5-2010

Financial Feasibility of High Performance Low Rise Steel Buildings

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Recommended Citation

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FINANCIAL FEASIBILITY OF HIGH PERFORMANCE LOW RISE STEEL BUILDINGS

by

Yolanda María Báez Batista

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

UTAH STATE UNIVERSITY
Logan, Utah

2010

ABSTRACT

Financial Feasibility of High Performance Low Rise Steel Buildings

by

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Utah State University, 2010

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Comparative performance evaluation including life cycle cost is currently being conducted on a series of conventional and base-isolated case study buildings. Alternative design approaches and their influence in cost were to be evaluated. This investigation is intended to contribute in the development of isolated structures by allowing engineers to communicate the cost of higher performance systems to their clients. The reported effort is part of a larger cost-benefit study for isolated steel buildings, and the purpose of this thesis is to compare initial investment of 3-story conventional and isolated steel buildings and determine how isolation affects the cost of the structure.

The relative cost of seismic isolation, as a percentage of the total cost, may be higher in this study than for typical U.S. isolation applications because the relative premium is greater for a short building than a tall building. The cost of isolation layer for this building is in the order of 11.7% to 12.4% of the total cost. Such a large cost premium may be a huge restraint for most owners; therefore, strategies to reduce the isolation premium cost need to be investigated in detail.

(95 pages)

ACKNOWLEDGMENTS

Thanks to God for giving me the opportunity of being here today surrounded by such wonderful people in my life. I would like to thank my family and friends, especially to my parents (Ingris and Esteban Baez) and Jose L. Camilo, for their unconditional love, moral support and encouragement throughout these years. I love you all and I am blessed to have you with me.

I wish to express my deepest appreciation to my major advisor, Dr. Keri Ryan, for allowing me to be part of this research study and for guiding me in the creation of this thesis. Her assistance, encouragement, support, dedication, and patience helped me stay motivated and focus throughout the entire process.

I would also like to express my appreciation to my committee members, Dr. Kevin Womack and Dr. Gilberto Urroz for their assistance and review of this thesis. I also wish to thanks Dr. Troy Morgan for providing us with the building's design and Peter Morris for giving me all the information and knowledge required to do these cost estimates.

Finally, this study was possible thanks to the funding provided by National Science Foundation (Grant Number CMMI-0724208), through Utah State University. I would also like to give special thanks to the Dominican Republic Government for granting me the scholarship that allowed me to obtain both degrees, a bachelor and master of science, in Civil Engineering at USU.

Yolanda M. Báez Batista

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INTRODUCTION

Background information

Each year, natural hazards are responsible for tremendous damage around the world. These events, including earthquakes, are capable of causing deaths, injuries and property damage. Earthquakes have occurred for millions of years and will continue to occur in the future as they have in the past. However, the worst aspect of these natural phenomena is the impossibility to predict them. For this reason, earthquakes are a serious natural hazard of unpredictable intensity that defy human understanding. Nevertheless, it is still possible to mitigate the effects of strong earthquakes to reduce the number of lives lost and the dollar amount of injuries and damage.

Earthquakes represent a global problem. Nowadays, people in many areas of the world live with a significant risk to their lives and property from earthquakes. The most memorable and dramatic images of earthquake damage are those of structural collapse (Kramer, 1996). Billions of dollars of public infrastructure are continuously at risk of earthquake damage.

There is a minimum level of protection demanded by design building codes to ensure life safety such as prevent falling hazards on structures that endanger human lives. However, even though current seismic design codes appear to provide adequate life safety in structures, the public deems this requirement alone as no longer sufficient (Kawashima and Miyaji, 2006). Due to the value of the technology inside the buildings, the socio-economic impact of business damage may far offset the cost of the structural system (Gupta, 1999). For example, if a hospital has to be closed due to lack of functionality, even for a couple of hours, this means that many lives that could have been saved are now at risk. Alternatively, corporate owners whose livelihood may depend on the resumption of operation soon after an earthquake might want options for investing beyond the minimum code requirements. As a result, the economic and social implications of poor performance of a structure during an earthquake need to be incorporated in future seismic design and evaluation methodologies. This means that the structure performance has to be related to the functional objectives of the structure considering both risk and cost-benefit tradeoffs (Gupta, 1999).

Performance-based earthquake engineering (PBEE) implies design, evaluation, construction, monitoring the function and maintenance of facilities whose performance under common and extreme loads responds to the diverse needs and objectives of owners and society. It is based on the premise that performance can be predicted and evaluated to help the client make, intelligent and informed decisions based on life-cycle considerations and trade-offs rather than construction costs alone (Bozorginia and Bertero, 2004).

Under this new performance-based approach, we want to consider alternative structural systems that can provide better performance economically. Seismic base isolation is a newer technology that is frequently considered for buildings that must remain operational in the design earthquake. The goal of base isolation is to reduce both drifts and accelerations which together can reduce structural and nonstructural damage and costs associated with earthquakes (Jangid, 2007). By shifting the natural period away from the dominant period of the ground shaking, the isolation system decouples the structure from the horizontal components of the earthquake ground motion. The isolators are much more flexible than the superstructure so the building behaves as a rigid structure during an earthquake as the isolators endure the large deformations. However, an owner is generally motivated by cost rather than performance, and the high cost of constructing a seismic isolated building has prevented this mechanism from being widely used in the United States (Bozorgnia and Bertero, 2004). For this reason we need to evaluate alternative and conventional approaches from a life cycle cost perspective.

The Network for Earthquake Engineering Simulation (NEES) Tools for Isolation and Protective System (TIPS) project is intended to contribute to development of performance-based evaluation and demonstrate whether an owner can expect to recover his investment in high performance isolation over the lifetime of the building. As a result, comparative performance evaluation including life cycle cost evaluation is currently being conducted on a series of conventional and base-isolated case study buildings. However, even if alternative approaches are proven to be wise from a life cycle perspective, owners are slow to accept this and will always be concerned about initial cost. Thus, we need to carefully evaluate initial cost of protective technologies and find ways to minimize them.

Objective

The primary objective of this work is compare initial investment of three story isolated and conventional steel buildings, each considering both braced and moment resistant frames for lateral resistance. The emphasis of this project is to determine the initial cost increase for seismic isolation relative to the conventional structure. In addition, alternative design approaches and their influence on cost will be evaluated. This investigation is intended to contribute in the development of isolated structures by allowing engineers to communicate the cost of higher performance systems to their clients.

COMPARATIVE LATERAL SYSTEMS

In every structure, some members must be designed to resist and protect the structure against lateral wind and seismic forces. Shear walls, braced frames, and moment-resisting frames are the principal types of lateral-force-resisting elements (ATC, 2010). The purpose of this section is to introduce the different types of lateral systems used in the project.

The cost of the same building, configured as conventional or isolated, with different lateral systems will be compared. Steel braced and moment-resisting frames are the lateral system used in the design of theme buildings of this project. In most cases, these lateral systems were designed to satisfy minimum code requirements.

Moment Resisting Frame Systems

In moment frames, the bending of beams and columns provides the resistance to lateral forces (ATC, 2010). According to Hamburger et al (2009), "the principal advantage of moment frame structures is that they do not have structural walls or vertically oriented diagonal braces." As a result, they are more laterally flexible than shear wall and braced frames. In addition, moment resisting frames are preferred by architects for their freedom in design, since they allow open bays and unobstructed view lines.

Due to the flexibility of a moment frame, member selection is typically drift controlled and follows strong-column/weak-beam provisions. As a result, member sizes have to be increased over the strength requirement to satisfy maximum drift limits, requiring labor intensive connections. For this reason, moment frame structures can be more expensive to construct than braced frame or shear wall structures. However, moment frames usually impose smaller forces on foundations than do other structural systems, resulting in somewhat more economical foundation systems (Hamburger et al, 2009).

There are three primary types of moment frames: ordinary, intermediate and special. An intermediate moment resisting frame (IMRF) is used in low to mid-seismic areas. They are intended to withstand limited inelastic deformations in their members and connections when subjected to the forces resulting from the motions of the design earthquake (AISC, 2005). On the other hand, special moment-resisting frames (SMRF) are detailed to ensure ductile behavior of the beam-to-column joints and are normally used in zones of higher seismicity. Special detailing requirements are essential in resisting strong earthquake shaking with substantial inelastic behavior.

The following background information explains the provisions differentiating SMRF and IMRF lateral systems. Over the past 14 years, many methods have been proposed to improve the ductility of steel moment resisting frames following the unexpected brittle failures of steel moment frame connections in the Northridge Earthquake. In an SMRF building it is expected that most of the inelastic deformation will take place as rotation in beam "hinges," with some inelastic deformation in the panel zone of the column. The inelastic deformation capacity depends on the connection types used.

Beams, columns, and beam-column connections in SMRFs are proportioned and detailed to resist flexural, axial, and shearing actions that result as a building sways through multiple inelastic displacement cycles during strong earthquake ground shaking (Hamburger et al, 2009). Because of these additional requirements, SMRFs improve the inelastic response characteristics of moment frames in comparison with less stringently detailed intermediate and ordinary moment frames.

Fully restrained beam-column connections should be configured both using welded joint design and quality assurance measures, or by forcing the plastic hinge away from the column face (FEMA, 2000). According to AISC-358-Suplement 1, the latest can be done either by local reinforcement of the connection, or by locally reducing the cross section of the beam at a distance away from the connection (AISC, 2009). An effective method to improve the behavior in steel moment resisting frames is the reduced beam section (RBS) approach (FEMA, 2000).

In the RBS configuration, portions of the beam flanges at a section away from the beam end are narrowed, transferring the zone of plasticity away from the column while improving the overall ductility capacity of the beam-to-column assembly (Lee and Foutch, 2000). The typical geometry of a circular RBS is depicted in Figure 1. The flange is tapered starting at of 3/4 of the beam flange width from the face of the column over a length of ¾ of the beam depth, with a peak reduction of 50% of the flange width in the middle of the taper (Sayani et al, 2009). These connections are expected to be capable of sustaining an interstory drift angle of at least 0.04 radians. For this study, conventional moment frames are detailed as SMRFs with RBS connections.

In seismically isolated buildings, the structure above the isolation system are expected to remain essentially elastic during design level earthquakes and, therefore, the special detailing requirements of a SMRF are not required. For this study, isolated moment frames are detailed as IMRFs. The IMRF uses "welded unreinforced flange, welded web (WUF-W)" beam-column connections. These connections are expected to demonstrate an interstory drift angle of at least 0.02 radians. As shown in Figure 2, only weld metal is used to join the flanges. In addition, web joints for these connections are made with slip-critical, high-strength bolts connecting the beam web to a shear tab that is welded to the column flange (FEMA, 2000).

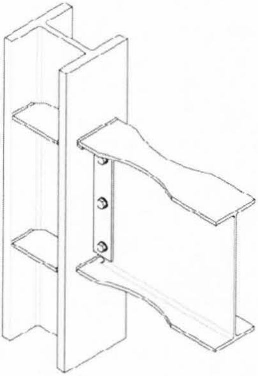


Figure 1. RBS connection sample (Reproduced from Hamburger, 2009).

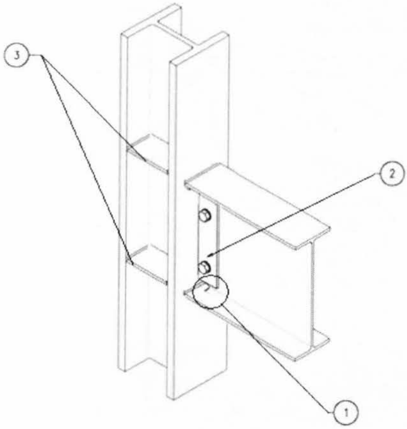


Figure 2. WUF-B connection: 1) flange weld, 2) bolted shear tab, and 3) continuity plates.

Braced frame systems

Braced frames are vertical, cantilevered trusses that are provided to a building system to resist lateral forces. They may be either concentric or eccentric in configuration. Concentric braced frames have diagonal braces located so that the centerlines of members that meet at a joint intersect at a point to form a vertical truss system that resists lateral loads along the direction of their longitudinal axis. Because of their configuration, members are mostly subjected to axial forces in the elastic range but, during a moderate to severe earthquake, these members and their connections should experience significant inelastic deformations into the post-buckling range. As a result, reversed cyclic rotations occur at plastic hinges in the same way as they do in beams and columns in moment frames (AISC, 2005).

Bracing members of this type of system can be expected to yield and buckle at story drifts of about 0.3 to 0.5 percent (AISC, 2005). In a severe earthquake, the braces could undergo post-buckling axial deformations 10 to 20 times their yield deformation. In order to minimize inelastic demands, recent seismic codes require the use of higher design loads to increase the strength and stiffness of the braces. In addition, requirements for ductility and energy dissipation capability have also been added.

