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Buildings and civil engineering works — Seismic resilience assessment and strategies — Compilation of relevant information

Bâtiments et ouvrages de génie civil — Eevaluation de la résilience sismique et stratégies — Compilation des informations pertinentes

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Contents

Page

Foreword

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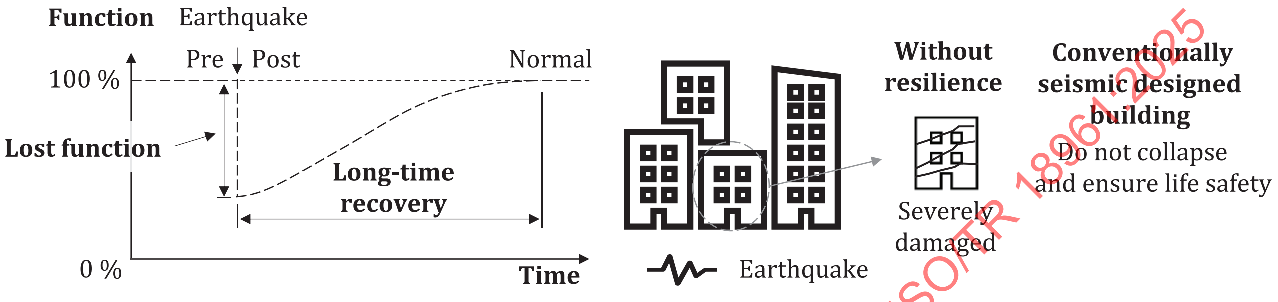
This document was prepared by Technical Committee ISO/TC 59, *Buildings and civil engineering works*.

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.

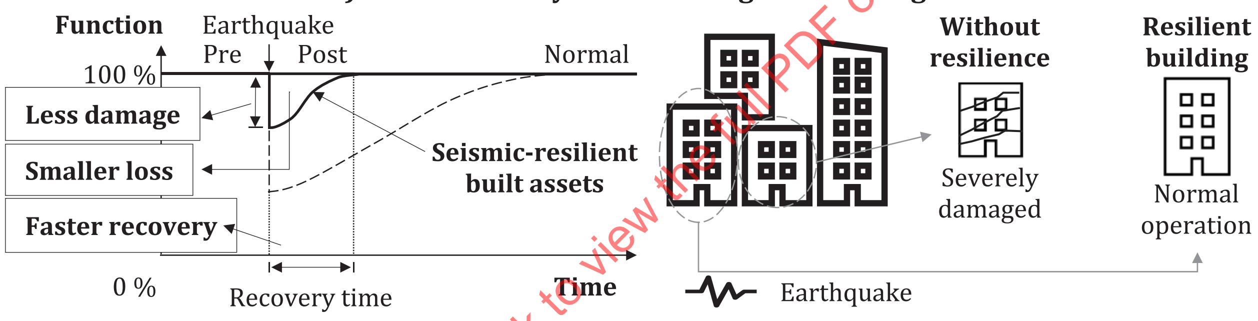
Introduction

With the issue of the "Sendai Framework for Disaster Risk Reduction 2015–2030"[1], resilience for disaster risk reduction has become a global consensus. Seismic resilience, as a critical capacity for built assets, needs to be prioritized. It considers the social, environmental and economic aspects based on conventional seismic design, ensuring the desired recovery time, tolerable losses and minimal casualties while preventing collapse.

As a typical example, the conventionally designed building shown in Figure 1 a) underwent severe damage and lost key functions during an earthquake. By contrast, the building in Figure 1 b), which was designed for seismic resilience, sustained minimal damage and rapidly regained full postearthquake functionality.



a) Conventionally seismic designed building



b) Seismic-resilient building

Figure 1 — Comparison between buildings designed based on conventional seismic design and seismic-resilient design concepts

Consequently, seismic resilience has emerged as a critical global concern that necessitates prioritization. Some countries have standards for assessing and boosting resilience; however, many still overlook its importance because of inadequate knowledge sharing. ISO documents on the seismic resilience of buildings and civil engineering works play a critical role in raising awareness worldwide. The development of this document assists in gathering information on assessment frameworks, metrics and guidelines for improving seismic resilience.

