A New Paradigm for Residential Construction in Regions of High Seismicity

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ABSTRACT

21st Century construction will be deeply connected to the concepts of sustainability. To date, sustainable design has mostly focused on the carbon emissions associated with the operation of buildings; however the total life-cycle carbon associated with the construction is rarely, if ever, considered. Additionally, in regions of high seismicity, the carbon associated with seismic damage resulting in demolition, repair and reconstruction can be significant. Cost-benefit comparisons, probable seismic damage, and consideration of operational downtime are especially important in considering building system selection for all disciplines.

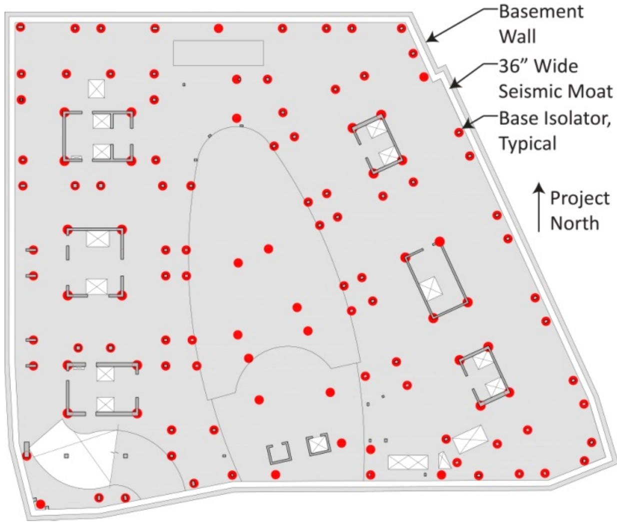
In what follows, a case study on a future condominium development to be located in downtown San Francisco, California, which includes two residential buildings base isolated on a common ground level with a Triple Friction Pendulum™ system is discussed. The Environmental Analysis Tool™ is used to calculate life-cycle environmental and fiscal impacts.

OVERVIEW

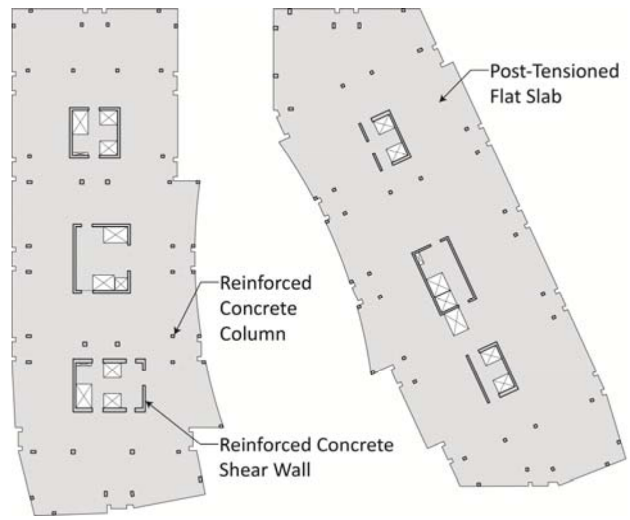
Initiatives such as the California Energy Efficiency Strategic Plan (CPUC, 2011), which establishes as a goal that new construction "will reach zero net energy performance for all new single and multi-family homes by 2020", is a clear examples that connect 21st Century residential construction to sustainability. Undoubtedly, new residential developments should be targeted towards an integrated and sustainable design of all the systems which form the building, establishing performance-based objectives beyond the traditional design approaches.

From a structural engineering perspective, sustainable solutions focus on innovation in the use of materials and systems, and on the development of appropriate assessment tools which inform the decision-making process at the early stages of the design. This becomes of critical importance in regions of high-seismicity where structural and non-structural damage, and associated repair costs, can be a considerable factor when the life-cycle costs of building are studied. In such cases, enhanced seismic force resisting systems and performance-based engineering assessments are of particular interest.