According to the ASCE-07 (2005) there are two types of concentrically braced frame systems: Ordinary Concentric Braced Frames (OCBF), and Special Concentric Braced Frames (SCBF). In addition to SCBF and OCBF systems, an advanced braced frame system is used for high seismic performance, buckling restrained braced frames (BRBF).

Seismic design codes distinguished between OCBF and SCBF based on design forces and detailing requirements such as slenderness and compactness limits, brace capacity, stitch and column requirements.

Building codes have reduced the design load level for SCBF below that required for OCBF due to their strict design and detailing requirements. SCBF were developed to exhibit stable and ductile behavior when subjected to high energy demands imposed by a major earthquake. They have lower required base-shear capacity and are expected to achieve stable hysteretic behavior in the post buckling range to accommodate cyclic excursions with resisting forces near yield capacity of the braces (SEAOC, 2008).

Code regulations introducing SCBFs order to improve the post-buckling behavior of concentric braced frames, required braces to be selected from seismically compact sections, closer spacing between stitches, and special design and detailing of connections (Goel, 1992). According to AISC 341-05, to improve the out-of-plane stability of the SCBF bracing system, the brace connections should be designed such that the beams or columns of the frame are not interrupted "to allow for a continuous brace element". In addition, to avoid fracture due to brace rotations, these connections should have either sufficient ductility to accommodate brace-end rotations or enough strength to restrain inelastic rotation of the bracing member. In the newest seismic provisions (AISC, 2005) the slenderness (Kl/r) limit for SCBF has been increased significantly relative to previous codes.

For this study, isolated braced frames are detailed as OCBFs. As mentioned earlier, since the structure above the isolation system is expected to remain elastic, provisions that are intended to accommodate significant inelastic response are not required for their design. As result, regular provisions for OCBF are considered to be excessive since the forces on the isolated system are limited and buckling of braces is not anticipated. For instance, slenderness limitation of less than or equal to 4 $\sqrt{(E/F_y)}$ is applied to all type of braces and beams are not required to be seismically compact.

Buckling restrained braced frames are a special class of concentrically braced frames in which overall brace buckling is precluded at expected force demands of the brace (SEAOC, 2008b). Buckling-restrained braced frames are expected to withstand significant inelastic deformations when subjected to the forces resulting from the motions of the design earthquake.

Bracing members are composed of a structural steel core and a casing system that restrains the steel core from buckling (see Figure 3). The steel core is designed to resist the entire axial force in the brace and the use of splices is prohibited. Plates used in the steel core are usually at least 2 inches thick (AISC, 2005).

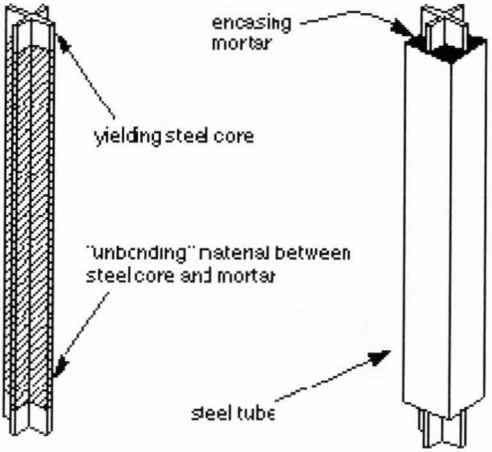


Figure 3. BRBF brace sample (Reproduced from Sabelli et al, 2003).

According to SEAOC (2008b), some of the characteristics of BRBF system include braces with positive post-yield stiffness, lack of strength degradation, and large repeatable hysteretic loops. The buckling-restraining system must prevent buckling of the steel core in BRBF for deformations corresponding to at least 2.0 times the design story drift (ASCE, 2005).

Because of their efficiency in compression, BRBs are generally not designed with inherent overstrength (SEAOC, 2008b). At interstory drifts of less than 0.50%, BRBs will experience axial yielding either in tension or in compression. In a study made by Sabelli Mahin, and Chang (2003), researchers concluded that "the behavior of the frames with the buckling-restrained braces is comparable and often better than that associated with conventional concentric braced frames and moment frames," because once BRBF's braces yield they will dissipate energy and not experience strength degradation. This means that their inelastic drifts are lower than those in a SCBF since HSS are susceptible to fracture under inelastic cycles from a design earthquake.

DESCRIPTION OF BUILDINGS

For this study, several alternative lateral systems were design for a 3-story steel building subjected to high seismicity. The building was assumed to be located in downtown Los Angeles, CA (*Lat:* 34:50 *N, Long:* 118:2 *W*) on stiff soil. In addition, it was designed for office occupancy based on the provisions of ASCE 7-05, AISC 341-05 and the 2006 IBC using the *equivalent lateral force method.*

The building has dimensions of 120 feet by 180 feet in plan, with 15 feet floor heights and 30 feet bays in each direction. A penthouse with dimensions of 60 feet by 30 feet is located on the roof. When the building is isolated, 6 feet of additional excavation is required to house the isolation layer. A 3-D view of the building is shown in Figure 4.

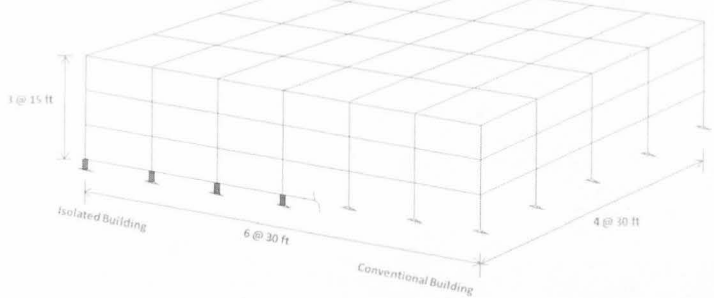


Figure 4. View in 3-D of the conventional and isolated building.

Structural systems

The structural systems for the building were designed by Forell/Elsesser Engineers in collaboration with Troy Morgan. The conventional lateral systems were designed for high ductility demands while the lateral systems of the isolated building were designed for less stringent detailing as they are expected to sustain lower ductility demands. In order to ensure proper design, the relevant code requirements for gravity, wind, and seismic demands were considered. Both minimum code complaint and higher performing lateral systems were developed for both conventional and isolated buildings.

Lateral resistance is provided by either braced frames or moment resisting frames over part of the building. Beams/girders and columns were selected from standard W-shaped sections of A992 steel. Braces were selected from HSS sections made of A46 steel. These sections are consistent with the assumption of design yield strength of 50 and 46 ksi for frame members and braces, respectively.

The floor slabs consist of 2 inch steel metal deck with 3.25 inches light concrete at all levels. The steel deck and concrete slab is assumed to provide a rigid diaphragm condition. The stiff slab attracts and distributes seismic forces uniformly to lateral support. Fireproofing is applied to steel members, and retaining walls and slab of the isolation layer.

Moment resisting frame.

Three moment resisting frame lateral systems were designed for this study: two conventional and one isolated. Recall that SMRF detailing is used for conventional buildings while IMRF detailing is used for isolated superstructures. A fourth design was added by putting the code complaint SMRF on isolators and assuming IMRF connections. The following nomenclature is used through this study to identify each building. Numbers 1 through 3 designate which lateral system was used.

- MRF 1: code compliant SMRF.
- MRF_{iso} 2: code compliant isolated IMRF.
- HPMRF 3: high performance SMRF
- $HPMRF_{iso}$ 1: high performance isolated IMRF (code compliant SMRF on isolators.)

The gravity members for all moment frame buildings are the same while the lateral-force resisting elements vary for each lateral system designed. The configuration of the lateral systems is the same for all building is indicated by bold lines in Figure 5. The lateral system consists of two 5-bay perimeter moment frames in the longitudinal, and two 3-bay perimeter and two 2-bay interior moment frames in the transverse.

Table 1 lists the structural components with their respective quantities for each building based on the lateral system. The member sizes in Table 1 are an indication of self weight of the members, which is directly proportional to the construction cost of these buildings (see methodology section).

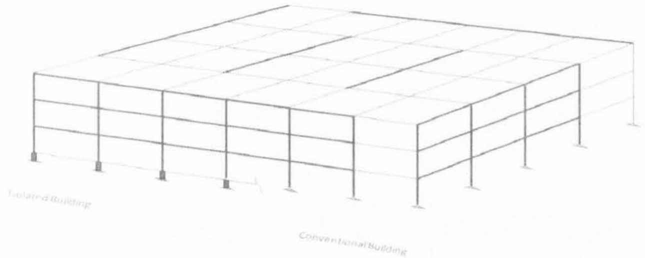


Figure 5. Moment resisting frame lateral system for conventional and isolated buildings.

Table 1.Frame members for moment resisting frame lateral systems

Component	Span [ft]	Section/ Type	Quantity			
			MRF 1	MRF_{iso} 2	HPMRF 3	HPMRF_{iso} 1
Beams and Girders	10	W14X22	72	72	72	72
	30	W16X31	59	59	59	59
	30	W21X50	12	12	12	12
	30	W18X35	139	187	139	187
	30	W18X50	4	4	4	4
	30	W18X60	-	20	-	-
	30	W18X71	4	4	4	4
	30	W24X55	24	24	24	24
	30	W24X76	16	36	16	16
	30	W24X84	-	20	-	-
	30	W24X94	-	58	-	58
	30	W27X102	20	-	-	20
	30	W30X99	-	-	-	-
	30	W33X130	20	-	20	20
	30	W33X141	20	-	-	20
	30	W36X182	-	-	40	-
Columns	45	W10X33	9	9	9	9
	11	W14X109	-	26	-	-
	34	W14X176	-	26	-	-
	11	W14X211	26	-	-	26
	34	W14X370	26	-	-	26
	11	W14X370	-	-	26	-
	34	W14X500	-	-	26	-
Connections	-	Moment	120	236	120	236

Braced frame.

Four braced frame lateral systems were designed for this study: two conventional and two isolated. The conventional buildings include an SCBF and a BRBF. Based on the building's height, the code prescribes that an isolated OCBF be designed with a reduction factor of R=1. However, an R=2 design was also considered to assess the impact of relaxing code requirements to cut costs. In addition, a fifth design was added by putting the code complaint SCBF conventional building on top of isolators but using OCBF connections. The following nomenclature is used through this study to identify each building:

- CBF 1: code compliant SCBF.
- CBF_{iso} 2 : code compliant base isolated OCBF with R=1
- CBF_{iso} 3 : base isolated OCBF with R=2
- $\text{HPCBF}_{\text{iso}}$ 1: high performance isolated OCBF (code compliant SCBF on isolators).
- BRBF: high performance buckling resisting braced frame.

The gravity members for the braced frame buildings are mostly the same in all building; however some beams and columns were designed to be collectors since they carry axial loads transferred from the braces, and thus are different from standard gravity members. In addition, the lateral-force resisting elements vary for each braced frame system designed.

The configuration of the lateral system for the CBF 1 and BRBF buildings is shown in Figure 6; where the bracing system consists of two single bay chevron braced perimeter frames in the longitudinal and transverse direction. In order to distribute overturning forces more evenly at the isolation level, the bracing in the CBF_{iso} 2 and CBF_{iso} 3 is fanned outward from the top down to the base of a 3-bay perimeter frame as shown in Figure 7.

A list of the structural components with their respective quantities for the five braced frame buildings can be found on Table 2. This table indicates a significant number of moment connections are included in the isolated buildings. The reason behind this is that an extra floor layer was added at ground level due to the isolation layer and moment connections for all members at base level were used to rigidly tie it together directly above the isolation system.

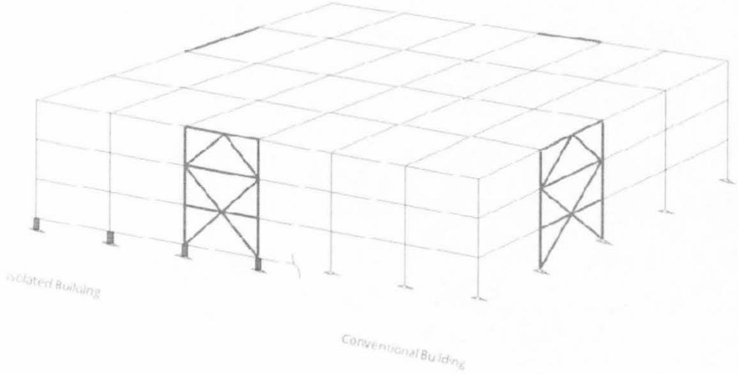


Figure 6. Braced frame lateral system for CBF 1, HPCBF$_{iso}$ 1 and BRBF.

