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Seismic Isolation and Response Control

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Preface

The seismic resilience of new and existing structures is a key priority for the protection of human lives and the reduction of economic losses in earthquake-prone areas. The implementation of modern seismic codes for the design of new earthquake-resistant buildings and the advances in techniques for the repair and strengthening of existing deficient structures have focused on the upgrade of the structural performance of the new and existing structures. However, in many cases, it is preferable to mitigate the effects of earthquakes by reducing the induced loads in the structures using seismic isolation and response control devices. The main principle is that the use of appropriate seismic isolation and response control devices at the base of the structures will offer increased flexibility and energy absorption characteristics preventing resonance and significantly reducing the induced loads and deformations. The reduction of the deformations is also one of the main reasons for using these methods in cases of buildings with special requirements such as limited induced displacements in case of earthquakes (e.g. museums, hospitals, precision instruments and other equipment sensitive to displacements and accelerations etc.).

The use of seismic isolation and response control systems has become a quite popular technique not only for the design of new but also for the upgrade of existing structures. Various systems have been developed, and some limited information is also included in modern seismic codes for the design of new buildings with seismic isolation. However, the limited expertise on the selection of the appropriate system and its design for new and existing structures is the main challenge for practitioners and hinders the extensive use of seismic isolation and response control systems in practice. This is even more challenging for the application of these systems in existing structures where additional practical difficulties during the installation process are to be anticipated. The selection of the appropriate system depends on a large number of parameters, including the requirements and the particular characteristics of the examined structures. The engineers need to consider various possible systems, and the selection of the appropriate technology as well as the design process is in many cases a process with many iterations and alternatives.

The first part of this document is focused on the collection of the most commonly used seismic isolation and response control systems and the critical evaluation of the main characteristics of these systems. Then a comparison of the key parameters of the design processes for the design of new buildings with seismic isolation is presented, followed by four case studies from New Zealand, Greece, and Mexico and one case study on response control systems from Japan. The application of seismic isolation systems and response control systems for the retrofitting of existing structures were also examined. Two case studies on the application of seismic isolation systems in Turkey and Greece are presented, followed by three case studies on the application of response control systems in existing structures in Japan, Turkey and New Zealand. Finally, post-earthquake survey observations from seismic isolated structures are described to evaluate the efficiency of the application of these systems.

The main aim of this document is to provide a practical guide for the selection of seismic isolation and response control systems and explain the main steps of the design and application process. This work has been conducted as one of the main tasks of IABSE Task Group 1.1 'Improving Seismic Resilience of Reinforced Concrete Structures', which is part of Commission 1 'Performance and Requirements'.

This work was coordinated by the IABSE Task Group 1.1 Chairman Dr Andreas Lampropoulos (Editor) and presents a teamwork of the following members (listed in alphabetical order): Dr Eftychia Apostolidi, Professor Stephanos Dritsos, Mr Christos Giarlelis, Professor Jose Jara. Professor Fatih Sutcu, Professor Toru Takeuchi and Dr Joe White.

Chapter 1 (Introduction) was led by Professor Stephanos Dritsos and Chapters 2 (Seismic Isolation and Response Control Systems), 3.1 (Design of New Buildings with Seismic Isolation), and 3.2 (Basics of Seismic Isolation Design) were led by Professor Fatih Sutcu, Professor Toru Takeuchi and Mr Christos Giarlelis. Mr Christos Giarlelis also led the preparation of the three case studies in Greece. Professor Jose Jara led the preparation of the case study in Mexico. Professor Fatih Sutcu led the preparation of the two case studies in Turkey. Professor Toru Takeuchi led the preparation of the two case studies in Japan. Dr Joe White led the preparation of the two case studies in New Zealand. Dr Eftychia Apostolidi worked on the enhancement and completeness of the main part of the document. All the authors of the list contributed to various sections of this document which represents the outcome of a collective effort.

The Editor would like to express his appreciation and sincere thanks to the reviewers, Prof. Fabrizio Palmisano (Chief Reviewer, Editorial Board), Prof. Alberto Pavese and Asst. Prof. Bahadir Sadan, for their comprehensive and valuable comments and suggestions.