The collated information includes the following:

— concept of seismic resilience and its development history; recent earthquake disasters have underscored the need for seismic resilience, as evidenced in a typical case;

— assessment tools for seismic resilience levels; standards, codes and documents were collected from various entities; these tools assess earthquake-related economic impacts, recovery times and casualties by providing assessment methods, data, information-acquisition methods and indicators;

— strategies for enhancing seismic resilience; these were collected from investigative documents focusing on constructing newly built resilient assets and retrofitting existing assets.

The compiled information serves as a valuable resource for stakeholders, guiding them in strategizing to enhance the seismic resilience of built assets, thereby minimizing earthquake-induced damage. This document can be useful for standard setters, policymakers, users, architects, engineers, and construction and manufacturing sectors.

Buildings and civil engineering works — Seismic resilience assessment and strategies — Compilation of relevant information

1 Scope

This document provides an index of typical existing information on the concept, assessment and strategy for seismic 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 terminology databases for use in standardization at the following addresses:

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

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

4 Abbreviated terms

ASCE	American Society of Civil Engineers
DS	damage state
FEMA	Federal Emergency Management Agency, an agency of the United States
GIS	geographic information system
MOHURD	Ministry of Housing and Urban-Rural Development, a ministry of the People's Republic of China
NIST GCR	National Institute of Standards and Technology of the United States, Grant/Contractor Reports
NZSEE	New Zealand Society for Earthquake Engineering
JSCE	Japan Society of Civil Engineers
PACT	Performance Assessment Calculation Tool provided in FEMA P-58[17]
PGA	peak ground acceleration
PGV	peak ground velocity
SPUR	San Francisco Bay Area Planning and Urban Research Association

5 Concept of seismic resilience

Seismic resilience includes the capacity to withstand, adapt to or promptly recover from earthquake damage to preserve or restore the intended functionality. The concept of seismic resilience is derived from the broader concept of resilience; and its developmental history is depicted in Figure 2.