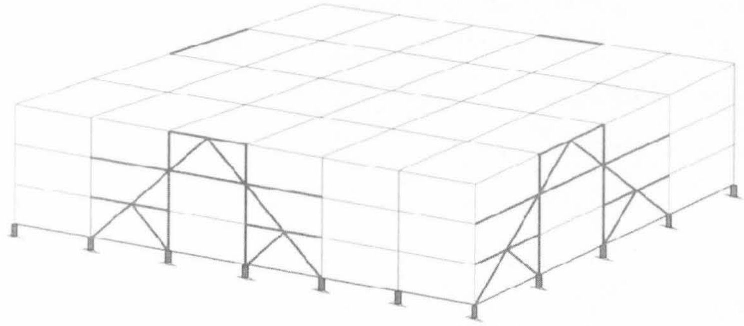


Figure 7. Braced frame lateral system CBF$_{iso}$ 2 and CBF$_{iso}$ 3.

Table 2. Frame members for braced frame lateral systems

Component	Span [ft]	Section/ Type	Quantity				
			CBF 1	$\mathrm{CBF}_{\mathrm{iso}}$ 2	$\mathrm{CBF}_{\mathrm{iso}}$ 3	$\mathrm{HPCBF}_{\mathrm{iso}}$ 1	BRBF
Beams and Girders	10	W14X22	30	-	-	30	-
	30	W16X31	65	59	59	65	65
	30	W21X50	12	12	12	12	12
	30	W18X35	139	187	187	187	139
	30	W18X50	2	16	16	2	2
	30	W18X60	-	4	4	-	-
	30	W18X71	8	8	8	8	8
	30	W18X76	-	-	-	-	12
	30	W18X97	16	-	-	16	16
	30	W24X55	24	24	24	24	24
	30	W24X76	40	48	48	40	40
	30	W24X84	-	8	8	-	-
	30	W24X94	-	58	58	58	-
	30	W27X84	4	-	-	4	-
	30	W30X99	4	-	-	4	-
	30	W36X150	4	-	-	4	-
Braces	21.21	BRB-400K	-	-	-	-	8
	21.21	BRB-500K	-	-	-	-	8
	21.21	BRB-550K	-	-	-	-	8
	21.21	HSS 6x6x0.25	-	-	8	-	-
	21.21	HSS 6x6x0.3125	-	-	8	-	-
	21.21	HSS7X7X0.5	-	8	-	-	-
	21.21	HSS8X8X0.3125	-	-	8	-	-
	21.21	HSS8X8X0.375	-	-	8	-	-
	21.21	HSS8X8X0.5	8	-	-	8	-
	21.21	HSS8X8X0.625	-	8	-	-	-
	21.21	HSS6X6X0.375	-	8	-	-	-
	21.21	HSS10X10X0.625	8	8	-	8	-
	21.21	HSS12X12X0.625	8	-	-	8	-
Columns	45	W10X33	27	35	35	27	27
	11	W12X65	-	-	-	-	8
	34	W12X120	-	-	-	-	8
	11	W14X109	8	-	-	8	-
	34	W14X176	8	-	-	8	-
Connections	-	Braced	48	64	64	48	48
	-	Moment	-	116	116	116	-

Foundation

The foundation system consisted of concrete spread footings designed for each building. Footing dimensions ranged in size from 12'X12'X2.5' to 6'X6'X2.5'. Footings were designed against "punching" shear, "beam" shear, and bending forces according to the ASCE 07. Steel reinforcement was placed accordingly to strengthen the footings against these undesired effects. Details of the foundation system for each lateral system are listed below:

Table 3. Footing dimensions

Footing Type	Reinforcement [lb/CY]	Section	Quantity			
			Moment Frame		Braced Frame	
			Isolated	Conventional	Isolated	Conventional
Interior	100	10'X10'X2.5'	15	15	15	-
	100	8'X8'X2'	-	-	-	15
Corner	100	8'X8'X2.5'	16	-	16	8
	100	10'X10'X2.5'	-	16	-	-
	150	12'X12'X2.5'	-	-	-	8
Edge	100	8'X8'X2.5'	4	-	4	-
	100	10'X10'X2.5'	-	4	-	-
	100	6'X6'X2'	-	-	-	4
Grade beam	-	2'X20'X2'	-	20	-	-
	-	1.5'X22'X2.5'	20	-	20	-

As can be seen, both the moment resisting and braced frame isolated buildings use with the same foundation system. A 4 inch thick slab on grade (concrete) with #4 bar located at 18 inches of center is placed at grade level.

Isolation system

The isolation devices have not been designed in detail so as to keep the study neutral with respect to isolation system. One isolator is located beneath each column for a total of 35 isolators, which rest on 3.5'X3.5'X2' pedestals. A moat cover and an 8 inch retaining wall provide an enclosed area for the isolators and other mechanical equipment and "seal" the basement section of the structure (see Figure 8).

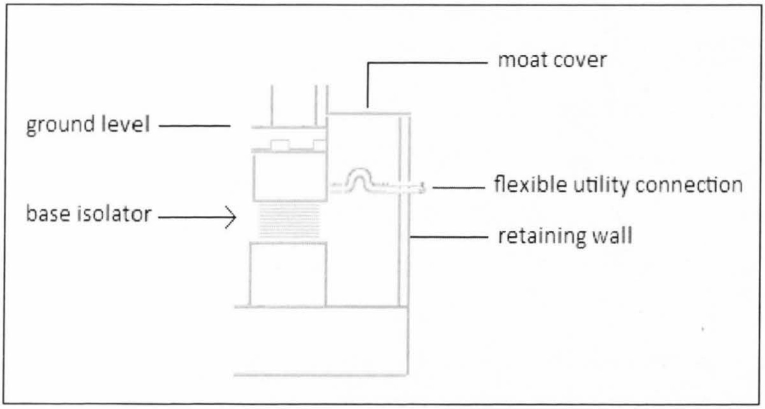


Figure 8. Foundation view of isolated structure (schematic).

Non-structural and utilities components

Non-structural components and utilities are essentially the same in every building, except for special details across the isolation interface. For this project these components were not designed in detail; and the cost estimation was based on representative quantities.

Cost estimates for the three stories buildings consider 4 entry doors to the structure, 2 circulation stairs, 4 exit stairs and 2 elevators. As an interior finish to exterior walls, gypsum board (tapped and sanded) is used while a single ply roof with insulation is used as roofing. Exterior wall framing uses 6 inch metal stud with batt insulation. Also, exterior finish consisted of metal panel with rain screen with intermittent aluminum framed windows. The interior partitions are made of metal stud and dig wall framing. Interiors doors are located every 30 ft according to code.

Fully automatic fire sprinklers and drainage systems are provided in the roof or in the isolation crawlspace. In addition, standard variable air volume (VAV) ventilation system and a cooling tower are used across the buildings.

DESIGN INFORMATION

As mention before, the buildings were designed for a high seismicity region on site class D. The design spectral accelerations are S_{DS}= 1.47g at short period and S_{D1}= 0.74g at a 1.0 second period, respectively. All buildings were designed for occupancy category II with importance factor *I*=1 with the exception of the high performance lateral systems (HPMRF 3 and BRBF) which were designed for I=1.5.

Seismic masses were calculated from unfactored gravity loads on the floors and roof excluding live loads. Superimposed dead load includes roofing, ceilings, flooring, mechanical and electrical equipment, and partitions. A summary of the loading information provided is described below:

- Steel framing: as designed.
- Decking: 42 psf.
- Superimposed dead load: 23 psf per floor and 25 psf at roof.
- Exterior cladding load: 20 psf (including 4 ft parapet at roof level).
- Live Load: 50 psf.

The total seismic weight of the buildings, which varied for each lateral system design, is on the order of 5600 kips for conventional buildings and 7000 kips for isolated buildings.

The design displacement D_D and maximum displacement D_M of the isolators in the design and maximum considered earthquake (MCE), respectively, at the center of rigidity are computed as (ASCE, 2005):

$$D_D = \frac{g S_{D1} T_D}{4\pi^2 B_D} \quad (1)$$

$$D_M = \frac{g S_{M1} T_M}{4\pi^2 B_M} \quad (2)$$

where T_D and T_M are effective isolation periods, B_D and B_M are coefficients that modify the spectrum for damping, and S_{D1} and S_{M1} are 1 second spectral accelerations for the corresponding events.

Target values of T_M= 3.07 sec and effective damping ratio β_M= 16% were chosen for the MCE, while design values T_D and β_D were determined by iteration. Based on the design spectral accelerations, the design displacement D_D= 12.7 in for the design earthquake at an effective period T_D= 2.77 sec and an effective damping ratio β_D= 24.2%, and MCE displacement D_M= 24.3 in. The total isolator displacement in the MCE (including amplification due to torsion) is 29.4 in.

The period of the conventional buildings, upon which design forces were based, were estimated using equation 12.8-7 of ASCE-7. The force reduction factor and drift limits of each building were taken from table 12.2-1 and 12.12-1 of ASCE 7-05, respectively. A summary of the design information can be found in Table 4.

As seen from Table 4, the force reduction factor (R) varies depending on the lateral system. Isolated buildings are generally designed for 3/8 of the prescribed R of the lateral system with an upper bound of 2. In addition, conventional buildings were designed for drift limits of Δ = 2.5%, while the isolated buildings and high performance buildings were designed for a drift limit of $\Delta = 1.5\%$. Complete characterization data for HPMFiso 1, CBFiso 3, and HPCBFiso 1 is not available.

Table 4. Design information for each building

Component		**Design Information**					
		T_{code}	T_{model}	**R**	**I**	V/W_{eff}	**Drift Limit**
Moment Frame	**MRF 1**	0.59	0.88	8	1	0.157	2.5%
	MRF_{iso} 2	2.77	3.23	1.67	1	0.106	1.5%
	HPMRF_{iso} 1	2.77	-	-	1	-	1.5%
	HPMRF 3	0.59	0.72	8	1.5	0.236	1.5%
Braced Frame	**CBF 1**	0.35	0.43	6	1	0.244	2.5%
	CBF_{iso} 2	2.77	3.12	1	1	0.173	1.5%
	CBF_{iso} 3	2.77	-	2	1	0.087	1.5%
	HPCBF_{iso} 1	2.77	-	-	1	-	1.5%
	BRBF	0.35		7	1.5	0.314	1.5%

COST ESTIMATING

Cost estimating is the process of developing a "well-formulated prediction" of quantities, price of resources, and probable construction cost required by the scope of an asset investment of a specific project. Unit rates are based on historical data and discussions with contractors and subcontractors. As a prediction, an estimate must address risks and uncertainties.

Cost estimates are prepared by professionals known as costs estimators and they usually have an engineering or architectural background (Butcher, 2003). An estimator should be qualified based on his/her experience. Cost estimating can be a laborious process and is often weighed down when important cost considerations are missed (SPAR Associates, 2002). Even though the theory of estimating is important, a good cost estimator also requires experience with the construction industry and actually quantifying the effort required to produce work (Butcher, 2003). Detailed information about a project is not always available, and in this case greater experience is needed.

A project budget generally includes the total construction cost as well as the "soft costs" and non-construction related fees that are estimated as a percentage of the construction cost. Cost estimates are project and owner specific and usually involve the various design stages of the project. There are two types of cost estimates: conceptual and detailed estimates.

A conceptual estimate is often completed before the actual design of a facility has been developed. According to Butcher (2003), the conceptual cost estimate is a tool for determining required initial capital or funding and to weigh the needs of a project. Since the owner is interested in achieving the lowest possible overall project cost that is consistent with his/her investment objectives, this type of estimate is very important to him/her.

In the detailed cost estimate, the cost estimator works together with the design team to evaluate decisions made throughout the design phases against the conceptual model. Here the estimate is prepared by breaking down the components of the building or work at hand in an orderly and logical basis, determining the cost of each item from experience, and summing to arrive at a total (Butcher, 2003).

Methodology

The initial cost of these buildings was computed with the help of Mr. Peter Morris, a professional cost estimator. A detailed estimation approach was used to determine the budget and predict the initial cost of each theme building in this project. The cost estimates produced for this study represent probable construction cost based on Morris' best judgment and experience in the construction industry. The estimates are developed with reference to fair market prices for mid-2008. As a result, the cost estimator has no control over the cost of labor, material, equipment, market conditions at the time of bid, among others conditions. The accuracy of the estimates depend on various external factors, but are in general expected to be within 5% of the average bid (Butcher, 2003; Popescu, 2003). The estimates are expected to capture the relative cost differences between different design options to greater accuracy than the absolute cost.

The cost estimate of structural components is generally based on quantities provided in the drawings or specifications. To complete the estimate, all dimensions and quantities of the materials used (such as steel, concrete, and building area) were taken from the drawings (see appendix A), and the perimeter and areas of the buildings were calculated. The cost of moment and brace connections were estimated from representative connection details since the connections were not designed in detail. The cost of non-structural items could not be determined from the design drawings because architectural details were not provided. Quantities of such components were estimated based on Morris' experience.

