IABSE Bulletins

Structural Engineering Documents

16

Characteristic Seismic Failures of Buildings

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International Association for Bridge and Structural Engineering (IABSE)

Characteristic Seismic Failures of Buildings

Earthquakes can cause considerable fatalities, injuries and financial loss. The forces of nature cannot be blamed, as the problem lies with the structures in seismic regions that may not have been designed or constructed to a sufficient degree to resist earthquake actions or they may have design flaws. This Structural Engineering Document (SED) concerns reinforced concrete and masonry buildings together with geotechnical aspects and presents in a concise and practical way the state of the art of current understanding of building failures due to earthquakes. It classifies the different types of seismic failure, explains the reasons for each failure, describes good practices to avoid such failures and also describes seismic retrofitting/ upgrading procedures for pre-earthquake strengthening and post-earthquake repair and/or strengthening techniques for deficient buildings. Carefully selected photographs and diagrams illustrate the different failure types. This document could be considered as quite unique, as this is the first time such material concerning characteristic seismic failures of buildings has been presented together in one single document. It is intended to be a valuable educational reference textbook aimed at all levels of experience of engineers. It provides background information, ideas, guidance and reassurance to engineers in earthquake regions faced with the task of building a safer future for the public and to protect lives.

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Preface

Earthquakes are not going to stop happening. In terms of worldwide fatalities and financial loss, earthquakes can be considered one of the most destructive natural hazards known to humanity. For years, seismic code provisions only referred to new structures. However, in the last 20 years, a new generation of codes for the assessment, repair, and strengthening of existing structures has started to appear. This reflects the need to preserve and possibly upgrade the building stock for social reasons related to life safety of the people, as well as accounting for cost effectiveness, environmental issues, or aesthetics. A lot of work has been performed relating to code development along with an impressive progress in theoretical and experimental research on earthquake engineering. Nevertheless, a comprehensive knowledge on the subject cannot be achieved without the observation of what happens in real conditions when an earthquake strikes. Although there has been any number of earthquake reconnaissance reports produced, there are no complete publications that (a) categorize the structural deficiencies that earthquakes exploit or (b) explain good practice in structural design and retrofitting. Thus, the primary object of this SED publication is education. The document attempts to present in a concise and practical way the state of the art of our current understanding of building failures due to earthquakes.

Aristotle said that knowledge starts from observation. From a structural engineering point of view, any seismic event is a real test of thousands of buildings. Lessons learnt from the aftermath of earthquakes and specifically from observed failures are the best way to improve our knowledge by filling the gap between research and real practice.

Therefore, from the very beginning when IABSE Working Group 7 was first established in 2009, a study of characteristic seismic failures was recognized as one of the main topics of the group. From 2009 to 2013, data from seismic failures were collected and analysed by a team of members and guests comprising, in alphabetical order: Anton Antonov, Prof. Stephanos E. Dritsos, Christos Giarlelis, Jack López Jara, Prof. Dharam V. Mallick (sadly deceased), Serge Montens, Dr. V. J. “Jon” Moseley, and Dr. Kyriakos Stathopoulos. Initial coordination was performed by Group Chairman Prof. Stephanos E. Dritsos, and a first internal draft report “Characteristic Seismic Failures” was welcomed at the 2011 Technical Committee meeting in London. A final draft coordinated by Jack López Jara was uploaded to the Working Group 7 website in 2013. This present SED is a follow-up of the above-mentioned work.

The document is a teamwork coordinated by Stephanos E. Dritsos, and material has been shared between the authors. However, the proposal of each chapter was drafted by a leading author, in the following chapter order: Jon Moseley (Chapter 1), Andreas Lampropoulos (Chapter 2), Eftychia Apostolidi (Chapter 3), and Christos Giarlelis (Chapter 4).

