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Collapse performance of seismically isolated buildings designed by the procedures of ASCE/SEI 7

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ABSTRACT

This article presents an analytical study of the seismic collapse performance of seismically isolated buildings and comparable non-isolated buildings. The study is based on archetypical 6-story perimeter frame seismically isolated buildings designed with special concentrically braced frames (SCBF), ordinary concentrically braced frames (OCBF) and special moment resisting frames (SMF) for a location in California using the minimum criteria of ASCE/SEI 7-10 and ASCE/SEI 7-16 and also using a number of enhanced designs. The isolation system consists of triple Friction Pendulum (FP) isolators with stiffening behavior at large displacement. Additionally, double concave sliding isolators are considered and designed per minimum criteria of ASCE/SEI 7 and without a displacement restrainer, a practice permitted by the standards. Non-isolated structures, also with braced and moment frame configurations, are designed using the minimum criteria of ASCE/SEI 7 and studied. The study concludes that seismically isolated buildings designed by the minimum criteria of ASCE/SEI 7 of either 2010 or 2016 may have unacceptable probability of collapse in the Risk-Targeted Maximum Considered Earthquake (MCE_R). The probability of collapse in the MCE_R becomes acceptable when they are designed with enhanced criteria of $R_I = 1.0$ and with isolators having a displacement capacity at initiation of stiffening equal to 1.5 times the demand in the MCE_R. It is also observed that designs that meet the minimum criteria of ASCE/SEI 7 of either 2010 or 2016 and without any displacement restrainer have unacceptably high probabilities of collapse.

1. Introduction

Many seismically isolated buildings have been designed and analyzed according to the minimum requirements of Chapter 17 of ASCE/SEI 7-10 standard [1]. ASCE/SEI 7-16 [2] specifies the current ASCE minimum requirements for isolated structures. Both ASCE standards require that the isolation system be detailed to accommodate the displacement demand calculated in the Risk-Targeted Maximum Considered Earthquake (MCE_R), where this displacement is the average of peak values calculated in seven nonlinear response history analyses. Both procedures permit the use of a response modification coefficient (R_I factor) between 1.0 and 2.0 depending on the seismic force-resisting system used. For the case of the ASCE/SEI 7-10 standard, the forces and drifts for the design are based on calculations using the design response (DE) spectrum, which is defined as being 2/3 of the MCE_R spectrum. For the case of the ASCE/SEI 7-16 standard, the forces and drifts for the design are based on calculations using the MCE_R spectrum. While many seismically isolated buildings in the United States have been designed using the minimum requirements of ASCE/SEI 7-10, there are exceptions in which stringent criteria have been employed. Examples are hospitals in California where often project-specific design criteria require the use of an R_I factor of unity for the effects of the DE or MCE_R and larger displacement capacity isolators than the minimum allowed by ASCE/SEI 7.

The use of the minimum requirements of the ASCE/SEI 7 standards presumably ensures the minimum acceptable level of safety by preserving the lives of the occupants. It is well recognized that these minimum ASCE design requirements do not serve the resiliency objective of avoiding damage in order to maintain facility functionality. An Executive Order issued in 2016 by the President of the United States (Executive Order 13717 [3,4]) clearly recognizes this fact and states the following: “The Federal Government recognizes that building codes and standards primarily focus on ensuring minimum acceptable levels of earthquake safety for preserving the lives of building occupants. To achieve true resilience against earthquakes, however, new and existing buildings may need to exceed those codes and standards to ensure, for example, that the buildings can continue to perform their essential functions following future earthquakes.” The Executive Order continues

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to instruct all federal agencies to “go beyond the codes and standards and ensure that buildings are fully earthquake resilient.”

Questions may then arise. (a) Is the probability of collapse of seismically isolated structures designed by the minimum design criteria acceptably low? (b) What should be the criteria for design in terms of R_I and isolator displacement capacity to achieve an acceptable probability of collapse? (c) What does isolation achieve in terms of performance measures like peak story drift, residual story drift and floor accelerations?

Some studies have already addressed issues related to these questions. Kikuchi et al. [5] studied the inelastic response of a two-degree-of-freedom (2-DOF) representation of seismically isolated structures without any consideration for failure of either the structural or the isolation system. The study raised a concern that designs of seismically isolated structures with reduced lateral shear force (equivalently, with a large R factor) can have significant inelastic action and unacceptable behavior. A more recent study [6] again made use of the 2-DOF system but enhanced to have non-simulated generic isolation system failure and superstructure failure (assumed to occur at ductility of 4.0) and employed contemporary procedures to determine the collapse margin ratio based on the FEMA P695 procedures [7]. The main contribution of the work was to study the effects of limiting the displacement demand on the isolators by use of moat walls of varied clearance and behavior. Following the Japanese practice of seismic design, the strength of the superstructure was assumed in the range of 0.15–0.40 of the superstructure weight (common practice in Japan is the use of 0.3). The study observed that isolated structures have a low level of damage (essentially elastic response) until a certain level of seismic intensity is reached where significant inelastic action occurs for small increases in the seismic intensity.