Morris provided the prices of the components/materials used. Such prices are based on unit volume, area or weight of raw materials (Table 5). Pricing units include cubic yard (CY), square feet (SF), linear feet (LF), tons (TN), each (EA), and lump sum (LS). Cubic yard units are primarily used for items in the foundation system based on volume such as excavation. Square ft units are used for items based on area such as partition walls, floors, and ceilings. Linear feet apply to items that were measured in a line such as moat cover. The cost of beams and columns were computed using unit weight costs. Some items, such as isolators, were based on a cost per individual item. Finally, a composite rate or LS applies when the entire cost of implementing the item is based on a fixed cost rather than a unit rate. Certain costs related to seismic isolation were represented as LS premiums.

Table 5. Cost estimate unit rate

Description	Unit	Rate ($)
Foundations		
Mass excavation	CY	12.00
Shoring	SF	45.00
Structural backfill	CY	20.00
Dispose off site, avg 20 miles	CY	15.00
Excavation for spread footing	CY	30.00
Formwork	SF	12.00
Concrete	CY	350.00
Reinforcing	LB	1.20
Isolators	EA	15,000.00
Slab on grade (mud slab)	SF	4.50
Moat cover (sacrificial)	LF	75.00
Vertical/Floor and Roof Structure		
WF/HSS Steel members	TN	4,000.00
BRB braces	Kip	8.00
Braced connections		
OCBF	EA	760.00
SCBF	EA	893.33
BRBF	EA	605.00
Moment connections		
WUF-W or conventional	EA	350.00
RBS connections	EA	400.00
Fireproofing to steel	TN	450.00
Moat retaining wall, 8"	SF	45.00
Metal deck with concrete fill	SF	8.00
Fireproofing to steel at base level	TN	600.00
Exterior Cladding		
Metal stud, 6"	SF	6.00
Batt insulation	SF	1.10
Metal panel rain screen	SF	75.00
Gypsum board, taped and sanded	SF	4.00
Aluminum framed windows	SF	70.00
Entry doors	EA	3,000.00
Roofing, Waterproofing & Skylights		
Waterproofing at basement for Retaining walls and slab	SF	5.00
Single ply roof with insulation	SF	13.00
Interior Partitions, Doors & Glazing		
Metal stud and drywall framing	SF	15.00
Interior doors	EA	2,000.00
Allowance for interior glazing (3%)	SF	45.00
Floor, Wall & Ceiling Finishes		
Floor		
Lobby & primary circulation	SF	20.00
Ceramic tile	SF	15.00
Carpet/VCT	SF	5.00
Walls		
Lobby & primary circulation	LS	10,000.00
Ceramic tile	SF	15.00
Paint	SF	1.20
Ceiling		
Lobby & primary circulation	SF	25.00
Gypsum board, taped and sanded	SF	20.00
Lay in acoustic tile	SF	5.00
Function Equipment & Specialties		
Built in fittings	SF	3.00
Stairs & Vertical Transportation		
Primary circulation stairs, fully finished	-	40,000.00
Exit stairs	-	25,000.00
Pitless traction elevators	EA	120,000.00
Premium for suspended shaft at isolator plane (elevator)	EA	50,000.00
Plumbing Systems		
Domestic fixtures	EA	6,500.00
Roof drainage	SF	5.00
Basement drainage	SF	3.00
Premium for flexible connections at isolator plane	LS	45,000.00
Heating, Ventilation & Air Conditioning		
HVAC system, standard VAV, Chiller/Cooling tower	SF	45.00
Electrical Lighting, Power & Communication		
Electrical systems	SF	35.00
Premium for flexible connections at isolator plane	LS	50,000.00
Lighting for isolator crawl space	SF	2.00
Fire Protection Systems		
Fully automatic fire sprinkler system	SF	6.00
Sprinklers at isolator crawl space	SF	6.00
Premium for flexible connections at isolator plane	LS	20,000.00

Components of a cost estimate

A cost estimate is generally expressed in different formats depending on the fees that have been included.

The "Total Building and Site Cost" (TBSC) is the sum total of the raw building construction cost and site cost. These costs are expressed in a direct or absolute cost format. Total building construction cost includes parts of building systems that have a specific function like the shell, interiors, equipment and vertical transportation, and mechanical and electrical systems. The building shell is composed of the following items:

- Foundation: Basement excavation and disposal material or backfill, supporting members driven into or resting on ground such as spread footings, slabs, and tie beams.
- Vertical, floor and roof structure: All columns, beams, girders and trusses, connections, unfinished floor or roof decks, and necessary fireproofing.
- Exterior cladding: Any non-structural member, finish color or curtain wall added to enclose the building; insulation and waterproofing of the enclosing walls; all glazing, windows and doors in exterior walls.
- Roofing and waterproofing: Exterior or interior roofing insulation, skylights and roof glazing. Waterproof membranes on floors or walls and skylighting.

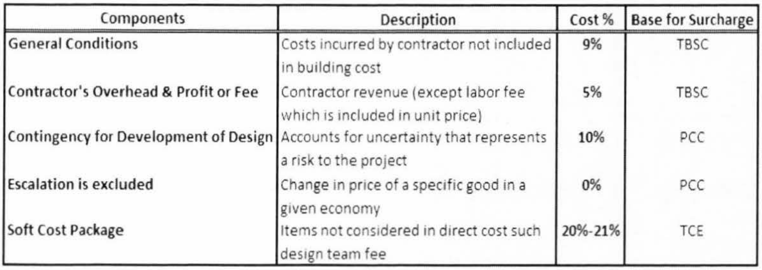
The building interior consists of interior partitions, doors, gypsum board and glazing, and floor/wall/ceiling finishes. Finishes include ceramic tile, carpets, paint and any decorations. Equipment and vertical transportation contains built-in fixed shelving, cabinetry and appliances, stairs and elevators. Finally, mechanical and electrical systems consist of plumbing, heating, and electrical and fire systems.

The contribution of site cost to TBSC includes the following subcomponents: site preparation and demolition, paving, structures and landscaping, and utilities on site. For the purpose of this study, the buildings are assumed to be located on a clean site with no acquisition cost. The costs for site paving, structures and landscaping (such as sidewalks curb and gutter) were disregarded (assumed to be zero) since they are common to all buildings. In addition, the cost of bringing utilities within 5 foot of the perimeter of the building was also assumed to be zero.

For the purpose of cost estimation the remaining cost of the building that are not a direct part of the construction and site costs are generally estimated as a percentage of the TBSC.

"Planned Construction Cost" (PCC) includes the TBSC and surcharges, such as general conditions and contractor's overhead and profit, estimated as a percentage of TBSC. "Total Cost Estimate" (TCE) includes PCC and surcharges, such as contingency for development of design and escalation, estimated as a percentage of PCC. Finally, the "Recommended budget" includes TCE and soft costs estimated as a percentage of TCE. The following table shows the surcharge rates and base cost used in calculating surcharges that were assumed for each of these items in this project.

Table 6. Surcharge percentage and based line



Components	Description	Cost %	Base for Surcharge
General Conditions	Costs incurred by contractor not included in building cost	9%	TBSC
Contractor's Overhead & Profit or Fee	Contractor revenue (except labor fee which is included in unit price)	5%	TBSC
Contingency for Development of Design	Accounts for uncertainty that represents a risk to the project	10%	PCC
Escalation is excluded	Change in price of a specific good in a given economy	0%	PCC
Soft Cost Package	Items not considered in direct cost such design team fee	20%-21%	TCE

As explain in Table 6, "General conditions", taken as 9% of TBSC, refers to the costs incurred by contractor that are not a direct result of or not included in the building cost. For example, temporary equipment or special staff that the contractor would need to do the construction. The "Contractor's overhead and profit or fee" (5% of TBSC), as its name indicates, is the contractor revenue or income beyond the cost of labor, which is included in the unit price.

"Contingency for development of design" makes an allowance for uncertainty that represents a risk to the project. Since the estimators are familiar with these risks, they can estimate the cost based on past experience, which is referred to as contingency cost. In this project, the contingency for development of design subcategory accounts for things that have been missed, such as design mistakes and changes within the scope. For this reason, the owner is recommended to budget additional funds up-front instead of scrambling for funds later. Contingency is assumed to be 10% of the PCC in this study.

Escalation is the change in price of specific goods in a given economy over a period of time. Similar to inflation, escalation is driven by changes in technology and especially in supply-demand that are specific to a service in a given economy (Hollmann, 2007). For example, the price of steel increased around 50% during 2003-2007 due to supply and demand inequity. However, since this is a comparative analysis, this risk fund is not included in the cost estimate.

Soft Costs are the items not considered in direct construction costs such as architectural, engineering, and legal fees. Soft costs are usually around 20% and no lower than 18% of the total cost estimate. The design team fee, including the architect and structural engineer, ranges from 8 to 10% of the TCE. For this study, the following percentages were assumed to calculate the soft costs.

Table 7. Soft cost items and their percentage

Components	Description	Cost %
Architect Fee	design team fee	**8%**
Structural Engineer Fee	design team fee	**1%-2%**
Conventional		1%
Base Isolated		2%
Change Order Contingency	Accounts for big changes that the owner might make	**5%**
Testing and Inspection	Weld and concrete testing, field inspection, etc	**2%**
Owner's Project Management	Owner's representation team during the design and construction process	**2%**
Move In and Commission	Team that ensures that systems are designed, installed and operating as planned.	**2%**

COMPARATIVE ANALYSIS OF INITIAL INVESTMENTS

The results of the cost estimation, using the methodology previously described are now presented. The total project costs for each building are presented in Figure 9 for moment frames and Figure 10 for braced frames. In addition, these figures illustrate the relative percent change in the total recommended budget with respect to the code compliant SMRF for moment frames (MRF 1) and SCBF for braced frames (CBF 1), which are considered to be standard or default options for a typical project.

For moment frame buildings, the MRF_{iso} 2 has an 8.3% premium relative to the MRF 1 . Moreover, $HPMRF_{iso}$ 1 and HPMRF 3 experience a 12.2% and 2.8% relative cost increase, respectively. As can be seen in Figure 10, the cost of isolated code complaint braced frame buildings (CBF_{iso} 2 and CBF_{iso} 3) increases by about 12.6% relative to CBF 1. Modifying the strength of the frame by changing the design strength from R=2 to R=1 has almost no influence on its cost. Only the R=1 design is code compliant. In addition, the cost of HPCBF 1 increases by 13.7% while the BRBF experiences a cost decrease of 0.24%.

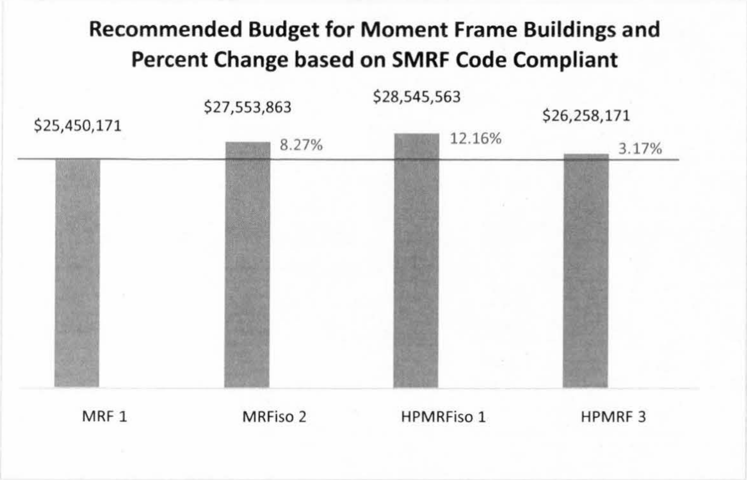


Figure 9. Budget for MRF buildings and percent change relative to MRF 1.

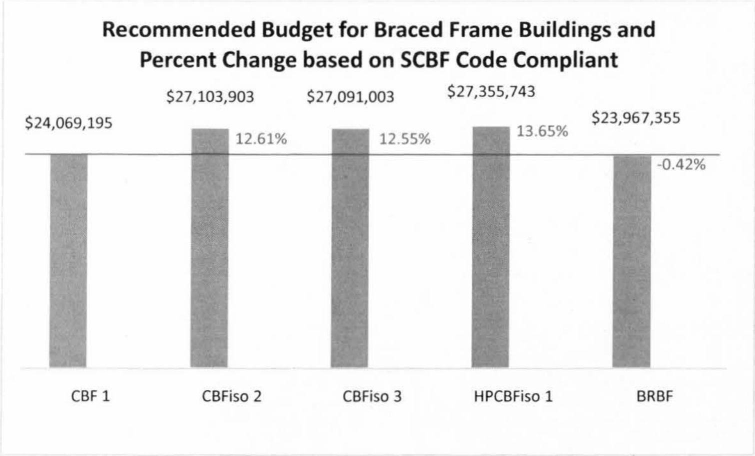


Figure 10. Budget for BF buildings and percent change relative to CBF 1.

