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A comparative evaluation of design provisions for seismically isolated buildings

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ABSTRACT

Seismic isolation method is an innovative mature performance enhancement strategy to mitigate the earthquake risk on structures. As a result of the targeted response modification, feasible engineering solutions can be achieved during the service life of structures. For both bridges and buildings simplified analysis procedure of seismic isolation systems are set forth in guide specifications and design provisions. Equivalent lateral force (ELF) method in buildings can be considered as the simplest method of analysis with high importance. This procedure can be directly used in the analysis and design of seismically isolated structures or it can be used in the establishment of lower-bound limits to nonlinear time history analysis. This paper focuses on the overview of design procedures of isolated buildings and comparison of the analysis results of ELF procedure based on selectively well-known codes and guidelines used in pioneering countries. The buildings were equipped with two commonly used isolation systems named as lead rubber bearing and curved surface friction sliders. A comparison of the 2016 Edition of the Turkish Seismic Design Code with the US(ASCE/SEI 7–10), the European (Italian version of the Eurocode (EC-8) application, NTC-08) and the Japanese (Building Standard Law-2013) codes is conducted on the implementation of the ELF Method for parametric study of structures located at sites of similar probabilistic earthquake hazard in respective countries. Recommendations and concerns associated with the current-state of practice and ongoing development new reference section of TSDC are highlighted by comparing code compliance approaches and practical applications.

1. Introduction

In modern engineering practice, structural control has a long history and firstly applied in mechanical and aerospace engineering fields. For structural engineering, history of control application goes back to the end of 19th century by patented devices. Seismic isolation systems and energy dissipative systems can be considered as a relatively mature innovative technology with more than 10,000 worldwide applications [28]. Seismic isolation (SI) and energy dissipation systems (ED), shape memory alloy (SMA) devices and shock transmission units (STU) are used effectively in earthquake prone regions more than four decades to mitigate the earthquake risk.

Japan, US, Europe and New Zealand had pioneering roles in the development of currently available seismic isolation techniques in design and retrofit projects. However, apart from Japan, the number of seismically isolated structures in these countries are typically limited and essentially used for important or critical facilities such as health care facilities, cultural heritages, high-tech facilities, terminal buildings and data storage centers that have functional performance objectives beyond life safety [28,63]. Widespread use of seismic isolation in Japan is a result of streamlined process which can be attributed to extended practice to the office and ordinary type of buildings, knowledge accumulation before the 1995 Kobe Earthquake and lessons learned from frequent moderate size and rare large earthquakes occurred in the region. Particularly for Japanese case, complexity in the design and analysis of isolated buildings were reduced by the collaboration and experience of scientists, engineers and manufacturers. In Japan, relatively large scale companies in the industry are in charge of supplying the isolation devices and as a common state of practice, these companies provide pre-approved and detailed catalogues for facilitating the work of designers. Accordingly, the number of isolated buildings in Japan has greatly increased when all the factors positively encourage the use and facilitate the design of the earthquake-protection systems.

Design concept of passive seismic isolation system mainly relies on decoupling of the entire structure or floor levels through the installation of isolation devices at key interfaces [12,44,47,58].

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From this aspect, nonlinear displacement demands are often accommodated at isolation level to avoid inelastic response of the superstructure while preserving the stability of the entire isolation system. The design of isolated buildings through provisions and guidelines has two major goals, achieving life safety in a major earthquake and reducing the structural and nonstructural damages. Thus, performance based design objectives need to be fulfilled through code-based multi-level limit states. At this point, seismic design codes and specifications address the design principles of earthquake protection systems, load assignment criteria and testing requirements for the isolated structures through determined mechanical characteristics of isolation units. Traditionally, single mode, multi-mode and the response history analysis were employed for the design and analysis of building type of structures. Although design rules and guide specifications for control systems are already available in most countries, the state of practice differs from one to another and the use of IS/ED systems are restricted by the peer review and approval processes.

This paper aims to review and address the code-based design practice in Turkey, Europe, Japan, and US with special emphasis to ELF procedure. This common procedure takes a place in many well-known design provisions like the 2016 revised version of Turkish Seismic Design Code [60], Eurocode-8 [20], NTC-08 [49], BSLEO-2013 [10], ASCE/SEI 7-10 [5] and AASHTO-2010 [8] for the analysis and design of seismically isolated structures due to its simplicity and ease of applicability. Because of this reason many research studies were focused on the improvement of accuracy estimates of ELF procedure by incorporating equivalent linearization.

Equivalent linearization of idealized bilinear force-displacement hysteresis in the literature can be classified into two main groups where accuracy of the key response parameter estimation was aimed to be improved. First group incorporates the secant stiffness at design displacement for determining the effective stiffness (K_{eff}) and viscous damping ratio (β_{eff}) of substitute structure [37,12,66,17,34,35,26,57,44,47] whereas the second group of equivalent linearization methods relies on the empirical formula or fitted curves as a result of regression analysis [27,29–32,54,67].

