Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

SEISMIC DESIGN OF DATA CENTERS FOR TIER III AND TIER IV RESILIENCE: PROJECT EXAMPLES

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ABSTRACT

This paper presents the structural and seismic design of two data centers with Tier III and Tier IV class resilience levels that are located in a region with high seismicity. The first project is a commercial facility that will be one of the largest data center of Turkey and intended to have Tier III rating. During the design of this project, it is observed that the tier requirements for structural and seismic design of data centers are not given in detail in the related IT standards. A detailed design basis, which is presented in the first paper of this study, is developed by authors to facilitate the design after a thorough multidisciplinary design process. As the key objectives, operational level performance is set for the structural and nonstructural components for the design basis and maximum considered earthquake levels. Acceleration limits are set for sensitive computer equipment based on the feedback from IT professionals. Seismic base isolation of the complete building with high-performance friction pendulum isolators is utilized to achieve stringent design objectives. Superstructure is comprised of a steel structure with large spans resting on a thick reinforced concrete isolation slab, which allows large white spaces and future modifications. Substructure is comprised of short columns and mat foundation that provides ample maintenance space. Fundamental results of the design including the structural member sizes, isolator parameters, isolation displacements, isolation and first floor shears, floor accelerations are presented. Design of nonstructural components, anchorages and other components are reviewed and representative details are provided. The second data center is a confidential project with Tier IV class resilience, and a similar design basis is utilized. Structural and base isolation systems of the second project are similar to the first project, and basic results for this project are presented. It is shown that the seismic design of the data centers satisfy the requirements of the design basis and provide a seismic safety suitable for Tier III and Tier IV operational resilience.

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Erkus B, S. S. Polat and H. Darama. Seismic Design of Data Centers: Project Examples. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

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This paper presents the structural and seismic design of two data centers with Tier III and Tier IV class resilience levels that are located in a region with high seismicity. The first project is a commercial facility that will be one of the largest data center of Turkey and intended to have Tier III rating. During the design of this project, it is observed that the tier requirements for structural and seismic design of data centers are not given in detail in the related IT standards. A detailed design basis, which is presented in the first paper of this study, is developed by authors to facilitate the design after a thorough multidisciplinary design process. As the key objectives, operational level performance is set for the structural and nonstructural components for the design basis and maximum considered earthquake levels. Acceleration limits are set for sensitive computer equipment based on the feedback from IT professionals. Seismic base isolation of the complete building with high-performance friction pendulum isolators is utilized to achieve stringent design objectives. Superstructure is comprised of a steel structure with large spans resting on a thick reinforced concrete isolation slab, which allows large white spaces and future modifications. Substructure is comprised of short columns and mat foundation that provides ample maintenance space. Fundamental results of the design including the structural member sizes, isolator parameters, isolation displacements, isolation and first floor shears, floor accelerations are presented. Design of nonstructural components, anchorages and other components are reviewed and representative details are provided. The second data center is a confidential project with Tier IV class resilience, and a similar design basis is utilized. Structural and base isolation systems of the second project are similar to the first project, and basic results for this project are presented. It is shown that the seismic design of the data centers satisfy the requirements of the design basis and provide a seismic safety suitable for Tier III and Tier IV operational resilience.

Introduction

In the first paper of this study, a design basis is proposed for the structural and seismic design of Tier III and Tier IV data centers [2]. The design basis is developed during the design of a major data center located in a seismic region of Turkey. The data center is intended to have a Tier III certification, which corresponds to a very high IT resilience and very low levels of downtime durations. To ensure that the intended operational continuity and resilience of the IT services is achieved, the management team requested that the highest possible seismic safety measures are implemented. On the other hand, IT standards that are used for the design of data centers states only that necessary precautions should be taken for natural hazards such that the required IT resilience is achieved [3], yet specific criteria, that the structure will be accepted to have the

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required precautions for seismic events when satisfied, are not given [2]. The design basis is established after an intense multidisciplinary design and coordination process with a mutual understanding and agreement of all engineering disciplines.