All of these percentages are quite substantial with the exception of 0.24% decrease in BRBF. This is consistent with the prediction made by Sabelli (2007), that as the building height increases "BRBF can yield significant cost savings over conventional SCBF systems." The fact that owners can get a high performance BRBF building at no cost premium relative to an SCBF, or a high performance moment frame with only 3% cost premium relative to a conventional SMRF can be very attractive to them. However, the increase in member sizes indicates an increase in the seismic mass which results in higher acceleration and nonstructural damage.

A more detailed summary of the cost for each building is provided in Table 8. Due to the general conditions, contractor's overhead and profit, contingency for development of design, and soft cost package surcharges, the recommended budget for each project is about 50% higher than the total building and site cost (see Table 8). The only difference in the assumed surcharges is an increased design fee for the isolated building (2% versus 1% for the conventional building), which is reflected in the soft cost package. Table 9 shows the cost breakdown of the total soft cost surcharges for each building.

The costs are broken down by the categories contributing to "Total Construction and Site Cost" in Table 10. Items 1-5 contribute to the Shell, 6-7 to the Interiors, 8-9 to Equipment and Vertical Transportation, and 10-13 to Mechanical and Electrical Systems.

Table 8. Contributions to recommended budget

Components	Moment Resistant Frame				Braced Frame				
	MRF 1	MRF_{iso} 2	HPMRF_{iso} 1	HPMRF 3	CBF 1	CBF_{iso} 2	CBF_{iso} 3	HPCBF_{iso} 1	BRBF
TOTAL BUILDING & SITE	**$16,847 K**	**$18,089 K**	**$18,739 K**	**$17,381 K**	**$15,932 K**	**$17,793 K**	**$17,784 K**	**$17,959 K**	**$15,864 K**
General Conditions	$1,516 K	$1,628 K	$1,686 K	$1,564 K	$1,434 K	$1,601 K	$1,601 K	$1,616 K	$1,428 K
Contractor's Overhead & Profit or Fee	$918 K	$986 K	$1,021 K	$947 K	$868 K	$970 K	$969 K	$979 K	$865 K
PLANNED CONSTRUCTION COST	**$19,281 K**	**$20,703 K**	**$21,446 K**	**$19,892 K**	**$18,234 K**	**$20,364 K**	**$20,354 K**	**$20,554 K**	**$18,157 K**
Contingency for Development of Design	$1,928 K	$2,070 K	$2,145 K	$1,989 K	$1,823 K	$2,036 K	$2,035 K	$2,055 K	$1,816 K
Escalation is excluded	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL COST ESTIMATE	**$21,209 K**	**$22,773 K**	**$23,591 K**	**$21,881 K**	**$20,057 K**	**$22,400 K**	**$22,389 K**	**$22,609 K**	**$19,973 K**
Total Soft Cost Package	$4,241 K	$4,781 K	$4,955 K	$4,377 K	$4,012 K	$4,704 K	$4,702 K	$4,747 K	$3,994 K
RECOMMENDED BUDGET	**$25,450 K**	**$27,554 K**	**$28,546 K**	**$26,258 K**	**$24,069 K**	**$27,104 K**	**$27,091 K**	**$27,356 K**	**$23,967 K**

Table 9. Breakdown of soft cost package

Components	Moment Resistant Frame				Braced Frame				
	MRF 1	MRF_{iso} 2	HPMRF_{iso} 1	HPMRF 3	CBF 1	CBF_{iso} 2	CBF_{iso} 3	HPCBF_{iso} 1	BRBF
Architect Fee	$1,697 K	$1,822 K	$1,887 K	$1,750 K	$1,605 K	$1,792 K	$1,791 K	$1,809 K	$1,598 K
Structural Engineer Fee	$212 K	$455 K	$472 K	$219 K	$201 K	$448 K	$448 K	$452 K	$200 K
Change Order Contingency	$1,060 K	$1,139 K	$1,180 K	$1,094 K	$1,003 K	$1,120 K	$1,119 K	$1,130 K	$999 K
Testing and Inspection	$424 K	$455 K	$472 K	$438 K	$401 K	$448 K	$448 K	$452 K	$399 K
Owner Project Management	$424 K	$455 K	$472 K	$438 K	$401 K	$448 K	$448 K	$452 K	$399 K
Move In and Commission	$424 K	$455 K	$472 K	$438 K	$401 K	$448 K	$448 K	$452 K	$399 K
TOTAL SOFT COST PACKAGE	**$4,241 K**	**$4,781 K**	**$4,955 K**	**$4,377 K**	**$4,012 K**	**$4,704 K**	**$4,702 K**	**$4,747 K**	**$3,994 K**

Table 10. Contribution of individual components to TBSC

Components	Moment Resistant Frame				Braced Frame				
	MRF 1	MRF_{iso} 2	$\text{HPMRF}_{\text{iso}}$ 1	HPMRF 3	CBF 1	CBF_{iso} 2	CBF_{iso} 3	$\text{HPCBF}_{\text{iso}}$ 1	BRBF
Shell	**$6,357 K**	**$7,264 K**	**$7,913 K**	**$6,891 K**	**$5,442 K**	**$6,968 K**	**$6,959 K**	**$7,133 K**	**$5,374 K**
1. Foundations	$363 K	$1,088 K	$1,088 K	$363 K	$272 K	$1,088 K	$1,088 K	$1,088 K	$272 K
2. Vertical Structure	$983 K	$698 K	$1,143 K	$1,356 K	$341 K	$451 K	$442 K	$546 K	$300 K
3. Floor & Roof Structures	$1,757 K	$2,222 K	$2,426 K	$1,917 K	$1,574 K	$2,173 K	$2,173 K	$2,244 K	$1,547 K
4. Exterior Cladding	$2,942 K	$2,942 K	$2,942 K	$2,942 K	$2,942 K	$2,942 K	$2,942 K	$2,942 K	$2,942 K
5. Roofing, Waterproofing & Skylights	$313 K	$313 K	$313 K	$313 K	$313 K	$313 K	$313 K	$313 K	$313 K
Interiors	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**	**$3,005 K**
6. Interior Partitions, Doors & Glazing	$1,876 K	$1,876 K	$1,876 K	$1,876 K	$1,876 K	$1,876 K	$1,876 K	$1,876 K	$1,876 K
7. Floor, Wall & Ceiling Finishes	$1,128 K	$1,128 K	$1,128 K	$1,128 K	$1,128 K	$1,128 K	$1,128 K	$1,128 K	$1,128 K
Equipment and Vertical Transportation	**$637 K**	**$737 K**	**$737 K**	**$637 K**	**$637 K**	**$737 K**	**$737 K**	**$737 K**	**$637 K**
8. Function Equipment & Specialties	$217 K	$217 K	$217 K	$217 K	$217 K	$217 K	$217 K	$217 K	$217 K
9. Stairs & Vertical Transportation	$420 K	$520 K	$520 K	$420 K	$420 K	$520 K	$520 K	$520 K	$420 K
Mechanical and Electrical Systems	**$6,849 K**	**$7,084 K**	**$7,084 K**	**$6,849 K**	**$6,849 K**	**$7,084 K**	**$7,084 K**	**$7,084 K**	**$6,849 K**
10. Plumbing Systems	$640 K	$758 K	$758 K	$640 K	$640 K	$758 K	$758 K	$758 K	$640 K
11. Heating, Ventilating & Air Conditioning	$3,249 K	$3,249 K	$3,249 K	$3,249 K	$3,249 K	$3,249 K	$3,249 K	$3,249 K	$3,249 K
12. Electric Lighting, Power & Communications	$2,527 K	$2,625 K	$2,625 K	$2,527 K	$2,527 K	$2,625 K	$2,625 K	$2,625 K	$2,527 K
13. Fire Protection Systems	$433 K	$453 K	$453 K	$433 K	$433 K	$453 K	$453 K	$453 K	$433 K
Site Construction	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
14. Site Preparation & Demolition	$0	$0	$0	$0	$0	$0	$0	$0	$0
15. Site Paving, Structures & Landscaping	$0	$0	$0	$0	$0	$0	$0	$0	$0
16. Utilities on Site	$0	$0	$0	$0	$0	$0	$0	$0	$0

Appendix B contains more detailed information about these cost estimates shown in two parts: a detail sheet and a summary page. In the detail sheets, the contributions of individual line items to TBSC (Table 10) are provided in more depth. On the other hand, the summary page provides an overview of the total cost summary with a cost per square foot for each building component.

Analysis Strategy and Discussion

An objective of this comparison study is to determine how isolation affects the cost of the structure. For convenience, the total building construction cost subcategories were rearranged as follows:

- Foundation: Includes reinforced concrete spread footings and slab on grade.
- Structural Elements: Includes frame members, connections and floor slabs (with fireproofing and metal deck). The cost of the base layer directly above the isolators is excluded from this subcategory.
- Non-structural elements: Includes cladding and partitions walls, glazing, doors, fittings, etc. (Items 4-7 of Table 11)
- Utilities: Consists of function equipment, elevators, mechanical, electrical systems and plumbing. (Items 8-13)
- Isolation: Includes all additional components associated with isolation system. A key cost is the additional floor level directly above the ground level which includes structural framing, moment connections, and floor slabs.

Other components included in this category are isolation devices, basement excavation, moat cover and retaining wall, base isolator pedestals, and premiums for flexible connections.

The cost of the previous categories is shown below for both lateral systems:

Table 11. Moment resisting frame TBSC by rearranged subcategories

Components	Total			
	MRF 1	MRF_{iso} 2	$\text{HPMRF}_{\text{iso}}$ 1	HPMRF 3
Foundation	\$362,908	\$331,388	\$331,388	\$362,908
Structural Elements	\$2,739,146	\$2,038,946	\$2,688,646	\$3,273,146
Isolation	-	\$1,973,412	\$1,973,412	-
Nonstructural elements	\$6,896,285	\$6,896,285	\$6,896,285	\$6,896,285
Utilities	\$6,848,832	\$6,848,832	\$6,848,832	\$6,848,832
Total Building cost	**\$16,847,171**	**\$18,088,863**	**\$18,738,563**	**\$17,381,171**
Recommended Budget	**\$25,450,171**	**\$27,553,863**	**\$28,545,563**	**\$26,258,171**

Table 12. Braced frame TBSC by rearranged subcategories

Components	**Total**				
	CBF 1	**CBF_{iso} 2**	**CBF_{iso} 3**	**$\text{HPCBF}_{\text{iso}}$ 1**	**BRBF**
Foundation	\$271,852	\$331,388	\$331,388	\$331,388	\$271,852
Structural Elements	\$1,915,226	\$1,742,986	\$1,734,086	\$1,908,826	\$1,847,386
Isolation	-	\$1,973,412	\$1,973,412	\$1,973,412	-
Nonstructural elements	\$6,896,285	\$6,896,285	\$6,896,285	\$6,896,285	\$6,896,285
Utilities	\$6,848,832	\$6,848,832	\$6,848,832	\$6,848,832	\$6,848,832
Total Building cost	**\$15,932,195**	**\$17,792,903**	**\$17,784,003**	**\$17,958,743**	**\$15,864,355**
Recommended Budget	**\$24,069,195**	**\$27,103,903**	**\$27,091,003**	**\$27,355,743**	**\$23,967,355**

The nonstructural elements and utilities are observed to be the same for all buildings in Table 11 and Table 12. This is not surprising given that the buildings have identical plan and the price of such items has been based on area and is unaffected by the presence of isolation system. For this reason, these subcategories will not be discussed thoroughly during this analysis. However, detailed information about the costs of the individual components of these subcategories can be found in Appendix C. The remaining categories, foundation, structural components and isolation elements are discussed in turn in the following sections.

Foundation

To determine how isolation affects foundation design cost, the different components involve were analyzed and the results are shown in Table 13 and Table 14. Additional contributions to foundation cost for isolated buildings that ordinarily need not be considered for conventional buildings were omitted from consideration here, such as excavation, retaining wall, and moat covers.

