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The REDACt project Educational Hub

Earthquake Damage to Structures and Infrastructure

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1.1. Scope and Objectives

Earthquake imposed crises, invoke the entire community including all of its structural components. They put into test the operational capacity of services, their response efficiency and the response of the population, which strongly affects the dynamics and progress of response actions, both during the event and after that.

Response of the population is strongly related to the level of **communication**, of **comprehending the risks** and of **being able and trained** to respond. Scope of the deliverable is to provide simple guidelines, which combined with the content of the REDACt Educational Hub and the short tutorials given, can support citizens to develop their own emergency plans, in line with the State issued guidelines.

The document is a part of the REDACt Educational Hub (Edu-Hub). It capitalizes on respective material published by competent Authorities at National and Regional Levels and is based on research carried out during the project and on internationally recognized and widely acceptable principles.

The International Hellenic University led this effort and partners contributed with data, information and translations.

1.2. Related Documents

1.2.1. Input

Table 1. List of former deliverables acting as inputs to this document

Document ID	Descriptor
D.T.3.5.1	**The REDACt project Educational Hub**

1.2.2. Output

Table 2. List of other deliverables for which this document is an input.

Document ID	Descriptor
D.T3.1.	

2. SEISMIC MOTION AND PERFORMANCE OF STRUCTURES AND INFRASTRUCTURE

When a strong earthquake occurs, seismic waves propagate in the ground and reach the surface, causing intense ground motion. At each point on the ground surface, the dynamically varying seismic motion can be recorded as velocity (in m/s), or as acceleration (in m/s^2 - often expressed as a percentage of the acceleration of gravity g). The respective dynamic displacements can be then indirectly calculated through a mathematical (integration) process.

An indicative image of such a recording is shown in Figure 1, where the recording of the acceleration on the ground surface over time is depicted.

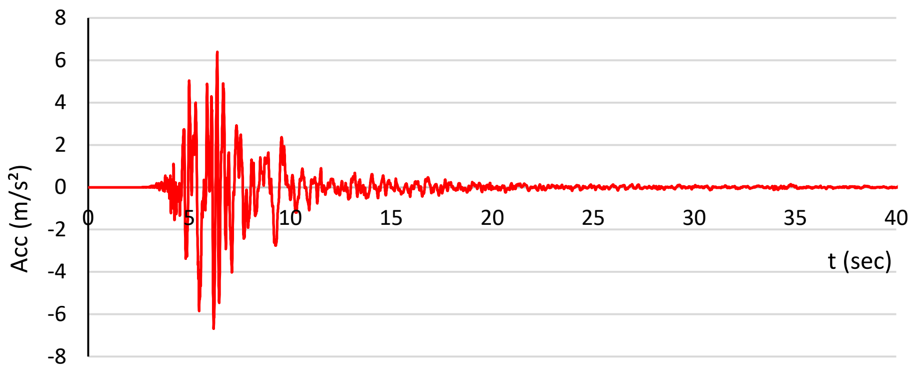
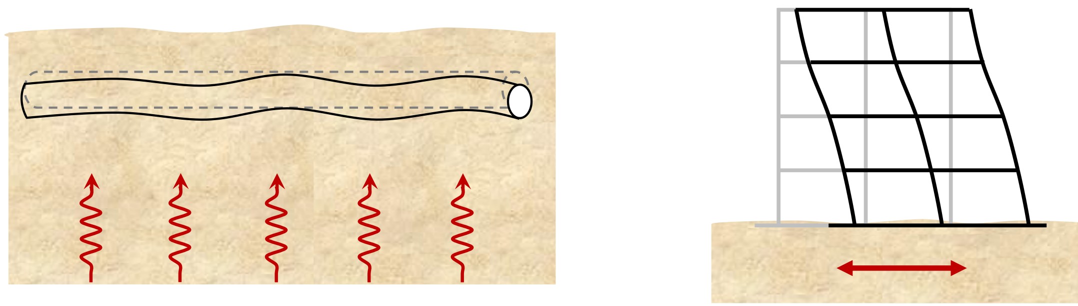


Figure 1. Accelerogram (acceleration time-history) of an earthquake.

The way in which the spatial distribution of seismic motion is recorded for a seismic event in the wider area of the fault is described in the tutorial titled "From Earthquake Focus to induced Damage".

