16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4552 (Abstract ID)

Registration Code: S-M1461002381

PERFORMANCE-BASED DESIGN: SUPPLEMENTARY DAMPING FOR RETROFIT OF A TALL STEEL MOMENT FRAME BUILDING

G.C. Hart[(1)], L.M. Joseph[(2)], C. Chamberlain[(3)], C.J.F. Smith[(4)], R. Wong[(5)], C.C. Simsir[(6)]

[(1)] *Principal Emeritus, Thornton Tomasetti, ghart@thorntontomasetti.com*
[(2)] *Principal, Thornton Tomasetti, ljoseph@thorntontomasetti.com*
[(3)] *Managing Principal, Nishkian Chamberlain, cchamberlain@nishkian.com*
[(4)] *President, EQC Global, csmith@eqcglobal.com*
[(5)] *Project Engineer, Nishkian Chamberlain, rwong@nishkian.com*
[(6)] *Senior Associate, Thornton Tomasetti, csimsir@thorntontomasetti.com*

Abstract

An evaluation and upgrade of building seismic resistance was triggered by proposed new use as a school. The building existing framing was designed and constructed in the 1980's based on building code provisions that did not reflect improved, current practices for steel frame seismic systems. The role of the Peer Reviewer and the sharing of education and experience in this seismic strengthening project is explained. This paper illustrates selected key inputs and decisions made by the design and peer review team in the evaluation and strengthening of an existing four-story steel moment frame building located in southern California. While the building department defined scope was the evaluation and strengthening be performed to implement the intent of ASCE 41-13, the project benefitted from viewing the design using ATC-63/FEMA P695 contributions to performance based design.

Keywords: Evaluation and strengthening, viscous dampers, steel building, performance based design, ASCE 41-13

1. Introduction

The primary focus of this paper is the building shown in Fig. 1 located in southern California. The charter school NOVA Academy Early College High School acquired a four-story building to expand enrollment to 450 students. With an occupant load of more than 250, the existing building is required by the Santa Ana building department to be seismically retrofitted to comply with the requirements of the ASCE 41-13 [1] Standard and the California Building Code (CBC), Section 3417, *Earthquake Evaluation and Design for Retrofit of Existing Buildings*.

The building has a quarter circle footprint is approximately 39,000 SF (3,600 m^2) with a 5,400 SF mechanical roof penthouse. The building is of construction Type IIA built in the early 1980s in accordance with the requirements of the 1976 edition of the Uniform Building Code. The roof and floor systems are normal weight concrete over metal deck supported by steel beams, girders and columns. The lateral force resisting system consists of discrete bays of welded steel moment resisting frames with non-ductile pre-Northridge beam-to-column connections. The foundations consist of deep cast-in-place piles and pile caps with interconnecting grade beams. A change to "E" occupancy requires a change in the building's Risk Category from II to III (2013 CBC, Chapter 16 Table 1604.5).

ASCE 41-13 follows two levels of site-specific design earthquake, a 225 year return period earthquake, BSE-1E and a 975 year return period earthquake, BSE-2E. In order to meet and exceed the required post-earthquake performance objectives for the retrofitted building and its contents for both design earthquakes, the best approach was determined to be the addition of thirty-five (35) velocity dependent fluid viscous dampers. The dampers are installed as diagonal braces running column to column, floor to floor, in architecturally acceptable bays distributed throughout the building on all levels. This approach offered benefits from excellent quality control of damper production and the future potential to "upgrade" the dampers with "smart" dampers that may further reduce earthquake forces through active control technology.

Key features of the retrofitted building reduced seismic response are as follows:

a. The existing lateral force resisting system steel moment frame beams and columns remain elastic for the BSE-1E earthquake with a ductility demand less than 1. A small amount of yielding occurs in 6% of the moment frame elements for the BSE-2E earthquake with a ductility demand of less than 1.5.
b. The interstory drift is less than 1% for the BSE-1E earthquake and 2% for the BSE-2E earthquake.
c. The horizontal floor accelerations are reduced by over 60% from those that would have been experienced in the acquired building for both the BSE-1E and BSE-2E earthquakes.
d. No existing foundation retrofit is required for both the BSE-1E and BSE-2E earthquakes because maximum forces at damper-braced bays occur out of phase with maximum forces in existing moment frames.