Table 13. Moment Frame foundation cost

Components	Total			
	MRF 1	MRF_{iso} 2	$HPMRF_{iso}$ 1	HPMRF 3
Reinforced concrete spread footings	**\$254,620**	**\$223,100**	**\$223,100**	**\$254,620**
Excavation	\$11,490	\$9,570	\$9,570	\$11,490
Formwork	\$63,120	\$63,600	\$63,600	\$63,120
Concrete	\$134,050	\$111,650	\$111,650	\$134,050
Reinforcing	\$45,960	\$38,280	\$38,280	\$45,960
Slab on grade (mud slab)	**\$108,288**	**\$108,288**	**\$108,288**	**\$108,288**

Table 14. Braced frame foundation cost

Components	Total				
	CBF 1	CBF$_{iso}$ 2	CBF$_{iso}$ 3	HPCBF$_{iso}$ 1	BRBF
Reinforced concrete spread footings	**$163,564**	**$223,100**	**$223,100**	**$223,100**	**$163,564**
Excavation	$7,620	$9,570	$9,570	$9,570	$7,620
Formwork	$30,144	$63,600	$63,600	$63,600	$30,144
Concrete	$88,900	$111,650	$111,650	$111,650	$88,900
Reinforcing	$36,900	$38,280	$38,280	$38,280	$36,900
Slab on grade (mud slab)	**$108,288**	**$108,288**	**$108,288**	**$108,288**	**$108,288**

The cost of the slab on grade is the same for all buildings since its price is based on area rather than volume. The foundation system of all isolated buildings cost the same because the isolation system, which controls the forces transmitted to the foundation, was assumed to be the same for all cases. However, the foundation costs in conventional buildings vary among the different lateral systems. Even though the foundation system for CBF 1 and BRBF, and MRF 1 and HPMRF 3 were assumed to be same (respectively), foundation systems should probably have been redesigned for the high performance buildings since higher forces could be transmitted to the foundation.

The percent change of the total foundation costs for each moment and braced frame structures, relative to their respective code compliant conventional building, are shown Figure 11. The cost of the foundation system in an isolated moment frame building was reduced by 8.7% relative to the conventional moment frames, while the foundation costs in isolated braced frame superstructures increased by 21.9% relative to conventional braced frames.

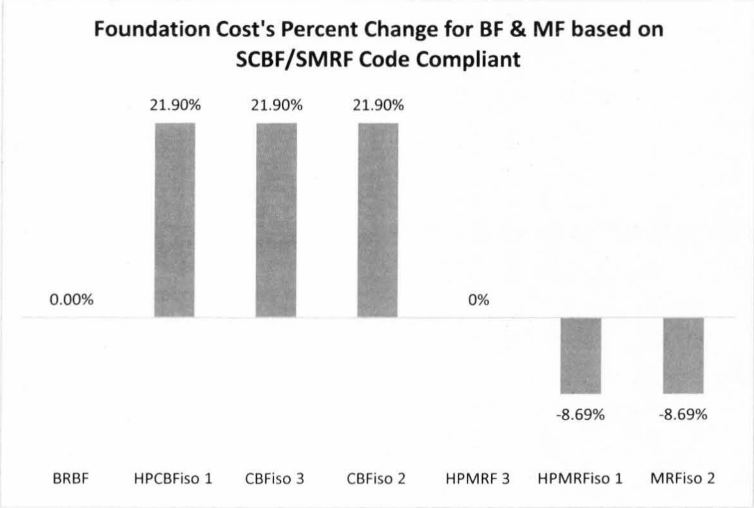


Figure 11. Percent increased of foundation system of MF/BF base on MRF 1/CBF 1.

The isolation system not only protects the structure and its contents but also allows reduced member sizes. As a result, the footing sizes and their cost are expected to be reduced. This is especially true for moment frame buildings as predicted by Hamburger et al (2009). The reinforced concrete spread footings of the isolated moment resisting frame superstructure are 12.4% less expensive than the conventional moment frame. However, the cost of the spread footing in the isolated braced frame buildings is 36.4% more expensive than in the conventional braced frame structure. One possible reason might be that MRF_{iso} 2 has a greater reduction in member sizes than

CBF_{iso} 2 or CBF_{iso} 3 did. Finally, the foundation system for all conventional moment frame ends up being 35.8% more expensive than conventional braced frame system.

Structural Elements

The structural framing costs vary for conventional and isolated buildings because the lateral systems are redesigned for different design forces and deformation limits. In this study, the superstructures of the isolated buildings were found to have lighter members than the conventional ones for minimal compliance. The high performance isolated structure member sizes were deliberately selected to be larger (the same as the code complaint) to lead to improved performance. The cost of structural elements of both moment and braced frame buildings are summarized in Table 15 and Table 16, respectively.

Table 15. Cost of moment frame structural elements

Components	Total			
	MRF 1	**MRF_{iso} 2**	**$HPMRF_{iso}$ 1**	**HPMRF 3**
Columns	**$982,500**	**$487,000**	**$932,000**	**$1,356,300**
WF steel columns	$840,000	$400,000	$800,000	$1,176,000
Moment connections	$48,000	$42,000	$42,000	$48,000
Fireproofing to steel	$94,500	$45,000	$90,000	$132,300
Elevated floor structure	**$1,218,564**	**$1,071,714**	**$1,218,564**	**$1,343,164**
WF Structural steel	$776,000	$644,000	$776,000	$888,000
Metal deck with concrete fill	$355,264	$355,264	$355,264	$355,264
Fireproofing to steel	$87,300	$72,450	$87,300	$99,900
Roof structure	**$538,082**	**$480,232**	**$538,082**	**$573,682**
WF Structural steel	$324,000	$272,000	$324,000	$356,000
Metal deck with concrete fill	$177,632	$177,632	$177,632	$177,632
Fireproofing to steel	$36,450	$30,600	$36,450	$40,050

Table 16. Cost of braced frame structural elements

Components	**Total**				
	CBF 1	**CBF_{iso} 2**	**CBF_{iso} 3**	**HPCBF_{iso} 1**	**BRBF**
Columns	**\$341,030**	**\$239,990**	**\$231,090**	**\$334,630**	**\$299,890**
WF steel columns	\$268,000	\$172,000	\$164,000	\$268,000	\$156,000
RB braces	-	-	-	-	\$92,800
Braced connections	\$42,880	\$48,640	\$48,640	\$36,480	\$29,040
Fireproofing to steel	\$30,150	\$19,350	\$18,450	\$30,150	\$22,050
Elevated floor structure	**\$1,062,814**	**\$1,040,564**	**\$1,040,564**	**\$1,062,814**	**\$1,053,914**
WF Structural steel	\$636,000	\$616,000	\$616,000	\$636,000	\$628,000
Metal deck with concrete fill	\$355,264	\$355,264	\$355,264	\$355,264	\$355,264
Fireproofing to steel	\$71,550	\$69,300	\$69,300	\$71,550	\$70,650
Roof structure	**\$511,382**	**\$462,432**	**\$462,432**	**\$511,382**	**\$493,582**
WF Structural steel	\$300,000	\$256,000	\$256,000	\$300,000	\$284,000
Metal deck with concrete fill	\$177,632	\$177,632	\$177,632	\$177,632	\$177,632
Fireproofing to steel	\$33,750	\$28,800	\$28,800	\$33,750	\$31,950

The cost of the metal deck with concrete fill in the floors and roof of all buildings are the same.

The percent difference of the structural components between each moment and braced frame structures, relative to the respective code compliant conventional building, are shown in the Figure 12. The cost of structural elements was reduced by 0.33% to 9.46% in the braced frame structures. On the other hand, the cost of structural elements in the HPMRF 3 increased by 19.5% (relaive to MRF 1), while the cost of structural elements in MRF_{iso} 2 and HPMRF_{iso} 1 reduced by 25.6% and 1.8% respectively.

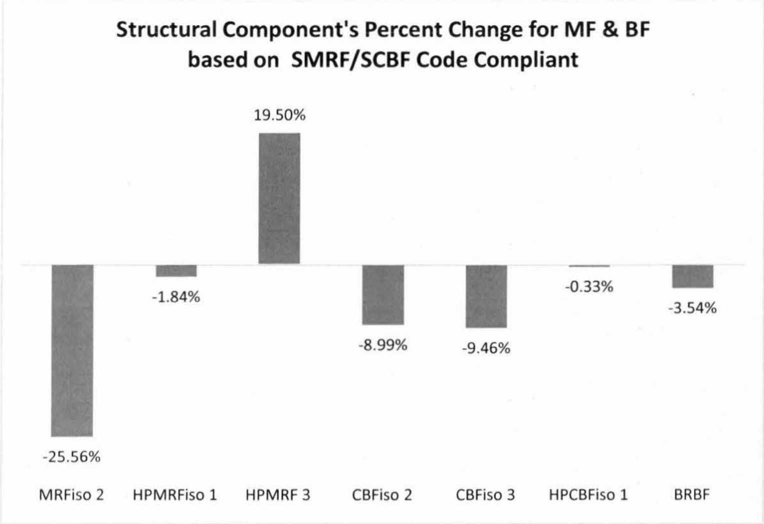


Figure 12. Percent change in structural components of MF/BF base on MRF 1/CBF 1.

Relative to MRF 1, the structural framing with fireproofing of the MRF_{iso} 2 and $\text{HPMRF}_{\text{iso}}$ 1 is $694,200 and $44,500 less expensive respectively. However, the HPMRF 3 structural components ended up being $534,000 more expensive. The $\text{HPMRF}_{\text{iso}}$ 1 ended up costing less because of a difference in length of the first floor columns. In addition, the moment connection unit cost for isolated moment frame building is $350 while for conventional is $400, which led to a $6,000 reduction in connection for isolated IMRF buildings. As mentioned earlier, RBS connections require more detailing than WUF-W connections for this reason their cost is higher.

For the braced frame buildings, relative to CBF 1, the structural framing with fireproofing of the CBF_{iso} 2, CBF_{iso} 3, and BRBF, is \$360,656, \$351,756, and \$465,056, respectively, less expensive than the conventional code compliant structure. The moment connection unit cost for CBF 1 is \$5,760 cheaper than CBF_{iso} 2 and CBF_{iso} 3. This is due to the layout of the CBF_{iso} 2 and CBF_{iso} 3 which have more braces than CBF 1. Also, the $\text{HPCBF}_{\text{iso}}$ 1 and BRBF connections cost \$6,400 and \$13,840 less than those for CBF 1. Therefore, there is a significant saving in BRBF connections since they are less expensive than those in CBF 1.

A graphical illustration of the relative costs of structural elements is given in Figure 13.

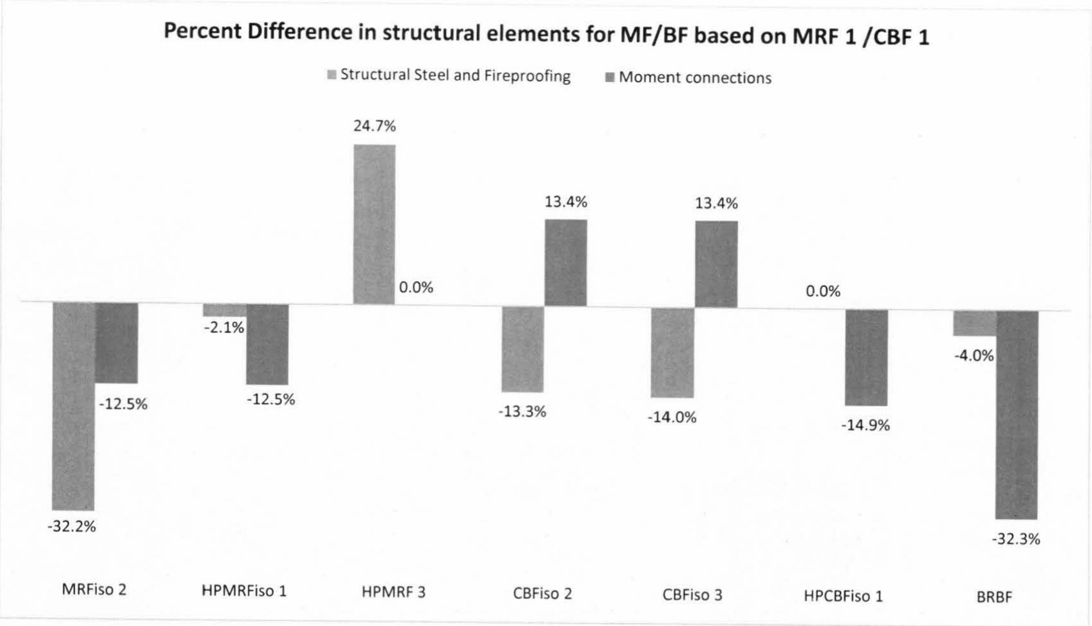


Figure 13. Percent change in structural elements for MF/BF based on MRF 1/CBF 1.

Isolation

The basic cost of the isolation layer, which is essentially the same for all isolated buildings is determined next. The cost premium seen from Figure 14, was found to be $1,973,412 which is about 11.7% and 12.4% of the total for MRF 1 and CBF 1, respectively. The majority of this cost comes from the extra base layer and the isolators. The extra structural steel, metal deck and fireproofing placed at the base/ground level costs $669,832 which is 45% of the isolation layer cost (Figure 14). Moreover, $525,000 (35%) was expended to buy and test the isolators. The cost of the other components is shown in Table 17.