Table 1. A summary of the proposed design basis with essential requirements [2]

Part of the Data Center	**Performance Goal and Acceptance Criteria**
a) Structure	Operational Level for DBE and MCE events.
Structural members	- Structure behaves elastic - Design for R = 1 - Consider vertical ground acceleration
Connections, anchorages, collectors, drag-strut elements	- A minimum ordinary ductility requirements should be satisfied - Use overstrength factors - Isolation shear capacity are used where applicable
b) Nonstructural Components	Operational Level for DBE and MCE events.
Displacement-sensitive	- Satisfy 1.25 D_p (D_p: estimated relative displacements) - R = 1
Acceleration-sensitive	- Designed for the forces estimated - R = 1
Anchorages and critical connections	- Use overstrength factors - Isolation shear capacity are used where applicable - No yielding allowed
c) Sensitive Computer Equipment	Operational Level for DBE and MCE events.
Enclosure, cabinets and raised floor	- Use requirements of Nonstructural Components
Computer equipment	- Maximum Acceleration < 0.20g for the X- and Y-directions - Maximum Acceleration < 0.30g for resultant

The design basis uses a performance-based framework defined for three parts of the project: (a) structure, (b) nonstructural components, and (c) sensitive computer equipment [2]. A summary of the essential requirements of the design basis is given in Table 1. Important aspects of the proposed design basis are elastic behavior of superstructure under DBE and MCE events, stringent acceleration limits on sensitive computer equipment and use of isolator shear capacity or an adequate overstrength factor for nonstructural components and critical connections with R = 1. In overall, it is considered that proposed design basis establishes a physical infrastructure that ensures resilience of overall operations of the computer network of the data center.

This paper presents the structural and seismic design of two data centers projects that are located in a seismic region of Turkey and that have Tier III and Tier IV IT resilience. Both projects are designed using the proposed design basis [2] and have similar structural configurations and design intentions. The first project is explained in more detailed, while a brief summary of the basic characteristics and results of the design of the second project is provided. For the first project, first seismicity of the region is provided. Second, structural system selected and structural design are explained along with the design constraints that lead to the selected system. Third, isolation system design, procurement and testing of isolators are explained. Then, results of the performance evaluation of the final design are presented. Finally, design of nonstructural components is reviewed. Both projects are peer-reviewed by committees of independent reviewers, although this is not required by the structural regulations of the local jurisdiction.

Seismicity

The first project is located in the Tuzla town of Istanbul, Turkey. A site-specific seismic hazard study is conducted for the project site [4] with a coordination with the design team. It is discussed by the peer-review committee that long-period modelling of the seismic hazard used in this study results spectral accelerations that are lower than other models that are more frequently used in practice. Therefore, a second site-specific seismic hazard study is conducted by a different group of researchers [1], which is deemed suitable by the peer-review committee. It is observed that Turkish seismic code [5] yields spectral accelerations larger than the values given by the site-specific studies. Therefore, envelope of three design spectra is used in the linear design of the data center. Vertical design spectra is also provided by [1], which was developed by the available literature on vertical ground acceleration [6], and it is compared with the 2/3 of the MCE spectra provided by the code. In the linear static design, maximum value of the vertical spectra obtained from the site-specific study is used. A summary of the two site-specific hazard study, code requirements and the final spectra used in the linear design are shown in Figure 1.

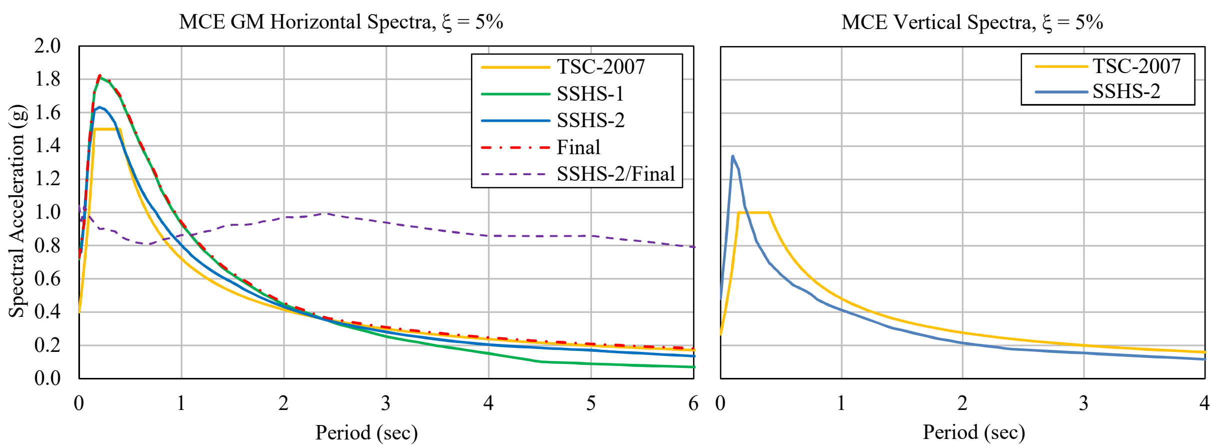


Figure 1. Comparison of MCE level spectra and the final spectra used for the linear design

