TECHNICAL REPORT

ISO/TR 22845

First edition
2020-08

Resilience of buildings and civil engineering works

Reference number
ISO/TR 22845:2020(E)

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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 59, *Buildings and civil engineering works*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Resilience is not a new concept. It is widely used in many fields such as human psychology, ecology, disaster risk management and product specification.

With an increasing impact, resilience is contributing to sustainable development on humanitarian issues at a global level, focusing on providing the general public, including vulnerable groups, with an environment that can better adapt to future disaster risks.

In view of the increasing demand for resilience of buildings and civil engineering works, this document attempts to collect and summarize typical relevant existing information to provide reference for research and standard preparation. Information is aggregated mainly on concept, disaster risk and countermeasure:

1) For concept, this document sorts out some perspectives of resilience in different contexts and definitions of resilience that have appeared in ISO documents.

2) For disaster risk, this document describes three categories of disaster risk closely related to buildings and civil engineering works, i.e. climate-induced, earthquake-induced and human-induced, and indexes some typical related reports and data.

3) For countermeasure, this document summarizes typical relevant information from the two dimensions of strategy and measurement. Some of this information is relatively mature, already in the form of standards, guidelines, etc., some are implemented in cases, and some are at the research stage.

Resilience of buildings and civil engineering works involves interested parties and participants which can include specialists in the field of buildings and civil engineering works (such as material manufacturers, engineers, architects, constructers and estimators, etc.), scientists, standard setters, investors and financial institutions, regulatory agencies, communities, residents and occupiers, government administrative departments, etc.

Resilience of buildings and civil engineering works

1 Scope

This document provides an index of typical existing information on concept, disaster risk and countermeasure for resilience of buildings and civil engineering works.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Concept

4.1 Perspectives in different contexts

Resilience is derived from the Latin word "resilio" for bounce[2] and in most cases its use retains this concept either literally or figuratively. The Oxford Dictionary of English gives two explanations of resilience, "the ability of a substance or object to spring back into shape" and "the capacity to recover quickly from difficulties"[3], which could be understood as mechanical and functional resilience respectively. Some domains also have understandings of resilience from different perspectives. Table 1 is a summary of some typical descriptions of resilience in different contexts, extracted from the literature found.

Table 1 — Resilience in different contexts

Context	Perspective	Citation
Ecology	A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.	Holling, C.S. 1973[4]
Risk management	Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back.	Wildavsky, A. 1988[5]
	The ability to recoil effectively from adversity and enhancing the likelihood of exposure to adversity leading to growth.	Paton, D. and Johnston, D. 2001[6]
Building	A resilient built environment should be designed, located, built, operated and maintained in a way that maximises the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate for the impacts of extreme natural and human-induced hazards.	Bosher, L. 2008[7]
	Resilience is the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance.	Resilient Design Institute[8]

Table 1 *(continued)*

Context	Perspective	Citation
Urban	The capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience.	Rockefeller Foundation[9]
The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.		UNDRR[10]

4.2 Definitions in ISO documents

There are 26 hits when searching for definitions of "resilience" on the ISO Online Browsing Platform (ISO OBP). In material and product standards, different forms of mechanical resilience are defined. Standards dealing with systems, on the other hand, focus on forms of functional resilience appropriate to the systems. Table 2 shows examples of these two types of definitions in ISO documents.

Table 2 — Definitions in ISO documents

Type	Term	Definition	Source
Mechanical resilience	resilience	ability of ceramic fibres to spring back after compression to 50 % of thickness	ISO 836:2001, 113
	resilience	ability of a textile floor covering to regain thickness after a static or dynamic compression	ISO 2424:2007, 9.1.2.1
	rebound resilience	ratio between the returned and the applied energy of a moving mass which impacts a test piece	ISO 4662:2017, 3.1
	elasticity, noun springiness, noun resilience, noun	mechanical textural attribute relating to: the rapidity of recovery from a deforming force; and the degree to which a deformed material returns to its original condition after the deforming force is removed	ISO 5492:2008, 3.50

Table 2 *(continued)*

Type	Term	Definition	Source
Functional resilience of system	resilience	ability of an organization to resist being affected by disruptions	ISO/IEC 27031:2011, 3.14
	resilience	ability to absorb and adapt in a changing environment	ISO 22300:2018, 3.192
	resilience fault tolerance	tolerance of a system to malfunctions or capacity to recover functionality after stress	ISO 18457:2016, 3.9
	organizational resilience	ability of an organization to absorb and adapt in a changing environment	ISO 22316:2017, 3.4
	resilience	ability to recover from security compromises or attacks	ISO/IEC 29180:2012, 3.2.10
	resilience	adaptive capacity of an organization in a complex and changing environment	ISO Guide 73:2009, 3.8.1.7 ISO 28002:2011, 3.44 ISO 18788:2015, 3.47 ISO 37101:2016, 3.33 ISO 37100:2016, 3.1.3 ISO 37123:2019, 3.6
	fault tolerance resilience	ability of a functional unit to continue to perform a required function in the presence of faults or errors	ISO/IEC 2382:2015, 2123055
	resilience	capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation	ISO 14080:2018, 3.1.3.6

According to the ISO OBP, there are currently some 320 standards in which reference is made to resilience, by title and/or content, although often without defining what is meant by the term. Below are some examples of ISO standards which explicitly focus on resilience. Two of these relate to mechanical resilience and one to functional resilience of systems:

— ISO 8307, prepared by ISO/TC 45, Rubber and rubber products;

— ISO 4662, prepared by ISO/TC 45, Rubber and rubber products;

— ISO 28002, prepared by ISO/TC 292, Security and resilience.

The following standard is concerned with mechanical resilience but refers to it as "elastic recovery":

— ISO 7389, prepared by ISO/TC 59/SC 8, Sealants.

5 Disaster risk

5.1 General

Since resilience is the ability to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard[10], it is necessary to understand the status of disaster risks, which is a prerequisite for the development of resilience standards for buildings and civil engineering works.