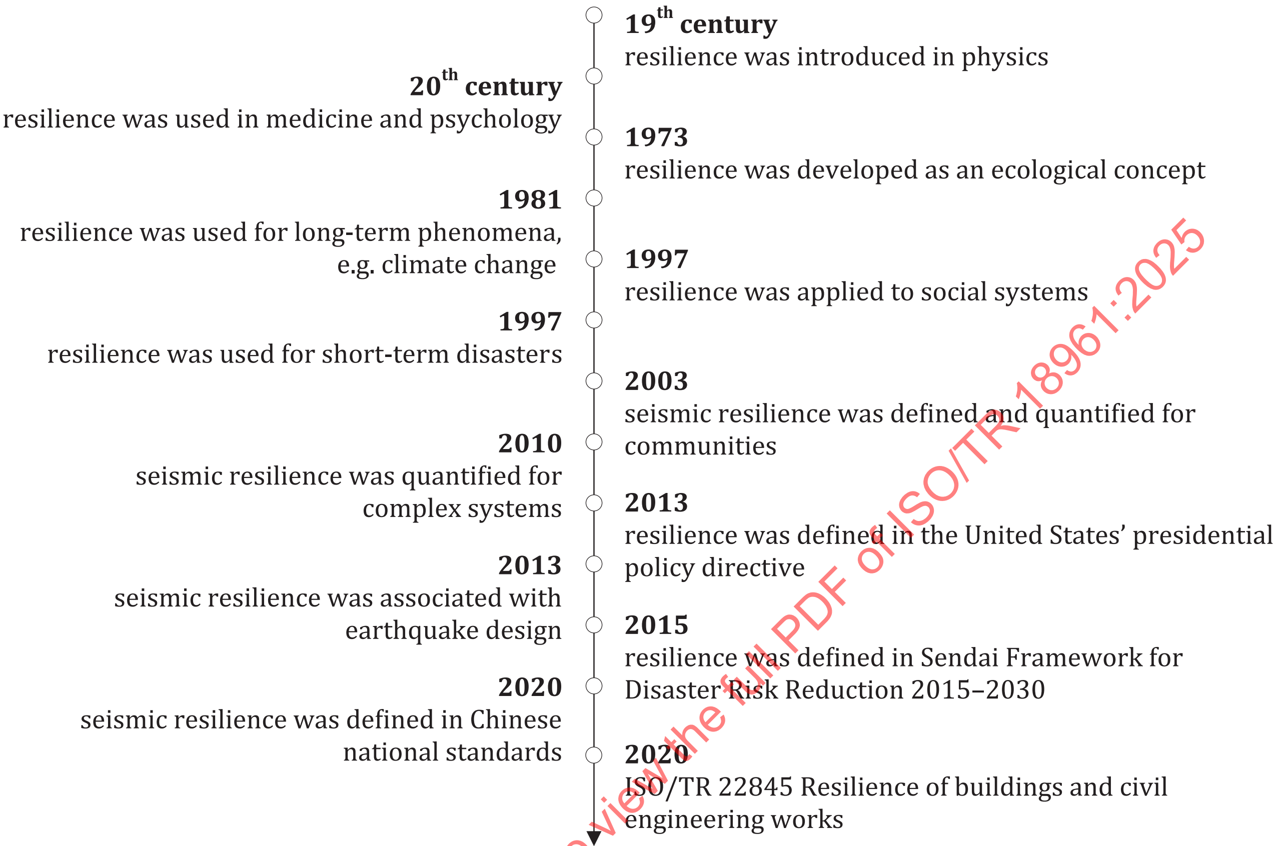


Figure 2 — Development of the concept of seismic resilience[2-15]

Seismic resilience was exemplified by the 2011 Christchurch earthquake.[16] On February 22, 2011, a strong earthquake hit Christchurch, New Zealand. Although many built assets in the struck area were constructed according to traditional seismic design for human safety, many minimally damaged assets were beyond economic repair and were demolished, resulting in significant economic losses and downtime. By contrast, a hospital located north of the area and built with a focus on seismic resilience endured the earthquake with slight damage and swiftly resumed operations.

In drawing lessons from the Christchurch earthquake, the focus is on the following two pivotal elements:

a) evaluating the current seismic resilience of built assets;

b) developing strategies to enhance their seismic resilience.

6 Assessment

6.1 General

Assessment is crucial for seismic resilience because it indicates the mechanical response of built assets under earthquake action, derives the induced losses and identifies the resilience level of the assets. Seismic resilience assessment[11,13,17] involves obtaining the seismic response in step 1 and assessing the resilience indicators in step 2 (see Figure 3). The datasets provide a foundation for this analysis. Figure 3 illustrates this method.