This document concerns reinforced concrete buildings and masonry buildings. It attempts to categorize the types of seismic failures, explain the reasons of each failure, and propose good practices to avoid such a failure. Suggestions for pre-earthquake strengthening of weak structures or elements together with post-earthquake retrofitting measures when damage has occurred are also presented. This document is intended as a comprehensive educational reference textbook to benefit the engineering society and our society as a whole community. In addition, it is aimed at all classes of engineers from novice to expert, as well as students, and it could be a unique document that may be of considerable benefit to the IABSE community and practicing civil and structural engineers in general. It may have considerable impact in developing countries where the infrastructure is still being built, because it addresses, among other things, non-engineered construction practice. The document's purpose is to give background information, stimulate focus on the earthquake problem, extend knowledge concerning earthquakes, and to give ideas and reassurance to those faced with the task of building a safer future for the public and to save lives.

Specific thanks are due to Jon Moseley for his participation in this project from the very beginning, for his invaluable insights and comments during the internal review process, and for his time-consuming dedication when correlating the individual chapters and integrating them into one document.

Finally, we would like to thank IABSE and specifically IABSE Vice-President Dr. Christian Cremona and Dr. Harshavardhan Subbarao, Chair of the Editorial Board, and its board for providing full support for publishing this document.

Stephanos E. Dritsos
University of Patras

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MAURER

Structural Protection Systems

STRUCTURAL BEARINGS | EXPANSION JOINTS | SEISMIC DEVICES | **VIBRATION ABSORBERS** | MONITORING

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Job Description: Structural protection for the new landmark in Delhi, displaying a 150 m high pylon with asymmetrically arranged stay cables.

Project scope: 38 nos. MAURER MSM® Spherical Bearings, of this two pylon bearings which have to support a vertical load of up to 23,000 tons. Moreover, eight rocker bearings will accommodate 17,500 kN tensile forces each from the stay cables and transfer these loads into the foundation.

MOSQUE ALGIERS, ALGERIA

Job Description: The third biggest mosque in the world requires an innovative seismic protection, with a design life of 500 years.

Project scope: 246 nos. sliding isolation pendulum bearings SIP with a rotational hinge (design specification 3 % dynamic friction and 2,400 mm effetive radius), as well as 80 nos. MAURER Hydraulic Dampers MHD with a response force of 2,500 kN.

DANUBE CITY TOWER, AUSTRIA

Job Description: Reduction of the horizontal acceleration of the structure caused by wind and earthquake at a high rise building of 220 m height, to generate sufficient comfort.

Project scope: Two MAURER adaptive hydraulic dampers with a response force of up to 80 kN and +/– 700 mm stroke, which dampen the 300 ton mass-pendulum. Including a monitoring system for displacements, forces and accelerations.

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forces in motion

Chapter

1

Introduction

1.1 Some Basics

While there are a few earthquakes that are due to volcanic activity, collapse of underground caves, or mining activities, most earthquakes are of tectonic origin and take place at or near to the edges of the world's tectonic plates. The vast majority of these tectonic earthquakes are caused by a sudden slippage along a fault, which releases energy and causes seismic waves that make the ground shake. *Figures 1.1* and *1.2* present the maps of the world's major tectonic plates and the world's recorded earthquakes, respectively.[1] The coincidence of plate boundaries and earthquake locations can be clearly seen by comparing these two figures. In fact, recording the location of earthquakes over time has led to defining the current boundaries between the world's tectonic plates. Plate boundaries represent transform, divergent, convergent or zones. That is, they either grind past each other, slide apart from each other, collide (with one disappearing beneath the other), or form regions, where the boundaries and interactions between plates are not clear.[2] These interactions cause earthquakes. The following are some examples of movements at the plate boundaries: transform motion of the San Andreas Fault Zone (≈5 cm/year),[2] divergence of the Mid-Atlantic Ridge (≈2.5 cm/year),[2] divergence of the East Pacific Rise (≈15 cm/year),[2] and India converging on the Himalayas (≈5 cm/year).[3]

In line with other past and contemporary visionaries, Alfred Wegener in 1912 proposed the concept of continental drift,[4] which provoked disagreement, debate, and finally proof. This resulted in the development of the scientific theory of plate tectonics in the second half of the twentieth century.[5] Plate tectonic theory states that the rigid crust of the earth (the lithosphere) is broken up into "plates" moving on a low-viscous layer (the asthenosphere) with a fluid mechanics behaviour. The very cause of earthquakes is, thus, the movement of such large plates that compose the outer shell of the earth's crust. Heat from the layers below the lithosphere and the difference between the light density of the lithosphere and the heavy density of the underlying asthenosphere explain such movements and are viewed as the most important source of energy that drives plate tectonics. The difference in density also allows the asthenosphere to sink into the deep mantle at subduction zones (where plates converge). Tectonic plates include continental crust, oceanic crust, or both.