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Dr Andreas Lampropoulos
(Editor)

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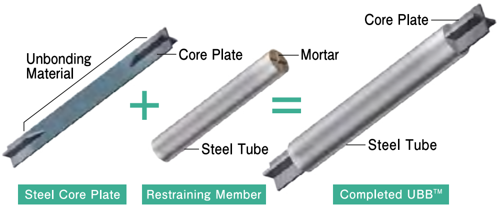

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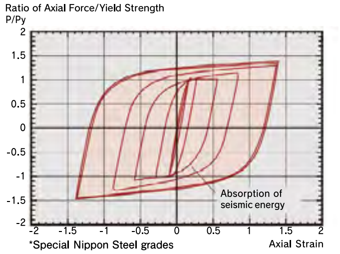

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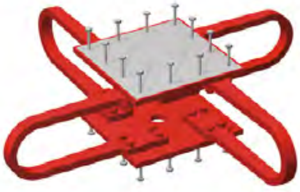

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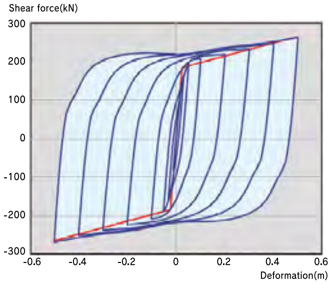

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List of Abbreviations

AIJ	Architectural Institute of Japan
BRB	Buckling-Restrained Braces
CFD	Computational Fluid Dynamics
DBE	Design Basis Earthquake
DCLS	Damage Control Limit State
EEI	Environmental Energy Innovation
ELFM	Equivalent Lateral Force Method
FPS	Friction Pendulum System
FVD	Fluid Viscous Dampers
HDRB	High Damping Rubber Bearings
HVAC	Heating, Ventilation and Air Conditioning
IBC	International Building Code
LDD	Low Damage Design
LDRB	Low Damping Rubber Bearings
LRB	Lead-plug Rubber Bearings
MCE	Maximum Considered Earthquake
MEP	Mechanical, Electrical and Plumbing
NLTHA	Non-Linear Time-History Analysis
NRB	Natural Rubber Bearings
PGA	Peak Ground Acceleration
PRB	Polymer Plug Rubber Bearings
RC	Reinforced Concrete
RSA	Response Spectrum Analysis
SB	Sliding Bearings
SDOF	Single Degree of Freedom
SNFCC	Stavros Niarchos Foundation Cultural Centre
SSI	Soil-Structure Interaction
ULS	Ultimate Limit State

Chapter 1

Introduction

Traditionally, the design of structures has steadily followed the safety verification rule that, in any element of the structure, the design action effects should be lower than the respective resistance. Until now, the above verification is mainly performed in terms of forces. This so-called Force-Based Design has been the main design procedure adopted in our codes. Based on this approach, the safety of the whole structure can only be ensured when safety verification criteria are satisfied for all the elements of the structure without investigating the performance of the structure when the capacity of one or more structural elements is exceeded.

In the last 25 years, the engineering community has adopted the concept of displacement-based design, in which the safety verification is performed in terms of displacements not only of the members but also of the structure as a whole. Moreover, since the displacements are determined, the functionality of the structure can be verified as well.

Recently, the idea to integrate verification for safety, integrity, stability and functionality of a structure in a holistic way, through global verification criteria, for a set of earthquake scenarios has gained more and more ground/attention. The contribution of each element to the whole performance of the structure is considered, but, in general, there is no need to verify the integrity of each one of them, accepting a level of damage depending on the importance of the examined structure. This has been now introduced in the codes, using specific performance or damage levels where the relevant losses are addressed to the structure as a whole. Displacement-based design is a breakthrough approach for seismic engineering.

However, the increased needs of the modern overdeveloped and overpopulated societies and the alarming consequences of extreme events (e.g. earthquakes) can lead to a significant amount of fatalities and depleting resources and the subsequent collapse of the society. Therefore, there is an urgent need for the development of a 'resilient'-based approach.

A key factor for the development of this approach is the consideration and quantification of a wide range of direct and indirect losses. The engineering community is traditionally focused mostly on the repair and reconstruction costs after seismic events. However, losses of human life, monuments, historic structures, or exhibits in museums may have more value than the repair and reconstruction cost of damaged structures. In addition to these 'direct' consequences, indirect losses should be considered. These include not only the economic activity losses due to the inability of the people to continue their jobs or to use their houses, but also the diminishment of the quality of their lives.

