estimation of the wind impact on the structural environment. The most common one, among them, is the wind velocity or wind pressure, which is used during the assessment of the wind load along with additional parameters such as turbulence intensity, terrain category, reference height, orography, upstream slope, neighbouring buildings and the special characteristics of the building (shape, dynamic characteristics, natural frequencies, modal shapes, equivalent masses, logarithmic decrements of damping, slenderness, roughness, structural factors, solidity, reference area, etc.). Specifications of the local wind loads are given nationally based on meteorological measurements demonstrated in maps. The wind loads can be characteristic for specific regions.

The fundamental value of the basic wind velocity, $v_{b,0}$, is the characteristic 10 minutes mean wind velocity, irrespective of wind direction and time of year, at 10 m above ground level in open country terrain with low vegetation, such as grass and isolated obstacles with separations of at least 20 obstacle heights. There are maps with the thresholds of basic wind velocities in Europe. Most damage occurs because various building elements have limited wind resistance due to inadequate design, poor installation, or material deterioration. The magnitude and frequency of strong windstorms vary by locale. When wind interacts with a building, both positive and negative pressures occur simultaneously. Wind loads are transferred through the structure's envelope to the structural system, where in turn they must be transferred through the foundation into the ground. The characteristics of the terrain (i.e. ground roughness and surface irregularities of a building) influence the wind loading.

The effect of the wind on the structure (i.e. the response of the structure), depends on the size, shape and dynamic properties of the structure: quasi-static response (the majority of building structures). For structures when the lowest natural frequency is so high that wind actions in resonance with the structure are insignificant, the wind action is called quasi-static dynamic and aeroelastic response (lightweight structures e.g. steel chimneys). The dynamic response is significant for structures, if the turbulence (or gust effect) of the wind is in resonance with the structure's natural frequency whereas the aeroelastic response occurs if an interaction between the movement of a particular structure and the circumfluent wind flow exists [42].

In most Codes and Standards in Europe or worldwide (USA, Canada, New Zealand) the basic wind speed is determined for the design of wind loads. Abrupt changes in topography, such as isolated hills, ridges, and escarpments, increase the wind to speed. Therefore, a building located near a ridge would receive higher wind pressures than a building located on relatively flat land. Taller buildings are exposed to higher wind speeds and greater wind pressures. The highest uplift pressures occur at roof corners because of building aerodynamics (i.e., the interaction between the wind and the building). The response of structures should be calculated from the characteristic peak velocity pressure, qp, at the reference height in the undisturbed wind field for the determination of the wind actions on structures and accounts for the mean wind and the turbulence component. EN 1991-1-4 indicates qp as a function of: wind climate (through the basic wind velocity vb at a given site), local factors (e.g. terrain roughness [$c_r(z)$], orography [$c_0(z)$]), height above the terrain (z) and structural factor $c_s c_d$).

Table 9 Critical climatic parameters and thresholds of wind for buildings

Assets	Thresholds EN 1991-1-4
Buildings, civil engineering works (maximum height 200 m) Bridges (maximum span 200 m)	*Fundamental basic wind velocity [m/s]* wind actions are characteristic values, determined from basic values of wind velocity or velocity pressure (values having annual probabilities of exceedance of 0.02 ≙ return period 50 years)
Control rooms CI company buildings Public transport stations Gasoline stations Rescue coordination centres Fire dispatch centres	*Basic wind velocity [m/s]* = $c_{dir}\, c_{season}\, v_{b,0}$ v_b, modified to account for wind direction function of wind direction and time of year at 10 m above ground of terrain category II *Mean wind velocity at height z* $v_m(z) = c_r(z)\, c_o(z)\, v_b$ v_b modified to account for effect of terrain roughness and orography

Lighthouses Base stations Call centres Dispatch centres Military buildings Police stations Detention rooms Public buildings Jails Hospitals	$c_r(z)$ = roughness factor $c_o(z)$ = orography factor (1.0 unless otherwise specified)
	Wind pressure w [kN/m²] external wind pressure: $w_e=qp*cp_e$ internal wind pressure: $w_i=qp*cp_i$ qp = peak velocity pressure cp = pressure coefficient (external/ internal pressure)
	Peak velocity pressure q_p and Reference mean velocity pressure q_b $q_p(z)= [1+7I_v(z)](1/2)\rho v^2{}_m(z)=c_e(z)q_b$ *qb=(1/2)ρv2b* ρ = air density, depends on altitude, temperature, barometric pressure during wind storms (e.g. 1,25 kg/m³) $c_e(z)$ = exposure factor For flat terrain where cO(z) = 1,0 q_p equal to q_b plus contribution from short-term pressure fluctuations Aeroelastic response considered for flexible structures (cables, masts, chimneys, bridges)
	Standard deviation of the turbulence σ_v turbulent component of wind velocity has a mean value of 0 and a standard deviation σ_v
	Turbulence factor k_I recommended value = 1.0
	Turbulence intensity $I_v(z)$

Table 10 Critical climatic parameters and thresholds of wind for bridges

Wind pressure [kn/m²]			
Height above ground [m]	**Bridge with traffic load**		**Bridge without traffic load**
	Without parapets	***With parapets***	***With/without parapets***
0 - 20	1.75	1.45	0.9
20 – 50	2.1	1.75	1.1
50 - 100	2.5	2.05	1.25

w_e : Wind pressure on external surfaces (EN 1991-1-4)

$$w_e = q_p (z_e) c_{pe}$$

$q_p(z_e)$ is the peak velocity pressure
ze is the reference height for the external pressure
$c$pe is the pressure coefficient for the external pressure
w_i : Wind pressure on the internal surfaces of a structure.

$$w_i = q_p (z_i) c_{pi}$$

$q_p(z_i)$ is the peak velocity pressure
z_i is the reference height for the internal pressure
c_{pi} is the pressure coefficient for the internal pressure, depending on the size and distribution of the openings in the building envelope. When in at least two sides of the buildings (facades or roof) the total area of openings in each side is more than 30 % of the area of that side, the actions on the structure should not be calculated