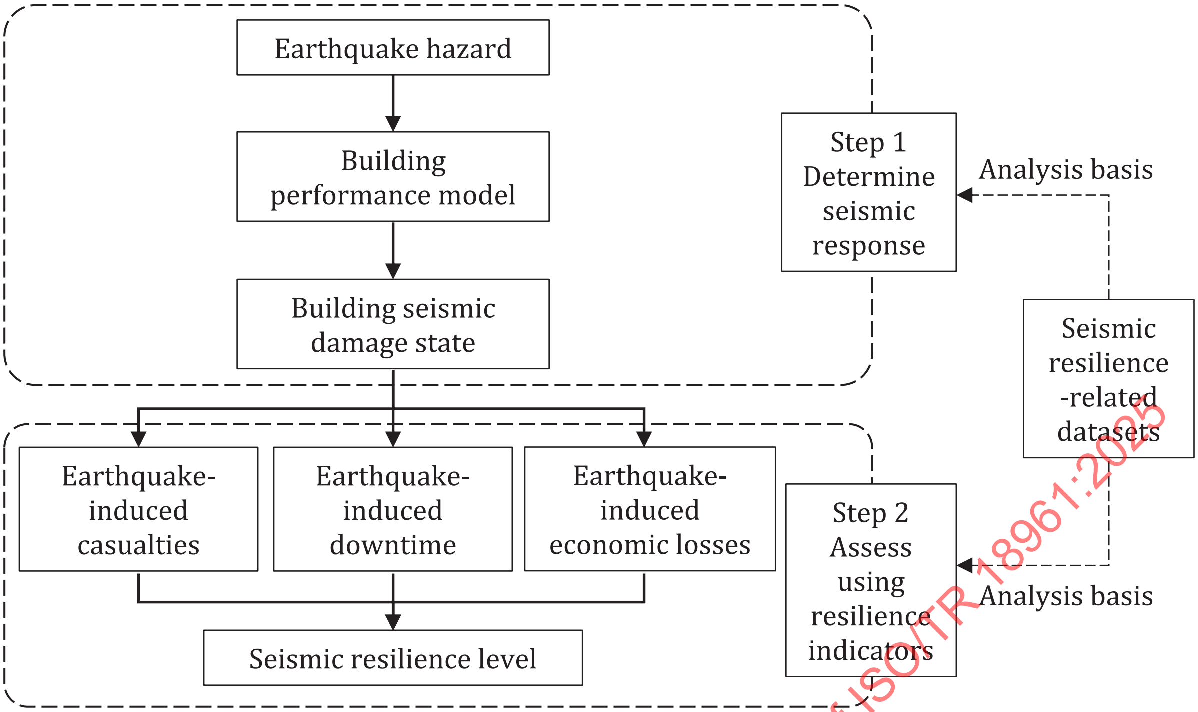


Figure 3 — Method for assessing seismic resilience

Methods for assessing seismic resilience are now well-developed globally, with contributions from organizations, such as FEMA,[17,18] Arup,[11] ASCE,[19] MOHURD,[13] NZSEE,[20] and JSCE.[21] Some standards provide comprehensive introductions to seismic resilience assessment methods, whereas others focus on specific critical aspects of the assessment process. Tables 1 to 3 summarize the main steps outlined in these standards.

Table 1 — Determining seismic response

	FEMA P58[17]	Hazus 5.1[18]	ASCE/SEI 41-17[19]	REDi[11]	GB/T 38591-2020[13]	NZSEE[20]	JSCE[21]
Earthquake hazard	√	√	√		√	√	√
Building performance model	√	√	√		√		
Building seismic damage state	√	√	√		√		

Table 2 — Assessment using resilience indicators

	FEMA P58[17]	Hazus 5.1[18]	ASCE/SEI 41-17[19]	REDi[11]	GB/T 38591-2020[13]	NZSEE[20]	JSCE[21]
Casualties	√	√			√		
Downtime	√	√		√	√		
Economic loss	√	√		√	√		
Seismic resilience level	√			√	√		

Table 3 — Seismic resilience-related datasets

	FEMA P58[17]	Hazus 5.1[18]	ASCE/SEI 41-17[19]	REDi[11]	GB/T 38591-2020[13]	NZSEE[20]	JSCE[21]
Datasets	√	√			√		

The following are some detailed examples of the seismic resilience assessment procedure.

EXAMPLE 1 The flowchart of the performance assessment methodology based on FEMA P58 encompasses:

a) establishing the building performance model;

b) specifying earthquake hazards;

c) analyzing building responses;

d) formulating collapse fragility;

e) evaluating performance[17].

EXAMPLE 2 REDi[11] adapted the PACT (FEMA P-58[17]) loss assessment method to incorporate practical repair strategies, delays caused by "impeding factors" and utility disruption times. This update enables forecasting of the time to reoccupancy, functional recovery or full recovery. Users select the desired recovery state for downtime analysis through calculations considering the building components impeding the selected recovery state.

EXAMPLE 3 GB/T 38591-2020[13] outlines a building assessment procedure that includes:

a) integrating building data;

b) building a structural model;

c) deriving engineering demand parameters from nonlinear time-history analysis;

d) assessing damage states using fragility data;

e) estimating the repair time, repair costs and casualties for a specific earthquake level;

f) assessing the seismic resilience level based on the estimated index.

EXAMPLE 4 Hazus 5.1[18] offers a community assessment procedure comprising:

a) selecting the study area;

b) establishing the earthquake hazard scenario;

c) incorporating local soil and geological data;

d) integrating local inventory data;

e) applying Hazus formulae;

f) calculating direct economic loss, casualties and shelter needs;

g) evaluating postearthquake fire impacts;

h) quantifying and characterizing debris.

6.2 Determining seismic response

6.2.1 Earthquake hazard

Earthquake hazards serve as inputs for analyzing seismic responses. These hazards can be characterized by the response spectrum and ground motion history.

EXAMPLE 1 FEMA P-58[17] outlines performance assessment types based on ground motion intensity.

— Intensity-based assessments utilize user-defined acceleration-response spectra, such as code design spectra.

— Scenario-based assessments use spectra from specific earthquake magnitudes and distances calculated using ground-motion prediction equations (attenuation relationships).

— Time-based assessments rely on seismic hazard curves and the corresponding spectra selected for a particular annual exceedance probability.

EXAMPLE 2 GB/T 38591-2020[13] delineates a method for defining seismic ground motion, ensuring that the parameters for the time-history analysis of seismic response, including the ground motion amount, duration, amplitude and spectrum, align with the Chinese code for the seismic design of buildings (GB50011-2010).[22] The peak acceleration and velocity of the input earthquake are specified according to relevant regulations.

