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SEISMIC ISOLATION DESIGN FOR CONTINUED FUNCTIONALITY

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Abstract: *Continued functioning of buildings, bridges, and industrial facilities after a major earthquake is necessary for minimizing disruption to society. ASCE 7-16 Functionality requirements for Category IV structures now mandate that the facility be functional immediately following the design level earthquake. Over the past 40 years worldwide seismic isolation design strategy has been implemented by structural engineers seeking a reliable and viable solution for seismic design of variety of structures. The minimal additional cost to the owners for implementing seismic isolation has been justified with an "expectation" that their facilities will likely remain functional and operational after a major earthquake. However, the respective code provisions developed as guidelines for the design of isolated structures were based on the premise of "equal performance" with the conventional code compliant ductile structure design approach; i.e. "collapse prevention", not continued functionality. There is a disconnect between what owner's expect and what has been implemented following code provisions. Continued Functionality design objectives in structures are achieved by absorbing seismic displacement in isolation bearings, maintaining an elastic structure, and minimizing in-structure accelerations and drifts. FEMA 58 "Seismic Performance Assessment" software is used to calculate the expected seismic damage at different strengths of earthquake shaking. Post-earthquake functionality is typically retained when seismic damage is limited to less than 2% of the replacement costs. The paper presents the current pitfalls of code compliant seismic isolation provisions, and a way forward for the right approach for implementing seismic isolation following the "Continued-Functionality Standard" to meet the owner's expectation. Examples resilient isolated structures worldwide designed and constructed at lower costs than conventional ductile structures are presented.*

Building Codes for Seismic Design

If we can rewind the time as far as possible in the history to observe how great structures were built all over the world, the common construction materials consisted of stone, wood, cast metals, and limestone/sand/water mixtures as bonding agents. Master builders and craftsmen developed skills and techniques on the shapes and forms that were compatible with the forces and laws of nature. Gravity was the main force that dictated structure forms and shapes, like arches and domes. Wind forces were never any design consideration as structures built for gravity forces were heavy. Earthquake forces were considered an act of God and thus largely ignored.

The first recording of an earthquake ground acceleration occurred during the 1940 El Centro earthquake. This was a major milestone that led to the development of seismic design codes that are now practiced all over the world. Engineers thought that designing structures for realistic earthquake forces was not cost-effective. Thus, they adopted a "ductility life-safety" based code that allowed structures to get damaged during an earthquake, but largely intended to avoid "collapse" so that human lives would be protected. Over the years this approach was refined with new construction materials and methods. However, till date the basic code objective for earthquake design all over the world has remain unchanged; i.e. "Collapse Prevention". The 2010 Mag. 8.8 earthquake in Chile and the Mag. 6.3 earthquake in New Zealand have demonstrated that Engineers have accomplished the basic objective of "Collapse Prevention"

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as only 22 buildings collapsed amongst thousands. Earthquake damage of over US $ 60 billion has nevertheless, left communities devastated.

The Building Code objectives should now change from “Collapse Prevention” to “Damage Prevention”. The world of automotive industry has already started shifting from “Occupant Safety” to “Collision Prevention” with the integration of smart sensors and advanced braking technology.

In the US both the Building Code requirements and Building Industry practices are shifting towards resiliency in design and construction to minimize earthquake damage. The American Society of Civil Engineers (ASCE) latest Building Code Standard ASCE 7-16 Section 1.3.3 on Functionality requires Essential Facilities (Risk Category IV Structures) to remain functional and operational after a design level earthquake (ASCE Standard 7-2016).

When it comes to Building Code requirements for earthquakes all over the world there is a major disconnect between the Owners expectation and what the Codes deliver for post-earthquake functioning. Owner’s expectations for their buildings are consistent with the great advancement in other industries like computers, cell phones, mechanical, agricultural and automotive industries. Owners today expect that a new building is earthquake proof or earthquake resistant. However, this is far from reality. New Zealand which has one of the highest seismic design code requirements realized this fact after the Magnitude 6.3 earthquake in 2011. Only 2 buildings collapsed, but more than 70% of buildings in downtown Christchurch suffered architectural, non-structural, and structural damage and had to be eventually demolished.

Designing Buildings with Seismic Isolation

Implementing appropriately seismic isolation technology in building design provides the highest level of safety and damage prevention compared to any available alternate construction technology. Seismic isolation was invented in New Zealand in early 70’s and Japan took the major lead in the development and implementation of seismic isolation technology. In simple terms seismic isolation is a design approach where the structure is separated from ground by specially manufactured isolators, so that during an earthquake the isolators absorb a majority of ground movement, and thereby allowing the structure to move gently. Without isolators the structure moves violently with the ground during an earthquake causing damage, or even collapse. It is like a filter system that is placed on top of foundation which reduces earthquake forces by almost 90%. Over the last decade following the lessons learned from the 2010 Chile & 2011 New Zealand earthquakes isolators are being used on many important and essential facilities.