When the area of the openings at the dominant face is twice the area of the openings in the remaining faces,

$$c_{pi} = 0{,}75\ c_{pe}$$

When the area of the openings at the dominant face is at least 3 times the area of the openings in the remaining faces,

$$c_{pi} = 0{,}90\ c_{pe}$$

c_{pe} is the value for the external pressure coefficient at the openings in the dominant face.
Open silos and chimneys c_{pi} = - 0,60
Vented tanks with small openings c_{pi} = - 0,40

5.2.1. Wind forces

F_w : Wind force, acting on a structure or a structural element may be determined by vectorial summation of the forces $F_{w,e}$, $F_{w,i}$ and F_{fr} calculated from the external and internal pressures and the frictional forces.

$$F_w = c_s c_d \ c_f \ q_p(z_e) \ A_{ref}$$

$$F_w = c_s c_d \ c_f \ \sum_{elements} q_p(z_e) \ A_{ref}$$

$c_s c_d$ is the structural factor
c_f is the force coefficient for the structure or structural element

	
Damage state 0: ≤ 2 % roof cover loss	**Damage state 1:** 2 % - 15 % roof cover loss
	
Damage state 2: more than one window but less than the greater of 3 or 20 % of windows	**Damage state 3:** more than 3 pieces of failed roof sheeting, but less than 15 % panels missing

Damage state 4: complete roof failure, more than 25 % of roof sheeting missing, wall failure

Figure 3 Wind damage states for buildings

$q_p(z_e)$ is the peak velocity pressure at reference height z_e
A_{ref} is the reference area of the structure or structural element
w_e is the external pressure on the individual surface at height z_e
w_i is the internal pressure on the individual surface at height z_i,
A_{ref} is the reference area of the individual surface
c_{fr} is the friction coefficient
A_{fr} is the area of external surface parallel to the wind

For the purposes of calculating the wind force, the structure should be divided into a series of sections, where a section comprises several identical panels. In determining the wind force under iced conditions, the projected areas of structural elements and ancillades should be increased to take due account of the thickness of ice as relevant. Towers and masts should be examined for gust induced vibrations (causing vibrations in the direction of the wind), vortex induced vibrations for towers or masts containing prismatic cylindrical or bluff elements or shrouds (causing vibrations perpendicular to the direction of the wind), galloping instability (causing vibrations of the guys) and rain-wind induced vibrations.

The effect of the wind on the structure (e.g. the response of the structure), depends on the size, shape and dynamic properties of the structure. The majority of building structures respond quasi - static. When the lowest natural frequency is so high that wind actions appear in resonance with the structure, the wind action is called quasi-static-dynamic and causes aero-elastic response (especially affecting lightweight structures like steel chimneys). For buildings made using non-engineered wood and materials, damage normally begins on the roof and on the outer walls, and, if the connections are not properly anchored, the damage usually leads to the complete collapse of the building. For buildings made using engineered materials with greater resistance, damage is normally concentrated on the roof, on the outer walls, and on the windows. When any of those elements suffer damage, the impact extends to the inner elements of the building, such as thin partition walls, ceilings and, naturally, the contents.

Wind vulnerability of buildings is highly dependent on the construction class, the level of country development (overall construction quality, design codes), the complexity of urban areas (cities with high complexity are likely to better monitor the compliance of design criteria) and the location (buildings in areas with specific meteorological characteristics according to wind actions are often constructed with high resilience to wind). The derivation of *wind damage functions* includes the:

- Definition of the geometry and physical characteristics of each construction class,
- Estimation of resilience and capacity of the main individual components for each construction class,
- Distribution of maximum pressure on different components for each construction class, for discrete levels of reference maximum wind velocity,
- Damage assessment according to the capacity-demand ratios of the critical components and

Total damage level for each intensity level, in terms of mean damage ratios, taking into account the weighting that the damage represents out of the total value of the building. The Hazus Hurricane Wind User and Technical Manuals provide information on the model outputs, uncertainties, running basic and advanced analyses, damage functions, debris generation, shelter requirements, storm surge, and impacts such as direct economic loss and building damage (https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals). The Hazus

Hurricane Wind Model provides improvements over existing loss estimation models because of the wind hazard-load-damage-loss framework (Figure 3).

5.3. Snow damage models

Risk indexes are based on meteorological data, and usually involve the quantitative estimation of a natural hazard and more rarely qualitative approaches. In the case of snow risk assessment several critical climatic parameters are taken into account, either in the design of new critical infrastructure or in the assessment of the existing assets. Depending on the local conditions, snow on the ground will have different qualities in relevance with the temperature changes, winds blow, or on the time that it remains on the ground.

The variables that usually are applied for the snow risk assessment are the *weight of snow* or the *weight density* and sometimes in combination with the local wind. Critical design thresholds for the snow load are applied for group regions in Europe with similar latitudes and dependent on their altitude. For this purpose measured data of hundreds of meteorological stations in Europe were analysed and the characteristic values of the ground snow load were determined by means of extreme value statistics.

The EN 1991-1-3 [34] gives guidance to determine the values of loads due to snow for the structural design of buildings and civil engineering works for sites at altitudes above 1500 m (Table 11). In the case of altitudes above 1500 m, advice may be found in the appropriate National Annex. For bridges, which are specific engineering works, along with Eurocodes, the German DIN standards were applied. The design thresholds for snow on bridges is defined in DIN 1055 [44], discriminating two cases: when a bridge is open or when it is under construction. Once the design load is exceeded, damage will start to be developed on structure depending on the local situations (material, structural system, magnitude of snow load, environment). The severity of damage will belong either in Serviceability Limit State with minor damages or in Ultimate Limit State with major and most severe damages. Structural failure from snow load is influenced by the characteristics of the building [45]. The snow loads affect mainly the roof of structures. The variables in roof snow load are roof geometry and roofing material, exposure to wind, and insulation.