This document collects three categories of disaster risks closely related to buildings and civil engineering works: climate-induced, earthquake-induced and human-induced, and indexes some related reports and data sets of these disaster situations. Since the life of a building or civil engineering work will be tens or even hundreds of years, it is also necessary to pay attention to future possibilities of disaster risks.

5.2 Climate-induced

For climate-induced disaster risks, this document mainly collects some typical reports and data. From them, the following can be seen:

1) **The frequency and economic losses of global meteorological disasters have increased**: Under the background of global climate change, the frequency and economic losses of meteorological disasters have an obviously upward trend, being detrimental to the safety of human life and property and the sustainable economic and social development.

2) **The global climate risks will continue rising**: Looking ahead to the coming decades of the 21st century, global climate risks will continue rising due to climate change and increased exposure and vulnerability brought about by urbanization. Among them, changes of risks such as **high temperature, low temperature, heavy precipitation, tropical cyclone, drought** and **sea level rise** can have certain impact on buildings and civil engineering works. These impacts have important implications for considering the resilience standard of buildings and civil engineering works in the long term. Table 3 shows projected changes of global annual mean temperature, high temperature, low temperature, heavy precipitation, tropical cyclone, drought and sea level rise in the 21st century, extracted from the collected data.

Table 3 — Projected changes of global annual mean temperature, high temperature, low temperature, heavy precipitation, tropical cyclone, drought and sea level rise in the 21st century under different emission scenarios[30],[31],[32],[33]

Annual mean temperature	**RCP2.6**		**RCP4.5**		**RCP8.5**	
	Mid-21st century	Late 21st century	Mid-21st century	Late 21st century	Mid-21st century	Late 21st century
	(1,0 ± 0,3) °C	(1,0 ± 0,4) °C	(1,4 ± 0,3) °C	(1,8 ± 0,5) °C	(2,0 ± 0,4) °C	(3,7 ± 0,7) °C
High temperature	The 1-in-20-year extreme daily maximum temperature will likely increase by about 1 °C to 3 °C and 2 °C to 5 °C by the mid- and late 21st century respectively, depending on different regions and emission scenarios. A 1-in-20-year hottest day is likely to become a 1-in-2 and 1-in-5-year event by the end of 21st century for the high and low emission scenarios respectively. The heat related risks increase with greater degrees of warming. 13,8 % of the world population would be exposed to severe heat waves at least once every 5 years under 1,5 °C of global warming, with a threefold increase (36,9 %) under 2 °C warming.					
Low temperature	Cold days and cold nights are very likely to become much less frequent. Further decreases in the number of cold days/nights and an increase in overall temperature of cold extremes would occur under 1,5 °C of global warming compared to under the present-day climate (1 °C of warming), with further changes occurring towards 2 °C of global warming. And in some regions, cold-related mortality is projected to decrease with increasing temperatures.					
Heavy precipitation	A 1-in-20-year annual maximum daily precipitation amount is likely to become a 1-in-5 to 1-in-15-year event by the end of the 21st century in most regions under higher emission scenarios. Projected increase in heavy precipitation will contribute to rain-generated local flooding in some catchments or regions. Over the global land monsoon region, an estimated 25 % (18 % to 41 %) and 36 % (22 % to 46 %) of area and population, respectively, could be relieved from the baseline 1-in-20-year events over the present-day level, if global warming were limited to 1,5 °C instead of 2 °C.					
Tropical cyclone	The global frequency of tropical cyclones will either decrease or remain essentially unchanged in 21st century. Average tropical cyclone maximum wind speed will likely increase, although it is possible that increases will not occur in all ocean basins. There is limited evidence that the global number of tropical cyclones will be lower under 2 °C of global warming compared to under 1,5 °C of warming, but with an increase in the number of very intense cyclones. In coastal regions, increases in heavy precipitation associated with tropical cyclones combined with increased sea levels can lead to increased flooding.					

Table 3 *(continued)*

Drought	Droughts will intensify in the 21st century in some seasons and areas, and extreme drought is projected to act as the normal climatological state by the end of the 21st century under the high emission scenarios in many mid-latitude locations. Duration of droughts are also projected to increase in some regions of the world.		
Sea level rise	0,4 m (0,26 m to 0,55 m) rise by the late 21st century	0,47 m (0,32 m to 0,63 m) rise by the late 21st century	0,63 m (0,45 m to 0,82 m) rise by the late 21st century

Meanwhile, there are some online map tools for visualizing global or national climate projections. Some of them show changes in risks such as temperature, precipitation and sea level rise in different periods of the 21st century under different emission scenarios. These projections can play a supporting role in the decision-making of investment, standards and design for the resilience of buildings and civil engineering works.

Some countries and organizations have proposed initiatives and action plans to address climate change, targeting parts of cities, communities, buildings, infrastructure, etc., which can have certain implications for the resilience of buildings and civil engineering works.

5.3 Earthquake-induced

For earthquake-induced disaster risks, this document mainly collects some typical data on seismic risk. From them, the following can be seen:

1) **The global seismic risk remains severe:** Earthquake is one of the most catastrophic natural hazards to human beings. With rapid urbanization in recent years, an increasing amount of population as well as property will be exposed to seismic risks. At the same time, aging and changes in strength and stiffness can also impair the seismic safety and serviceability of the existing engineering structure.

2) **It is challenging to meet the demand for resilience via traditional seismic resistance methods:** In certain recent earthquakes, although some buildings did not collapse, they could hardly be repaired due to the severe damage, causing enormous economic loss and substantial social impact. For example, after the Christchurch earthquake in New Zealand in 2011, none of the 51 tallest buildings in the city collapsed owing to the rigorous seismic standards of New Zealand. Nonetheless, 37 of these tall buildings had to be demolished due to their severe damage and potentially high costs to repair[34]. Furthermore, other seismic resilience issues also occurred in the Great East Japan earthquake in 2011, and in the Haiti earthquake in 2010.