This conference paper, intended to supplement a paper that is expected to be published in 2017 in the Wiley journal entitled "The Structural Design of Tall and Special Buildings" presents a successful application of ASCE 41-13 retrofit criteria, and some of the benefits of having Peer Review team input in the development of the project plans and specifications.

Fig. 1 – Building North and East Elevations

2. Education and Experience

It is self-evident that when a design team, no matter how great it is, is aided by the additional education and experience of Peer Review, the final design documents will benefit. The primary reason for this win / win situation is that structural engineering has many dimensions and structural engineers typically have one area where they excel because of their particular passion to learn and share in that area. Specifically, in this case, co-authors Dr. Hart, Mr. Joseph and Dr. Simsir of Thornton Tomasetti as Peer Reviewers each have their unique area of focus as did the design team of co-authors Mr. Chamberlain, Mr. Smith and Ms. Wong.

Regardless of the evolution of analytical tools available the single most significant part of structural engineering evaluation and strengthening of buildings is the application of education and experience. Hundreds of years ago and prior to structural mechanics, buildings were designed only using the education and experience of the design team. With ever more prescriptive provisions in design codes and standards, education and experience are often overlooked but should be applied at almost all stages of a good creative design.

Application of education and experience can be explained using Fig. 2 illustrating the evolution of successful technology transfer. Each clover leaf identifies a part of the design provisions in ASCE 41-13 (and all codes and standards). However, the primary objective of codes and standards is to apply to a subclass of all buildings and not a specific building. So where does application of the education and experience of the document authors in each of the four areas of Fig. 2 appear?

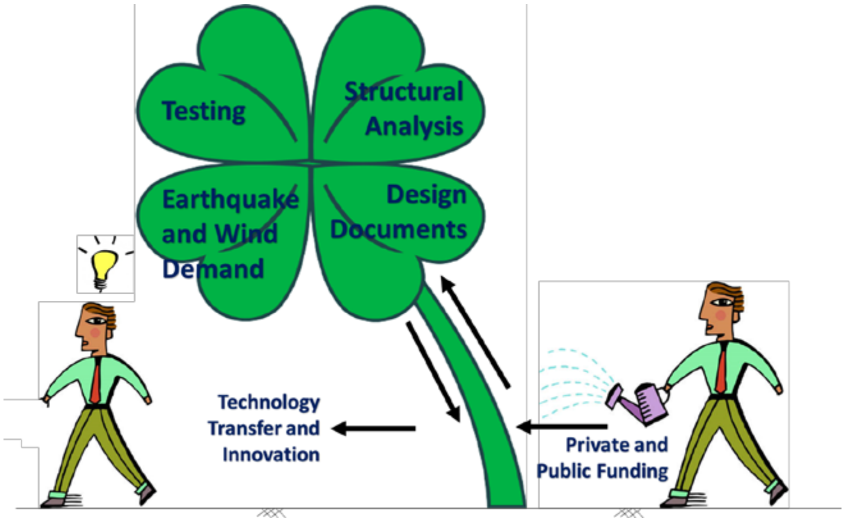

Fig. 2 The Structural Engineers Four Leaf Clover

The senior author of this paper has co-authored two papers that present in part his position that the ATC-63/FEMA P695 [2] report regarding quantification of seismic performance is one of the great reports of the last half century. To see how the Peer Reviewers viewed this project through "ATC-63 glasses" view the contributions to this project from each of the clover leaf by considering the following, drawn from the ATC-63/FEMA P695 report.

(1) Earthquake Demand Variability in Responses

For response to different ground motion records ATC-63 Coefficient of Variation (COV) values range from 0.2 to 0.4. Typical building model values of COV are 0.35 to 0.45; the ATC-63 examples use 0.40. ATC-63 tells us for limited ductility COV= $(0.1+.01\mu)$ where μ is ductility demand. For this project more confidence and less uncertainty exists when strengthening with viscous dampers that result in limited ductility demand and also more confidence in damper load / deformation performance.

In ATC 63-1/FEMA P795 [3] language, there is only a Fair Degree of Confidence, i.e. COV = 0.40, for conventional collapse prevention design. The structural design team subjectively knew that they had Superior Confidence in the performance of viscous dampers as structural elements and with Peer Review input they learned that COV=~20% vs. ~40%.

(2) Design Requirement Uncertainty

Completeness of design requirements:

High: Extensive safeguards against unexpected failure modes. All-important design and quality assurance issues are addressed.

Medium: Reasonable safeguards against unexpected failure modes. Most of the important design and quality assurance issues are addressed.