The Eurocode prEN 1991-1-3 maps give the characteristic values of the snow loads on sea level for the relevant European countries. Several snow load maps are available for different climatic regions. The maps for the several climatic regions are subdivided into snow load zones Z. In addition to the values of the altitude the numbers Z of these zones are the basic input parameters for the determination of the characteristic value of the ground snow load s_k. The characteristic value of snow load on the ground s_k [kN/m^2] (annual probability of exceedence of 0.02 with return period of 50 years, excluding exceptional snow loads) is given in EN 1991-1-3 discrimanting Europe in specific regions.

The snow loads mainly affect the roof. The snow layers on a roof depend on the characteristics of the roof. Properties of a roof or other factors causing different patterns can include: a) the shape of the roof; b) its thermal properties; c) the roughness of its surface; d) the amount of heat generated under the roof; e) the proximity of nearby buildings; f) the surrounding terrain; g) the local meteorological climate, in particular its windiness, temperature variations, and likelihood of precipitation (either as rain or as snow). The variables in roof snow load are roof geometry and roofing material, exposure to wind, and insulation. The snow load on the roof is derived from the snow load on the ground, multiplying by appropriate conversion factors (shape, thermal and exposure coefficients). In absence of wind or with very low wind velocities (< 2 m/s), snow deposits on the roof in a balanced way and generally forms a uniform cover. For wind velocities above 4 - 5 m/s, snow particles can be picked up from the snow cover and re-deposited on the lee side, on lower roofs in the lee side or behind obstructions on the roof. The snow load on the roof s [kN/m^2] is evaluated based on the equation:

For the persistent/ transient design situations

$$s = \mu_i C_e C_t s_k$$

μ_i is the snow load shape (roof shape) coefficient
s_k is the characteristic value of snow load on the ground for the relevant altitude
s_{Ad} is the design value of exceptional snow load on the ground for a given location
C_e is the exposure coefficient Ct is the thermal coefficient

For the accidental design situations where exceptional snow load is the accidental action

$$s = \mu_i C_e C_t s_{Ad}$$

For the accidental design situations where exceptional snow drift is the accidental action and where Annex B applies

$$s = \mu_i s_k$$

Table 11 Critical climatic parameters and thresholds of snow in Eurocode EN 1991-1-3

Design threshold			Impact on asset
Weight (kg)			Structural failure from snow load is influenced by the
Alpine region	Zone 1, Altitude A = 0 m	71.38kg/m²	
	Zone 2, Altitude A = 0 m	132.56 kg/m²	
	Zone 3, Altitude A = 0 m	193.74 kg/m2	characteristics of the building[6]
	Zone 4, Altitude A = 0 m	295.72 kg/m2	
Central East	Zone 1, Altitude A = 0 m	30.59kg/m²	
	Zone 2, Altitude A = 0 m	50.99kg/m²	
	Zone 3, Altitude A = 0 m	81.58 kg/m²	
	Zone 4/5, Altitude A = 0 m	122.37 kg/m²	
Greece	Zone 1, Altitude A = 0 m	40.79kg/m²	
	Zone 2, Altitude A = 0 m	81.58kg/m²	
	Zone 4, Altitude A = 0 m	173.35 kg/m²	
Iberian Peninsula	Zone 1, Altitude A = 0 m	10.20kg/m²	
	Zone 2, Altitude A = 0 m	30.59kg/m²	
	Zone 4, Altitude A = 0 m	71.38 kg/m²	
Mediterranian region	Zone 1, Altitude A = 0 m	30.59kg/m²	
	Zone 2, Altitude A = 0 m	81.58kg/m²	
	Zone 3, Altitude A = 0 m	132.56 kg/m²	
	Zone 4/5, Altitude A = 0 m	203.94 kg/m²	
Central West	Zone 1, Altitude A = 0 m	10.20kg/m²	
	Zone 2, Altitude A = 0 m	20.39kg/m²	
	Zone 3, Altitude A = 0 m	40.79 kg/m²	
	Zone 4/5, Altitude A = 0 m	71.38 kg/m²	
Sweden, Finland	Zone 1, Altitude A = 0 m	122.37kg/m²	
	Zone 2, Altitude A = 0 m	203.94kg/m²	
	Zone 3, Altitude A = 0 m	275.32 kg/m²	
	Zone 4/5, Altitude A = 0 m	397.69 kg/m²	
UK, Ireland	Zone 1, Altitude A = 0 m	4.08 kg/m²	
	Zone 2, Altitude A = 0 m	20.39 kg/m²	
	Zone 3, Altitude A = 0 m	30.59 kg/m²	
	Zone 4/5, Altitude A = 0 m	50.99 kg/m²	
	Region I	76.48 kg/m²	
	Region II	107.07 kg/m²	

Czech Republic	Region III	152.96 kg/m^2	
	Region IV	229.44 kg/m^2	
	Region V	> 229.44 kg/m^2	
Iceland	Region 1	214.14 kg/m^2	
	Region 2	224.34 - 387.49 kg/m^2	
	Region 3	397.70 - 622.03 kg/m^2	
	Region 4	> 622.03 kg/m^2	
Poland	Zone 1, Altitude 0.007 A – 1.4	≥71.38 kg/m^2	
	Zone 2	91.77 kg/m^2	
	Zone 3, Altitude 0.006 A – 0.6	≥122.37 kg/m^2	
	Zone 4	163.15 kg/m^2	
	Zone 5, Altitude 0,93exp(0.00134 A)	≥203.94 kg/m^2	
Weight density of snow γ (kN/m^3)			It increases with the duration of the snow cover and depends on the site location, climate and altitude
	• Fresh • Settled (several hours or days after its fall) • Old (several weeks or months after its fall) • Wet	• 1,0 • 2,0 • 2,5 - 3,5 • 4,0	

[6] Risk Management Series Snow Load Safety Guide FEMA P-957 / January 2013

The thresholds contained in the Eurocode document are applicable to the CI sectors energy (control rooms and buildings), transport (public transport stations, gasoline stations, road bridges, rescue coordination centres, fire dispatch centres, lighthouses, bridges) and public (base stations, call centre, dispatch centre, military personnel buildings, police station, detention rooms, jails, public buildings, hospitals). Once the design load is exceeded, damage will start to be developed on the building depending on the local situations (material, structural system, magnitude of snow load, environment).