Chapter 2

Seismic Isolation and Response Control Systems

Seismic isolation and response control are seismic protection methods that are used to protect structures, non-structural components and contents of buildings from the damaging effects of earthquakes.

Seismic isolation is a method that is implemented to shift the natural vibration period of a structure to the long period range of approximately 2.0~4.0 secs by placing isolation bearings usually at the foundation level in order to physically decouple the structure from the ground. However, there are exceptions where seismic isolation may be used in the upper floors of a structure or that the fundamental period of the isolated structure exceeds 4.0 secs. The isolation layer consists of horizontally flexible devices that are capable of reducing the lateral stiffness of the superstructure combining structure re-centring and energy dissipation capability. Energy dissipation in the bearings (or separate dampers placed in parallel) can increase the effective damping ratio of the whole system. The result is a reduction of the acceleration and shear force response. This approach is most suitable for low-to-mid-rise stiff structures where a clear separation between the natural period of the flexible isolator bearings and a stiff superstructure minimises the transfer of lateral accelerations. In these cases, typically, a seismic isolation system can be designed that enables the superstructure to remain elastic even after a Maximum Considered Earthquake (MCE) event.

Response control, on the other hand, is a technique where structures are equipped with energy dissipating devices that will improve the structural integrity, reduce the dynamic responses of the structures or enable the control of higher mode effects during dynamic excitations such as seismic events or winds.

With their given merits, these methods provide the highest possible seismic protection for building structures. Often, equally important, damage to non-structural items (partitions, ceilings, façades and building services etc.) can be prevented or significantly reduced. Furthermore, the contents of the structures are better protected since the induced accelerations are lower. When a building and/or its contents are of high importance (such as hospitals, data centres, transportation facilities, etc.), seismic isolation and response control techniques enable the buildings to remain functional even after a major earthquake. Similarly, these techniques can be implemented in industrial buildings, bridge

Chapter 3

Design of New Buildings with Seismic Devices

In this chapter, the design of seismic devices for new structures is discussed. The main international code provisions are summarised, followed by a description of the basic design philosophy and representative case studies.

3.1 Design of New Buildings with Seismic Isolation

In this section, the basic descriptions of the main design codes and recommendations worldwide concerning seismic isolation systems (i.e. Eurocode, ASCE, Japanese, Mexican, and Turkish building codes) are presented.

EN 15129 [41] covers the design of seismic isolation devices that are assembled in structures, with the aim of modifying their response to the seismic action. It specifies functional requirements and general design rules of the devices for seismic and non-seismic design situations, material characteristics, manufacturing and testing requirements, as well as assessment and verification of constancy of performance, installation and maintenance requirements. This European Standard covers the most important types of devices and their combinations. In EN15129 [41], seismic isolation devices are divided into three categories:

1) Elastomeric Isolators (Chapter 8.2 of [41]): These are divided into High Damping Rubber Bearings (HDRB) and Low Damping Rubber Bearings (LDRB). LDRB can include Lead-plug or Polymer plug (LRB or PRB) for achieving the desired level of damping.
2) Curved Surface Sliders (Chapter 8.3 of [41]): These are friction pendulum system (FPS) bearings that dissipate energy by friction and provide a restoring force depending on displacement for re-centring.
3) Flat Surface Sliders (Chapter 8.4 of [41]): These sliders should be used with other devices that provide re-centring.

According to EN 15129 [41], it is not recommended to use displacement limiting/stopping rings in sliding devices. That is why triple pendulum bearings are not compatible with this code.

Chapter 4

Seismic Retrofit Using Seismic Isolation and Response Control

This chapter presents detailed information on seismic devices for seismic isolation and response-controlled systems available for improving the seismic performance of existing reinforced concrete structures.

Facilities such as schools and hospitals have a substantial role in civil protection in order to guarantee the continuity of the main services, especially after a major seismic event. Therefore, the continuous upgrade and compliance of these buildings to the most recent standards is of primary importance to enable the uninterrupted operation of these facilities. Recently, the development of innovative materials and subsequent advances in seismic isolation and response control systems have led to a continuous improvement of seismic protection techniques. These new methods are commonly used in structures with structural irregularities both in plan and in height, especially when they are in high seismic zones and when there are increased performance requirements.