For performance evaluations, seven historical ground acceleration data that belongs to the earthquakes generated by the faults similar to the faults close to the project site. Spectral matching as detailed in [7] is used to obtain MCE spectrum compatible ground acceleration, and the results are shown in Figure 2 for horizontal spectra. Since maximum rotated (MR) spectra should be used for the isolator design of base isolated structures, MR spectra is also obtained from geometric mean (GM) spectra using factors provided by [8]. These factors are shown in Figure 3.

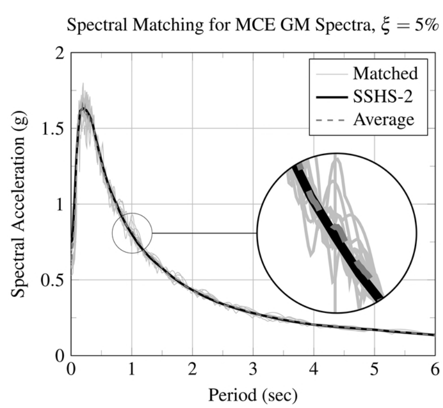


Figure 2. Spectral matching

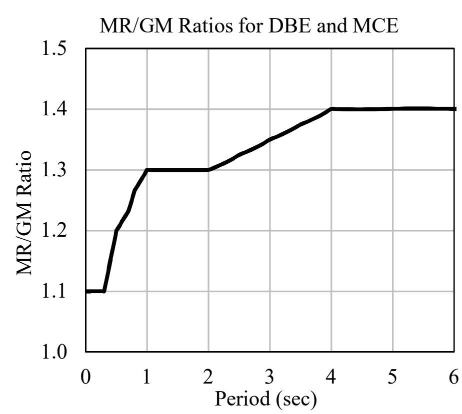


Figure 3. MR to GM ratios

Table 2. Ground acceleration data used for performance evaluation [1]

Record No	**Earthquake Name**	**Duration / Δt**	**Magnitude**	**Dist. To Fault**	**V_{s30}**
RSN882	Landers, U.S., 1992	99.8 sec / 0.005 sec	7.28 M	26.8 km	345 m/s
RSN1110	Kobe, Japan, 1995	90.0 sec / 0.010 sec	6.90 M	24.8 km	256 m/s
RSN1166	Kocaeli, Turkey, 1999	30.0 sec / 0.005 sec	7.51 M	30.7 km	477 m/s
RSN1762	Hector Mine, U.S., 1999	60.0 sec / 0.020 sec	7.13 M	43.1 km	383 m/s
RSN3758	Landers, U.S., 1992	56.9 sec / 0.005 sec	7.28 M	36.9 km	334 m/s
RSN5836	El Mayor, Mexico, 2010	87.5 sec / 0.005 sec	7.20 M	26.8 km	345 m/s
RSN6953	Darfield, N.Z., 2010	54.0 sec / 0.005 sec	7.00 M	24.8 km	256 m/s