Low: Material, component, connection, assembly and system behavior fairly understood and accounted for. Several important testing issues not addressed.

Completeness of design requirements for this project as placed on the plans and specifications rate this aspect of design as high. Special field construction tasks were added to plans at potential overload hot spots based on extensive nonlinear analyses. This construction related / quality hot spot information is, we believe, a new approach not previously used on projects and resulted from Peer Review and design team discussions.

(3) Test Data Uncertainty

Completeness of test data to define system. Uncertainty closely associated with but distinct from modeling uncertainty:

High: Material, component, connection, assembly and system behavior well understood and accounted for. All or nearly all important testing issues addressed.

Medium: Material, component, connection, assembly and system behavior generally understood and accounted for. Most important testing issues addressed.

Low: Material, component, connection, assembly and system behavior fairly understood and accounted for. Several important testing issues not addressed.

The rating here is High because of extensive test data was developed thanks to project specific testing of the viscous dampers. Also, the limited ductile behavior of pre-Northridge moment frames was recognized in the 1990's and extensive test data was developed thanks to funding provided by the FEMA Steel Buildings project. Also a phased approach to field testing resulted from Peer Review and design team discussions combined with nonlinear structural analysis results.

(4) Modeling Uncertainty

How well models represent full range of structural response.

High: Models capture the full range of structural behavior.

Medium: Models are generally comprehensive and representative of behavior.

Low: Significant aspects of behavior not captured.

Again, a High rating here because nonlinear responses are limited, not extensive, and the modeling of the viscous dampers has a high degree of confidence.

Peer reviews can provide an effective way to engage education and experience. The requirement for a building design to have a peer review was first introduced in the 1980's for buildings using base isolators, primarily for reviewing the nonlinear structural analysis model. Collaboration and sharing of the education and experience of the peer reviewers and design team was not a goal. The benefits, some of which are described above, are in addition to that original goal.

After it is rehabilitated, a building is ultimately the "child" of the Structural Engineer of Record (SEOR). On this project SEOR Craig Chamberlain sought and shared through discussion and assignments the education and experience of his design team and the peer reviewer. While building officials may expect peer reviewers to just provide an approve or disapprove recommendation on this project, the co-authors shared their combined 100+ years of experience and they, the SEOR and the key additional members of the team all learned and the final design documents benefitted.

Three examples illustrate the result of open discussions of ideas based on past education and experience:

(1) Recognize that contractors may not, and sometimes cannot, implement what is on the plans. This is despite the inspection, etc. of others including structural observation specified on the plans. Therefore, on this project based on structural analysis results, education and experience, certain members with acceptable but high Demand / Capacity values are called out to have extra inspection of the contractor's work.

(2) Use damped linear analysis to help understand other analysis results. In prescriptive seismic design we use a linear structural model and reduce demands by a large R factor. We also build in minor damping to account for energy dissipation of structural members. The most obvious example of this is for wood structures where the behavior of stucco and drywall are in a non-transparent way included in the design but still using a 5% damped design spectra. In this viscous damper project, a nonlinear dynamic analysis was performed with inherent damping 2%. However, the Peer Reviewers asked what value of damping would give approximately the same demands as the nonlinear analysis if we

took the results of this nonlinear dynamic analysis and performed a linear response spectra analysis. This value was approximately 25%. This was consistent with our expected results based on education and experience and also provided a new data value for our experience database.

(3) The 1994 Northridge earthquake taught us all the importance of understanding the influences on reliability of connections in steel buildings.

For this project, reliability or variability was key to determining acceptance. When utilizing ASCE 41-13, there are sections that either require or recommend lower-bound values. These lower-bound values are often stated as corresponding to the Mean value minus one Standard Deviation. In our structural engineering education and experience, we typically do not relate uncertainty to a value of standard deviation, but to a value of Coefficient of Variation (standard deviation / mean) because it is non-dimensional and can be used to mentally relate or compare our uncertainty from one random variable to another. This is discussed in the LATB-1 report [4] and examples are in Table 1.