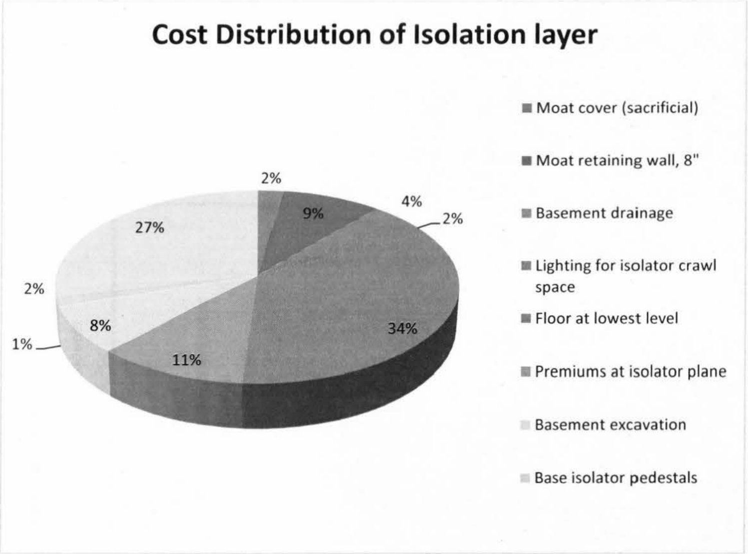


Figure 14. Cost distribution of isolation layer.

Table 17. Components of base isolation layer and their cost

Components	Total	Moment Resistant Frame		Braced Frame	
		Unit Cost ($/SF footprint area)	Unit Cost ($/SF total area)	Unit Cost ($/SF footprint	Unit Cost ($/SF total area)
Moat cover (sacrificial)	**$47,400**	**$1.97**	**$0.66**	**$1.97**	**$0.66**
Moat retaining wall, 8"	**$170,640**	**$7.09**	**$2.36**	**$7.09**	**$2.36**
Basement drainage	**$72,192**	**$3.00**	**$1.00**	**$3.00**	**$1.00**
Lighting for isolator crawl space	**$48,128**	**$2.00**	**$0.67**	**$2.00**	**$0.67**
Floor at lowest level	**669,832**	**$27.84**	**$9.28**	**$27.84**	**$9.28**
WF Structural steel	$428,000	$17.79	$5.93	$17.79	$5.93
Metal deck with concrete fill	$177,632	$7.38	$2.46	$7.38	$2.46
Fireproofing to steel	$64,200	$2.67	$0.89	$2.67	$0.89
Premiums at isolator plane	**$215,000**	**$8.93**	**$2.98**	**$8.93**	**$2.98**
Suspended shaft (elevator)	$100,000	$4.16	$1.39	$4.16	$1.39
Flexible connections (plumbing)	$45,000	$1.87	$0.62	$1.87	$0.62
Flexible connections (electric lighting)	$50,000	$2.08	$0.69	$2.08	$0.69
Flexible connections (fire protc. syst.)	$20,000	$0.83	$0.28	$0.83	$0.28
Basement excavation	**$155,900**	**$6.48**	**$2.16**	**$6.48**	**$2.16**
Mass excavation	$68,400	$2.84	$0.95	$2.84	$0.95
Structural backfill	$8,000	$0.33	$0.11	$0.33	$0.11
Dispose off site, avg 20 miles	$79,500	$3.30	$1.10	$3.30	$1.10
Base isolator pedestals	**$28,720**	**$1.19**	**$0.40**	**$1.19**	**$0.40**
Formwork	$11,760	$0.49	$0.16	$0.49	$0.16
Concrete	$11,200	$0.47	$0.16	$0.47	$0.16
Reinforcing	$5,760	$0.24	$0.08	$0.24	$0.08
Moment connections	**$40,600**	**$1.69**	**$0.56**	**$1.69**	**$0.56**
Isolators	**$525,000**	**$21.82**	**$7.27**	**$21.82**	**$7.27**

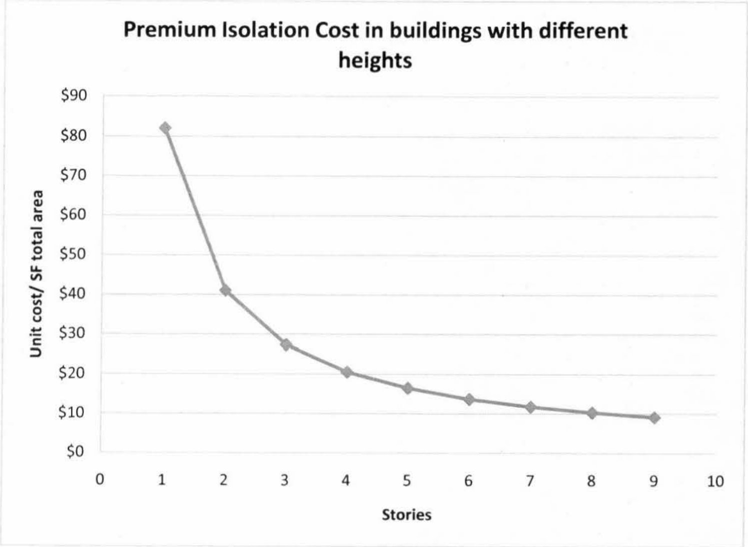


Figure 15. Premum isolation cost for buildings with "x" stories.

CONCLUSIONS

Minimum code compliant and higher performing lateral systems (both moment resistant and braced frame) were designed for a 3-story low rise steel building configured as conventional or isolated. Cost estimates of the buildings were carried out. The reported effort is part of a larger cost-benefit study for isolated steel buildings, and the purpose of this paper was to compare initial investment of 3-story conventional and isolated steel buildings and determined how isolation affected the cost of the structure. The analysis of the cost estimate has led to the following conclusions:

- Cost of isolation layer for this building was \$1,973,412 which is about 11.7% to 12.4% of the total cost for conventional code compliant. Because some of this cost was affected by reduction in structural framing and foundations, the overall cost premium ended up being 8.3% to 12.2% for a moment frame building and 12.6% to 13.7% for a braced frame building.
- Based on the building's height, the code prescribes that an isolated OCBF be designed with a reduction factor of R=1. It was found that the strength of braced frame, as affected by isolation design requirements (changing from R=2 to R=1), had almost no influence on its cost.
- Buckling restrain braced frame buildings are cheaper than the conventional code compliant braced frame system. This is consistent with the prediction made by Sabelli (2007), in which he stated that as the building height

increases "BRBF can yield significant cost savings over conventional SCBF systems."

- Owners can get a higher performance building up to 3% more than the relative cost for their respective conventional minimum code complaint. However, the increase in member sizes indicated an increase in the seismic mass which results in higher acceleration and nonstructural damage.
- The relative cost of seismic isolation, as a percentage of the total cost, may be higher in this study than for typical U.S. isolation applications because: the relative premium is greater for a short building than a tall building, and the relative premium is greater for standard classes of buildings (office, residential) than for buildings with expensive contents (hospitals, emergency response). A cost premium of 8-14% is a huge constraint for most owners, and strategies to reduce this cost should be investigated in detail.

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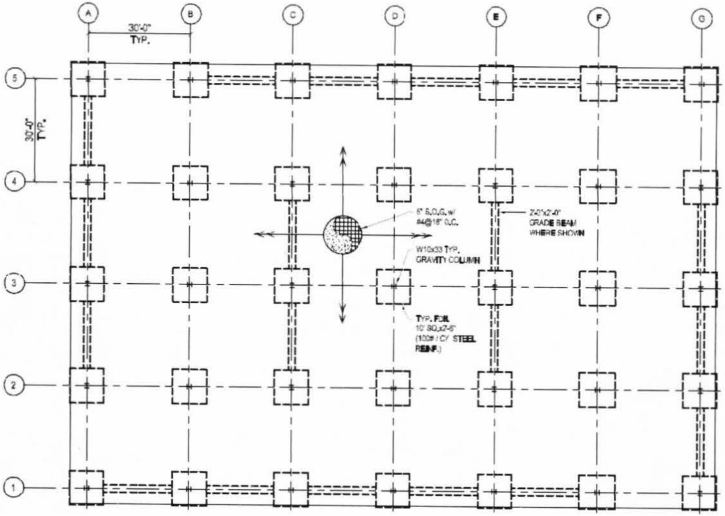
APPENDICES

Appendix A: Structural Drawings



FOUNDATION PLAN

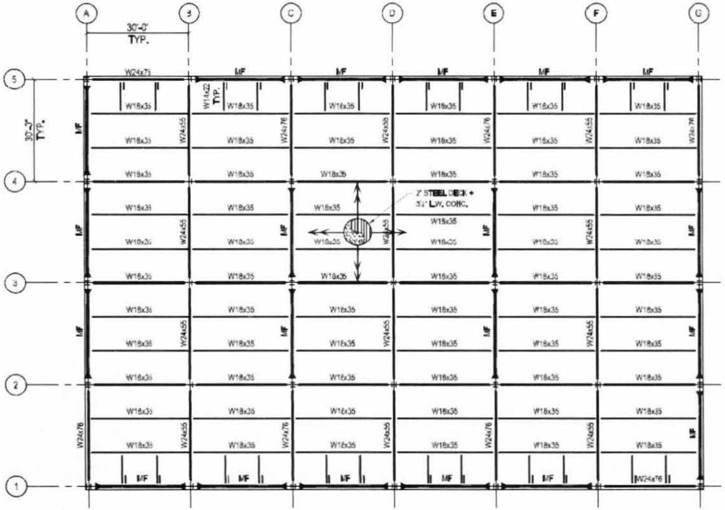
1"=20'

NEES - TIPS Research

3-STORY
SMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 1



STORY 1 & 2 PLAN

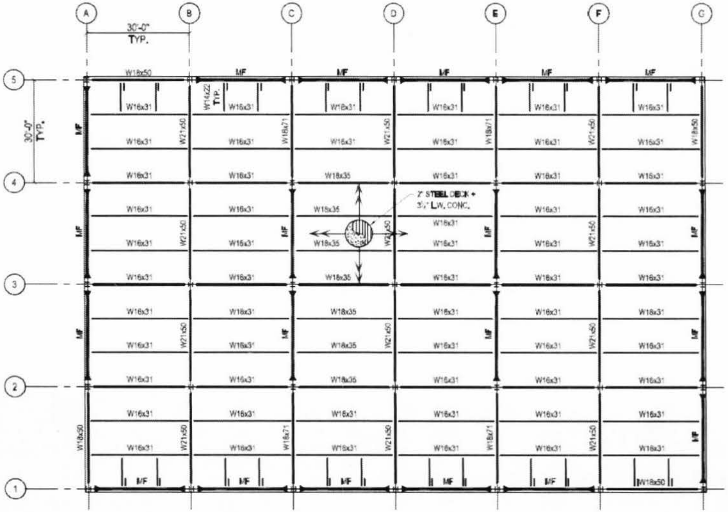
1"=20'

NEES - TIPS Research

3-STORY
SMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 2



ROOF PLAN

1"=20'

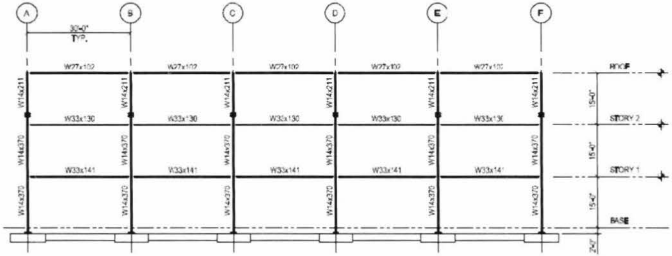
NEES - TIPS Research

3-STORY
SMRF
LOS ANGELES

DATE: JUNE 30, 2008

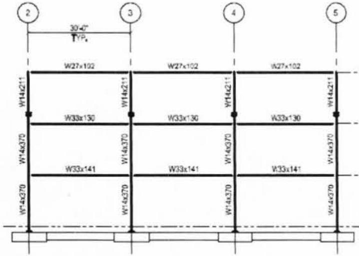
FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 3



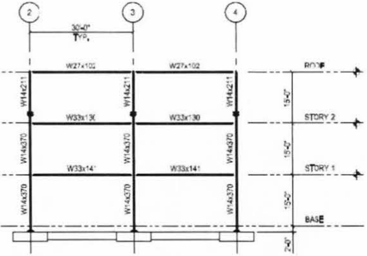
MF ELEVATION ON LINE 1 (LINE 5 SIM.)

1"=20'



MF ON LINE A (LINE G SIM.)