The intense and dynamically changing ground motion results in the creation of strain and, consequently, stress on constructions and infrastructure that is mainly related to:

a) the deformation of infrastructure and underground constructions or the part of them that is in contact with the ground, due to the soil deformation during the earthquake, or even permanent soil deformation that can occur in case of a strong excitation (Figure 2a).
b) the inertia of the constructions, which results in the oscillation of the superstructure with a delay compared to the vibration of the soil surface, thereby introducing deformation and stress into the construction (Figure 2b).



(a) (b)

Figure 2. Strain on constructions and infrastructure during the earthquake (a) due to the deformation of the ground and/or (b) due to the inertia of the construction.

3. Seismic design of structures and infrastructure

The design of constructions and infrastructure follows a techno-economic approach, where the goal is to ensure the required safety level of the project at a reasonable cost, without additional financial overruns.

Consequently, the aim is not to construct a project that will withstand every level of external loading, something that is not feasible anyway since there is always the possibility of exceeding the maximum considered load due to an extreme natural or man-made event. The design of the project aims ultimately to prevent human loss due to total collapse, and also inherently incorporates some safety margins, for the case of exceedance of the expected actions, as has happened many times with severe earthquakes.

Modern philosophy of earthquake-resistant design of structures and infrastructures is therefore directly linked to their performance, that is, the behavior they will exhibit and the level of damage that is considered acceptable to sustain for given levels of seismic loading. In recent decades, the following performance levels (Figure 3) have been internationally accepted, which are related to the state in which a structure is expected to be immediately after an earthquake (HAZUS-MH MR5, 2010, FEMA 389, 2004):

- Operational: no or very low damage
- Immediate Occupancy: limited damage, mainly to nonstructural elements
- Life Safety: significant structural and nonstructural damage
- Collapse Prevention: extensive damage, repair and restoration is probably not practically achievable

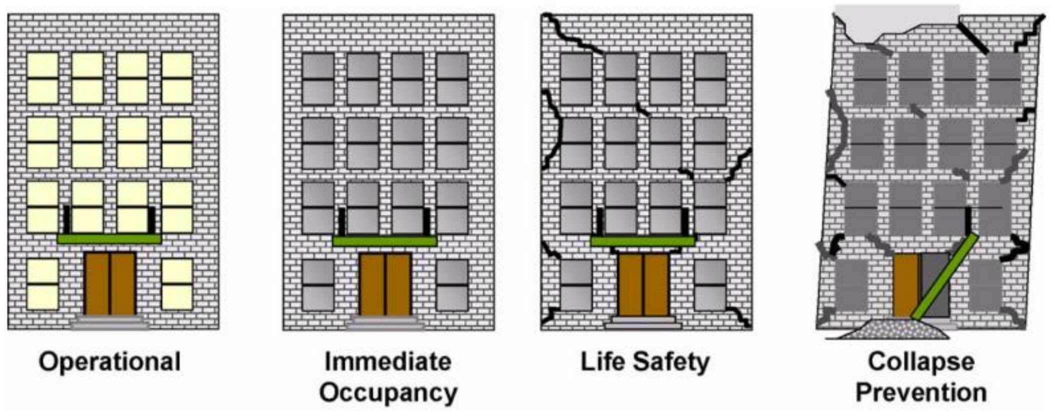


Figure 3. Graphic illustration of performance levels (FEMA 389, 2004).

The requirements of modern seismic codes for buildings, such as Eurocode 8, EAK2000 in Greece, the Turkish Building Seismic Code (2018) etc., take into account the minimum acceptable response during the theoretical life span of a project, which is 50 years for ordinary buildings (residences, offices). Specifically, for common buildings, they prescribe immediate occupancy in the case of relatively frequent earthquakes (return period of 72 years or an exceedance probability of 50% in 50 years), while they accept the life safety performance level for earthquakes that are rarer (return period of 475 years or an exceedance probability of 10% in 50 years). Therefore, it is observed that there is a difference in the desired behavior depending on the level of seismic action.

Similar provisions, with potential variations depending on the nature and importance of the structure, are found for each type of construction or infrastructure project. For example, in more significant projects (e.g., hospitals, major highways, and critical infrastructures), the theoretical lifespan increases from 50 to 100 years. More stringent rules apply to even more critical structures (e.g. long bridges, nuclear power plants etc.).