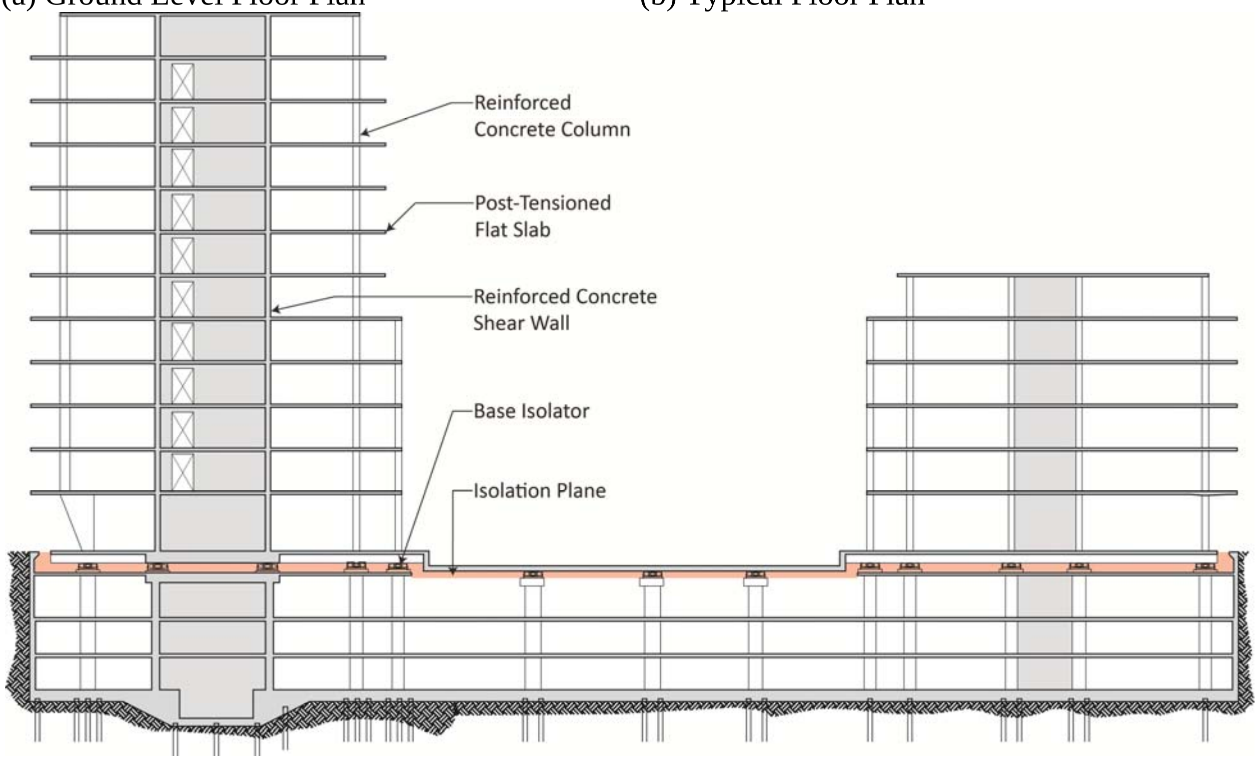
As a result of a collaborative design process in accordance with oncoming green building design goals, Skidmore, Owings & Merrill LLP (SOM) has applied a series of innovative methodologies and design solutions to a future condominium development to be located in downtown San Francisco, California. The project, presents a new paradigm in residential construction, and includes two apartment buildings, 12 and 6 stories high, separated by a private courtyard at ground level, where communal spaces are combined with retails and restaurants. Both residential buildings share a seismic base isolation system under the first floor, and three basement levels below with resident and public parking. The main superstructure elements are entirely built with concrete, presenting a post-tensioned flat slab system, reinforced concrete columns and reinforced concrete shear wall cores. See Figure 1 for typical floor plans and a building section.



(a) Ground Level Floor Plan



(b) Typical Floor Plan



(c) Overall Building Section and Isolation Detail

Figure 1. Building Plans and Section

This paper presents two of the most significant sustainable design considerations of this project. First, the Environmental Analysis Tool™ (EA Tool) is presented; software developed by SOM which calculates the carbon footprint of the structural system based on basic design information, seismic hazard, etc. By means of tools such as the EA Tool, the benefits of an enhanced seismic system could be quantitatively analyzed and presented to the developer for discussion during the schematic design phase, leading to a high-performance structure with Triple Friction Pendulum™ seismic isolators (developed by Earthquake Protection Systems, Inc. (EPS)) with a minimal increase on project budget (approx. 2% of construction cost) and robust protection of investment. An overview of the isolation system and some relevant design coordination topics are discussed.

SUSTAINABLE DESIGN PROCESS

In recent years, much attention has been given to sustainable buildings through organizations such as LEED (USGBC, 2012) which consider, among other components, operational systems such as mechanical, electrical, and plumbing systems. These operational factors are important to the carbon footprint of a building, but do not fully represent the total life-cycle impact a building has on the environment. Recent reports by Sturgis Carbon Profiling (2010) suggest that as much as 45% of the total life-cycle carbon footprint of office buildings and 30% of residential buildings is embodied in the materials which compose the building. There are numerous materials which are needed to conceive a building and include the foundations, structural system, exterior enclosure, roofing, and finishes. One area of great impact which has received little attention is the carbon embodied in the structural system. Additionally, in regions prone to seismic risk, significant carbon once embodied in a building can be lost due to damage in earthquakes. Seismic damage levels can range from modest repairs of finishes to complete demolition and reconstruction.