With over 5000 applications which use seismic isolation there are less than 50 isolated structures that have been designed to meet the owner’s expectation. Various degrees of damage have been reported for code designed seismically isolated structures after earthquakes in Japan, New Zealand & United States with resulting loss of facility use and significant repair costs (Japan Property Central, 2012, Kuang et. al. 2012)

Seismically isolated structures designed for minimum code compliance can not only have damage exceeding 70% of replacement costs, but they also do not comply with the probability of structure failure/collapse limits listed in ASCE 7 Table 1.3-2.

In contrast, seismically isolated structures designed in accordance with the “Continued-Functionality Standard” can achieve greater than 90% reliability of limiting seismic damage to less than 2% of replacement costs, and qualify for the REDi Resiliency Ratings. More importantly they also comply with the probability of structure failure/collapse limits listed in ASCE 7 Table 1.3-2.

Continued Functionality

Minimizing seismic damage and maintaining continued functionality and operation has always been desired performance objective of engineers, architects, owners, developers, and planners in earthquake prone regions all over the world. Nowhere this intent is more relevant than in the design of hospitals. Every year many people die when hospitals are not able to function after an earthquake and provide care for the injured persons.

The World Health Organization, and Pan American Health Organization, have published directives that a new hospital needs to be constructed "with a level of protection that best guarantees its capacity to continue functioning" at its "maximum capacity after earthquakes" (WHO, 2010).

Ministries and departments of health in over 194 countries, including the USA, Japan, Europe, Turkey, and Central and South America, have adopted these directives. In some countries, national laws specify that new hospitals must be designed and constructed to maintain their maximum capacity to care for patients after earthquakes (Pan American Health Organization 2007).

The US Resiliency Council (US Resiliency Council), REDi Resiliency Rating (ARUP), and the Federal Emergency Management Agency (FEMA, 2012) provide guidelines for how to minimize earthquake damage and loss of use. The design criteria specified for the Platinum Resiliency Rating satisfies the Health Ministry requirements for hospitals. Structural engineers have been using these methodologies to advise their clients regarding the expected damage and loss of use for hospitals and other buildings.

So far more than 5 million square meters of new hospitals, including the new hospitals shown in this paper, have been designed by structural engineers to minimize seismic damage to the architectural components, equipment, and contents. These hospitals satisfy Health Ministry directives for post‐earthquake functionality. These new hospitals shown in the photos use specially designed seismic isolators to limit seismic damage to less than 2% of replacement costs (Zayas, 2013).

Based on the results of the FEMA P58 Seismic Performance Assessment seismic damage calculations performed for these hospitals, the below criteria will on average limit seismic shaking damage to the architectural components, contents, and structure, to less than 2% of the replacement costs.

The design criteria to achieve "Continued Functionality" are:

1) Elastic structure design, with R=1 for the Design Basis Earthquake
2) Seismic story lateral drifts limited to less than .003 times the story heights for the Design Basis Earthquake
3) Limit the median floor spectra accelerations to less than 0.4g for each occupied floor, over the frequency range of 0.2 hz to 20 hz, for the Design Basis Earthquake.

These design criteria apply equally for buildings with or without seismic isolators.

Example seismic damage calculation performed on the Goztepe Hospital in Tukey are shown in Table-1 for four types of structures; Triple Pendulum isolated structure, Single Pendulum isolated structure, Code Compliant isolated structure, and conventional fixed based structure. For the design level earthquake the Triple Pendulum isolated structure results in seismic damage of < 2%, while the Code Compliant isolated structure results in 4 times more seismic damage. Of interest is to note that the ration of damage between Triple and Code Compliant isolated structure increases with decreasing earthquake intensity. Even though the seismic damage calculations are not precise and accurate, they are a valuable tool that allows owners/engineers to make risk and value based decisions, since the relative expected damage between the four structural systems would be of the same order as shown in Table-1.

Achieving Continued Functionality with Seismic Isolation

Installing seismic isolators that are designed for code compliance do not satisfy Continued Functionality design criteria. More importantly they do not satisfy the basic code objective of limiting probability of collapse specified for various structure categories. Building codes have endeavoured for decades to eliminate dangerous “soft stories.” Isolated structures are extreme soft stories, which can be very dangerous. There are no ASTM or NIST standards for generic materials and fabrication of generic isolators. When isolators are fabricated using inadequate materials and fabrication standards, an isolated structure becomes an extremely dangerous soft story structure.

Isolated structures designed for minimum code compliance, that install isolators fabricated by un‐qualified fabricators, can have FEMA P695 (FEMA-P695, 2009)] calculated collapse risks 10 times greater than traditional non‐ isolated structures (Zayas, Mahin, et.al, 2016, & Shao et. al., 2016).

Isolated structures designed according to Euro Code 8, with the isolators fabricated according to EN15129, appear to be some of the most dangerous new structures worldwide. The Euro Code 8 required isolator displacement capacity has a 10% probability of being exceeded in 50 years. About 10 earthquakes per year cause ground shaking that exceed this design level. EN15129 prohibits safety retainer rings for pendulum isolators, which essentially designs in by code isolator collapse for these stronger earthquakes. Rubber isolators made with poor materials and fabrication are even more dangerous.