4. SEISMIC ASSESSMENT OF EXISTING STRUCTURES AND INFRASTRUCTURE

In the case of existing structures and infrastructure, seismic loading may result in the development of damage that can range from minor to partial or complete failure (collapse), similar with the description of performance levels mentioned in the previous section.

The assessment of the seismic performance of an existing construction and the estimation of its expected behavior is usually done in one of the following ways:

a) Using grading methods for each construction, after the evaluation of its specific characteristics that are directly related to the seismic response (e.g., construction material, number of floors, age, etc.).
b) Using methods to estimate the extent of damage that the construction is expected to develop under a given level of an intensity measure, applying probabilistic approaches (fragility curves) and determining appropriate damage states.

The latter approach has gained significant acceptance from the scientific community in recent decades. The general characteristics of the methodology are common between constructions and infrastructure, after certain modifications. A typical image of fragility curves for building structures is shown in Figure 4.

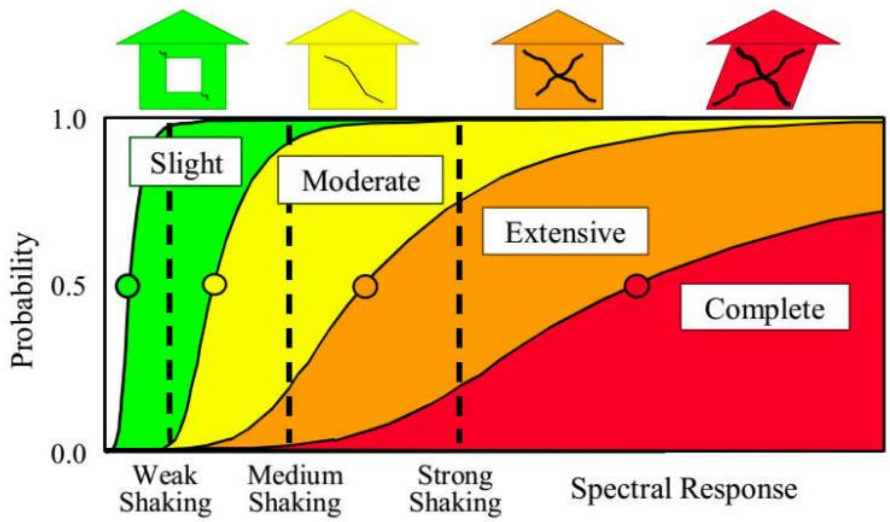


Figure 4. Typical fragility curves for buildings (HAZUS-MH MR5, 2010).

Given the value of the seismic intensity measure (macroseismic intensity, acceleration, displacement, etc.), the fragility curves estimate the probability of the structure to exceed the threshold of a specific damage level during the earthquake (minor, moderate, extensive damage, complete failure). It should be noted that fragility curves can refer to a specific structure/infrastructure (e.g., building, bridge, etc.). When a broader area such as an urban center is studied, the fragility curves usually refer to groups of constructions with common characteristics (typologies), e.g. "reinforced concrete buildings, of medium height, designed according to modern regulatory provisions" etc.

Based on the aforementioned approaches, the development of seismic risk studies for structures and infrastructure has become feasible. The goal is to assist the State/Authorities in obtaining a picture of the expected losses and to provide the necessary data to prioritize and organize more effective pre-seismic and post-seismic actions in order to mitigate the consequences of a strong earthquake.

5. SEISMIC DAMAGE TO BUILDING STRUCTURES

Damage to buildings is the foremost concern of citizens during a strong seismic event, as it is directly related to the safety of their life and their property.

The existing building stock consists of buildings of various typologies, with different characteristics that are related to their seismic behavior and the potential forms of damage. The most fundamental of these characteristics can be summarized as follows:

- The construction **material.** In recent decades, reinforced concrete has become the predominant building material in urban areas of Black Sea countries. However, in some cases (industrial buildings, high-rise structures, etc.), steel constructions are often being chosen. Furthermore, there is still a significant percentage of older constructions made from load-bearing masonry (stone masonry, brick masonry, etc.), especially in rural areas. Additionally, there is a smaller percentage of buildings made from other materials, such as timber, composite structures, prefabricated buildings, etc.
- The **age** of the buildings, which is directly related to the level of **design regulatory provisions** (the prevailing seismic codes at the time of construction). The continuous improvement of seismic regulations has clear results in the observed damage after strong seismic events, with older buildings appearing more vulnerable. In modern seismic codes, special emphasis is given to issues related to the ability of buildings to undergo significant residual deformations (damage) without, however, leading to collapse (a property described as “high ductility”).