EXAMPLE 3 Hazus 5.1[18] generates ground motion estimates as GIS-based contour maps and stores them in relational databases, providing location-specific seismic demands. The characterization of the ground motion includes spectral responses based on the standard spectrum shape, peak ground acceleration (PGA), and peak ground velocity (PGV).

6.2.2 Building performance model

The building performance model, which considers both structural and nonstructural components and performs nonlinear seismic response time-history analyses, is crucial for capturing the response of buildings.

EXAMPLE 1 FEMA P-58[17] outlines key structural modeling and analysis considerations:

— modelling force–deformation relationships, geometric nonlinearity, gravity loads, damping, diaphragms, soil–structure interaction, and foundation embedment, and accounting for the nonsimulated deterioration and failure modes;

— determining the necessary number of analyses;

— assessing the floor velocity, acceleration and effective drift;

— implementing quality assurance measures;

— addressing analysis uncertainties.

EXAMPLE 2 GB/T 38591-2020[13] details the modeling and analysis methods:

— using a three-dimensional computational model for seismic response analysis, considering P-Δ effects, large deformations and the impact of stairs on the dynamic response;

— ensuring that the representative value of the gravity load in the elastic–plastic analysis complies with the Chinese code for the seismic design of buildings and the load code for building structures;

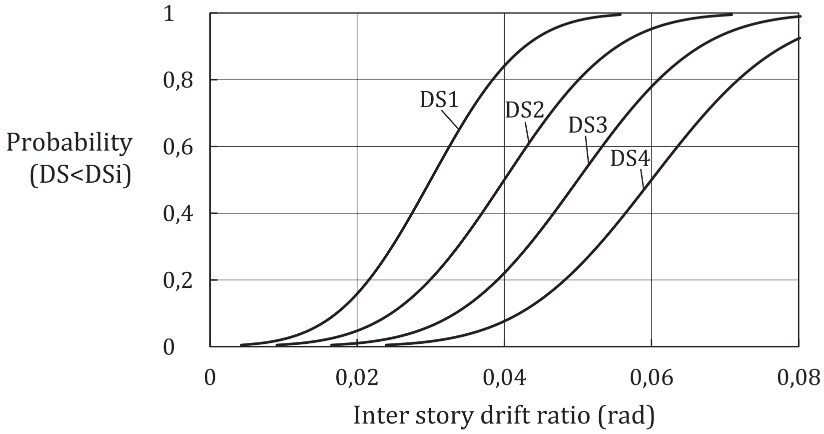
— the mechanical model for the applicable building types must satisfy the corresponding requirements and select reasonable material constitutive relationships and damping ratios.

6.2.3 Building seismic damage state

Damage states can be delineated using fragility curves or discrete-state descriptions, with the former offering a quantitative assessment and the latter being perceptual. Assessing the damage state of a building involves evaluating both the structural and nonstructural components against a fragility database and engineering criteria. Component fragility data are characterized by a probability distribution that aligns with engineering demands. This approach covers both component- and building-level damage states, with the latter derived from the aggregate of individual component states.

See EXAMPLEs 1 to 3 for component-level damage states and EXAMPLEs 4 and 5 for building-level damage states.

EXAMPLE 1 FEMA P-58[17] characterizes component damage with uncertainty. The fragility functions that follow lognormal distributions depict the probability of damage at specific demand levels. Figure 4 illustrates the need for distinct fragility functions for each sequential and mutually exclusive or simultaneous damage state.



NOTE DS represents the damage states, with DS1–DS4 indicating increasing severity from slight to severe damage. The term, probability (DS<DSi), signifies the likelihood that the damaged state surpasses the *i*-th state. The interstory drift ratio, expressed in radians, indicates the deformation of a component. The fragility curves depict the probability of each damage state occurring at specific interstory drift ratios.

Figure 4 — Example family of fragility curves

EXAMPLE 2 GB/T 38591-2020[13] determines the likelihood of various component damage states by integrating the engineering demand parameters with the component fragility data.

EXAMPLE 3 Hazus 5.1[18] defines structural and nonstructural damage states using discrete state descriptions, in terms of one of five ranges of damage or "damage states": "none," "slight," "moderate," "extensive" and "complete".

EXAMPLE 4 GB/T 38591-2020[13] determines the damage states of structural and nonstructural components based on the member vulnerability database and engineering demand parameters. The fragility data of the components are represented using a probability distribution that varies with the engineering demand parameters.

EXAMPLE 5 SPUR[23] defines the damage state using discrete state descriptions, as listed in Table 4.