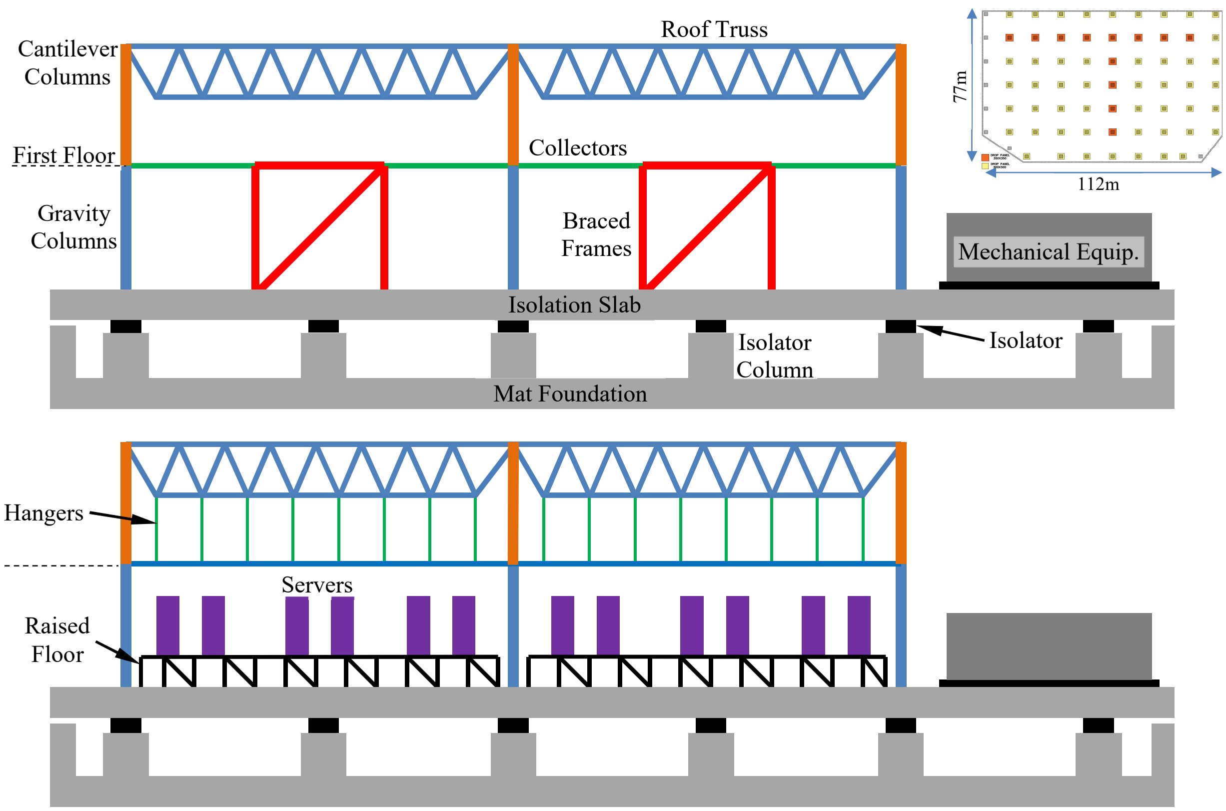


Figure 4. A sketch of the structural system of the first data center in one direction

Structural System

For the first project, several structural systems are evaluated by the structural design team in collaboration with the architect, IT and mechanical engineers and the contractor. It is known that typical data centers are single story industrial type structures, and servers are placed on the raised floor, which is directly connected to the foundation. *I.e.* ground motion is almost a direct input to the server cabinets, which will result server accelerations similar to ground accelerations, particularly if the raised floor has large stiffness. To prevent large accelerations of servers, three options are considered: cabinet isolation, floor isolation and complete structure isolation. It is discussed by the IT team that data centers has many components other than the servers that are part of the whole IT network, and all off these components should be operational during a seismic event. Cabinet isolation only isolates the servers, and floor isolation only isolates the cabinets and the raised floor. Both of them do not isolate crucial mechanical equipment such as air conditioning and backup power supplies. They also require spaces and flexible cables around them. There are also issues regarding the cooling system since raised floor is also uses as air ducts and the space should be enclosed. Considering all these challenges, complete structure isolation is concluded to provide the most effective isolation system for the project. Therefore, a single story base isolated structure, where servers will placed at the ground level, is selected as the main option initially. As the project evolved, a second floor added with storage and office spaces without reducing the rigidity significantly. Two and three story structures, where servers are placed at the first and second floors are considered ineffective structurally, due to the amplification of the accelerations at upper floors, even if base isolation is utilized.

A schematic representation of the structural system is shown in Figure 4. Steel is selected as the material for the superstructure. Braced frame system is selected as the lateral system in oppose to moment-frame system to have a rigid superstructure for isolation system to be effective. In one direction, concentric braced frames are utilized in the first story and cantilever columns are used in the second story to allow large spans for the whitespaces. Gravity columns supporting cantilever columns are designed with code-required penalty and overstrength factors. Roof trusses are designed as gravity members that are designed for both roof loads and hanger loads above the white spaces. In the other direction, braced are used at both stories, which is not shown herein. Superstructure rests on a thick rectangular reinforced concrete slab with dimensions of 77mx112m that acts as the isolation diaphragm. Thick slab provides a rigid support to superstructure, effective transfer of forces to isolators and allows future architectural modifications. The number of isolator is 69, and certain parts of the isolation slab is thickened. This concept has the interesting feature that a large portion of the superstructure mass, which is due to servers and the thick slab, is located at the ground level. This requires careful evaluation of lateral force distribution when equivalent lateral force procedure is used [9].