With these challenges and opportunities in mind, an informed design process is undertaken for the considered residential buildings. Along with traditional metrics of cost, saleable area, and client intent, quantified metrics for carbon are included in the design decision making process. Synergies among building systems are identified and utilized for a new level of high performance design in residential buildings.

Environmental Analysis Tool™

The Environmental Analysis Tool™ has been developed by SOM for the quantification of equivalent carbon emissions embodied in structural materials for a variety of buildings with options for estimation of probable seismic damage and enhanced seismic force resisting systems. This approach to carbon footprint assessment is needed in all phases of design to inform designers of anticipated impacts design options may have.

When a bill of material quantities are known, they can be specified in the carbon footprint analysis, but this information is often only known in later phases of design after significant design decisions have already been made. When key decisions are made at early phases of design, engineers and architects need accurate estimations of material and carbon quantities to guide the design process. To facilitate this need, the EA Tool is capable of calculating the structural system's carbon footprint with knowing only:

1. The number of stories (superstructure and basement).
2. The total framed area in the structure or area average area per floor.
3. The structural system type.
4. The expected design life.
5. Geographic conditions related to expected wind and seismic forces.

With this limited amount of data, the program refers to a comprehensive database containing the material quantities for hundreds of previously designed SOM buildings. Based on these data, statistical models and curve fitting techniques are used to estimate average material quantities. Estimated material quantities can be completely overwritten or partially supplemented by project-specific information. Options for superstructure structural framing materials include structural steel, reinforced concrete, composite (combination of steel and concrete), wood, masonry, and light metal framing. Foundation materials include reinforced concrete for spread / continuous footings, mats, and pile-supported mats.

From concept-level decisions to fine grain details such as travel distances associated with construction processes, the EA Tool is scalable to all phases of design. Key concepts of the EA Tool are presented in Figure 2 and program interface in Figure 3.

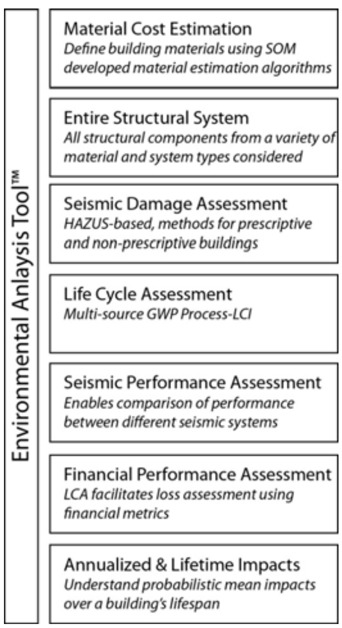


Figure 2. EA Tool

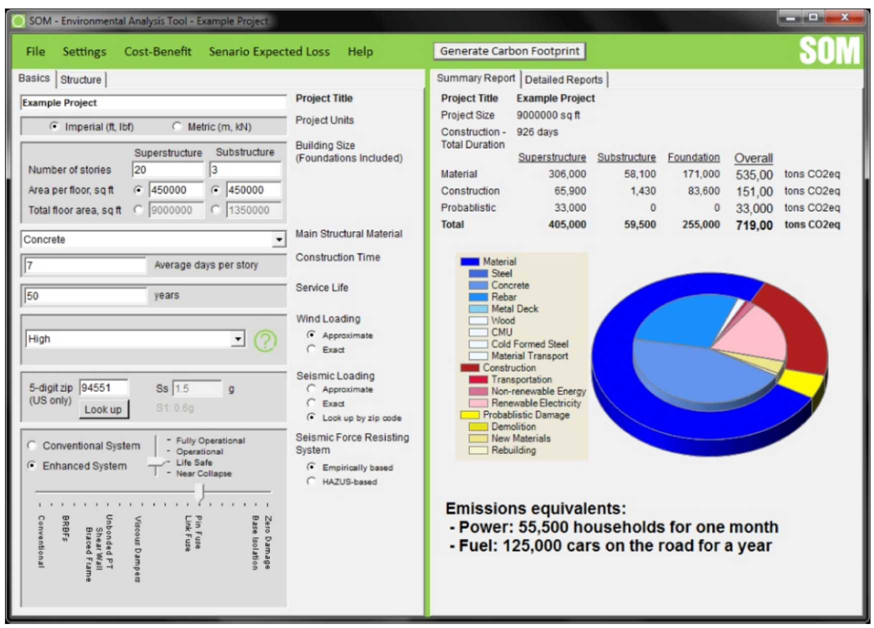


Figure 3. EA Tool User Interface

The selected seismic resisting system is important to a building's carbon footprint over the life of the structure. The contribution of carbon related to damage from a seismic event could account for 25% or more of the total carbon footprint for the structure. Furthermore, if a building is designed to code-minimum standards, then the building may need to be completely demolished after a design-basis earthquake. Conventional code-based structural systems are provided with the option to select enhanced systems such as seismic isolation, unbonded braces, viscous damping, and Pin-Fuse Seismic Systems (Sarkisian, in press). Potential seismic damage and the repair required are considered.