Table 4 — Damage state defined in SPUR[23]

Category	Buildings
A	Safe and operational
B	Safe and usable during repair
C	Safe and usable after repair
D	Safe but not repairable
E	Unsafe.

6.3 Assessment using resilience indicators

6.3.1 Earthquake-induced casualties

Personnel casualties from earthquakes include injuries and deaths. Deaths mainly result from structural collapse, and injuries are caused by damaged structural and nonstructural components. The calculation of casualties involves considering the potential collapse modes, population distribution and floor area of the building.

EXAMPLE 1 In FEMA P-58,[17] building-collapse casualties are assessed using potential collapse modes and the estimated occupant count. This count is derived from population models, which allocate a set number of people per 93 m^2 of the floor area. The damage state of each component details the life safety hazards and affected areas.

EXAMPLE 2 In GB/T 38591-2020,[13] the personnel casualties can be calculated using Formulae (1) and (2):

$$M_{\mathrm{H}} = \sum_{r=1}^{5} \left(r_{\mathrm{h}r} \sum_{k=1}^{n_{\mathrm{s}}} \left(\zeta_k A_{r,k} \right) \right) \quad (1)$$

$$M_{\mathrm{D}} = \sum_{r=1}^{5} \left(r_{\mathrm{d}r} \sum_{k=1}^{n_{\mathrm{s}}} \left(\zeta_k A_{r,k} \right) \right) \quad (2)$$

where

M_{H} is the number of injured persons;

M_{D} is the number of deaths;

$r_{\mathrm{h}r}$ is the nominal injury rate from r_{h1} to r_{h5}, which are the injury rates of floors subjected to different damage levels, r;

$r_{\mathrm{d}r}$ is the nominal death rate from r_{d1} to r_{d5}; which represents the death rates of floors subjected to different damage levels, r;

ζ_k is the density of persons indoor on floor k;

$A_{r,k}$ is the floor area of floor k subject to damage at level r (m^2).

EXAMPLE 3 In Hazus 5.1,[18] the casualties resulting from a postulated earthquake can be modeled using an event tree that traces the sequence of events leading to their occurrence. The earthquake-related casualty event tree starts with the initial earthquake scenario and depicts the potential chain of events that can lead to the loss of life or injuries.

6.3.2 Earthquake-induced downtime

Downtime is the time required for a building or infrastructure to regain its functionality after an earthquake. This includes different stages, such as reoccupancy, functional recovery and full recovery. Accurate downtime data can be difficult to obtain; therefore, repair time serves as a substitute in some cases.

EXAMPLE 1 FEMA P-58[17] assesses repair times by considering economies of scale and construction efficiency. Parameters, such as quantity ranges and time estimates, determine the repair duration for each damage state.

EXAMPLE 2 REDi[11] associates downtime with recovery states: reoccupancy (safety for shelter), functional recovery (restoring primary functions) and full recovery (aesthetic repair to pre-earthquake conditions). The REDi methodology assesses downtimes attributed to repairs, utility disruptions and delays.

EXAMPLE 3 GB/T 38591-2020[13] defines the building repair time as the period for the functional recovery of damaged components, excluding preparatory tasks. The calculations involve estimating the repair hours for members in various damage states, adjusting for scale and efficiency and converting these hours into nominal repair times based on worker availability and floor area requirements.

EXAMPLE 4 Hazus 5.1[18] divides the repair time for a damaged building into construction and clean-up times and the time required for financing, permits and design. In lower damage states, the construction time reflects the actual repairs; however, higher damage levels add tasks that extend the overall repair duration. These tasks include decision making, negotiations with agencies and insurers, financing, contract negotiations, inspections, document preparations, permit acquisition and postconstruction activities.

6.3.3 Earthquake-induced economic losses

Earthquakes cause both direct and indirect economic losses. Direct losses are quantifiable and involve repair costs for damaged buildings and infrastructure, including structural and nonstructural elements. Repairs involve restoration, dismantling or replacement of damaged parts. Indirect losses such as those from business interruptions are challenging to assess and lack precise quantification. These losses have varied impacts and are not easily translated into economic terms.

EXAMPLE 1 FEMA P-58[17] considers economies of scale and construction efficiency in terms of repair cost consequences. Contractor costs, including mobilization and overhead, decrease with the volume of similar work and affect unit rates. Repair costs are determined using parameters, such as quantity ranges and cost estimates.