EN 1991-1-3 does not give guidance on the following specialist aspects:

- “Impact loads” due to snow sliding off or falling from a higher roof,
- Additional wind loads resulting from changes in shape or size of the roof profile due to presence of snow or to the accretion of ice,
- Loads in areas where snow is present all the year,
- Loads due to ice,
- Lateral loading due to snow (e.g. Lateral loads due to drifts) and
- Snow loads on bridges.

Liel et al. [38] states that the snow loads on roofs are dependent on the ground snow load, the level of exposure, the thermal insulation of the building and the roof properties (materials and geometry). Among these, it is considered that the building exposure has the largest effect and the thermal factor is the second most significant [31]. Roof slopes larger than 30° generally hold less snow than flatter roofs, since the snow is sliding or falling off. Large ground snow loads tend to overestimate the roof loads in this approach [38]. The authors developed a model for the prediction of the roof snow loads in dependence on the ground snow load. Barbolini et al. [39] introduced a damage scale in order to assess the damages to buildings due to snow avalanches (Table 12).

Table 12 Scale used for the degree of damage (DD) of buildings subject to snow avalanches [39]

DD	Phenomena observed
4 (complete)	Partial or complete failure of the building
3 (heavy)	Heavy damage to structural elements
2 (medium)	Failed chimneys, attics or gable walls; damage or collapse of roof
1 (moderate)	No visible damage to structural elements, damage to frames, windows, etc.

5.4. High temperature and drought damage models

The term drought is used to define a temporary decrease in water availability due for instance to rainfall deficiency. Drought is an indistinct event, of water deficiency, that results from the combination of many complex factors and neither the beginning nor the end can be precisely defined [46]. WMO defines drought as "a marked unusual period of abnormally dry weather characterized by prolonged deficiency below a certain threshold of precipitation over a large area and persisting for timescale longer than a month".

Water scarcity is a long-term condition identified by the occurrence of differences between demanded and offered water resources. In order to classify a water shortage situation, spatial and temporal parameters are needed to define reference points for the comparison of current or projected supply and demand of water resources [47].

To identify drought events, it is necessary to define initially the normal conditions and then choose relevant threshold values. Drought indicators are used for the identification of the onset, the severity, and the end of a drought. These indicators need to be objective measures of the system status [48]. Common indicators are based on meteorological and hydrological variables such as rainfall, stream flow, soil moisture, reservoir storage, and ground water levels.

The European Drought Observatory of the Joint Research Centre uses the Combined Drought Index which is a complex index that uses in combination three different indexes to define Watch, Warning and Alert levels of drought. The indexes used by the Combined Drought Index are:

- Standard Precipitation Index (SPI-n) [49] which is a statistical indicator comparing the total precipitation received at a particular location during a period of n months with the long-term rainfall distribution for the same period of time at that location.
- Soil moisture anomaly (ΔfP), comparing the daily soil moisture with the long term average to assess the effects of the hydrological drought to plants providing information on spatial distribution of the soil water content and its time evolution.
- Anomaly of Fraction of Absorbed Photosynthetically (ΔfAPAR anomaly): Active Radiation focusing on the fraction of solar energy which is absorbed by the vegetation.

Droughts may lead to building damage due to shrinking and swelling of soil. Thus, a vulnerability curve due to drought correlates the intensity of drought, possibly expressed with a soil subsidence parameter, with the building damage. Several damage functions exist in the literature. Naumann et al. [40] developed damage functions for droughts.

5.5. Temperature difference

EN 1991-1-5 [35] gives design guidance for thermal actions arising from climatic and operational conditions on buildings and civil engineering works, including bridges, other structures with their structural elements, cladding and other appendages of buildings are also provided (Table 13).Table 14 presents critical climatic parameters and thresholds of bridges in Eurocodes. Characteristic values of thermal actions are presented for use in the design of structures which are exposed to daily and seasonal climatic changes. Structures not so exposed may not need to be considered for thermal actions. Thermal actions are classified as variable and indirect actions. Thermal actions are imposed on a structure or a structural element as a result from the changes of temperature fields within a specified time interval. The magnitude of the thermal effects is dependent on local climatic conditions along with the orientation of the structure, its overall mass, finishes (e.g. cladding in buildings) and in the case of building structures is dependent on heating and ventilation regimes and thermal insulation [35]. Loads and stress that impact the structural system vary depending on the geometric construction and the physical properties of the material. Most materials expand when they are heated, and contract when they are cooled. Temperature stress in buildings indirectly impacts the well - being and health of the habitants. Temperature vulnerability of buildings is both affected by the physical properties of the building and the environmental conditions (location, solar radiation, the external air temperature, relative atmospheric humidity, etc.) [50]. The strains and any resulting stresses, are dependent on the geometry and boundary conditions of the considered element and on the physical properties of the material. When materials with different coefficients of linear expansion are used compositely the thermal effect should be taken into account. Most materials expand when they are heated, and contract when they are cooled. Temperature difference will cause concrete to deform, expand or contract. The size of the concrete structure whether it is a bridge, a highway, or a building is irrelevant to the effects of temperature. The expansion and contraction with changes in temperature occur regardless of the structure's cross-sectional area. Concrete expands slightly as temperature rises and contracts as temperature falls. Temperature changes may be caused by environmental conditions or by cement hydration. Bridges expand and contract due to temperature change. This movement is accommodated by bearings and expansion joints or by deformation of the piers and abutments with integral construction. Bridge movements depend upon average bridge temperatures rather than air temperature. Bridge temperatures vary through the bridge cross section as a function of time. Temperature calculations are based on radiation, convection, and conduction heat flow, and these three mechanisms all contribute to the time dependent cross sectional variation.