Isolation System Design, Isolator Procurement and Detailed Design

There are several stages of the design and procurement of the isolation system. First, a preliminary design is conducted. Based on the results of the preliminary design, a request-for-proposal (RFP) is prepared, and proposals from several isolator manufacturers are received. Isolator type and manufacturer is selected considering various constraints. Based on the selected isolator and manufacturer's suggested isolator parameters, detailed design of the superstructure and substructure is performed. These stages are summarized below.

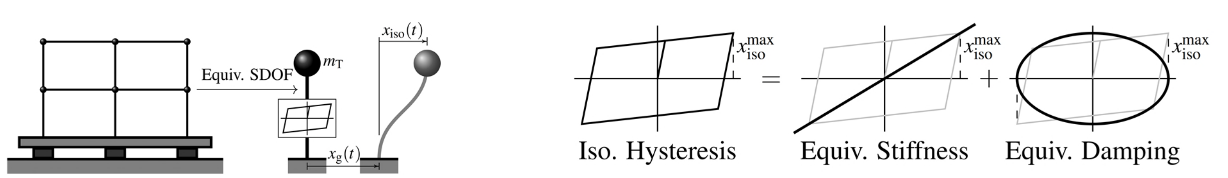


Figure 5. Equivalent SDOF system and equivalent parameters

In the preliminary design stage, two tasks are performed interactively. First task is the estimation of the effective period, effective damping, isolation displacement and isolation force based on the assumption that overall structure can be modelled by an equivalent SDOF system with a bilinear spring (Figure 5). Second task is to perform structural design based on the isolation force estimated using both equivalent lateral force procedure and response spectrum procedure. After obtaining superstructure mass and isolator axial forces, first and second tasks are repeated. Two isolator types are considered: elastomer-based and friction-based. Possible isolator properties based on past project experience are used. Damping reduction factors provided by [10] are utilized. Lower and upper bound parameters are selected considering design guide [11] and draft version of [12]. Lower and upper bound properties are used for estimation of isolation displacement and superstructure design, respectively. After the interactive design process, a structural weight of approximately 300,000 kN is obtained. For MCE-GM event, lower bound displacement is estimated as 420 mm. A minimum isolator displacement capacity of 650 mm is considered after applying factors for eccentricity, GM to MR conversion and a safety factor. Effective damping and effective period of the isolation system are approximately %25 and 3.3 seconds, respectively.

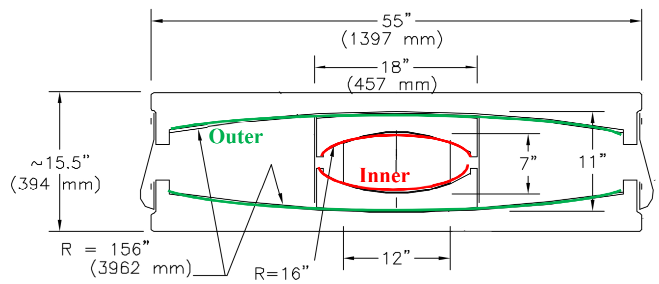


Figure 7. Isolator dimensions

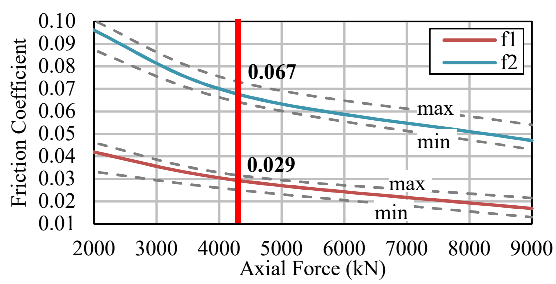
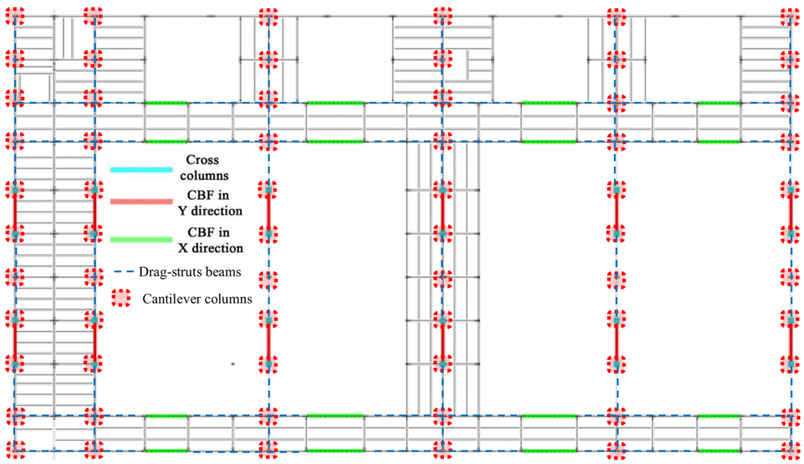