Structure design codes need to change to require that seismic isolators be used only to reduce seismic damage to below those occurring with traditional ductile structures. To avoid seismic isolation systems from causing a collapse, codes and standards should require that isolators retain their required strength capacities in an earthquake having a less than 1% chance of being exceeded in 50 years (Zayas, Constantinou, et.al, 2019).

The “Seismic Isolation Standard for Continued Functionality” specifies the means and methods to achieve safe isolated structures that retain functionality after earthquakes. Seismic isolator properties and capacities are specified to comply with the “Basic Requirements” of ASCE 7-16, Chapter 1. The ASCE 7 basic “Functionality” requirements specify that “Essential Facilities” have a “reasonable probability to have adequate structural strength and stiffness” that “would not prevent function of the facility immediately following” the design level earthquake. ASCE 7 also specifies “Target Reliability” that limits the “Probability of Failure” to 2.5% for the “Structural Stability” of primary structural components in essential facilities. Compliance with ASCE 7 requires compliance with these “Basic Requirements”.

ASCE 7 Sections 1.3.1.1 and 1.3.1.2 require that design loads not exceed the capacity limits specified by a materials standard, such that when applied together with ASCE 7, satisfy the requirements for structure reliability and functionality. The standard specifies the required isolator shear strength and displacement capacities, such that when applied together with the ASCE 7-16, has a reasonable probability of complying with the ASCE 7-16 requirements for reliability and functionality. This standard represent best practices for seismic isolator engineering and manufacture as evolved over 32 years, and validated through isolator performance during extreme MCER events, shake table tests, FEMA P695 and P58 structural analyses, and applications of isolators to more than one hundred million square feet of isolated buildings, bridges, and industrial facilities.

Constructing isolated structures without specifying an adequate isolator standard creates serous life safety hazards, and violates ASCE 7 Basic Requirements for material standards, reliability, and functionality.

To satisfy the ASCE 7 Functionality criteria this standard specifies that essential facilities be designed elastically using R=1 for the design earthquake “DE”, and limits structure drifts to 0.3% of the story heights, and limits median floor spectra accelerations to 0.4g. Compliance with these criteria is expected to limit building damage to less than 2% of the building replacement costs, consistent with the REDi Platinum seismic damage limit. For isolated or non-isolated structures that comply with these resiliency criteria, most architectural components and contents of most facilities will retain their ability to function after a DE event. For isolated structures that comply with this standard, any Seismic Force-Resisting System specified in ASCE 7 Table 12.2-1 may be used for structures located in any Seismic Design Category, at any structure height. Using structure types that are reliable and economic for non-seismic regions, combined with isolators that comply with this standard, often results in lower total structure costs as compared to non-isolated ductile structure types.

All hospitals shown in the photographs herein were designed for Continued Functionality using Triple Pendulum seismic isolators specially configured to minimize damage to the architectural components, equipment, and contents of the facilities, as well as the structures (EPS, 2013, ENR, 2013, & Zayas, 2013).

The displacement capacities for these Continued Functionality isolators are typically twice those for isolators designed for minimum code compliance. The effective periods are also longer, and the effective damping levels lower. These longer period and lower damping isolators reduce in-structure accelerations and inter-story drifts, and thereby limit the FEMA P58 calculated seismic damage to less than 2% of replacement costs, while retaining relatively normal upper structure design and construction (Zayas, 2013). The 2% limit in seismic shaking damage can reasonably assure post-earthquake functionality, and currently 2% is the lowest damage level that can be reliably engineered and delivered.

Structural engineers are society's guardians for minimizing earthquake deaths, loss of use, and economic losses. As a profession we need to go beyond providing designs for minimum cost for minimum code compliance, and protect our clients and society by minimizing earthquake damage and deaths. Implementing Continued Functionality designs with seismic isolation not only achieves owner's expectations, but also satisfies our professional and social responsibilities.

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Stanford University Hospital, San Francisco, California

Adana Hospital, 5.5 Million Sq. Ft, Turkey

Lutfi Kirdar Hospital, 3 Million Sq. Ft, Turkey

Elazig Hospital, 2.5 Million Sq. Ft, Turkey

Goztepe Hospital, 2 Million Sq. Ft, Turkey

Table 1 – FEMA P58 Seismic Damage (% of Replacement Cost) Estimate for Goztepe Hospital

Probability of Being Exceeded in 50 Years: EQ Recurrence	Triple Pendulum Bearings	Single Pendulum Bearings, Same Building	Code Designed Bearings, Same Building	Same Building without Seismic Isolation
90%: 22 year return	0.08%	0.40%	1.32%	2.89%
50%: 75 year return	0.61%	1.90%	5.10%	12.57%
10%: 475 year return (DBE)	1.89%	4.42%	8.18%	83.18%
2%: 2475 year return (MCE)	3.11%	5.17%	17.48%	98.35%