These issues indicate that resilience enhancement of buildings and communities is essential, which is illustrated in Figure 1.

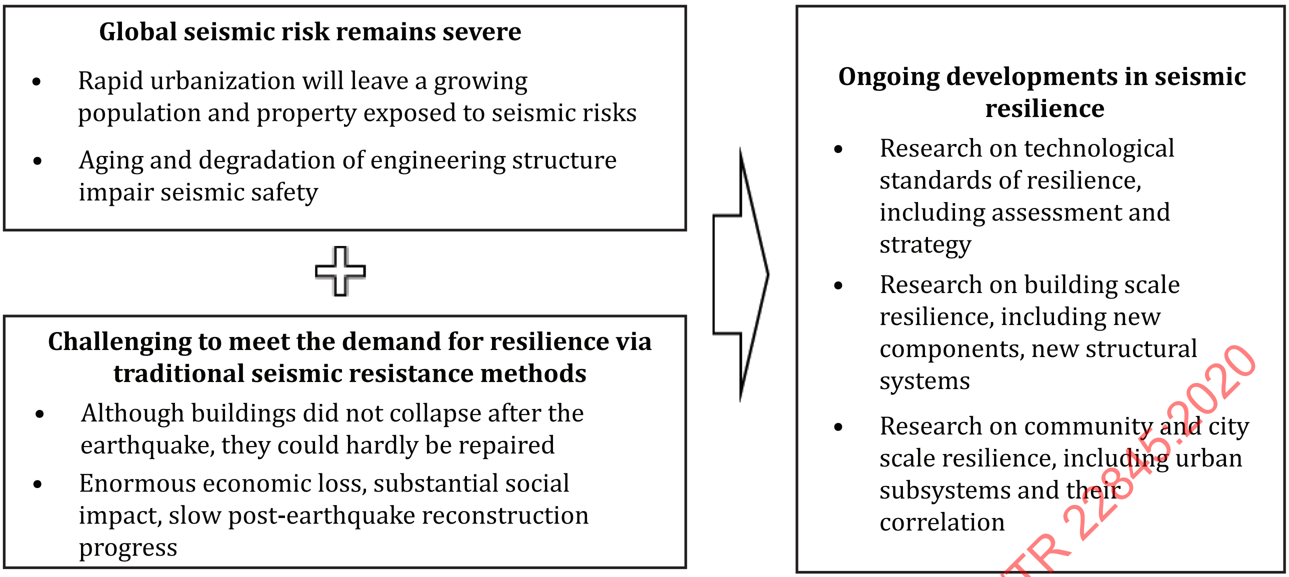

Figure 1 — Seismic resilience is essential

Meanwhile, some online map tools have been developed for the visualization of global or national seismic risk. They can support decision-making for investment, standardization and design related to seismic resilience of buildings and civil engineering works.

5.4 Human-induced

For human-induced disaster risks, this document focuses on collecting relevant information on global terrorist attacks. From them, the following can be seen:

1) **Global terrorist attacks are increasing:** Incidents involving hostage-taking, assassination, and attacks on facilities or infrastructure all increased over tenfold in the past two decades[35].

2) **Counter-terrorism engineering design is increasingly important for buildings and communities:** Some countries are now beginning to consider how building and engineering professionals can assist in reducing the impact of terrorism through design.

6 Countermeasure

6.1 Strategy

At present, practice and research on the resilience strategy of buildings and civil engineering works have progressed to a certain extent. The collected data shows the following characteristics:

In different forms: Some strategies are relatively mature, refined into systems such as standards and guidelines; some are implemented in cases; and some are still at the research stage.

For different types of disaster risks: Some systems are broad-spectrum, targeting multiple types of disaster risks, while some focus on one type.

Consider the future: For the sake of the future, some climate related strategies consider the impact of climate change on buildings and civil engineering works.

Table 4 sorts out some typical sources of these strategies according to the two dimensions of disaster risk categories (climate-induced/earthquake-induced/human-induced) and forms (system, case, research).

Table 4 — Summary of typical resources of resilience strategies

Resource	Disaster risk			Form		
	Climate-induced	Earthquake-induced	Human-induced	System	Case	Research
Community Resilience Planning Guide for Buildings and Infrastructure Systems - Volume I https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1190v1.pdf	√	√	√	√		
CRBCPI https://www.infrastructure.gc.ca/plan/crbcpi-irccipb-eng.html	√			√		
RELi http://c3livingdesign.org/?page_id=11817	√	√	√	√		
LEED IPpc98/IPpc99/IPpc100 https://leeduser.buildinggreen.com/credit/Pilot-Credits/IPpc98, IPpc99, IPpc100	√	√	√	√		
BREEAM Adaption to climate change https://www.designingbuildings.co.uk/wiki/BREEAM_Adaptation_to_climate_change	√			√		
DGNB criteria "Local environment" https://www.dgnb-system.de/en/system/version2018/criteria/local-environment/	√	√	√	√		
Climate Resiliency Design Guidelines https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v3-0.pdf	√			√		
Durability and Climate Change https://www.researchgate.net/publication/328538874	√					√
Inundation Mapping http://www.2030palette.org/inundation-mapping/	√					√
RDI http://www.resilientdesign.org/	√	√	√		√	√
Boston's Spaulding Rehabilitation Center designed with rising sea levels in mind http://plus.usgbc.org/building-for-the-flood/	√				√	
Cognitive infrastructure – a modern concept for resilient performance under extreme events https://doi.org/10.1016/j.autcon.2018.03.004	√	√	√			√
Strict building codes helped Anchorage withstand quake https://www.adn.com/alaska-news/2018/12/01/experts-alaska-quake-damage-could-have-been-much-worse/		√			√	
Earthquake Disaster Simulation of Civil Infrastructures: From Tall Buildings to Urban Areas https://www.springer.com/us/book/9789811030864		√				√

Table 4 *(continued)*

Resource	Disaster risk			Form		
	Climate-induced	Earthquake-induced	Human-induced	System	Case	Research
Resilient Design Tool: For Counter Terrorism https://www.securedbydesign.com/images/downloads/resilient-design-tool-for-counter-terrorism.pdf			√	√		
Integrating counter-terrorist resilience into sustainability https://www.icevirtuallibrary.com/doi/10.1680/udap.2008.161.2.75			√		√	√

6.2 Measurement

The measurement of the resilience of buildings and civil engineering works has progressed to some extent. The characteristics of collected data are similar to those of strategies. Some of them are relatively mature and have become standards, rating tools, etc.; and some are still at the research stage. Some are for multiple types of disaster risks, while some are for one type. Since boundaries between strategies and measurement of resilience are sometimes blurred, some collected resources can contain both types of information.