Table 1 Coefficient of Variation (%) [5]

Rolled Steel Yield Stress	8
Grade 50 Steel Tension Member	9
Reinforcing Bars (Grade 60) Yield Stress	9
Concrete Control Cylinders Compressive Strength (Excellent)	10
Concrete Control Cylinders Compressive Strength (Average)	15
Concrete Control Cylinders Compressive Strength (Poor)	20
Damping in Concrete Building	30
Concrete Modulus of Elasticity	20
Concrete Poisson Ratio	10
Steel Modulus of Elasticity	6
Damping in Steel Frame Building	20
Live Load	25
Maximum Annual Wind Speed	16
Maximum 50-Year Wind Speed	12
ATC 63 Quality Rating Superior Confidence	10
ATC 63 Quality Rating Good Confidence	20
ATC 63 Quality Rating Fair Confidence	35
ATC 63 Quality Rating Poor Confidence	50

How does this relate to determining acceptance? It affects the target or goal needed for acceptance, as explained in a Los Angeles Tall Building Structural Design Council course on the basics of structural reliability, LATB-1 [4].

Assume that X is a Random Variable that is the Capacity of a Limit State and define

X_D = Design Value of X

$\bar{X}$ = Expected Value (Mean) of X

σ_X = Standard Deviation of X

ρ_X = Coefficient of Variation of X

Many structural engineers wish to use design values that are less than expected/mean values, and thus their Design Value of the Capacity (i.e., X_D) is typically the Expected Value of the Capacity minus one Standard Deviation of the Capacity. Therefore, we can write

$$X_D = \bar{X} - \sigma_X \tag{1}$$

Dividing both sides of the equation by $\bar{X}$ we obtain

$$\left(X_D / \bar{X}\right) = 1 - \rho_X \tag{2}$$

Fig. 3 shows how the ratio $\left(X_D / \bar{X}\right)$ varies with the value of the Coefficient of Variation of X. Fig. 3 also presents the results in a form that can be related to uncertainty expressed in words. The relationship between the noted levels of confidence (e.g. Superior, Good and Fair) and values of the Coefficient of Variation, as shown in the figure are inspired by the ATC-63[1] definitions. In ATC-63/FEMA P695 Superior is a point value of 10%, and here we have made the ATC-63/FEMA P695 point estimates of Superior to be in the range of 5% to 15%. Similarly, Good and Fair Confidence are conversions of ATC-63/FEMA P695 point values of confidence to a range.

Fig. 3 shows us that if the Coefficient of Variation is 30%, then the Design Value of X is equal to 70% of the Expected Value (Mean) of the Capacity. When we use a Design Value of Capacity, X_D, that is 70% of the Expected Value (Mean) of the Capacity, we, as Peer Reviewers, were able to infer that ASCE 41-13 is assuming only a "Fair" level of confidence of X. If we have a Superior level of confidence in X, then the Design Value of Capacity (X_D) will increase to 85 to 95% of the Expected Value of the Capacity. Doing more and better testing, analysis, etc. as we did on this project can increase confidence and justify a larger effective $\left(X_D / \bar{X}\right)$ ratio.

In the context of this project, for any selected limit state used to define performance, it was possible, based on experience and education, e.g. using the FEMA Steel Building project research, to assign a level of confidence. For example, on the border between Good and Superior confidence, the coefficient of variation would be 15% and the Design Capacity would be 85% of the Mean Capacity.

Fig. 4 shows how the ratio $\left(X_D / \bar{X}\right)$ varies with the value of n and the value of the Coefficient of Variation of X, and if $n = 0.5$ is acceptable for a selected limit state, then for a COV of 15% the acceptable ratio increases to above 90%. The random variable X is a performance variable associated with Limit States on this project, e.g. it can be the Roof Drift Ratio, or the Inter-Story Drift Ratio, or the Yield Moment of a Beam, etc. Less critical or sensitive States may justify using a smaller 'n' and extremely critical States may require using a larger 'n'.

[1] ATC-63 entitled "Quantification of Building Seismic Performance Factors" is available on www.fema.gov.