Table 13 Critical climatic parameters and thresholds of buildings in Eurocodes

<table>
<tr><td>Assets</td><td></td><td></td></tr>
<tr><td rowspan="6">Control rooms
CI company buildings
Public transport stations
Gasoline stations
Rescue coordination centres
Fire dispatch centres
Lighthouses
Base stations
Call centres
Dispatch centres
Military buildings
Police stations
Detention rooms
Public buildings
Jails
Hospitals</td><td>Thermal differential between surface and interior of materials result in cracking, oversailing, buckling of walls, fracture of masonry units</td><td>Impacts</td></tr>
<tr><td>Initial Temperature T [°C]
Common characteristic values of thermal actions: 50-year return values</td><td rowspan="5">Thresholds
(EN 1991-1-5)</td></tr>
<tr><td>Inner environment temperature T_{in} [°C]
Summer: T_{in} = 20 °C
Winter: T_{in} = 25°C
(recommended)</td></tr>
<tr><td>Outer environment temperature T_{out} [°C]
Buildings above ground level:
<table>
<tr><td>Season</td><td colspan="2">Significant factor</td><td>T_{out} [°C]</td></tr>
<tr><td rowspan="3">Summer</td><td rowspan="3">Relative absorptivity</td><td>bright light surface</td><td>$T_{max} + T_3$</td></tr>
<tr><td>light surface</td><td>$T_{max} + T_4$</td></tr>
<tr><td>dark surface</td><td>$T_{max} + T_5$</td></tr>
<tr><td colspan="3">Winter</td><td>T_{min}</td></tr>
<tr><td colspan="4">If no data available: for regions between latitudes 45°N and 55°N the values T_3=0°C, T_4=2°C and T_5=4°C, for North - East facing elements and T_3=18°C, T_4=30°C and T_5=42°C for South - West or horizontal elements.</td></tr>
</table>
Buildings below ground level:
<table>
<tr><td>Season</td><td>Level</td><td>T_{out} [°C]</td><td rowspan="5">If no data available: for regions between latitudes 45°N and 55°N the values T_6=8°C, T_7=5°C and T_8=-5°C and T_9=-3°C</td></tr>
<tr><td rowspan="2">Summer</td><td>< 1 m</td><td>T_6</td></tr>
<tr><td>> 1 m</td><td>T_7</td></tr>
<tr><td rowspan="2">Winter</td><td>< 1 m</td><td>T_8</td></tr>
<tr><td>> 1 m</td><td>T_9</td></tr>
</table></td></tr>
<tr><td>Uniform temperature component ΔT_u [°C]
$\Delta T_u = T - T_0$</td></tr>
</table>

	difference between average temperature T of an element (climatic temperatures in winter or summer and operational temperatures) and its initial temperature T_0.	
	Linearly varying temperature component ΔT_M difference between outer and inner surface temperatures of a cross section or individual layers	
	Temperature difference of different parts ΔT_p difference of average temperatures of structure parts	
Industrial chimneys Pipelines Silos Tanks Cooling towers	15°C concrete pipelines: stepped temperature component round the circumference (causing both overall and local thermal effects), one quadrant of its circumference has a mean temperature higher than that of the remainder of the circumference	

Table 14 Critical climatic parameters and thresholds of bridges in Eurocodes

Thresholds (EN 1991-1-5)

Uniform temperature component [°C]

depends on T_{min} and T_{max} of a bridge

a) Steel deck (steel box girder, steel truss or plate girder)

b) Composite deck

c) Concrete deck (concrete slab, concrete beam, concrete box girder)

Surfacing thickness [mm]	Temperature difference				
	Heating [°C]				Cooling [°C]
	ΔT_1	ΔT_2	ΔT_3	ΔT_4	ΔT_1
Unsurfaced	30	16	6	3	8
20	27	15	9	5	6
40	24	14	8	4	6

Initial bridge temperature T_o [°C]

thermal effects include spalled concrete around bearings at the supports, bent and pulled-out anchor bolts, locked expansion joints due to uneven gap opening across the bridge [7]

Minimum and maximum shade air temperature T_{min} [°C] and T_{max} [°C]

Characteristic values for the site location obtained e.g. from national maps of isotherms

T_{max} with an annual probability of being exceeded of 0,02 (≙ mean return period 50 years)

Minimum and maximum uniform bridge temperature components $T_{e,min}$ [°C] and $T_{e,max}$ [°C]

based on daily temperature ranges of 10 °C

steel truss and plate girders: $T_{e,max}$ may be reduced by 3 °C
Uniform bridge temperature component $\Delta T_{N,con} = T_0 - T_{e.min}$
Maximum expansion range of the uniform bridge temperature component $\Delta T_{N,exp}$ $\Delta T_{N,exp} = T_{e.max} - T_o$ recommended values: (ΔTN,exp + 20)°C and (ΔTN,con + 20)°C if temperature at which the bearings and expansion joints are set is specified, recommended values are (ΔTN,exp + 10)°C and (ΔTN,con + 10)°C
Overall range of the uniform bridge temperature component $\Delta T_N = T_{e,max} - T_{e,min}$
Vertical temperature differences $\Delta_{TM,heat}$ *and* $\Delta T_{M,cool}$ a) Vertical linear component b) Vertical temperature components with non-linear effects considered by using equivalent linear temperature difference component with $\Delta T_{M,heat}$ and $\Delta T_{M,cool}$, valuesapplied between top and bottom of the bridge deck
Horizontal components - linear temperature difference between the outer edges If no other information available: 5°C recommended (linear temperature difference between outer edges of the bridge, independent from width)
Temperature difference components within walls of concrete box girders recommended value for linear temperature difference is 15 °C
Differences in uniform temperature component between different structural elements Recommended values: – 15°C between main structural elements (e.g. tie and arch) – 10°C and 20°C for light and dark colour, between suspension/stay cables and deck or tower
Linear temperature differences between opposite outer faces 5 °C (concrete piers, hollow or solid) 15 °C (walls between inner and outer faces)