An earthquake is a sudden, transient, and sometimes extremely violent movement of the earth's surface. In order for an earthquake to occur, a mechanism is needed to supply the energy and stress

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Chapter

2

Reinforced Concrete Building's Seismic Failures

2.1 Introduction

Reinforced concrete (RC) is one of the most common materials used to construct buildings worldwide. In seismic regions, the majority of existing RC buildings have been designed either to old seismic code provisions that are now understood to be inadequate or without any code provisions. As such, many of these buildings are highly vulnerable to earthquakes.[1–3] In this section, the most common failure types affecting RC structures in their entireties will be described, followed by typical failure modes of RC elements.

2.2 Global Vulnerability

2.2.1. Plan and Vertical Irregularities

The response of RC buildings under earthquake loading is highly dependent on the distribution of the mass and the stiffness in both the horizontal and vertical directions. These irregularities in the distribution of mass, strength, and stiffness are broadly classified as plan (horizontal) and vertical irregularities.[4]

During seismic excitation, horizontal inertia forces are generated in buildings, which are considered to act through the centre of the mass of the structure. The vertical elements of the structure resist these actions, which are assumed to act through the centre of rigidity. When the centre of mass does not coincide with the centre of rigidity, there is eccentricity. During an earthquake, torsion results as the centre of mass rotates around the centre of rigidity, which may lead to severe damage (*Fig. 2.1*). Buildings that have an irregular plan shape (such as Π, L, T, and I shapes, see Section 3.2.1.1 for more details) may also suffer from torsion for the same above reasons unless precautions have been taken.

In the building shown in *Fig. 2.1*, shear walls were concentrated mostly at the top and left side (in plan), leading to a significant deviation of the centre of rigidity from the centre of mass. This

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Chapter

3

Masonry Buildings' Seismic Failures

3.1 Introduction

Masonry structures are probably the most popular and ancient type of buildings all over the world. Easy access of its constitutive materials, which are basically stones, bricks, and mortar (which varies from region to region), makes masonry one of the everlasting construction methods from small residential buildings to the most important ancient and historic monuments. Some of the most significant monuments throughout the world made of masonry are presented in *Fig. 3.1*.

Some masonry buildings have proved to be resistant structures even in seismic prone areas, due to some specific structural characteristics that have been observed throughout the years and after many destructive earthquakes. In this chapter, an effort will be made to refer to and describe the most characteristic deficiencies in unreinforced and reinforced masonry buildings under seismic actions. Design recommendations for new earthquake-resistant structures will follow, and some retrofitting and strengthening strategies for existing masonry buildings will be proposed.

3.2 Unreinforced Masonry Buildings

Unreinforced masonry buildings usually consist of vertical structural elements (walls), which support the horizontal structural elements (floors and roofs), forming a box-type structural system. When unreinforced masonry buildings are carefully constructed, the gravitational loads acting on the floors (performing as horizontal flexural elements) are transferred first to the load-bearing walls (acting as vertical compression elements) and finally to the foundation. Floors and roofs, which should ideally act as rigid diaphragms, additionally transfer earthquake-induced horizontal inertia actions to the walls, resulting in shearing and/or bending effects on the walls. Furthermore, distributed inertia forces are induced by the distributed wall element masses, which may result in the out-of-plane bending of the walls.[1]