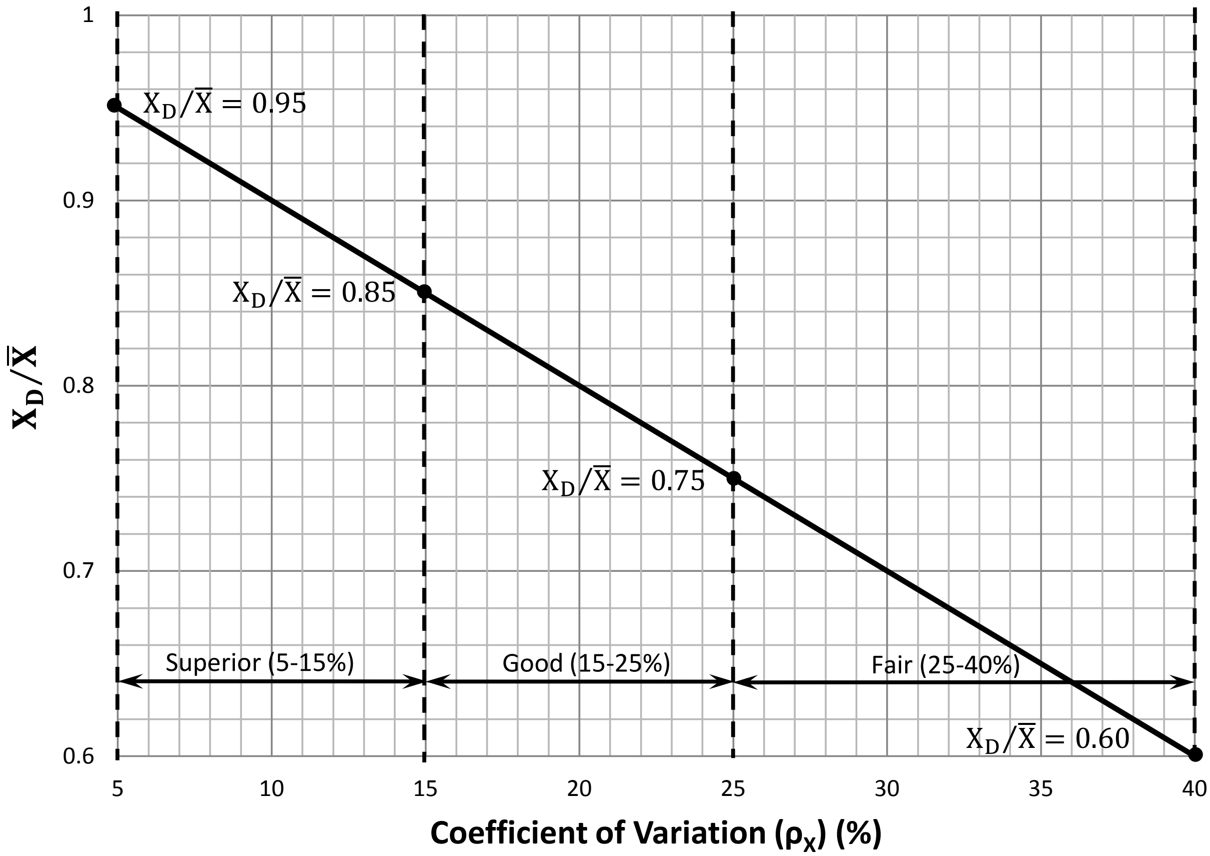

Fig. 3 – Ratio of Design Value of the Capacity of *X* to the Expected Value of the Capacity of *X* as a Function of Superior, Good and Fair Confidence in *X*