Table 5 is the summary of some typical resilience measurement according to the categories of disaster risks (climate-induced/earthquake-induced/human-induced).

Table 5 — Summary of typical resources of resilience measurement

Resource	Disaster risk		
	Climate-induced	Earthquake-induced	Human-induced
USRC Building Rating System https://www.usrc-portal.org/	√	√	
B-READY https://www.dnvgl.com/services/b-ready-106852	√	√	
FORTIFIED Commercial https://fortifiedhome.org/commercial/	√		
The Resilient City https://www.spur.org/featured-project/resilient-city		√	
Seismic Performance Assessment of Buildings https://www.fema.gov/media-library/assets/documents/90380		√	
Standard for Seismic Resilience Assessment of Buildings http://www.mohurd.gov.cn/zqyj/201809/t20180921_237686.html		√	
REDi https://www.arup.com/perspectives/publications/research/section/redi-rating-system		√	

7 Compilation of existing information

7.1 Concept

7.1.1 Terminology: Resilience[10]

Citation	United Nations Office for Disaster Risk Reduction (UNDRR)
Abstract	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.
Hyperlink	https://www.undrr.org/terminology/resilience

7.1.2 Built-in resilience through disaster risk reduction: operational issues[36]

Author	Lee Bosher
Citation	Building Research & Information, 2014, 42(2), 240–254
Abstract	It has been argued that the broad range of people responsible for the delivery, operation and maintenance of the built environment need to become more proactively involved in making the built environment resilient to a wide range of known and unforeseen hazards and threats. Accordingly, the (actual and potential) roles of a wide range of stakeholders associated with the integration of disaster risk reduction into the (re-)development of the built environment are examined.
Hyperlink	https://dx.doi.org/10.1080/09613218.2014.858203

7.1.3 Four concepts for resilience and the implications for the future of resilience engineering[37]

Author	David D. Woods
Citation	Reliability Engineering and System Safety, 2015, 141(C), 5–9
Abstract	The paper organizes the different technical approaches to the question of what is resilience and how to engineer it in complex adaptive systems. The paper groups the different uses of the label "resilience" around four basic concepts: (1) resilience as rebound from trauma and return to equilibrium; (2) resilience as a synonym for robustness; (3) resilience as the opposite of brittleness, i.e., as graceful extensibility when surprise challenges boundaries; (4) resilience as network architectures that can sustain the ability to adapt to future surprises as conditions evolve.
Hyperlink	https://dx.doi.org/10.1016/j.ress.2015.03.018

7.1.4 Sendai Framework for Disaster Risk Reduction 2015-2030[38]

Citation	United Nations
Abstract	The document outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster risks. It aims to achieve the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries over the next 15 years.
Hyperlink	https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

7.2 Climate-induced

7.2.1 Global Assessment Report on Disaster Risk Reduction[39]

Citation	United Nations Office for Disaster Risk Reduction (UNDRR)
Abstract	The United Nations Office for Disaster Risk Reduction (UNDRR) works with thinkers, practitioners, experts and innovators to investigate the state of risk across the globe, highlighting what's new, spotting emerging trends, revealing disturbing patterns, examining behaviour and presenting progress in reducing risk. The findings make up the Global Assessment Report on Disaster Risk Reduction (GAR), which is published every two years.
Hyperlink	https://gar.undrr.org/report-2019

7.2.2 Emergency Events Database (EM-DAT)[40]

Citation	Centre for Research on the Epidemiology of Disasters (CRED)
Abstract	The main objective of the database is to serve the purposes of humanitarian action at national and international levels. The initiative aims to rationalise decision making for disaster preparedness, as well as provide an objective base for vulnerability assessment and priority setting. EM-DAT contains essential core data on the occurrence and effects of over 22 000 mass disasters in the world from 1900 to the present day. The database is compiled from various sources, including UN agencies, non-governmental organisations, insurance companies, research institutes and press agencies.
Hyperlink	https://www.emdat.be/

7.2.3 Global Warming of 1,5 °C[32]

Citation	Intergovernmental Panel on Climate Change (IPCC)
Abstract	An IPCC special report on the impacts of global warming of 1,5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
Hyperlink	https://www.ipcc.ch/sr15/

7.2.4 Climate Change 2014: Synthesis Report[41]

Citation	Intergovernmental Panel on Climate Change (IPCC)
Abstract	The Synthesis Report (SYR) of the IPCC Fifth Assessment Report (AR5) provides an overview of the state of knowledge concerning the science of climate change, emphasizing new results since the publication of the IPCC Fourth Assessment Report (AR4) in 2007.
Hyperlink	https://www.ipcc.ch/report/ar5/syr/

7.2.5 Climate Change 2013: The Physical Science Basis[30]

Citation	Intergovernmental Panel on Climate Change (IPCC)
Abstract	The Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive assessment of the physical science basis of climate change since 2007 when the Fourth Assessment Report (AR4) was released.
Hyperlink	https://www.ipcc.ch/report/ar5/wg1/

7.2.6 Global Climate Risk Index[42]

Citation	Germanwatch
Abstract	The annually published Global Climate Risk Index analyses to what extent countries have been affected by the impacts of weather-related loss events (storms, floods, heat waves etc.).
Hyperlink	https://germanwatch.org/en/cri