DIN 1072	Temperature difference in 20 °C [K]	Linear temperature difference [K]			
		Under construction	Final satge	Under construction	Final stage
Steel	± 35	15	10	5	5
Composite	± 35	8	10	7	7
Concrete	+ 20; - 30	10	7	3.5	3.5

7 http://www.eng.auburn.edu/files/centers/hrc/IR-98-02.pdf

List of abbreviations

- *Pf*: Probability of failure
- R: Resistance
- S: Load effect
- EQU: Static equilibrium of the structure
- Ed ,dst: Design value of the effect of destabilising actions Ed ,stb design value of the effect of stabilising actions. C potential consequences of failure
- P: Probability
- $v_{b,0}$: Fundamental value of the basic wind velocity
- $c_r(z)$ roughness factor
- $c_{o(z)}$: Orography factor
- qb: Reference mean velocity pressure
- ρ: Air density
- $c_e(z)$ exposure factor
- σv: Sandard deviation of the turbulence
- k_I turbulence factor
- $I_v(z)$: Turbulence intensity
- W_e: Wind pressure on external surfaces
- $q_p(z_e)$: Peak velocity pressure at reference height ze
- ze reference height for the external pressure
- c_pe: pressure coefficient for the external pressure
- w_i: Wind pressure on the internal surfaces of a structure
- z_i reference height for the internal pressure
- c_{pi}: Pressure coefficient for the internal pressure
- F_w wind force
- c_sc_d: Structural factor
- c_f: Force coefficient for the structure or structural element Aref reference area of the structure or structural element
- w_e: External pressure on the individual surface at height ze
- w_i internal pressure on the individual surface at height zi
- c_{fr} friction coefficient
- A_{fr}: Area of external surface parallel to the wind
- Z snow load zones
- S_k: Characteristic value of snow load on the ground
- M_i: Snow load shape (roof shape) coefficient
- S_k: Characteristic value of snow load on the ground for the relevant altitude
- s_{Ad} design value of exceptional snow load on the ground for a given location
- C_e exposure coefficient
- C_t: Thermal coefficient
- SPI-n: Standard precipitation index
- ΔfP: Soil moisture anomaly
- ΔfAPAR: Anomaly of Fraction of Absorbed Photosynthetically
- $T_{o:}$ Initial temperature
- $T_{in:}$ Inner environment temperature
- $T^{out:}$ outer environment temperature
- ΔTu: uniform temperature component
- $\Delta T_{M:}$ linearly varying temperature component
- $\Delta T_{p:}$ temperature difference of different parts
- Tmin: minimum shade air temperature
- $T_{max:}$ maximum shade air temperature
- $T_{e,min:}$ minimum uniform bridge temperature components
- $Te,_{max:}$ maximum uniform bridge temperature components
- $\Delta T_{N,exp}$: Maximum expansion range of the uniform bridge temperature component
- $\Delta T_{M,heat}$ and $\Delta TM_{,cool}$: Vertical temperature differences

6. Conclusions

The current paper presents a review analysis and a state of the art regarding buildings damage and risk assessment towards specific climate hazards. Natural catastrophes have the potential to substantially affect the safety and functionality of European Critical Infrastructures (CI), particularly the energy, transportation sectors, buildings, marine and water management infrastructure with devastating impacts in EU appraising the social and economic losses. The targeted strategic objective of recent research is to move towards infrastructure network(s) that is resilient to today's natural hazards and prepared for the future changing climate. Buildings substitute a major part of critical infrastructure and urban environment with several uses and the disaster risk protection and the preservation of buildings towards natural hazards developing monitoring-decision support tools with best practices, adaptation strategies, action plans will add to the safety of the citizens. In this context, *EU-CIRCLE "A pan-European framework for strengthening Critical Infrastructure resilience to climate change"* project established an innovative framework for supporting the interconnected European Infrastructure's resilience to climate pressures. The current study was based on literature review within EU CIRCLE of frameworks for risk assessment, mainly derived from the following sources: international standards, description of similar projects implemented by cities, regions, nations, studies on risk assessment and distillation of most common approaches deployed for risk management. The most common climatic hazards are referred along with their critical parameters and thresholds. The identification of buildings climate vulnerabilities requires a detailed knowledge of climate change hazards and factors affecting the likelihood of each potential impact (e.g. region, geography, etc.). Climate change affects the climatic critical thresholds and hence the design values of the Codes may need to be redefined. A generic methodology for the damage assessment of buildings is described. Several damage scales and methodologies exist for the qualitative or quantitative assessment of damage. Once the asset/ network is thoroughly described and the hazard scenario is selected, the analysis is conducted producing a quantifiable information on how specific exposed structural types of buildings response to the induced climatic action with varying intensity levels in different time steps. The severity of damage is connected with the type of the developed damage of structural and non-structural damage (position, type, width of cracks, drifts, joint damages, bar buckling, failure of infills, failure of beams and columns, partial collapse etc.). The extent and severity of damage are both dependent on the structural type of the building and the type and intensity of hazard. The correlation between the severities of any type of hazard - provoking damage in a building could be expressed with different existing mathematical formulae. Several uses of buildings are referred that belong in critical sectors along with the thresholds and impacts of diffrenent natural hazards. Additionally, structural design principles for buildings according to Eurocodes and existing damage models are presented for specific climate hazards: flood, wind, snow, high temperature, drought and temperature difference. The preservation of buildings safety and functionality and the strengthening of the adaptation and resilience to future provoking climatic risk is considered crucial for the prosperity of the societies. Climate change impacts have consequences in the structural design of new buildings and the preservation of the existing building stock, as climatic actions on buildings have intensities that vary in time and the existing standards need to be revitalized. There is a consistent effort by the European Union to contribute to the standardization process in the examined research field in order to lift the results, in the domain of climate impact assessment and resilience of buildings and defense the societies from natural threatens.