Figure 6. Average Friction Coefficients

A detail request-for-proposal (RFP) is prepared, and proposals are received from several manufacturers. Friction-type isolator is selected for the project (Figure 7) after a careful review and comparison of the proposals. Further, selected isolators are based on the alternative design parameters proposed by the manufacturers, which has higher performance than the original design. Effective period and the damping are in the order of 4.0 seconds and 30%, respectively. Nominal friction properties recommended by the manufacturer are $f_1 = 0.03$ and $f_2 = 0.07$ for inner and outer surfaces, respectively for the isolator axial load of 4367 kN (average of 69 isolator axial loads). A thorough testing is performed on two prototype isolators, and average friction coefficients and their axial load dependency are obtained (Figure 7). For the average axial load, the average friction coefficients are obtained as $f_1 = 0.029$ and $f_2 = 0.067$ from the tests. These values are used for the detailed design of the superstructure and substructure. A summary of the structural system configuration and member sizes are shown in Figure 8. Superstructure fixed-based periods are 0.72 sec (X-dir) and 0.57 sec (Y-dir). Theoretical backbone curves of the isolators and the estimated displacements are shown in Figure 9. Effective periods for upper, nominal and lower bound properties are 3.611, 3.935, and 4.235 seconds, respectively. During the estimation of the isolator displacements using an equivalent SDOF system, it is observed that the results are very sensitive to the damping reduction factors. Reduction factors, as given by various structural codes, for the final effective damping values and for the 5% MCE-GM spectra are shown in Figure 9. As can be seen from this figure, lower bound factors can vary from 1.25 to 1.75, which result approximately 40% difference in the isolator displacements.

Design seismic base shear values for the nonstructural components including anchorages located at the isolation base are taken as 0.3g in single direction or 0.2g in both directions horizontally. For vertical seismic effect, 1.2g is used in addition to the selfweight of the component. Similar values are used for design of superstructure connections, steel column base plate and anchorages, drag-strut elements, columns supporting cantilever columns, isolator anchorage, isolator columns and foundation mat.



Element	Size
BF Columns	Cross HEA500-HEA450, HEA550, HEB300
Cantilever Columns	Cross HEA500-HEA450, HEA550, HEB300
Gravity Columns	HEA260
Vertical Braces	HEAB300, H320x300x20x12
Drag-Strut Beams	HEB450
Horizontal Braces	Φ219mm-6mm, HEB300
Truss Chords	HEA320, HEB220, HEA220
Truss Braces	HEA320, HEB220, HEA220
Gravity Beams	IPE240 – IPE400
Isolation Slab	1.4m, 0.8m thick
Isolation Column	1.7x1.7x2.0m height
Foundation Mat	1.0m tick
Foundation Capital	3.0x3.0x0.5m thick
Truss Span	24m
1st Story Height	5.25m
2nd Story Height	5.25m
Typical Span	5.5m – 7.5m