7.2.7 Climate Change Knowledge Portal (CCKP)[43]

Citation	World Bank Group
Abstract	The Climate Change Knowledge Portal (CCKP) provides global data on historical and future climate, vulnerabilities, and impacts. Explore them via country, region, and watershed views. Access synthesized country profiles to gain deeper insights into climate risks and adaptation actions.
Hyperlink	https://climateknowledgeportal.worldbank.org

7.2.8 CREAT Climate Scenarios Projection Map[44]

Citation	United States Environmental Protection Agency (EPA)
Abstract	The map provides easy-to-access scenario-based climate change projections drawn from Climate Resilience Evaluation and Awareness Tool (CREAT). The impacts from a changing climate, including extreme heat and more intense storms, present challenges to water, wastewater, and stormwater utilities and the communities they serve.
Hyperlink	https://epa.maps.arcgis.com/apps/MapSeries/index.html?appid=3805293158d54846a29f750d63c6890e

7.2.9 Climate Projections[45]

Citation	CSIRO, Bureau of Meteorology
Abstract	Climate projections show how Australia's climate may change in the future. They are spatially focused around natural resource management regions (or clusters) for which information, data and reports are available.
Hyperlink	https://www.climatechangeinaustralia.gov.au/en/climate-projections/

7.2.10 UK Climate Projections (UKCP)[46]

Citation	Met Office
Abstract	The UKCP is a climate analysis tool that forms part of the Met Office Hadley Centre Climate Programme. It provides the most up-to-date assessment of how the climate of the UK may change over the 21st century.
Hyperlink	https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

7.2.11 Climate Atlas of Canada[47]

Citation	Prairie Climate Centre (PCC)
Abstract	The Climate Atlas of Canada combines climate science, mapping and storytelling to bring the global issue of climate change closer to home for Canadians. It is designed to inspire local, regional, and national action and solutions.
Hyperlink	https://climateatlas.ca/

7.2.12 CEDIM Risk Explorer Germany[48]

Citation	Center for Disaster Management and Risk Reduction Technology (CEDIM)
Abstract	CEDIM Risk Explorer Germany is a web-based map viewer that offers users to retrieve maps of datasets developed within the project CEDIM risk map Germany, including natural and man-made hazards, vulnerability and risk as well as assets.
Hyperlink	http://cedim.gfz-potsdam.de/riskexplorer/

7.2.13 Sea Level Rise Viewer[49]

Citation	National Oceanic and Atmospheric Administration (NOAA)
Abstract	Use this web mapping tool to visualize community-level impacts from coastal flooding or sea level rise (up to 10 feet above average high tides). Photo simulations of how future flooding might impact local landmarks are also provided, as well as data related to water depth, connectivity, flood frequency, socio-economic vulnerability, wetland loss and migration, and mapping confidence.
Hyperlink	https://coast.noaa.gov/slr/#/layer/slr/10/-8319534.390784824/5177499.015449485/7/satellite/none/0.8/2050/interHigh/midAccretion

7.2.14 Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1,5 °C, 2 °C, and 3 °C global warming[50]

Author	Alessandro Dosio, Erich M. Fischer
Citation	Geophysical Research Letters, 2018, 45(2), 935–944
Abstract	Based on high-resolution models, the paper investigates the change in climate extremes and impact-relevant indicators over Europe under different levels of global warming, and specifically assess the robustness of the changes and the benefits of limiting warming to 1,5 °C instead of 2 °C.
Hyperlink	https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL076222

7.2.15 North China Plain threatened by deadly heatwaves due to climate change and irrigation[51]

Author	Suchul Kang, Elfatih A.B. Eltahir
Citation	Nature Communications, 2018, 9(1), 2894
Abstract	Based on an ensemble of high-resolution regional climate model simulations, this paper projects that climate change would add significantly to the anthropogenic effects of irrigation, increasing the risk from heatwaves in the North China Plain. Under the business-as-usual scenario of greenhouse gas emissions, North China Plain is likely to experience deadly heatwaves with wet-bulb temperature exceeding the threshold defining what Chinese farmers may tolerate while working outdoors.
Hyperlink	https://www.nature.com/articles/s41467-018-05252-y

7.2.16 Climate Change 2014: Impacts, Adaptation, and Vulnerability[52]

Citation	Intergovernmental Panel on Climate Change (IPCC)
Abstract	The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change since 2007 when the Fourth Assessment Report (AR4) was released.
Hyperlink	https://www.ipcc.ch/report/ar5/wg2/

7.2.17 National Climate Assessment[53]

Citation	U.S. Global Change Research Program
Abstract	The report provides an in-depth look at climate change impacts on the U.S. It details the multitude of ways climate change is already affecting and will increasingly affect the lives of Americans.
Hyperlink	https://nca2014.globalchange.gov/report

7.2.18 Myanmar National Framework for Community Disaster Resilience[54]

Citation	National Disaster Management Committee (NDMC)
Abstract	The Myanmar National Framework for Community Disaster Resilience seeks to achieve people-centered, inclusive, and sustainable socioeconomic development in the face of disasters triggered by natural hazards and climate change. The framework articulates a common understanding, proposes a coherent approach, and identifies potential opportunities for strengthening the resilience of communities in Myanmar.
Hyperlink	https://www.preventionweb.net/english/professional/policies/v.php?id=52573

7.3 Earthquake-induced

7.3.1 Global Seismic Risk Map[55]

Citation	Global Earthquake Model (GEM) Foundation
Abstract	The Global Seismic Risk Map (v2018.1) presents the geographic distribution of average annual loss (USD) normalised by the average construction costs of the respective country (USD/m^2) due to ground shaking in the residential, commercial and industrial building stock, considering contents, structural and non-structural components.
Hyperlink	https://maps.openquake.org/map/global-seismic-risk-map/#3/32.00/-2.00