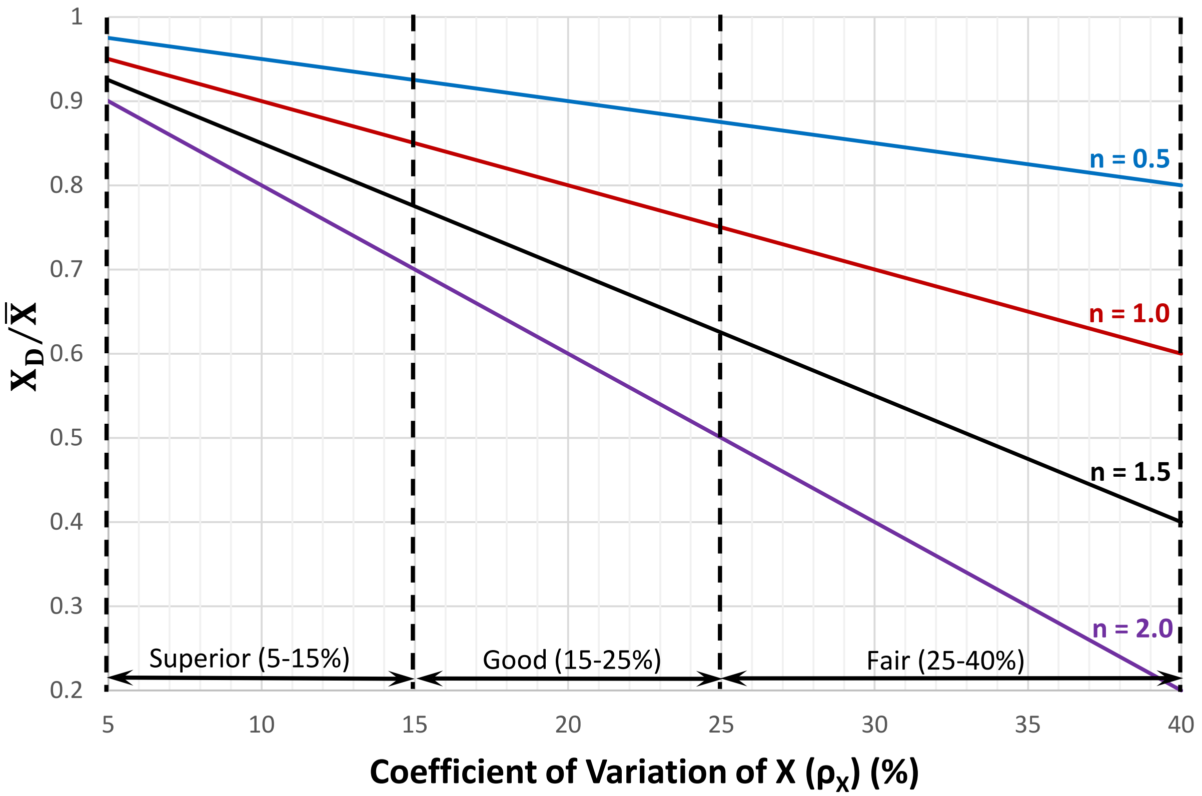

Fig. 4 – Ratio of Design Value of the Capacity of *X* to the Expected Value of the Capacity of *X* as a Function of *n* and the Coefficient of Variation of *X* $\left(X_o = \bar{X} - n\rho_x\right)$

With an excellent project team, the Peer Reviewers were able on many occasions to discuss issues and computer analysis results and make their decisions on a science-based comfort level. The uncertainty rating was Superior in most occasions and thus we used the information in Fig. 3 and 4 to accept the design. It is important to note that the results in Fig. 3 and 4 do not require an assumption on the type of probability density function of X.

3. Seismic Performance Objective

The target Performance Objective for this performance based design of an existing building is the Basic Performance Objective for Existing Buildings (BPOE) described in ASCE 41-13 Table 2-1 for a Tier 3 analysis and a Risk Category III building, see Table 2. The Basic Performance Objective is Limited Safety Structural Performance for BSE-2E (5% probability of exceedance in 50 years, i.e. a 975 yr. return period event) and Damage Control Structural Performance for BSE-1E (20% probability of exceedance in 50 years, i.e. a 225 yr. return period event).

The interesting point here is when the ASCE 41-13 design was looked at through the "ATC-63 glasses" with the benefits of increased confidence of performance as reflected on the plans, it is probable that the above noted performance objective would be satisfied even for a Maximum Considered Earthquake 2% Probability of Exceedance in 50 years. This is because of the reduction in uncertainty in both the existing condition of the building and the loads on the collapse and other limit states.

Table 2 – Basic Performance Objective

	Tier 3	
Risk Category	BSE-1E	BSE-2E
III	Damage Control Structural Performance Position Retention Nonstructural Performance	Limited Safety Structural Performance Nonstructural Performance Not Considered

4. Structural Systems Analysis

A three dimensional finite element model of the building was prepared. The building's lateral force resisting system was designed to resist stresses and limit deformations. All structural elements other than the viscous damping devices were modeled as linear elements.

A Nonlinear Dynamic Procedure (NDP) where the model is subject to response spectral and time history loading has been used to establish the suitability of the supplemental damping system to meet the performance objectives and demonstrate the demands and capacities of the lateral force resisting system structural elements are within suitable limits.

Inherent damping occurs principally in the structural components that are treated as elastic but where small inelastic cracking or yielding occurs, the architectural cladding, partitions, and finishes and the foundation and soil. The amount of inherent damping was assumed to be 2%.

All forces and deformations calculated using either the response spectrum or the response history method were multiplied by the product of the modification factors $C1$ and $C2$ defined in ASCE 41-13, Section 7.4.1.3 and further modified to consider the effects of torsion. Story drift checks were performed for BSE-1E and BSE-2E earthquakes including accidental eccentricity. The design story drifts (Δ) are not allowed to exceed the allowable story drift $\Delta_a = 0.015h_{xx}$ for the Damage Control structural performance level and BSE-1E, and $\Delta_a = 0.025h_{xx}$ for the Limited Safety structural performance level under BSE-2E where h_{xx} is the story height below level x.