Seismic retrofit using seismic isolation and response control systems is preferred particularly for the retrofitting of key buildings such as hospitals, governmental buildings or industrial facilities, where re-construction is not an option. These types of innovative retrofitting methods can be implemented while the building is in operation.

Many international codes provide a designated chapter for the assessment of existing buildings' structural performance and retrofitting design. However, the design of seismic isolation and response control systems is not sufficiently covered in most of these codes, and this is one of the main barriers to the implementation of these technologies. ASCE 41-17 [58], which is a code especially prepared for the seismic evaluation and retrofit of existing buildings, includes some provisions for these systems.

Retrofit design using seismic isolation or response control devices is quite similar to designing a new building with such devices. The only important difference is that the retrofit solution should be tailor-made to suit the already existing structural layout. Therefore, each retrofit project with seismic isolation or response control is a unique work that requires detailed planning and execution. In the next section, such retrofit projects are presented in a consistent format, in which the objective of each project is presented, followed by the performance requirements and information about the steps of the application.

Chapter 5

Post-Earthquake Survey Observations

Post-earthquake survey observations and monitoring can provide important information about the effectiveness of the examined seismic isolated and response-controlled structures. Visual inspection of the buildings is normally conducted after major earthquake events. However, the lack of specialised monitoring systems leads, mostly, to qualitative observations about the efficiency of the seismically isolated/response-controlled structures with limited reliability. Post-earthquake data from monitoring systems in these structures can offer valuable information about the effectiveness of the examined schemes. In this section, two such cases of buildings in Japan are presented.

5.1 Ishinomaki Red Cross Hospital, Seismically Isolated Hospital Building, Ishinomaki, Japan

Ishinomaki Red Cross Hospital is located in Ishinomaki city, Miyagi prefecture, Japan, which is the only hospital designated as a disaster hospital in Ishinomaki medical zone (Figure 5.1). In addition to emergency rescue, the hospital was given the role of accepting and transporting the sick and injured within the disaster area. The footprint and total floor area of the main hospital building are 10,173 m^2 and 32,486 m^2, respectively. The building has seven storeys above the ground level and one floor at the basement, with a total height of 26.2 m. The design was performed by Nikken Sekkei Co.Ltd. and the contractor was Kajima Corporation. The construction period was from August 2004 to June 2006 [69], [72].

The section and plan views of the main building are shown in Figure 5.2(a) and (b), respectively, where the location of the isolation systems is indicated. Natural Rubber Bearings (NRB) and flat sliding bearings are used as isolation bearings, and U-shape steel dampers were also added (Figure 5.2(b)). The natural period of the structure only with rubber bearings is 5.39 sec, which is reduced to 3.73 sec, including the equivalent stiffness of sliding bearings at a displacement of 490 mm. The total shear force of U-dampers and sliders equals almost 5 % of the total building weight.

During the Great East-Japan Earthquake on March 11th 2011, Ishinomaki city recorded the ground motion of $PGA = 633\ \mathrm{cm/sec^2}$, and the isolated layer of the building recorded a maximum displacement of 260 mm in the east-west direction. This is almost half

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Seismic Isolation and Response Control

The seismic resilience of new and existing structures is a key priority for the protection of human lives and the reduction of economic losses in earthquake prone areas. The modern seismic codes have focused on the upgrade of the structural performance of the new and existing structures. However, in many cases it is preferrable to mitigate the effects of the earthquakes by reducing the induced loads in the structures using seismic isolation and response control devices. The limited expertise in the selection and design of the appropriate system for new and existing structures is the main challenge for an extensive use of seismic isolation and response control systems in practice.

This document aims to provide a practical guide by presenting a collection of the most commonly used seismic isolation and response control systems and a critical evaluation of the main characteristics of these systems. Comparisons of the key parameters of the design processes for new buildings with seismic isolation are presented, while the application of seismic isolation systems and response control systems for the retrofitting of existing structures is also examined, followed by various case studies from Greece, Japan, Mexico, New Zealand, and Turkey.

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