7.3.2 Global Earthquake Fatalities and Population[56]

Author	Thomas L. Holzer, James C. Savage
Citation	Earthquake Spectra, 2013, 29(1), 155-175
Abstract	The paper introduces the severe situation of frequent earthquakes around the world and the casualties caused by earthquake disasters currently. Combining fatalities caused by the background rate with fatalities caused by catastrophic earthquakes (>100 000 fatalities) indicates global fatalities in the 21st century will be (2,57 ± 0,64) million if the average post-1900 death toll for catastrophic earthquakes (193 000) is assumed.
Hyperlink	https://doi.org/10.1193/1.4000106

7.3.3 Earthquakes[57]

Citation	U.S. Geological Survey (USGS)
Abstract	The website provides recent or historic earthquakes information of the U.S. and worldwide.
Hyperlink	https://www.usgs.gov/natural-hazards/earthquake-hazards/earthquakes

7.3.4 China Earthquake Networks[58]

Citation	China Earthquake Networks Center (CENC)
Abstract	The website provides detailed earthquake information of China and brief information of some severe earthquakes around the world. It helps people keep up to date on earthquake information.
Hyperlink	http://news.ceic.ac.cn/index.html?time=1573569704

7.3.5 Japan Meteorological Agency[59]

Citation	Japan Meteorological Agency (JMA)
Abstract	As part of Japan's government, the Japan Meteorological Agency (JMA) focuses its efforts on monitoring the earth's environment and forecasting natural phenomena related to the atmosphere, the oceans and the earth, as well as on conducting research and technical development in related fields.
Hyperlink	http://www.jma.go.jp/jma/en/menu.html

7.3.6 2011 Christchurch earthquake[60]

Citation	Wikipedia
Abstract	The website provides details of the M_W 6,2 Christchurch earthquake occurred in 2011. The earthquake caused widespread damage across Christchurch, killing 185 people in the nation's fifth-deadliest disaster.
Hyperlink	https://en.wikipedia.org/wiki/2011_Christchurch_earthquake

7.4 Human-induced — Global Terrorism Index 2018: Measuring the impact of terrorism[35]

Citation	Institute for Economics & Peace (IEP)
Abstract	The Global Terrorism Index (GTI) is a comprehensive study analysing the impact of terrorism for 163 countries and which covers 99,7 % of the world's population.
Hyperlink	http://visionofhumanity.org/app/uploads/2018/12/Global-Terrorism-Index-2018.pdf

7.5 Strategy

7.5.1 Community resilience planning guide for buildings and infrastructure systems - Volume I[61]

Citation	National Institute of Standards and Technology (NIST)
Abstract	The Guide outlines a practical six-step planning process to help communities improve their resilience by aligning priorities and resources with community goals.
Hyperlink	https://dx.doi.org/10.6028/NIST.SP.1190v1

7.5.2 Climate-Resilient Buildings and Core Public Infrastructure Initiative (CRBCPI)[62]

Citation	National Research Council Canada (NRC)
Abstract	CRBCPI is a 5-year initiative that began in 2016 as part of the Pan Canadian Framework on Clean Growth and Climate Change, which aims to integrate climate resilience into design guides, codes and related materials which will be the basis for future infrastructure builds and rehabilitation work in Canada.
Hyperlink	https://www.infrastructure.gc.ca/plan/crbcpi-irccipb-eng.html

7.5.3 RELi[63]

Citation	The RELi Collaborative
Abstract	RELi integrates a comprehensive package of resiliency criteria with the latest in proven design methods for developing next-generation communities, neighborhoods, buildings, homes and infrastructure. The Action List is a resource included in the RELi Green+Resilient Property Underwriting Standard and developed through a National Consensus process formally recognized by the American National Standards Association (ANSI).
Hyperlink	http://c3livingdesign.org/?page_id=11817

7.5.4 LEED IPpc98/IPpc99/IPpc100[64],[65],[66]

Citation	U.S. Green Building Council (USGBC)
Abstract	The LEED Pilot Credit Library is intended to facilitate the introduction of new credits to LEED. The process allows projects to test more innovative credits that haven't been through USGBC's complete drafting and balloting process. In LEED Pilot Credits, there are three points that focus on building resilience: Pilot-Credits IPpc98: Assessment and Planning for Resilience Pilot-Credits IPpc99: Design for Enhanced Resilience Pilot-Credits IPpc100: Passive Survivability and Functionality During Emergencies
Hyperlink	https://leeduser.buildinggreen.com/credit/Pilot-Credits/IPpc98 https://leeduser.buildinggreen.com/credit/Pilot-Credits/IPpc99 https://leeduser.buildinggreen.com/credit/Pilot-Credits/IPpc100

7.5.5 DGNB criteria "Local environment"[67]

Citation	German Sustainable Building Council (DGNB)
Abstract	In total, indicators are listed for 14 topics for evaluating the environmental risks in the local environment. The likelihood of natural disasters occurring is analysed for the purpose of the evaluation. Any auxiliary safety measures implemented on, around or for the building will also be reflected positively in the evaluation.
Hyperlink	https://www.dgnb-system.de/en/system/version2018/criteria/local-environment/

7.5.6 BREEAM Adaption to Climate Change[68]

Citation	Building Research Establishment (BRE)
Abstract	The aim of this credit is to identify how extreme weather conditions arising from climate change may affect the building's fabric and structure, and to mitigate against these effects.
Hyperlink	https://www.designingbuildings.co.uk/wiki/BREEAM_Adaptation_to_climate_change

7.5.7 Durability and Climate Change: Changing climatic loads as may affect the durability of building materials, components and assemblies[69]

Citation	CIB/NRC symposium
Abstract	The symposium focuses on "Durability and Climate Change" and more particularly on how the durability of building materials, components and assemblies may be affected by changing climatic loads as may arise due to climate change.
Hyperlink	https://www.researchgate.net/publication/328538874