Table 3 provides values of the building's drift ratios and Table 4 provides story accelerations.

Table 3 – Drift Ratios, %,

	BSE-1E		BSE-2E	
Level	x	y	x	y
R	0.51	0.71	0.95	1.53
L4	0.56	0.85	1.07	1.75
L3	0.54	0.74	0.99	1.42
L2	0.38	0.58	0.71	1.08

Table 4 – Story Accelerations (g)

	Retrofitted				Existing (2% damped)			
	BSE-1E		BSE-2E		BSE-1E		BSE-2E	
Story	x	y	x	y	x	y	x	y
R	0.44	0.41	0.63	0.66	1.57	1.62	2.21	2.58
L4	0.32	0.30	0.55	0.51	1.00	1.08	2.24	2.49
L3	0.38	0.38	0.50	0.44	1.40	1.46	1.72	1.74
L2	0.40	0.41	0.44	0.46	1.44	2.05	1.54	2.08

The energy from the earthquake was calculated at the suggestion of the Peer Reviewers and its distribution is shown in Fig. 5.

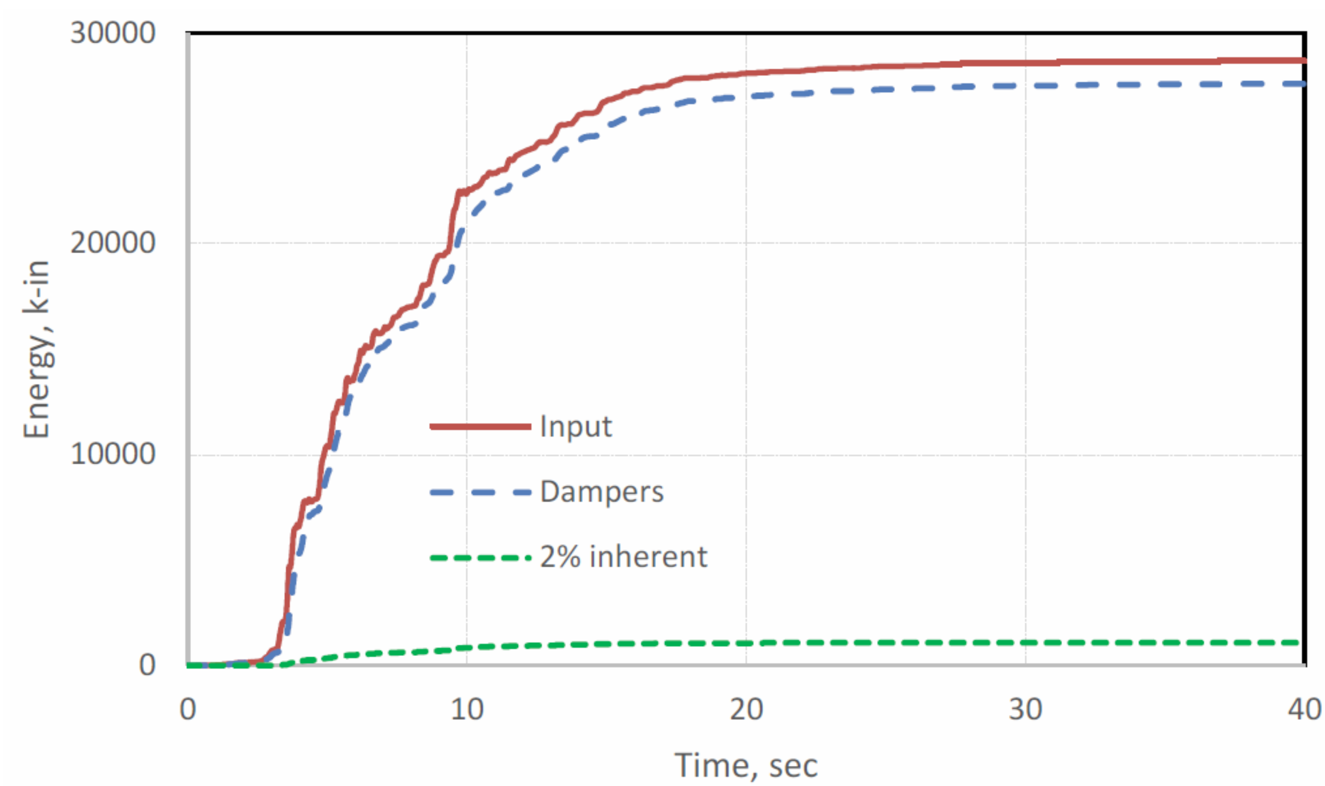

Fig. 5 – Steel Structure Damped Energy vs. Time

To demonstrate conformance with the basic performance objective, the floor and roof accelerations experienced in the undamped existing building were compared to the same parameters for the retrofitted building, see Table 4. The goal was that the existing building acceleration levels met a Life Safety Nonstructural Performance Level. The floor and roof accelerations and drifts experienced by the retrofitted building with the selected supplemental damping devices are reduced by more than 50% compared to values in the existing building.

The viscous dampers were modeled using a combination of springs and dashpots in series to represent the constitutive relation of the device and the steel brace member that pushes and pulls it. Nominal design properties of viscous dampers have been established from (a) prior prototype tests and (b) project specific manufacturing tests. These nominal design properties have been modified by lambda factors to account for (a) manufacturing tolerances, (b) device characteristics not explicitly accounted for during testing, (c) long-term environmental effects, and (d) aging, to develop upper- and lower-bound properties for the design and analysis of the energy dissipated structure. Upper-bound and lower-bound design and analysis properties for the selected device are within 15% of the considered properties. The energy dissipation devices are capable of sustaining larger displacements, velocities, and forces than the maximum calculated for BSE-2E or BSE-1E.

5. Conclusions

The use of ASCE 41-13 clearly demonstrates the benefits of utilizing professional experience within performance based design with project specific utilization of qualified structural peer reviewers in both structural design and structural reliability. This building could be a case study for the methodology of ATC-63/FEMA P695 as we are very certain it will show a cost benefit result and support the forward thinking of FEMA to fund ATC-63/FEMA P695 which directly incorporates the uncertainty reduction in equations and rewards innovation and research results.