Figure 8. Final structural configuration and member sizes

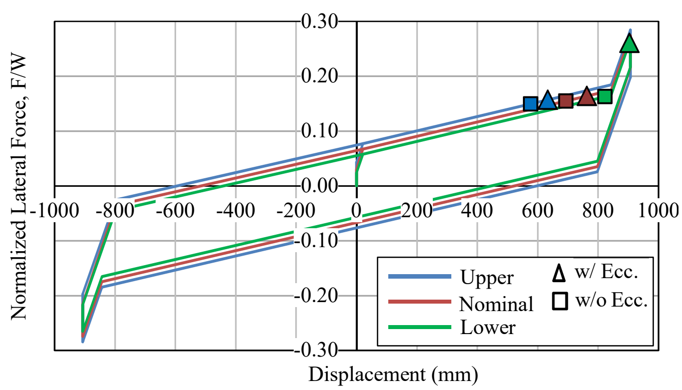


Figure 9. Isolator backbone curves and responses

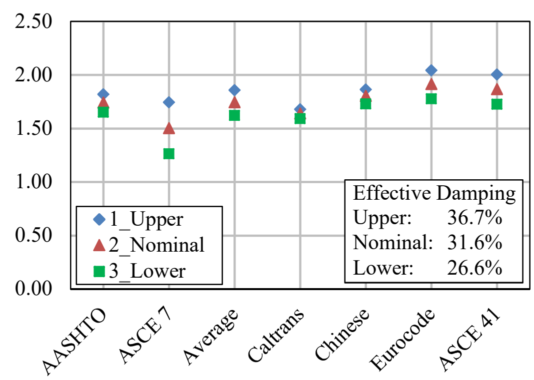


Figure 10. Damping reduction factors

Performance Evaluation

A performance evaluation using nonlinear time-history analysis is performed, where a popular computer program [13] is used. Nonlinear isolator model provided by the analysis software, where a bidirectional Bouc-Wen nonlinearity [14, 15] is used to model normalized lateral force. Bidirectional coupling is based on [16]. Vertical contact nonlinearity is also modelled, where axial rigidity is estimated by considering the effective slider area. Lateral force is obtained by multiplying the normalized lateral force by axial force on the isolator; therefore, dependency of the lateral force to the axial force is modelled. A rate parameter is used to model the friction coefficient dependency on the velocity [17, 18]. The dependency of the friction coefficient on the axial load is not modelled. To consider the axial load-friction dependency, friction coefficients for different isolator axials loads obtained from the test results are used. For isolator initial stiffness, values suggested by [11] are used. After some preliminary analyses, it is found that direct-time integration is more accurate and efficient than fast-nonlinear analysis due to existence of vertical ground motion and coupling of axial and lateral forces.

Table 3. Lower bound isolator displacements

Analysis	X-Dir (m)	Y-Dir (m)	Mag. (m)
Darfield-6953	0.707	0.586	0.880
Hector-1762	0.445	0.481	0.537
Kobe-1110	0.407	0.464	0.523
Kocaeli-1166	0.435	0.625	0.683
Landers-882	0.417	0.397	0.478
Landers-3758	0.629	0.492	0.679
Sierra-5836	0.448	0.455	0.495
Average	0.498	0.500	0.611
	GM: 0.510 m		MR: 0.611 m
Equiv. SDOF	GM: 0.587 m		MR: 0.822 m
RSA	GM: 0.585 m		MR: 0.820 m

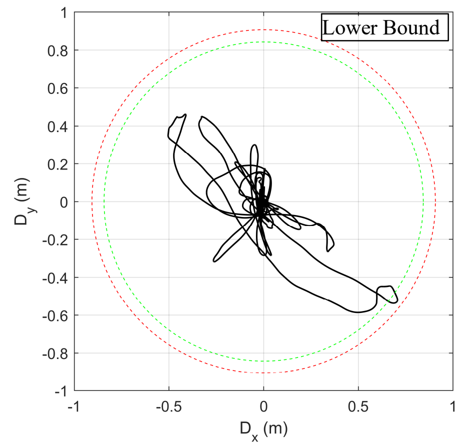


Figure 11. Isolator trace for Darfield eq.

Table 4. Upper bound base shear values

Analysis	X-Dir (g)	Y-Dir (g)	Mag. (g)
Darfield-6953	0.173	0.132	0.207
Hector-1762	0.119	0.135	0.145
Kobe-1110	0.128	0.140	0.155
Kocaeli-1166	0.131	0.150	0.156
Landers-882	0.133	0.127	0.133
Landers-3758	0.136	0.124	0.172
Sierra-5836	0.127	0.119	0.133
Average	0.135	0.132	0.157
	GM: 0.133 g		MR: 0.157 g
Equiv. SDOF	GM: 0.129 g		MR: 0.150 g
RSA	GM: 0.128 g		MR: 0.150 g

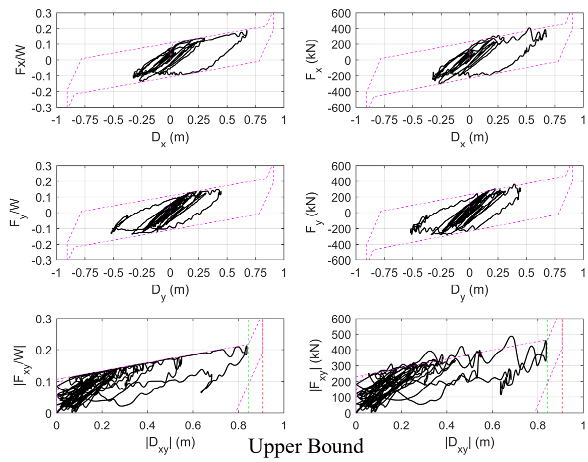


Figure 12. Isolator hysteresis for Darfield eq.