Comparative study based on country specific evaluation is deemed to be useful for designers and researchers to understand international code-based practices about seismic isolation over the world. In the meantime, such detailed comparison and assessment of differences between Japanese Code and its counterparts had already been conducted by several researchers [24,68,9,28,36]. However, ongoing studies of the 2016 Turkish Seismic Design Code [60] with reference section to isolated buildings and increased number of applications particularly for hospital buildings in Turkey turned the attention of designers and suppliers all over the world to Turkey. Thus, such efforts will also give an opportunity to re-evaluate the provisions stipulated in the 2016 version of Turkish Seismic Design Code with its counterparts that are in use more than 15 years. Seismic design code of New Zealand [50,51] is intentionally excluded among the cases evaluated because of missing reference section about the design of base-isolated structures.

Furthermore, European aspect in designing of seismic isolation systems was employed by considering the so called NTC-08 [49], Italian Seismic Design Code with supplementary sections of Eurocode-8 [20], EN-1337 and EN-15129 [21]. Similarly, US and Japanese approaches were represented through ASCE/SEI 7-10 [5] and Building Standard Law with the associated Enforcement Order (BSLEO, 2013 [10]) and appended Notifications of Minister of Land, Infrastructure and Transport (MLIT), respectively. In this study, BSLEO-2013 and supplementary Notifications of MLIT will be treated together and referred as Japanese Code. A typical steel structure equipped with two different seismic isolation systems was analyzed to demonstrate the rules of standards and analysis results. The design of example structure aims to highlight the requirements of codes and standards for two earthquake scenario by utilizing ELF procedure. In order to have a reliable evaluation, example structure is assumed to be located in regions subjected to comparable probabilistic earthquake hazard in each country.

2. Description of the equivalent lateral force(ELF) procedure

Seismic design codes and specifications of seismic isolation such as NTC-08 [49], Japanese Code [10], ASCE/SEI 7-10 [5] and the 2016 revision of the Turkish Seismic Design Code-2007 [59] introduce three procedures for the analysis and design of seismically isolated structures. Among these three methods, the ELF procedure is defined as the simplest procedure which incorporates the equivalent linearization of nonlinear isolation system. For bridges, this procedure is also referred as Uniform Load Method (ULM) in the AASHTO Guide Specifications for Seismic Isolation Design (AASHTO GSID-3, 2010, [8]). ELF procedure has a critical role from the preliminary design phase to the final design stage. Even though, ELF procedure is defined as the simplest method of analysis, it provides important insight about the system behavior and the demand parameters that are key in the design. Nonlinear isolation system is represented through the idealized bilinear hysteretic feature (Fig. 1). For the ELF method, calculation of demand parameters is based on assumption of a rigid superstructure, amplitude dependent effective stiffness, Keff and viscous damping ratio, βeff properties of the entire isolation system. Equal energy principle of equivalent structure is firstly employed by Jacobsen [33] and linear effective properties that are adopted in design codes relies on both secant stiffness concept [57] and equal energy principle. Based on the single degree of freedom (SDOF) model, the effective period, T_{eff} of the isolated building can be calculated by Eq. (1), where W is the seismic weight of the superstructure and g is the acceleration due to gravity.

$$Teff=2\pi\sqrt{\frac{W}{K_{eff}g}} \tag{1}$$

The peak resultant lateral displacement of the isolation system is the most critical parameter estimated by the ELF procedure. Peak resultant isolator displacement generally prescribes the amount of seismic gap for the unrestricted movement of the isolation system, stability requirements of elastomeric isolators that are associated with shear strains, the level of force transmitted and the spatial distribution of isolation devices. Accurate seismic demand estimates by incorporating ELF procedure is essential because the values computed herein are used either directly for the design under certain conditions or in the establishment of the lower bound values. The period of the isolated buildings generally corresponds to the constant velocity portion of the response

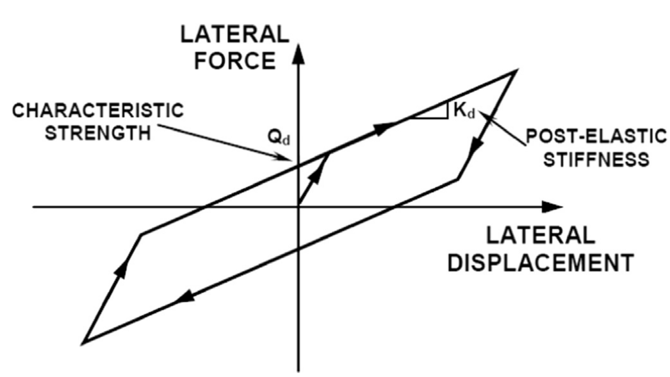

Fig. 1. Idealized bilinear force–displacement relation of isolation systems.