  In the regions of SE Europe, the appearance of regulations similar to modern seismic codes (e.g., Eurocode 8) began in the 1990s, while buildings constructed before the mid-20th century were not designed for seismic actions.
- The **height** of buildings affects their dynamic response. Hence, the interplay between the dynamic characteristics of a structure and the frequency content of seismic vibrations can result in certain earthquakes posing significantly graver threats to tall buildings due to resonance, in contrast to low-rise structures. Conversely, the opposite situation might occur in different seismic events (Figure 5).

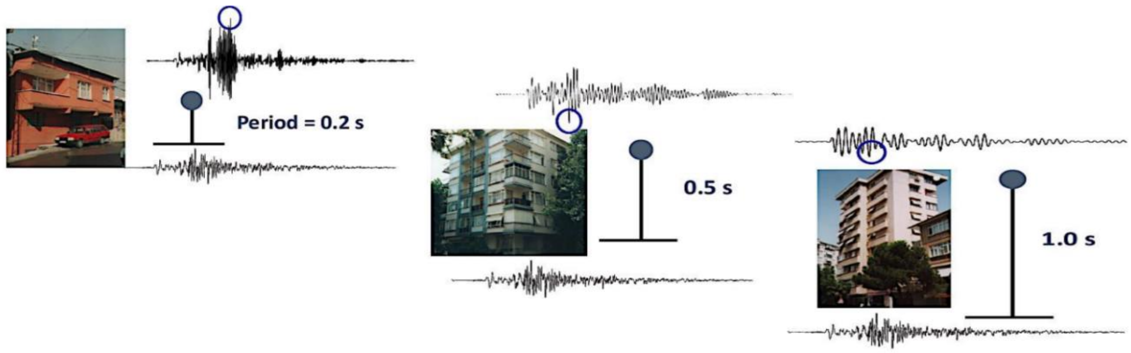


Figure 5. Different impact of the same seismic excitation on buildings of different heights (Theodoulidis, 2023).

- **Irregularities** in plan or elevation. Intense changes in a building's morphology may cause damage concentration in parts of the structure, leading to local failures or even complete collapse.
  A typical example is the soft-story mechanism in multi-story frame buildings, where the absence of wall infills on one floor (usually the ground floor to create parking spaces or shops with large façade windows) results in a significant reduction of its stiffness. As a result, this floor exhibits significantly larger relative displacements compared to the other floors (Figure 6a).
  Other forms of irregularity may be associated with inadequate torsional resistance/stiffness in some buildings (Figure 6b), abrupt changes in mass or stiffness, etc.
- **Additional variations in the structural system**, depending on the construction material, which lead to significantly different seismic responses and consequently forms of damage. In reinforced concrete buildings, this may relate to the number, location and form of shear walls, the presence and type of diaphragms and partitions in masonry-bearing buildings (Figure 6*c,d*), and the placement of lateral bracings in steel buildings (Figure 6*e,f*).

When referring to the seismic damage of a structure, it is essential to distinguish between structural and non-structural elements. The primary problem that can occur in a building during an earthquake is the development of damage to the load-bearing system of the structure. This refers to the structural elements responsible for bearing the weight and seismic forces imposed on the building, which vary depending on the type of the construction. Indicatively, they concern the beams, columns, and shear walls in reinforced concrete constructions, the corresponding steel elements in metal constructions, and the walls in buildings made of load-bearing masonry (stone or brick masonry) etc.

Specifically for masonry walls, it is noted that while in load-bearing masonry structures they constitute elements of the load-bearing system, they are not equally important when they function as infill walls (partition walls) in reinforced concrete or steel constructions.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 6. (a) Soft story collapse of a 3-floor reinforced concrete building during the Athens 1999 earthquake, Greece, (b) Collapse of a torsionally flexible building with stiff shear walls only at one corner of the structure, Athens 1999, (c, d) Seismic damage in masonry buildings during the Thessaly 2022 earthquake, Greece (source: Sarhosis et al., 2022), (e, f) Failure of flexible steel structures (source: Katsumi Kasahara/Associated Press, Michael Engelhardt).