Design Process

From concept, through most of the schematic design phase a traditional shear wall seismic force resisting system was considered. The shear walls would wrap around the elevator and service areas with additional 'wing walls' at the north and south end of each building. These walls were needed to provide additional stiffness in the east-west direction and to mitigate significant torsional motions of the building. Although effective structurally, the wing-walls are problematic for tenant layouts, programmatic needs, future flexibility, and displaced approximately 1,000 sq. ft. of valuable lease space.

During schematic design the client and design team considered several enhanced structural seismic force resisting systems to not only achieve code-superior performance in a seismic event, but address the issues outlined above. Probable seismic damage is a metric used to estimate potential damage associated with a seismic event. Although the exact magnitude and resulting damage cannot be predicted precisely, probabilistic modeling can estimate likely seismic amplitudes and associated damages.

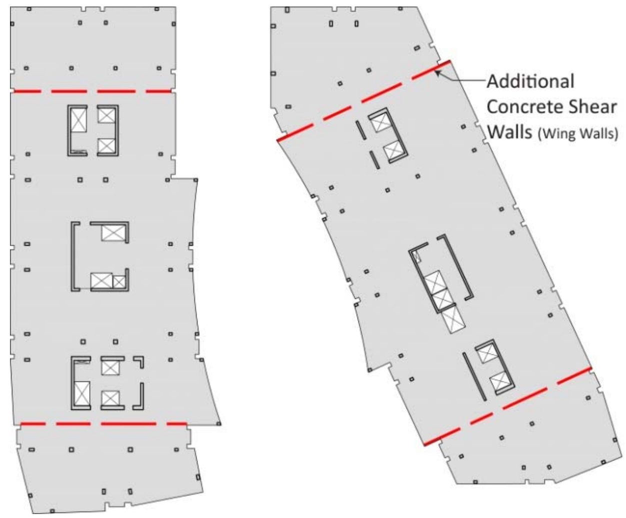


Figure 4. Floor Plan for Concpet Design

Using the schematic design fixed-based reinforced concrete shear wall scheme (Figure 4) as a baseline, several seismic force resisting systems were evaluated including viscous dampers and base isolation. By utilizing the EA Tool and its Cost/Benefit analysis component, fiscal and environmental impacts were quickly evaluated and discussed with the client and notable reductions in embodied carbon were identified with the employment of viscous damping and significantly more with base isolation (Figure 5). In fiscal terms, base isolation has a slightly better cost/benefit ratio, but the estimated savings from mean annual losses are almost ten times higher for base isolation. While viscous damper protect structural system components, they do not significantly reduce damage to non-structural components and contents. Base isolation significantly limits, and may even eliminate, damage to non-structural components and content.

Regarding tenant space, the viscous damper option would replace the wing walls with braces and dampers. Although a savings in concrete could be attained, the lease space would remain mostly unchanged. In the base isolation scheme, the wing walls would be eliminated due to the significant reduction in seismic forces and approximately 1,000 sq. ft. of valuable tenant space gained. Due to the high value of the tenant space this was a significant consideration.

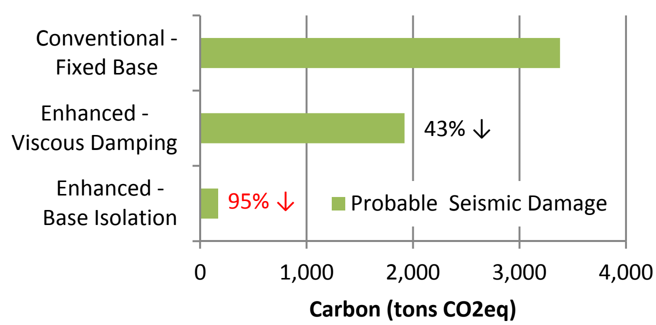


Figure 5. Carbon Footprint of Considered Seismic Systems at Schematic Design

Although base isolation may significantly reduce seismic damage and associated repair costs, the introduction of an isolation plane and ground-level seismic moat can present coordination and technical challenges as the isolated superstructure may move up to 34" relative to the basement levels for the considered residential building. The seismic plane was located just below ground level to maximize valuable parking space below grade. This introduced two challenges: one, an increase of excavation depth and basement construction, and two, mechanical, electrical, and plumbing (MEP) coordination issues with the superstructure movement. A synergy was identified in moving MEP components into the base isolation plane as shown in Figure 6. This reduced the excavation by moving MEP components out of the basement soffit into the isolation plane and permitted more freedom in MEP layout and improved basement parking aesthetics by hiding the MEP components. Furthermore, basement air intake and exhaust was moved to the seismic moat to avoid tenant areas.