7.5.8 Ocean at the door[70]

Citation	Climate Central, Zillow
Abstract	The map shows areas, homes and home value at risk of annual flooding or worse as sea levels rise, projected for the year 2050 (2100), assuming deep carbon cut (moderate carbon cuts / unchecked pollution) and early instability (stability) of Antarctica.
Hyperlink	https://rzh.climatecentral.org

7.5.9 Inundation Mapping[71]

Citation	2030 PALETTE
Abstract	Sea level rise and storm surge maps create a detailed picture of community resources and areas exposed or vulnerable to future inundation.
Hyperlink	http://www.2030palette.org/inundation-mapping/

7.5.10 Climate Resiliency Design Guidelines – Version 3.0[72]

Citation	NYC Mayor’s Office of Recovery and Resiliency
Abstract	The guidelines provide step-by-step instructions on how to supplement historic climate data with specific, regional, forward-looking climate change data in the design of city facilities.
Hyperlink	https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v3-0.pdf

7.5.11 Coastal Flood Resilience Design Guidelines[73]

Citation	Boston Planning & Development Agency (BPDA), City of Boston
Abstract	The document is a resource to help Boston property owners and developers make informed, forward-looking decisions about flood protection for existing buildings and new construction.
Hyperlink	http://www.bostonplans.org/getattachment/d1114318-1b95-487c-bc36-682f8594e8b2

7.5.12 Flood Resilient Homes Program[74]

Citation	Brisbane City Council, CitySmart
Abstract	The program is an initiative of Brisbane City Council, delivered in partnership with CitySmart, to help Brisbane residents prepare for, live through and recover from overland flow flooding events.
Hyperlink	https://www.citysmart.com.au/floodwise/

7.5.13 Designing flood resilience into new buildings[75]

Citation	Zurich Insurance Group
Abstract	The document describes some design measures, which could be considered during the planning stage of a new building, to improve building resilience to flood.
Hyperlink	https://www.zurich.com/-/media/project/zurich/dotcom/industry-knowledge/flood-resilience/docs/designing-flood-resilience-into-new-buildings.pdf?la=en

7.5.14 Resilient Design Institute[8]

Citation	Resilient Design Institute (RDI)
Abstract	RDI is a website that provides information on resilient design, including cases, principles and strategies.
Hyperlink	http://www.resilientdesign.org/

7.5.15 Boston's Spaulding Rehabilitation Center designed with rising sea levels in mind[76]

Author	Alison Gregor
Abstract	The article elaborates the panoply of resilient design strategies of Boston's Spaulding Rehabilitation Center which addresses risks such as rising sea levels.
Hyperlink	http://plus.usgbc.org/building-for-the-flood/

7.5.16 Cognitive infrastructure – a modern concept for resilient performance under extreme events[77]

Author	Naser M.Z., Kodur V.K.R.
Citation	Automation in Construction, 2018, 90, 253–264
Abstract	The paper proposes a coupled sensing-structural framework to assess the vulnerability of infrastructure under severe loading conditions, which extends principles of the recently developed "Internet of Things" (IoT) technology into civil infrastructure.
Hyperlink	https://doi.org/10.1016/j.autcon.2018.03.004

7.5.17 A framework to quantitatively assess and enhance the seismic resilience of communities[78]

Author	Michel Bruneau, Stephanie E. Chang, Ronald T. Eguchi, George C. Lee, Thomas D. O'Rourke, Andrei M. Reinhorn, Masanobu Shinozuka, Kathleen Tierney, William A. Wallace, Detlof von Winterfeldt
Citation	Earthquake Spectra, 2003, 19(4), 733-752
Abstract	The paper presents a conceptual framework to define seismic resilience of communities and quantitative measures of resilience that can be useful for a coordinated research effort focusing on enhancing this resilience.
Hyperlink	https://journals.sagepub.com/doi/pdf/10.1193/1.1623497

7.5.18 Earthquake Disaster Simulation of Civil Infrastructures: From Tall Buildings to Urban Areas[79]

Author	Xinzheng Lu, Hong Guan
Citation	Springer Singapore, 2017
Abstract	The book introduces the studies on the earthquake disaster simulation of civil infrastructures and seismic resilience, covering the novel computational models, high-performance computing methods, and realistic visualization of tall buildings and urban areas, with particular emphasis on collapse prevention and mitigation in extreme earthquakes, earthquake loss evaluation. Typical engineering applications to several tallest buildings in the world and selected large cities in China are also introduced to demonstrate the advantages of the proposed computational models and techniques.
Hyperlink	https://www.springer.com/us/book/9789811030864

7.5.19 Resilience of a hospital Emergency Department under seismic event[80]

Author	Gian Paolo Cimellaro, Marta Piqué
Citation	Advances in Structural Engineering, 2016, 19(5), 825-836
Abstract	The article presents a new simplified model for measuring the resilience of a hospital Emergency Department during a seismic event. The proposed Emergency Department model can be used not only to evaluate the performance of existing hospitals during an emergency, but also to design the proper size of a new Emergency Department in a region.
Hyperlink	https://doi.org/10.1177/1369433216630441

7.5.20 Strict building codes helped Anchorage withstand quake[81]

Author	Rachel D'Oro, Mark Thiessen
Abstract	The report introduces the magnitude 7,0 earthquake occurred in Anchorage, Alaska's largest city, in 2018, which caused cracked roads and collapsed highway ramps. However, there were no reports of widespread catastrophic damage or collapsed buildings, due to strict building codes that helped structures withstand earthquakes.
Hyperlink	https://www.adn.com/alaska-news/2018/12/01/experts-alaska-quake-damage-could-have-been-much-worse/

7.5.21 2019 Ridgecrest earthquakes[82]

Citation	Wikipedia
Abstract	The report describes the 2019 Ridgecrest earthquakes occurred in north and northeast of Ridgecrest and west of Searles Valley, California, with M_W 6,4, 5,4, and 7,1.
Hyperlink	https://en.wikipedia.org/wiki/2019_Ridgecrest_earthquakes