Furthermore, it should be noted that damage to building structures are not exclusively related to the load-bearing structure and the infill elements of the building itself, but also to its contents. Thus, damage frequently appears to furniture, machinery, installations (Figure 7a,b), as well as various contents of lesser value (Figure 7c). Serious injuries, or loss of life can occur due to collapsed non-structural components, even if the load-bearing system has not suffered serious damage. To avoid damage to invaluable (e.g. cultural heritage) items, the implementation of appropriate protective measures is essential (Figure 7d).

(a) (b)

(c) (d)

Figure 7. (a) Widespread damage to a ceiling system (source: Ferner et al., 2014), (b) Falling shelves in a library (source: NISEE-PEER), (c) Destruction of a signboard on the exterior of a hospital during the 1994 Northridge earthquake, USA (source: Robert Reitherman), (d) Statue of Hermes by Praxiteles at the Archaeological Museum of Olympia, Greece. Installation of a seismic isolation system for the protection of significant exhibits (source: Michael Constantinou).

Often, damage to buildings from earthquakes are due to the failure of the ground or the foundation of the building (Figure 8). Cases of differential settlement of the foundation can lead to significant damage to the superstructure, while more extensive phenomena, such as soil liquefaction, might result in the global failure of the construction.

(a) (b)

Figure 8. (a) Collapse of buildings due to soil liquefaction during the 1964 Niigata, Japan earthquake (photo: Joseph Penzien), (b) Differential settlement of the foundation of a reinforced concrete building in Türkiye, 1999

6. Seismic damage to infrastructure

Infrastructure includes civil engineering constructions that belong to the following basic categories (Pitilakis et al., 2014):

- Pipeline networks: These include networks of all types, such as water supply, sewage, natural gas, electricity, etc. Constructions directly related to the operation of a network, such as natural gas tanks, are included and evaluated together with the respective network.
- Road network: It includes roads, tunnels, bridges, road embankments, etc.
- Railway network: It includes the railway lines, tunnels, bridges, railway earthworks, etc.
- Port facilities: They include retaining walls of all types, embankments, heavy mechanical installations (cranes, tanks, etc.), buildings (offices, warehouses), etc.

It is observed that in most cases, infrastructure consists of a set of facilities of different types, as exemplified in road networks which, apart from the roads, also consist of bridges, tunnels, and embankments that accompany the operation of the whole network.

Each infrastructure, therefore, displays different mechanisms of damage and failures, which are directly related to the individual components it includes. Likewise, each infrastructure has different critical structural characteristics whose failure might lead to a disruption of its operation.

For instance, in natural gas pipeline networks, the material, diameter, and connection elements of the pipes play a significant role in estimating the level of damage/failures developed during an earthquake.

On the other hand, in the case of a road network, the behavior of the ground (settlements, lateral spreading, liquefaction) is crucial, as it can lead to subsidence, fractures, or other forms of failure in the road's embankments.

Especially for infrastructure elements that extend lengthwise, such as natural gas pipelines, the approach of fragility curves changes. These curves no longer describe the level of expected damage as in the case of a building, but rather the number of failures per unit length of the network (usually calculated per km).

Indicative photos of damage to infrastructure elements following significant earthquakes are shown in Figure 9 for various categories of infrastructure.

(a)

(b)

(c)

(d)

(e) (f)

Figure 9. (a) Natural gas network failure in the Loma Prieta earthquake, USA (1989) (photo:Bob Pepping/Contra Costa Times) (b) Failure in the railway line during the earthquake in Turkey (2023) (photo: AP/Francisco Seco), (c) Failure of a water supply network pipe during the Tohokou earthquake, Japan (2011) (photo: Miyajima, 2012), (d) Failure of port facilities during the Kobe earthquake, Japan (1995) (photo: Karen Kasmauski), (e) Failures in the road network during the earthquake of Kefalonia, Greece (2014) (photo: ITSAK), (f) Bridge collapse in the Loma Prieta earthquake, USA (1989) (photo: USGS)

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