Compliance with ethical standards

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References

[1] IPCC- The Intergovernmental Panel on Climate Change. (2014). Climate Change 2014, Impact, Adaptation and Vulnerability, Top-level findings from the working group II AR5 summary for policy makers https://www.ipcc.ch/site/assets/uploads/2018/03/WGIIAR5_SPM_Top_Level_Findings-1.pdf.

[2] EU Climate Adaptation Strategy. (2013). Adapting infrastructure to climate change. https://ec.europa.eu/clima/policies/adaptation/what_en#tab-0-1.

[3] Swiss Reinsurance Company (Swiss Re Grouup). (2011). The hidden risks of climate change: An increase in property damage from soil subsidence in Europe. Zürich. https://www.preventionweb.net/files/20623_soilsubsidencepublicationfinalen1.pdf.

[4] EU-CIRCLE "A pan-European framework for strengthening Critical Infrastructure resilience to climate change" Horizon 2020 project. http://www.eu-circle.eu/.

[5] Auckland Council. (2014). Natural Hazard Communication Toolbox. Natural Hazard Risk Management Action Plan. https://www.civildefence.govt.nz/resources/natural-hazard-risk-communication-toolbox.

[6] EN 1990: Eurocode: Basis of Structural Design – Eurocodes. https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-basis-structural-design.

[7] U.S. Department of Energy Office of Energy Policy and Systems Analysis. (2016). Climate Change and the Electricity Sector Guide for Climate Change Resilience Planning. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.energy.gov/sites/prod/files/2016/10/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf

[8] Pantazopoulou, S. J. (2013). State of the Art Report for the Analysis Methods for Unreinforced Masonry Heritage Structures and Monuments. European Centre on Prevention and Forecasting of Earthquakes (ECPFE). ecpfe.oasp.gr/en/node/89

[9] Choi, J., Deshmukh, A., Naderpajouh, N. and Hastak, M. (2017). Dynamic relationship between functional stress and strain capacity of post-disaster infrastructure. Natural Hazards, 87(2), 817–841.

[10] Pinto, P.E., Cavalieri, F., Franchin, P. and Vanzi, I. (2011). Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructure Safety Gain. doi: 10.2788/23242.

[11] De Groeve T, Poljansek K, Ehrlich D. (2013). Recording Disaster Losses: Recommendations for a European approach. EUR 26111. Luxembourg (Luxembourg): Publications Office of the European Union. JRC83743. DOI: 10.2788/98653.

[12] De Groeve T, Poljansek K, Ehrlich D, Corbane C. (2014). Current status and Best Practices for Disaster Loss Data recording in EU Member States: A comprehensive overview of current practice in the EU Member States. EUR 26879. Luxembourg (Luxembourg): Publications Office of the European Union. JRC92290. DOI: 10.2788/18330.

[13] Integrated Research on Disaster Risk. (2015). Guidelines on Measuring Losses from Disasters: Human and Economic Impact Indicators, DATA Project Report No. 2. https://climate-adapt.eea.europa.eu/en/metadata/guidances/guidelines-on-measuring-losses-from-disasters-human-and-economic-impact-indicators.

[14] Janssens, V., O'Dwyer, D.W. & Chryssanthopoulos, M.K. (2011). Building failure consequences. In M. Faber, H. Narasimhan, J. Sørensen, T. Vrouwenvelder & M. Chryssanthopoulos (Eds.) Robustness of structures: Proceedings of the Final Conference of COST Action TU0601. Prague: Czech Technical University in Prague, 169-188.

[15] Department of Homeland Security, FEMA. (2013). HAZUS MH Flood Model. https://www.fema.gov/sites/default/files/2020-09/fema_hazus_flood-model_technical-manual_2.1.pdf.

[16] International Code Council (ICC). (2001). ICC performance code for buildings and facilities, International Code Council, Falls Church Va. https://codes.iccsafe.org/content/ICCPC2015/preface

[17] Van Westen, C.J., Alkema, D., Damen, M.C.J., Kerle, N. and Kingma, N.C. (2011). Multi- hazard risk assessment: Distance education course, Guide book.

[18] Messner F, Penning-Rowsell E, Green C, Meyer V, Tunstall S, van der Veen A (2007) Evaluating flood damages: guidance and recommendations on principles and methods. FLOODsite Project Deliverable D9.1, Contract No: GOCE-CT-2004-505420

[19] Sterna, L. (2012). Pluvial flood damage modelling: Assessment of the flood damage model HOWARD-PREVENT. Master of Science Thesis. Department of Water Management Faculty of Civil Engineering and Geosciences Delft University of Technology, Delft. https://repository.tudelft.nl/file/File_6ded5787-3e7e-48c0-a54b-9b3184cd05a9?preview=1

[20] Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J. and Green,C. (2005). The Benefits of Flood and Coastal Risk Management:. A Handbook of Assessment Techniques. Middlesex University Press. https://dl.icdst.org/pdfs/files4/3a1260742ae7c15e3b203cbdaadfd6ab.pdf

[21] Genovese, E. (2006). A methodological approach to land use based flood damage assessment in urban areas: Prague case study. European Commission, Joint Research Centre.

[22] Hammond, M.J., Chen, A.S., Djordjević, S., Butler, D., Khan, D.M., Rahmann, S.M.M., Haque, A.K.E. and Mark, O. (Eds.) (2012). The development of a flood damage assessment tool for urban areas. 9th International Conference on Urban Drainage Modelling.