Studies of Erduran et al. [8] and Sayani et al. [9] compared the inelastic response of conventional and seismically isolated steel braced and moment-resisting 3-story frames designed by the minimum criteria of ASCE 7 (that of 2005) and with unlimited capacity for the isolators. The studies concluded that the seismically isolated frames exhibited lower structural yielding, story drifts, residual story drifts and floor accelerations than comparable conventional frames for seismic events characterized as frequent, design and maximum earthquake. The studies did not provide any information on the collapse of the analyzed structures as the structural model did not have capability of simulating large deformations in the elements of the structural system. However, the studies pointed to interesting observations that (a) allowing for inelastic behavior of the isolated structure limited the displacement demand in the isolators and (b) designing for elastic behavior could have resulted in failure of the isolators if they had limited displacement capacity.

A study of Terzic et al. [10] compared the lifecycle cost of seismically isolated structures designed with different structural systems of various R_I factors. The study demonstrated improved performance and significant reduction of lifecycle cost when the design utilizes an R_I factor of unity in the DE.

The development of the performance assessment methodologies of FEMA P695 [7] allowed for more rigorous studies of the performance of isolated structures. One of the examples in FEMA P695 involves seismically isolated buildings in which failure of the superstructure was simulated and the isolation system was represented by a generic model together with a displacement-limiting moat wall of various clearances. The structure was a 4-story reinforced concrete building of either a special perimeter moment frame or a special space frame. Concentrating on the code-complaint designs (with $R_I = 2$ in the DE), the study demonstrated acceptable collapse margin ratios, which progressively reduced as the moat wall clearance reduced and the space frame was changed to a perimeter frame.

A more recent study of Masroor and Mosqueda [11] utilized models similar to those in the studies of [8,9] and followed the paradigm of examples of the seismically isolated buildings in FEMA P695 [7], utilized three-dimensional building models with an improved moat wall model and bi-directional seismic excitation but did not consider failure of the isolators. The results showed that steel intermediate moment frames designed for the DE with an $R_I = 1.67$ and steel ordinary concentrically braced frames designed with $R_I = 1$ had acceptable collapse margin ratios per FEMA [7] when the size of isolators was sufficiently large to avoid failure of the isolator. Barely acceptable probabilities of collapse were calculated when the moat wall was placed at the minimum required displacement capacity in the MCE_R. The calculations were based on the use of adjusted values for accounting for the spectral shape effects (epsilon) using the FEMA P695 procedures [7]. It will be argued in this paper that the correction factors for the spectral shape effects provided in FEMA P695 do not apply for seismically isolated structures and that special studies are required to properly calculate the effects of spectral shape.

Chimamphant and Kasai [12] investigated the seismic response of nonstructural components in seismically isolated buildings and compared it to that of comparable conventionally designed buildings by using multi-degree-of-freedom shear-beam models. Failure in the superstructure or the isolation system was ignored and mechanisms that limit the isolator displacement (ex. retaining walls) were not considered. The study used the methodologies described in FEMA P695 [7] and FEMA P58 [13] and demonstrated that seismically isolated buildings have better performance than comparable non-isolated buildings but the improvement of performance reduces as the height of the building increases.

Recently, Shao et al. [14] focused on a 3-story concentrically braced steel frame structure designed for $R_I = 1$ in the MCE_R and investigated the reliability of the ASCE/SEI 7-16 minimum provisions [2], as well as enhanced designs by providing either increased isolator displacement capacity or providing isolators with hard (moat wall) or soft stopping mechanisms. The main conclusions of the study were that: (a) the isolator displacement capacity needs to be increased by at least 1.8 of the minimum code-prescribed value in order to achieve the code-targeted reliability when no displacement restrainers are provided; (b) smaller displacement capacities can be used when displacement restrainers are utilized but with additional requirements for increased ductility capacity in the superstructure and (c) a total isolator displacement capacity (including the capacity of soft stops) of at least 1.5 times the displacement demand in the MCE_R and an isolator shear strength of at least 3.0 times the base shear in the MCE_R are needed to achieve the required reliability. The study did not consider the spectral shape effects as the simplified method presented in FEMA P695 [7] for considering these effects does not truly apply for seismically isolated structures of large effective period. Accordingly, probabilities of failure must have been slightly overestimated.

This paper also investigates the reliability of the ASCE/SEI 7 provisions by concentrating on an archetypical 6-story perimeter frame building that has been previously studied in examples of seismic isolation design and analysis in McVitty and Constantinou [15]. Perimeter steel special concentrically braced frames (SCBF) and special moment resisting frames (SMF) for this building are designed for a location in California with an R_I factor of 2.0 (per minimum requirements of ASCE/SEI 7-10), 1.5 and 1.0 in the DE and with $R_I = 2.0$ (per minimum requirements of ASCE/SEI 7-16) and 1.0 in the MCE_R when seismically isolated. Also, the case of steel ordinary concentrically braced frames (OCBF) permitted by ASCE/SEI 7-16 with $R_I = 1.0$ is considered. The isolation system for these cases consists of triple Friction Pendulum (FP) isolators having a displacement capacity at initiation of stiffening equal to $1.0D_M$ (per minimum requirements of ASCE/SEI 7-10 and 7-16), $1.25D_M$ and $1.5D_M$, where D_M is the displacement demand in the MCE_R (torsion is not accounted for so the displacement considered is D_M instead of D_{TM}, which would be 1.1–1.2 times larger than D_M in the studied systems). For the OCBF the displacement capacity of the isolators at initiation of stiffening is $1.25D_M$, which is required by ASCE/SEI 7-16. The stiffening behavior of the triple FP isolators serves as a