7.5.22 Integrating counter-terrorist resilience into sustainability[83]

Author	Jon Coaffee, Lee Bosher
Citation	Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 2008, 161(2), 75–83
Abstract	The paper argues that the embedding of resilience into the planning, design and engineering of the built environment is about not only security and community safety concerns but also the environmental benefits that might be achieved by integrating secure and sustainable design. The authors also argue that to date there has been limited integration of security and sustainability construction principles but that significant opportunities exist in the future for such sustainable urbanism to be commonplace.
Hyperlink	https://www.icevirtuallibrary.com/doi/10.1680/udap.2008.161.2.75

7.5.23 Resilient Design Tool: For Counter Terrorism[84]

Citation	University of Birmingham, Loughborough University, University of Sheffield, Centre for the Protection of National Infrastructure, National Counter Terrorism Security Office, Association of Chief Police Officers, Engineering and Physical Sciences Research Council
Abstract	The Resilient Design Tool (RDT) helps key decision makers to consider the proportionate use of counter terrorism design features in new and existing developments planned for crowded public places. By considering counter terrorism at the earliest stage of a development or refurbishment, this tool helps project decision makers to develop the design and construction strategy in a cost-effective manner.
Hyperlink	https://www.securedbydesign.com/images/downloads/resilient-design-tool-for-counter-terrorism.pdf

7.5.24 Climate change resilience strategies for the building sector: examining existing domains of resilience utilized by design professionals[85]

Author	Nicholas B. Rajkovich, Yasmein Okour
Citation	Sustainability, 2019, 11(10), 2888
Abstract	The paper examines eighteen climate change resilience documents developed to provide guidance to building sector professionals in the United States. The analysis of these documents helps to understand how professionals are framing and possibly incorporating these strategies in their work.
Hyperlink	https://res.mdpi.com/d_attachment/sustainability/sustainability-11-02888/article_deploy/sustainability-11-02888-v2.pdf

7.6 Measurement

7.6.1 USRC Building Rating System[86]

Citation	U.S. Resiliency Council (USRC)
Abstract	USRC is a 501(c)3 non-profit organization for implementing and disseminating rating systems that describe the performance of buildings during earthquakes and other natural hazard events.
Hyperlink	https://www.usrc-portal.org/

7.6.2 B-READY[87]

Citation	DNV GL
Abstract	DNV GL's B-READY building resilience assessment tool helps building owners and managers translate climate-related, site-specific risks into actionable resilience strategies.
Hyperlink	https://www.dnvgl.com/services/b-ready-106852

7.6.3 FORTIFIED Commercial™[88]

Citation	Insurance Institute for Business & Home Safety (IBHS)
Abstract	FORTIFIED Commercial™ is a voluntary construction standard and designation program to help new and existing commercial structures stronger against severe weather.
Hyperlink	https://fortifiedhome.org/commercial/

7.6.4 Attributes and metrics for comparative quantification of disaster resilience across diverse performance mandates and standards of building[89]

Author	Oluwateniola Ladipo, Georg Reichard, Andrew McCoy, Annie Pearce, Paul Knox, Madeleine Flint
Citation	Journal of Building Engineering, 2019, 21, 446-454
Abstract	The paper demonstrates that attributes and corresponding metrics of disaster resilience for buildings can be consistently quantified by a function of Functionality and Time and subsequently used for disaster resilience assessments. A thematic analysis of a sample of relevant texts was conducted to validate the hypothesis theorized for measuring resilience.
Hyperlink	https://www.sciencedirect.com/science/article/pii/S2352710218310386

7.6.5 The Resilient City[90]

Citation	San Francisco Bay Area Planning and Urban Research Association (SPUR)
Abstract	The project is a comprehensive work led by SPUR to retrofit the buildings and infrastructure that sustain city life. This work aimed to ensure San Francisco's resiliency and its capacity to not only survive but thrive when a disaster strikes.
Hyperlink	https://www.spur.org/featured-project/resilient-city

7.6.6 Seismic Performance Assessment of Buildings[91]

Citation	Federal Emergency Management Agency (FEMA)
Abstract	The project develops a methodology for seismic performance assessment of individual buildings. The final products together describe the resulting methodology, as well as the development of basic building information, response quantities, fragilities, and consequence data used as inputs to the methodology.
Hyperlink	https://www.fema.gov/media-library/assets/documents/90380

7.6.7 Standard for Seismic Resilience Assessment of Building[92]

Citation	Ministry of Housing and Urban-Rural Development of The People's Republic of China (MOHURD)
Abstract	The Standard for Seismic Resilience Assessment of Buildings (for approval) mainly stipulates the seismic resilience assessment methods for buildings. According to the standard, the resilience assessment should be based on the results of seismic elastoplastic analysis of buildings and Monte-Carlo simulation, and the main indicators are repair cost, repair time and casualties.
Hyperlink	http://www.mohurd.gov.cn/zqyj/201809/t20180921_237686.html

7.6.8 REDi™ Rating System[93]

Citation	ARUP
Abstract	The REDi™ framework recognizes that resilient design and planning is the key to achieving a truly resilient facility. To qualify for a REDi™ rating, it is necessary to satisfy mandatory criteria for each of the Resilient Design and Planning (organizational resilience, building resilience, and ambient resilience) and Loss Assessment categories.
Hyperlink	https://www.arup.com/perspectives/publications/research/section/redi-rating-system

7.6.9 Framework for analytical quantification of disaster resilience[94]

Author	Gian Paolo Cimellaro, Andrei M. Reinhorn, Michel Bruneau
Citation	Engineering Structures, 2010, 32, 3639-3649
Abstract	The paper presents the concepts of disaster resilience and its quantitative evaluation, proposes and implements a unified terminology for a common reference framework for evaluation of health care facilities subjected to earthquake. Two applications of this methodology to health care facilities are presented in order to show the implementation issues.
Hyperlink	https://www.sciencedirect.com/science/article/pii/S014102961000297X