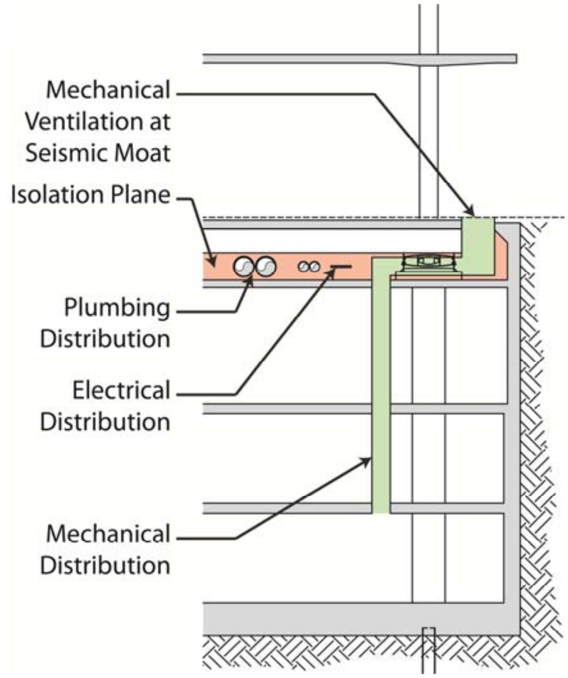


Figure 6. Basement Coordination with Isolation Plane and MEP Components

With considerations of cost, tenant space, construction, and other trades, a decision was made to incorporate base isolation into the building design through the detailed design phase. All trades were coordinated and cost assessments refined. Through the detailed design stage carbon quantities associated with structural system components were computed using the EA Tool and are presented in Figure 7.

As a refined bill of quantities was attained, the material quantity estimations of the EA Tool were replaced with as-designed quantities. As can be observed, a regular reduction in embodied carbon was achieved at each design milestone. These were achieved not only by incorporation of an enhanced seismic force resisting system, but with specification (i.e. fly ash replacement) and material quantity reductions through component design.

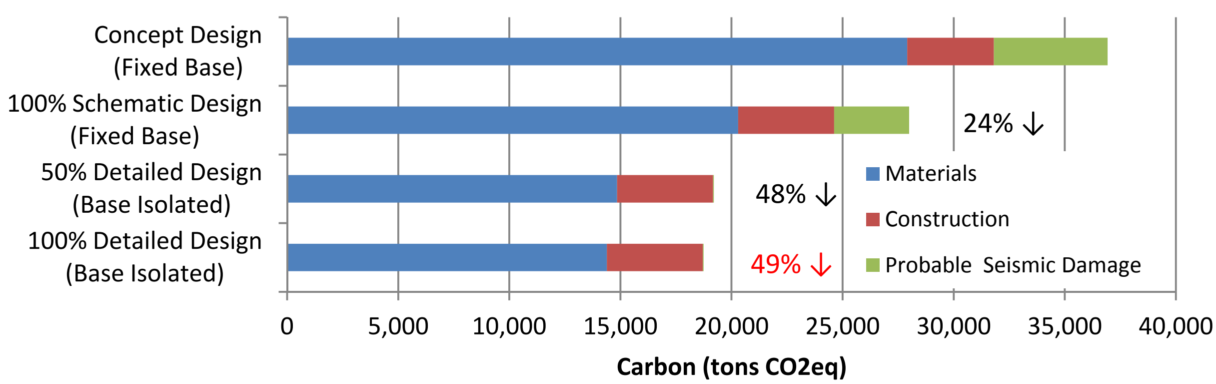


Figure 7. Carbon Footprint During Design Phases

TRIPLE FRICTION PENDULUM BASE ISOLATION

Through the last couple of decades seismic isolation techniques have become the landmark of high-performance structural systems for buildings in seismic regions. Perceptions of high initial cost and design complexity have limited their implementation in the United States to critical and public buildings required to remain functional after a major earthquake event, such as hospitals, research centers and other essential facilities. However, the recent growth of performance-based assessments and life-cycle cost analyses within the engineering community has facilitated quantifiable fiscal metrics to convey to owners and developers of residential buildings the long-term benefits that isolation systems can provide.