[23] Hammond M., Chen AS., Butler D. et al. (2014). Flood Damage Model Guidelines. https://ore.exeter.ac.uk/repository/handle/10871/21213

[24] Van der Veen, A. and Logtmeijer, C. (2003). A 10 - How vulnerable are we for follding? A GIS approach", in van der Veen, A., Vetere Arellano, A.L. and Nordvik, J.-P. (Eds.). In search of a common methodology on damage estimation: Workshop Proceedings, Delft, 181–193.

[25] Custer, R. and Nishijima, K. (2015). Flood vulnerability assessment of residential buildings by explicit damage process modelling. Natural Hazards, 78(1), 461–496.

[26] Dutta, D., Herath, S. and Musiake, K. (2001). Direct flood damage modeling towards urban flood risk management. Urban Safety Engineering, 127–143.

[27] Dutta, D., Herath, S. and Musiake, K. (2003). A mathematical model for flood loss estimation. Journal of Hydrology, 277 (1-2), 24–49.

[28] Kok, M., Huizinga, H.J., Vrouwenvelder, A. and Barendregt, A. (2004). Standard method 2004 damage and casualties Caused by Flooding. https://open.rijkswaterstaat.nl/@187575/standard-method-2004-damage-and/.

[29] Schwarz, J. and Maiwald, H. (2012), Empirical vulnerability assessment and damage for natural hazards following the principles of modern macroseismic scales. Conference: 15th World Conference Earthquake Engineering, Lisboa . Paper 5652. DOI: 10.13140/2.1.3455.4565.

[30] Kreibich, H. and Thieken, A.H. (2008). Assessment of damage caused by high groundwater inundation. Water Resources Research, 44(9), p. 314.

[31] Nikolowski, J., Goldberg, V., Zimm, J. and Naumann, T. (2013). Analysing the vulnerability of buildings to climate change. Summer heat and flooding. Meteorologische Zeitschrift, 22(2), 145–153.

[32] Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., Gericke, A., Neal, J., Aerts, J.C.J.H. and Ward, P.J. (2012). Comparative flood damage model assessment. Towards a European approach. Natural Hazards and Earth System Science, 12(12), 3733– 3752.

[33] Nafari, R.H. (2015). Flood Damage Assessment with the Help of HEC-FIA Model: Master of Science Thesis. https://www.politesi.polimi.it/bitstream/10589/86182/1/2012_13_Hasanzadeh%20Nafari.pdf

[34] European Union (2003), EN 1991-1-3: Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads: EN 1991-1-3. European Union (2003a), EN 1991-1-3: Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads: EN 1991-1-3. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.3.2003.pdf

[35] European Union (2003), EN 1991-1-5 Eurocode 1: Actions on structures - Part 1-5: General actions - Thermal actions: EN 1991-1-5. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.5.2003.pdf

[36] European Union (2005), EN 1991-1-4: Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions. Brussels: CEN/TC 250 - Structural Eurocodes. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.4.2005.pdf

[37] European Union (2005), EN 1993-1-2: Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1993.1.2.2005.pdf

[38] Liel, A., Jackson, K. and Geis, J. (2011) A framework for performance-based design and assessment of buildings subjected to extreme snow loads", in Nishijima, K. (Ed.), Applications of Statistics and Probability in Civil Engineering, CRC Press, 924–931.

[39] Barbolini, M., Cappabianca, F. and Sailer, R. (Eds.). (2004). Empirical estimate of vulnerability relations for use in snow avalanche risk assessment. Management information systems, WIT Press; For USA Canada and Mexico Computational Mechanics Inc, Southampton U.K., Boston Mass., Billerica MA.

[40] Naumann, G., Spinoni, J., Vogt, J.V. and Barbosa, P. (2015). Assessment of drought damages and their uncertainties in Europe. Environmental Research Letters, 10(12). **DOI** 10.1088/1748-9326/10/12/124013

[41] Eleftheriadou, A., Sfetsos, A. and Gounaris, N. (2015). Energy performance of buildings due to downscaled seasonal models. International Journal of Environmental and Ecological Engineering, 9(7), 852–855.

[42] https://www.apsei.org.pt/media/recursos/documentos-de-outras-entidades/CFPA-guideline- riscos naturais/cfpa_e_guideline_no_3_2013_n_1389624941.pdf.

[43] https://www.fema.gov/media-library-data/20130726-1557-20490-6102/fema543_chapter3.pdf.

[44] https://www.din.de/en

[45] https://www.fema.gov/media-library-data/7d8c55d1c4f815edf3d7e7d1c120383f/FEMA957_Snowload_508.pdf

[46] European Environment Agency. (2007). Addressing the challenge of water scarcity and droughts in the European Union. Brussels. https://www.eea.europa.eu/policy-documents/addressing-the-challenge-of-water

[47] EU (2007). Mediterranean Water Scarcity and Drought Report, Technical Report - 009 – 2007, produced by the Mediterranean water scarcity & drought working group (MED WS&D WG). https://op.europa.eu/en/publication-detail/-/publication/d1e25d61-c6f0-4759-988f-447377f1315b/language-en

[48] Water Scarcity Drafting Group. (2006). Waterscarcity management in the context of the WFD. MED Joint Process WFD /EUWI. https://docslib.org/doc/10285874/water-scarcity-management-in-the-context-of-wfd

[49] McKee T.B., Doeskin N.J., Kleist J., (1993). The relationship of drought frequency and duration to time scales, Proceedings of the 8th Conference on Applied Climatology, American Meteorological Society, Boston, 179-184.

[50] Nikolowski J., Goldberg V., Zimm J., Naumann T. (2013). Analysing the vulnerability of buildings to climate change: Summer heat and flooding. Meteorologische Zeitschrift 22(2):145-153, DOI: 10.1127/0941-2948/2013/0388.