EXAMPLE 2 REDi[11] calculates direct financial losses by dividing repair costs by the total building value, excluding indirect losses, such as business interruptions. Valuable contents exceeding 10 % of the replacement value must be included in the loss assessment.

EXAMPLE 3 GB/T 38591-2020[13] encompasses the cost of restoring all earthquake-damaged members and comprehensive restoration. This includes direct expenses for restoration, dismantling, replacement, material transport and labor by professional and technical workers. This assessment omits the costs of improving seismic resilience.

EXAMPLE 4 Hazus 5.1[18] provides methods for calculating direct economic losses, including building repairs and content losses. It establishes default models for time-dependent losses, such as recovery times and business interruptions. These procedures cover various time-dependent and indirect economic and social losses, such as population displacement and shelter needs.

6.3.4 Seismic resilience level

Resilience levels can be expressed using continuous indicators or discrete grades. Continuous indicators, expressed as numerical values, quantify seismic performance in terms of casualties, downtime and economic losses without specific grading. By contrast, discrete grades, such as platinum, gold, silver and stars, are derived from combined indicator assessments, presenting a summarized view of the overall resilience. This concise representation simplifies the interpretation of resilience performance.

EXAMPLE 1 FEMA P-58[17] introduces multiple continuous indicators instead of discrete performance levels for improved clarity. These indicators, expressed as numerical values, include “casualties”, “repair cost”, “repair time”, “environmental impacts” and “unsafe placarding”.

EXAMPLE 2 Typical seismic resilience levels used in REDi[11] are listed in Table 5.

Table 5 — Typical seismic resilience levels

Performance level	Indicators
Platinum	Downtime and functional recovery within 72 h; direct financial loss under 2,5 %; no injuries from building component failure.
Gold	Downtime and functional recovery within one month; direct financial loss under 5 %; no injuries from building component failure.
Silver	Re-occupancy and functional recovery within six months; direct financial loss under 10 %; no structural collapse; some injuries possible from building component failure.

EXAMPLE 3 In GB/T 38591-2020,[13] seismic resilience levels are calculated using indices derived from Monte Carlo simulations at an assurance rate of 84 %. These include the restoration cost, repair time and personnel loss indices. The seismic resilience level of a building is determined by assessing these three indices, with the lowest rating representing the resilience of the building.

6.4 Seismic resilience-related datasets

These datasets form the basis for assessing the seismic resilience of buildings and infrastructure. They include comprehensive information and models of seismic events with key elements, such as earthquake hazards, performance models, damage states and consequences of casualties, downtimes and economic losses.

EXAMPLE 1 FEMA P-58[17] details the fragility specifications in Volume 3 – Supporting Electronic Materials. These details can be accessed through the fragility manager in the Performance Assessment Calculation Tool (PACT), fragility database (an Excel workbook) or fragility specifications (a PDF file).

EXAMPLE 2 GB/T 38591-2020[13] includes datasets, such as structural- and nonstructural-member fragility data, including classifications, coding, groupings and damage states.

EXAMPLE 3 Hazus 5.1[18] provides fragility parameter values at the building scale.

7 Strategies

7.1 General

Strategies that mitigate casualties, downtime and losses caused by earthquakes are essential for improving the seismic-resilient performance of built assets. Figure 5 outlines critical strategies that encompass both design-related and indirect strategies. This report does not detail indirect strategies, such as pre-earthquake planning, backup systems and postearthquake responses.