Analysis for lower bound properties are used to evaluate isolator displacements and upper bound properties for design and accelerations. Table 3 shows lower bound isolator displacements. Figure 11 shows the isolator displacement trace for the most critical earthquake. It is observed that GM displacements of all analysis are in good agreement, while MR displacements estimated from equivalent SDOF and response spectrum analysis are conservative. Table 4 shows the base shear values normalized by the superstructure weight, and Figure 12 shows friction and force hysteresis of a corner isolator for the Darfield earthquake. Average vertical reaction is found to be 1.523g, which is similar to the vertical reaction obtained from the response spectrum analysis (0.544g). It is observed that superstructure elements stays linear during all earthquakes. To investigate a possible amplification of base shear, first floor base shear is also investigated. For the Darfield earthquake, first floor base shear values as normalized by the seismic weight above the first floor are approximately 12% higher than the values shown in Table 4. This is not a major amplification compared to structures with large isolation mass [9] (mass of the steel structure is about 17.4% of the total superstructure mass), which is possibly due to stiff superstructure. Absolute accelerations are shown in Table 5, which shows that accelerations requirements of the design basis are met.

Table 5. Ave. absolute accelerations

H(m)	Location	X (g)	Y (g)	|XY| (g)
0.00	Foundation	0.656	0.607	0.712
1.80	Bot. of Iso.	0.657	0.607	0.712
2.20	Top of Iso.	0.152	0.142	0.177
9.05	1.st Floor	0.159	0.142	0.178
14.30	Roof	0.201	0.17	0.218

Review of the Second Data Center

The second data center is very similar to the first data center except that it is a single story building with approximately 7.30m story height, and moment frames are the main seismic system instead of braced frames (Figure 13). Superstructure fixed-based periods are in the order of 0.50 seconds in both directions. Cross-shaped steel sections are used for columns, and build-up deep steel beams are used for beams. Design process followed is similar to the first project. An independent peer-review committee also reviewed the base-isolation design. Friction pendulum isolators are selected due to fast delivery times and lower base shear values. It is observed in this project that dynamic amplification is more significant. *I.e.* normalized first story shear obtained from time-history analyses is approximately 2.5 times the value obtained from the equivalent SDOF system. Therefore, amplification factors as suggested by [9] and implemented in [10, 12] are used for the superstructure design.

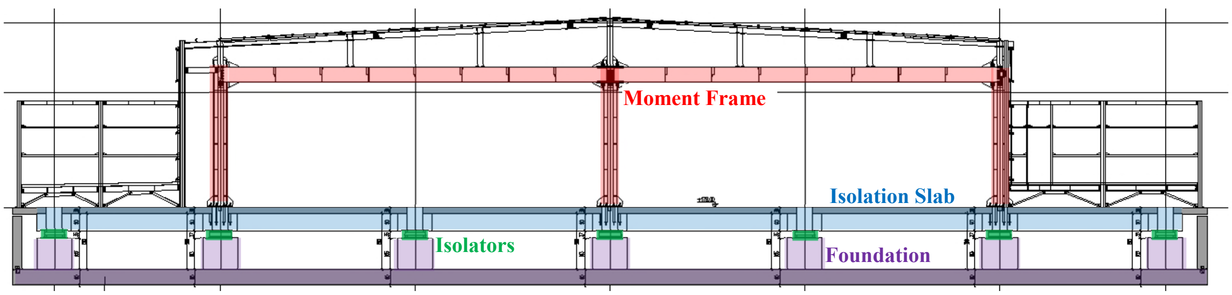


Figure 13. Structural system of the second project

Conclusions

Two data center projects with Tier III and Tier IV rating that are located in a seismic region are presented as examples of application of the proposed design basis. Design process, isolation system design, performance evaluation of the first project are given in detail. Critical requirements such as linearity of the superstructure, limiting absolute accelerations to 0.20g and 0.30g are met. Further, nonstructural components and critical connections are based on the maximum upper bound base shear that can be generated by the isolators. In overall, both structure are designed to be fully operational after a MCE event and satisfies the general seismic resilience requirements of Tier III and Tier IV ratings.

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