The Peer Review process contributed to both the quality of the final structural plans and also the educational base of both the Peer Reviewers and the design team. With well-planned and well-managed projects, there was no real negative impact on the project schedule. The readers who so desire can obtain copies of LATB-1, 2 and 3 [4, 6, 7] at no cost by emailing Kburnham@ThorntonTomasetti.com.

6. Acknowledgements

The two senior authors wish to especially acknowledge the vision of the SEOR, Mr. Chamberlain, to use viscous dampers and to enable us to be part of this project team. The authors also wish to acknowledge the education they have received from the many excellent discussions that have taken place at conferences like this one as well as the enjoyable reading of journal papers and ATC reports. We also wish to acknowledge the constructive and professional work of the City of Santa Ana building department and the assistance of Kendra Burnham.

7. References

[1] ASCE/SEI 41-13 (2013): Seismic Evaluation and Retrofit of Existing Buildings, American Society of Civil Engineers, Reston, VA.

[2] Applied Technology Council. ATC 63 / FEMA P695 (2009): Quantification of Building Seismic Performance Factors. Applied Technology Council (ATC), Redwood City, CA.

[3] Applied Technology Council. ATC 63-1 / FEMA P795. 2011. Quantification of Building Seismic Performance Factors: Component Equivalency Methodology. Applied Technology Council (ATC), Redwood City, CA.

[4] Hart GC. 2012. Performance Based Evaluation and Strengthening with Structural Reliability Foundation, *Report LATB-1*.

[5] Hart GC, Jain, A. 2014. Performance-based wind evaluation and strengthening of existing tall concrete buildings in the Los Angeles region: dampers, nonlinear time history analysis and structural reliability. *The Structural Design of Tall and Special Buildings*, 23(16), pp. 1256-1274. DOI: 10.1002/tal.1139

[6] Hart GC, Conte JP, Park K, Ellingwood BR and Wong KKF. 2013. Performance Based Evaluation and Strengthening of Tall Buildings Using Bayesian Structural Reliability, *Report LATB-2*.

[7] Hart GC, Conte JP, Park K, Ellingwood BR and Wong KKF. 2016. Performance Based Evaluation and Strengthening of Tall Buildings Using Bayesian Structural Reliability: Expected Value & Standard Deviation as Random Variables, *Report LATB-3*.