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Chapter

4

Geotechnical Aspects of Structural Failures

4.1 Introduction

Strong seismic shaking is recognized as the direct cause of structural failures. In many cases, however, the factor that initiates the structural damage is ground failure or ground displacement. This chapter deals with the identification of all geotechnical related structural failures. Surface fault rupture has been a well-acknowledged cause of failures of structures built across or near the fault, which are increasing in frequency as the man-made environment constantly expands to new areas. Seismically induced rockfalls, landslides and slope failures have also been associated with major disasters with an increasing frequency in some cases due to an expanding population, which encroach on areas with landslide risk or in other cases as result of the destruction of the natural environment (vegetation and water routes), which have protected these slopes in the past. Foundation damage may be a result of failure of shallow foundations or piles. In addition, although liquefaction and ground settlement are technically part of foundation failures, they are usually treated as separate, special cases. Retaining wall structures, usually considered as simple systems, may display a complex behaviour, which can be related to extensive seismic failures. Finally, not taking into account soil–structure interaction (SSI) may have a detrimental effect on the dynamic response of structures. Although SSI may never be the direct cause of a structural failure, it has proven to be, in several cases, the underlying reason for the analysis misconception that led to the failure.

Most of the contemporary seismic codes have acknowledged the significant role of geotechnical conditions in the seismic response of structures and attempt to incorporate their influence. This is usually achieved through the application of an amplification factor in the response spectrum or/and other parameters that affect its shape depending on the soil class (usually related to the shear wave velocity of the upper part of the soil stratum). In addition, recommendations are given regarding the near field conditions, soil liquefaction, etc., but also for the design of foundations and earth retaining structures. However, in many cases these recommendations are partly neglected in everyday practice especially in smaller projects in order to reduce the cost. Not uncommonly, the engineer in charge avoids a thorough geotechnical investigation and bases the design on parameters typical for the area, but partly inaccurate assumptions for the soil

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Structural Engineering Documents

Objective:

To provide in-depth information to practicing stuctural engineers in reports of high scientific and technical standards on a wide range of structural engineering topics.

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The International Association for Bridge and Structural Engineering (IABSE) operates on a worldwide basis, with interests of all type of structures, in all materials. Its members represent structural engineers, employed in design, academe, construction, regulation and renewal. IABSE organises conferences and publishes the quarterly journal *Structural Engineering International (SEI)*, as well as reports and monographs, including the SED series, and presents annual awards for achievements in structural engineering. With a membership of some 4,000 individuals in more than 100 countries, IABSE is the international organisation for structural engineering.

Publisher:

The International Association for Bridge and Structural Engineering (IABSE) was founded as a non-profit scientific association in 1929. Today it has more than 3900 members in over 90 countries. IABSE's mission is to promote the exchange of knowledge and to advance the practice of structural engineering worldwide. IABSE organizes conferences and publishes the quarterly journal Structural Engineering International, as well as conference reports and other monographs, including the SED series. IABSE also presents annual awards for achievements in structural engineering.

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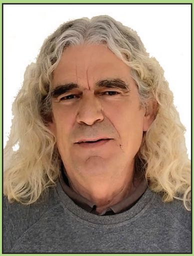

Dr V. J. "Jon" Moseley worked on large scale civil engineering projects before attending university as a mature student. At the University of Sheffield, he obtained a M.Eng (Mappin Medal) and a PhD (research assistant) in Civil and Structural Engineering. He has his own earthquake engineering office and is also a part-time consultant at the University of Patras.

Dr Andreas Lampropoulos is a Principal Lecturer and Course Leader for the BEng/MEng Civil Engineering courses at the University of Brighton. His main research interests span the areas of novel construction materials and seismic strengthening/retrofitting of existing structures. He currently serves as the Chairman of IABSE Task Groups 1.1 and 5.5, dealing with seismic resilience and seismic strengthening/retrofitting.

Eftychia Apostolidi received her civil engineer diploma (M.Eng) from the University of Patras, Greece. She is about to receive her PhD from the University of Natural Resources and Life Sciences, Vienna, Austria, where she works as a research associate. Her research interests include the seismic assessment and retrofitting of masonry structures. She is also involved in numerous Austrian and European projects.

Christos Giarlelis is a structural engineer with expertise in the fields of seismic design, soil-structure interaction, and seismic isolation and damping systems, both as a consultant and as a researcher. He is the co-founder of EQUIDAS Consulting Engineers and an adjunct lecturer at the University of West Attica, Greece.