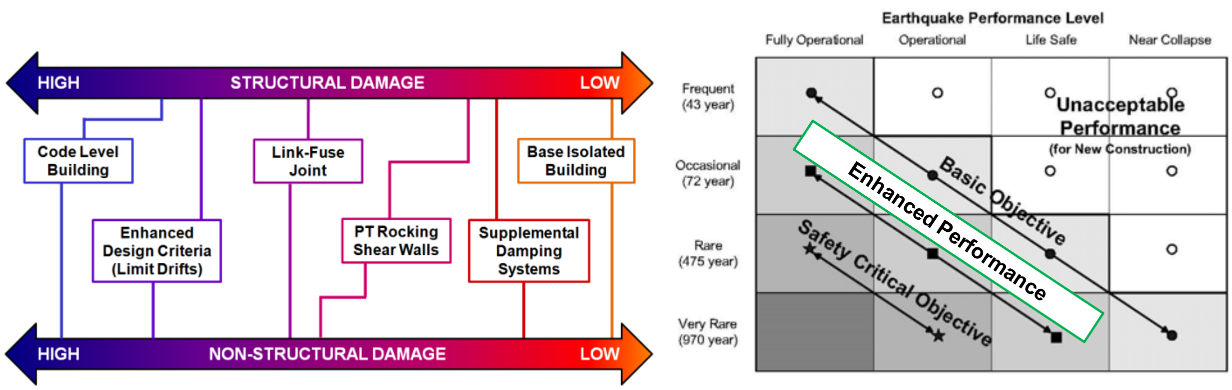


Figure 8. Enhanced Seismic Performance Systems considered for the project (Left). Basic Objective versus Enhanced Performance Level (SEAOC, 1995) (Right)

Prior to the commencement of the detailed design phase for this condominium project, several enhanced lateral seismic force resisting systems were studied (see Figure 8) and their global structural performance was compared. From them, base isolation is the only system that can assure low structural and non-structural damage for large earthquakes, and therefore leading to the lowest values of Expected Annual Loss and Probable Maximum Loss. Enhanced seismic performance not only facilitates a sustainable urban environment, but also protects the owner's investment and lowers earthquake insurance rates. These factors yield more marketable residential spaces for the client. With this premise, it was agreed with the client to design a base isolation system for the project.

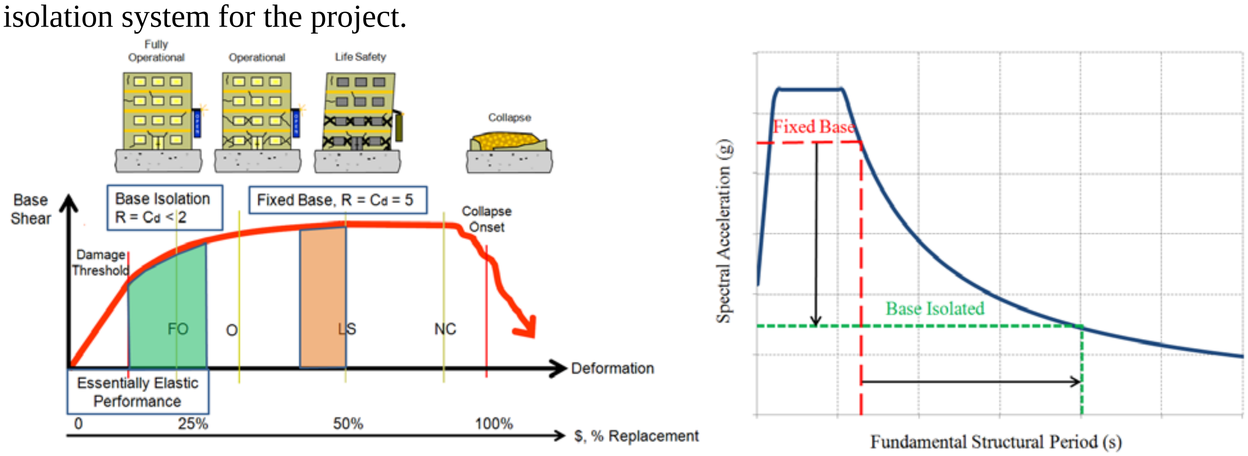


Figure 9. Qualitative performance comparison of fixed base versus base isolated building

In general terms, a base isolated building can be subdivided in three parts: superstructure, the isolation system itself, and the substructure. The superstructure is formed by all the elements of the building that sit on top of the seismic isolation bearings, which therefore will be subject to reduced structural and non-structural damage. The isolation system divides superstructure and substructure and it is typically located at the ground floor level of the building, consisting of the seismic isolation bearings, supporting pedestals, etc. The substructure is located under the isolation bearings, and it can be formed by several basement levels or just a foundation slab. None of the substructure elements are isolated, and they behave as a fixed-base structure.