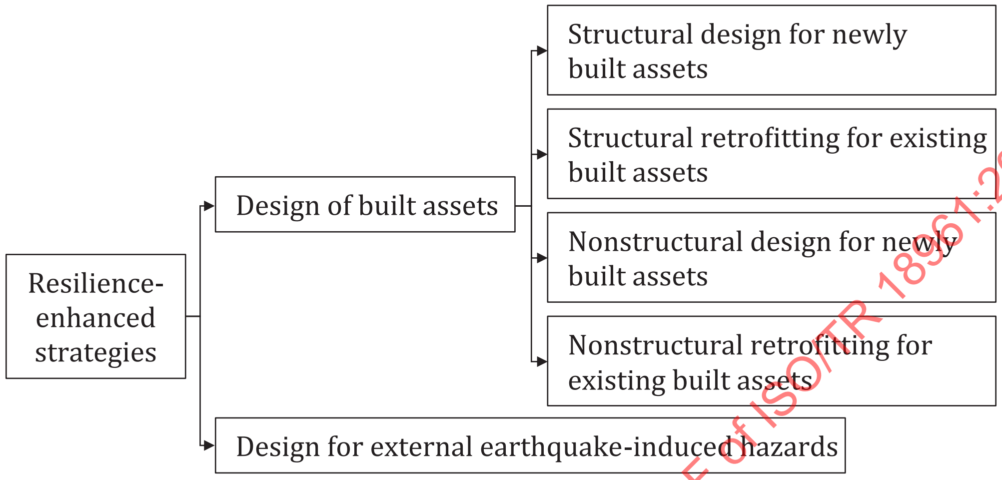


Figure 5 — Resilience-enhanced strategies

The development of strategies to improve earthquake resilience is relatively advanced in several countries and regions, including multiple specifications and reports, such as REDi,[11] the New Zealand National Center for Seismic Resilience[24] and NIST GCR 18-917-43.[25] Table 6 lists the strategies for seismic resilience improvement, as recommended in different specifications or reports.

Table 6 — Strategies for improving seismic resilience in different specifications and reports

Strategies	REDi[11]	New Zealand National Center for Seismic Resilience[24]	NIST GCR 18-917-43[25]
Design of buildings and infrastructures	√	√	√
Design for external earthquake-induced hazards	√		

7.2 Design of built assets

7.2.1 Structural design for newly built assets

The structural resilience of newly built assets can be enhanced by improving the relevant structural design requirements and implementing damage-control technologies. The former involves setting more stringent and rational performance criteria for seismic performance-based design, whereas the latter mainly applies techniques, such as base isolation and energy dissipation to achieve resilience.

EXAMPLE REDi[11] introduces structural design methods for enhancing seismic resilience, including the following.

— Improved structural design:

a) Structural and nonstructural components are designed to withstand higher values between the calculated and code-specified earthquake levels.

b) Impacts of vertical motion are essential to be considered for all elements.

c) The superstructure and its foundations are designed to remain primarily elastic, permitting controlled cracking under design demands.

d) The maximum residual drift is limited to 0,5 % during the design-level earthquake.

e) The lateral-resisting system elements that are expected to sustain damage are exposed for ease of replacement or repair.

— Damage-control technologies:

a) Seismic isolation can decouple structural movements from ground motion and reduce structural forces, accelerations, and deformations during severe earthquakes.

b) Energy-dissipation systems can absorb seismic energy and convert it into heat, thereby reducing both the displacement and acceleration pressures on the building.

7.2.2 Structural retrofitting for existing built assets

The structural resilience of existing built assets can be improved by retrofitting structural foundations, parapets, façades and masonry walls.

EXAMPLE Structural retrofit design methods from New Zealand National Center for Seismic Resilience[24].

— Foundation:

Pile foundations require repair or replacement if they are misaligned, undermined by subfloor excavations, missing, irregularly spaced, or in poor contact with the soil. Concrete piles with cracks or signs of deterioration and timber piles that exhibit splitting, rotting, or other damage require repair or replacement.

Braced foundations without perimeter foundation walls can be replaced with more effective solutions, such as sheets or diagonal bracing for strengthened structural support.

— Parapet: Securing parapets are applicable to reinforcing hipped roofs, gable sidewalls and other elements of roof frames and trusses in unreinforced masonry structures.

— Façade: Façades are secured by connecting them to the superstructure in buildings exceeding two stories.

— Masonry walls: Braces can strengthen unreinforced masonry walls and control their lateral movement.

7.2.3 Nonstructural design for newly built assets

Techniques for improving the nonstructural resilience of newly built assets include enhancing the nonstructural design and placement location selection. The main aim is to strengthen the nonstructural component connections and reduce their deformation, velocity, and acceleration responses.

— Enhancing nonstructural design

EXAMPLE 1 Technologies in REDi[11] include the following.

a) Anchorages are designed for elasticity, and components are engineered to handle relative displacements while minimizing aesthetic damage.

b) The functionalities of the critical components are rigorously tested to demonstrate their operational capabilities under a design-level earthquake.

c) Façades and curtain walls are designed to resist relative displacements, ensure elastic connections, and build an asset envelope to effectively prevent air and water intrusion.

EXAMPLE 2 Technologies in NIST GCR 18-917-43[25] include the following.

a) Systems such as base isolation or highly damped systems are adopted to reduce horizontal accelerations.

b) Component anchorages and braces are designed by adjusting the importance factor to account for increased forces and drift.

— Placement location selection