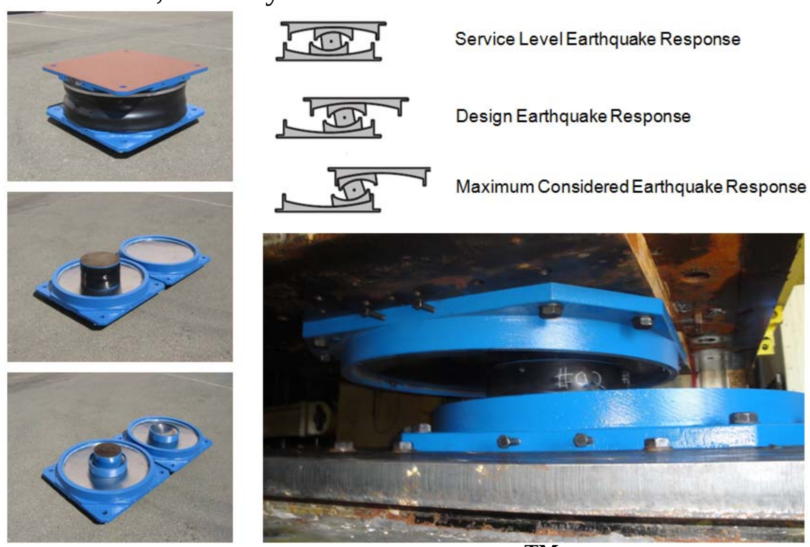


Figure 10. Triple Friction Pendulum^{TM} seismic isolation bearings

In base isolated structures, the global structural performance is fundamentally controlled by the characteristics of the isolation bearings. Bearings have very low stiffness, and therefore greatly increase the fundamental period, reducing significantly seismic forces on all components as well as superstructure drifts and accelerations (see Figure 9).

There are two types of isolation bearings typically considered, Lead-Rubber Bearing (LRB) systems and Friction Pendulum (FP) systems. Although both types can be designed to a comparable level of performance, the FP system presents several design advantages such as the independency of the fundamental isolated structural periods from the mass of the superstructure and the natural dissipation of any inherent and accidental torsion effects at the isolation plane (Zayas et al.). In addition, by utilizing the latest version of the FP assembly, the Triple Friction Pendulum^{TM} (TFP) bearings, the system can be tuned to an enhanced performance for different earthquake intensity levels, whereas the LRB system does not present this design flexibility. For this project, the asymmetric distribution of mass at the isolation plane (with the subsequent seismically-induced torsion) due to the presence of two buildings of significantly different heights, and the desire to protect drift and acceleration sensitive non-structural components for service level earthquakes (less than 100 years return period), clearly indicated the suitability of the project for a TFP system. By reducing the torsional demands, the 'wing walls' could be removed from the lateral system, hence improving the quality of the interior spaces designed for the client.

A common isolation plane located at ground level for the two residential buildings involved in the project was utilized. Under the isolation plane, a total of 125 TFP seismic isolation bearings were located under each main gravity column and under each corner of the shear wall cores. A global building structural analysis model was constructed using the commercial structural software ETABS (CSI, 2011).

For accurate estimation of drifts, forces and displacements, it is fundamental to calibrate the nonlinear element links utilized to model the isolators so that they match the physical properties provided by the manufacturer, EPS. This was done for all bearings types, by using a parallel model of ISOLATOR2 and GAP and HOOK link elements (CSI, 2011). See Figure 11 for a sample adjustment, for more information on advanced modeling of the bearing mechanics refer to Fenz et al. (2008) and Sarlis et al (2010).

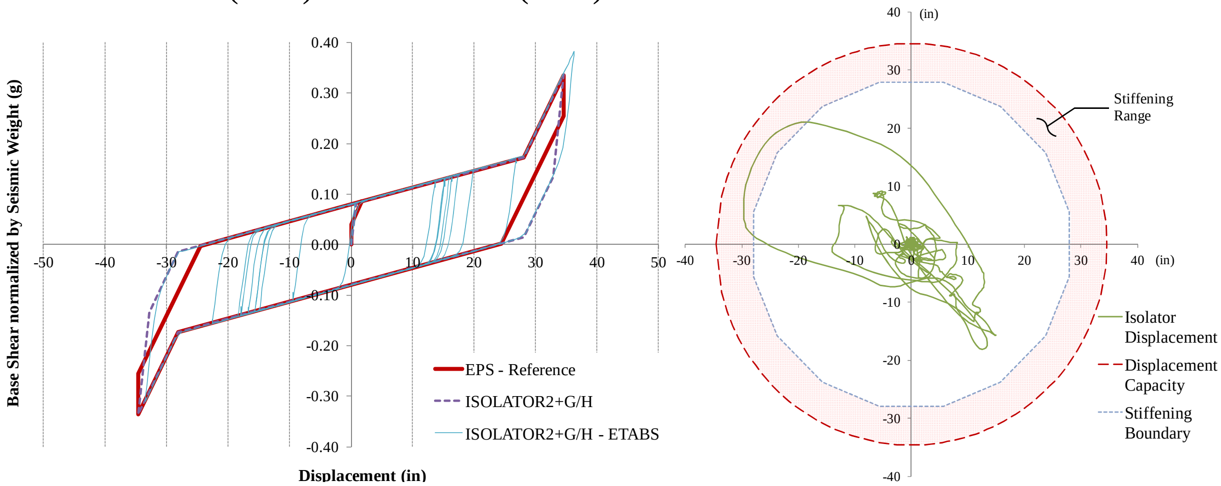


Figure 11. Example of analytical and numerical calibration of the TFP model to the prototype (left). Example Isolator Trajectory (right)

As the bearings were designed to reach the displacement capacity of the top and bottom plates (surfaces 1 and 4 on Figure 12) at the Maximum Considered Earthquake (MCE) level, it is critical to correctly envelope the boundary of the so-called "stiffening range" by adding several sets of GAP and HOOK elements at different orientations (Fenz et al.) to the analysis model. If this is not properly done, isolator displacement demands would be overestimated whereas other parameters such as uplift and superstructure drift underestimated. A total of 16 degrees of freedom were modeled for this case, which approximated the theoretical circular boundary with less than 2% overestimation (as shown on Figure 11).

Superstructure drifts obtained based on nonlinear time history analyses (average of 7 earthquake records) were limited to 0.77% for Design Earthquake (DE) level and upper bound friction properties and 1.15% for Maximum Considered Earthquake (MCE) and lower bound friction. Therefore, the essentially elastic performance criteria stated on ASCE 7-05 Chapter 17 were satisfied. The peak uplift was found to be 2.4 in at the core locations, within the allowable uplift criteria established for the project.

The total maximum displacement of the isolators was designed to be equal to 33.4 in, as determined from analysis, being the displacement capacity of the bearings equal to 34.0 in. In order to accommodate construction tolerances the seismic moat around the isolation interface was set to 36.0 in. Complex nonlinear analyses including ground motions with rotational components were performed to assess the degree of torsional displacement amplification experienced by the system. To that regard, the "stiffening range" acts positively as a rotation-dissipating mechanism which forces the system to have mainly

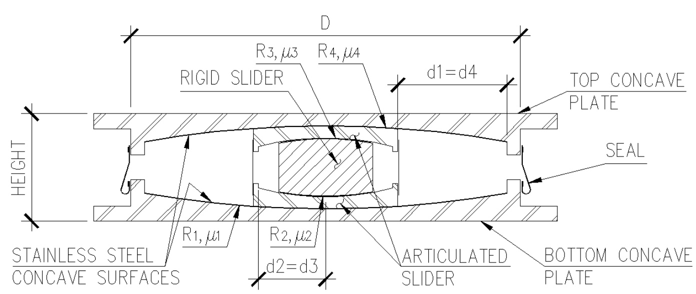


Figure 12. Typical TFP bearing section indicating main components and design parameters

translational components at the isolation plane. This allowed using a 4.3% displacement amplification factor, approved by the Peer Review Panel, instead of the non-specific 10% factor stated by ASCE 7-05 Chapter 17.

A VISION FORWARD

In seismically active regions, sustainable design in residential construction and innovation in structural engineering have to be synonyms. By adopting presented approaches in future residential developments, the following benefits are provided to the society, clients and architecture and engineering communities:

1. A common quantitative and economic language provided by applications such as the Environmental Analysis Tool™, in which designers can communicate to the client, starting at the early stages of the project, the impact that different structural system selections may have in the life-cycle cost, as well as assess the carbon footprint of such decision.
2. Protection of investment, society welfare and increased reputation of the technical communities by designing enhanced structural systems beyond minimum code-level performance. The case study has presented a design with a revolutionary technology, Triple Friction Pendulum™ base isolation, to produce, with minimal alteration to the construction cost, the most sustainable structural system within the design possibilities in hand.

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