1"=20'



MF ON LINES C & E

1"=20'

NEES - TIPS Research

3-STORY
SMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
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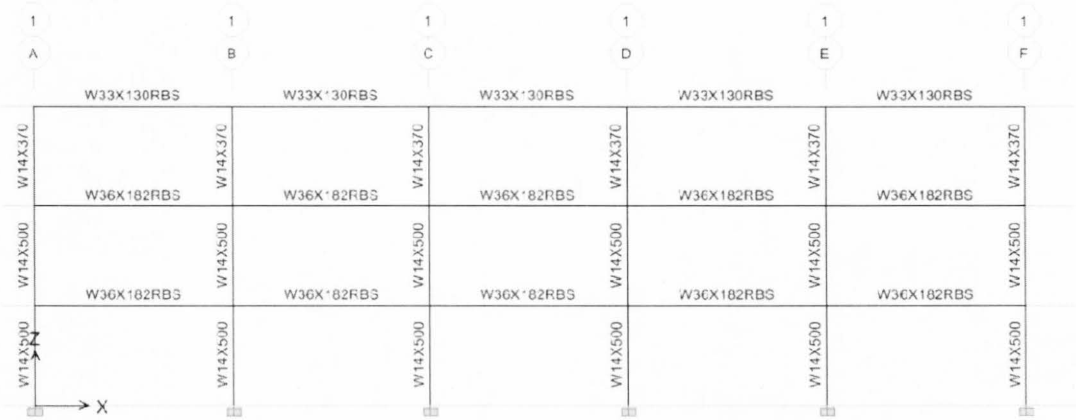
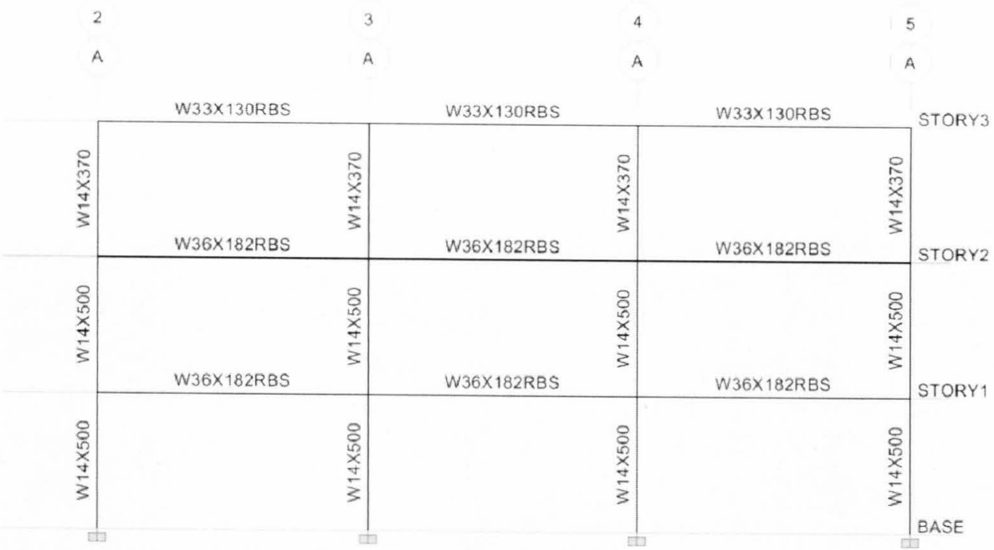
FIG. 4

High Performance Moment Frame Elevation View:

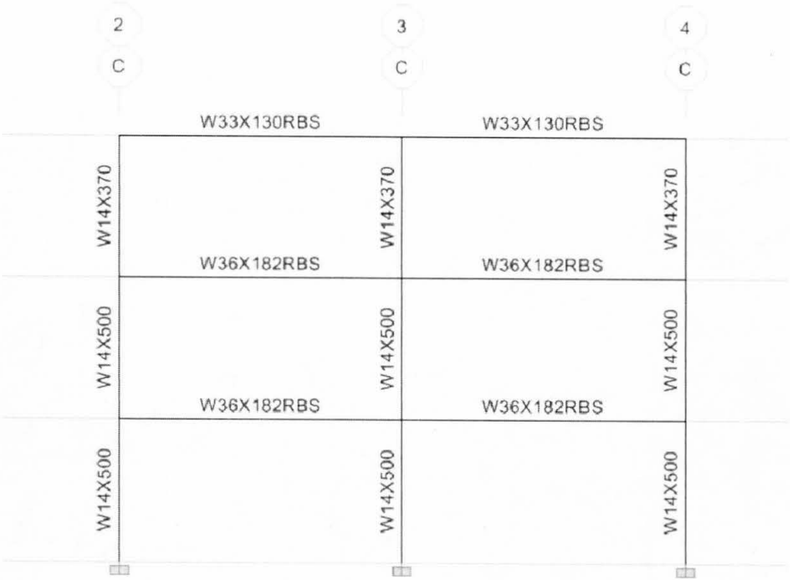
Moment Frame Elevation on Line 1 (Sim. on Line 5)

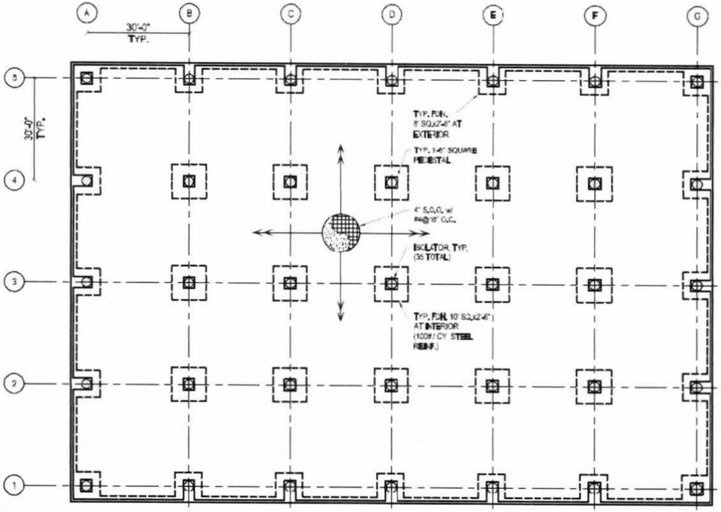


Moment Frame Elevation on Line A (Sim. on Line G)



Moment Frame Elevation on Line C (Sim. on Line E)





FOUNDATION PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED IMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
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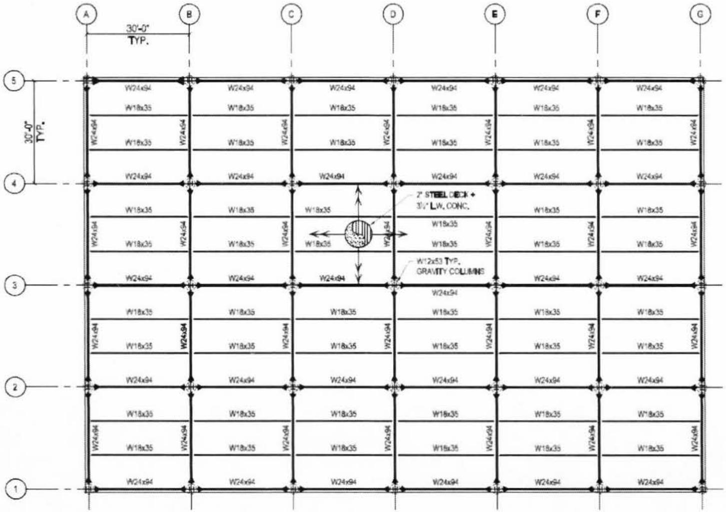
FIG. 1



BASE PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED IMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
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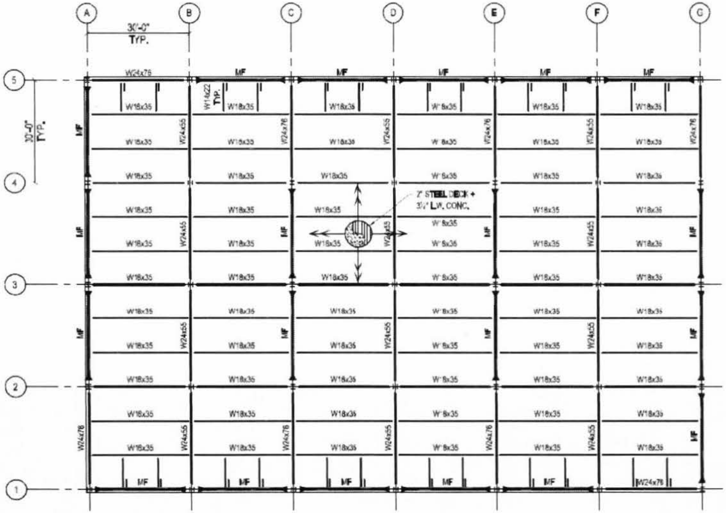
FIG. 2



STORY 1 & 2 PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED IMRF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
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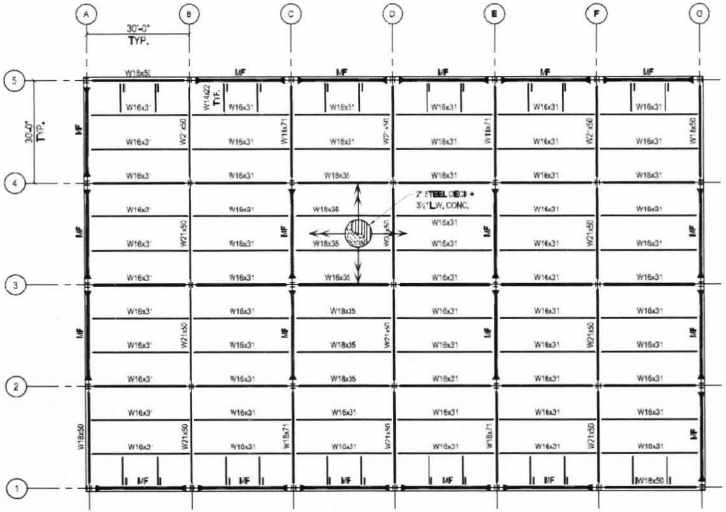
FIG. 3



ROOF PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED IMRF
LOS ANGELES **DATE:** JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
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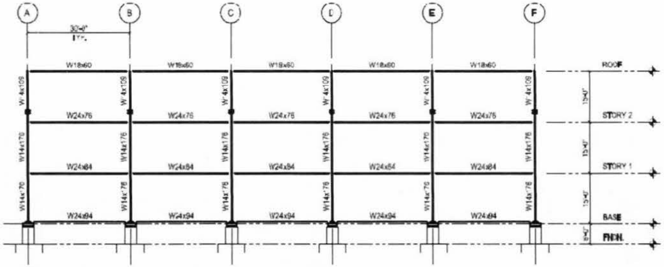
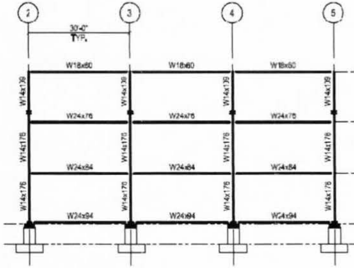
FIG. 4



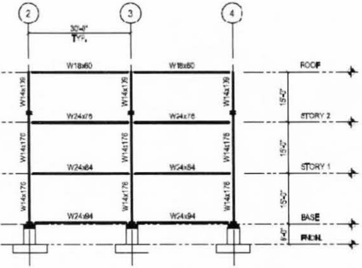
MF ELEVATION ON LINE 1 (LINE 5 SIM.)

1"=20'



MF ON LINE A (LINE G SIM.)

1"=20'



MF ON LINES C & E

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED IMRF
LOS ANGELES
DATE: JUNE 30, 2008

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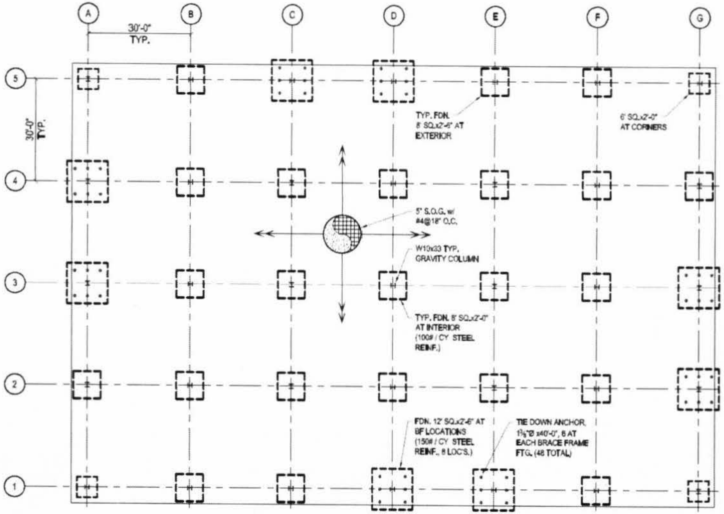
FIG. 5



FOUNDATION PLAN

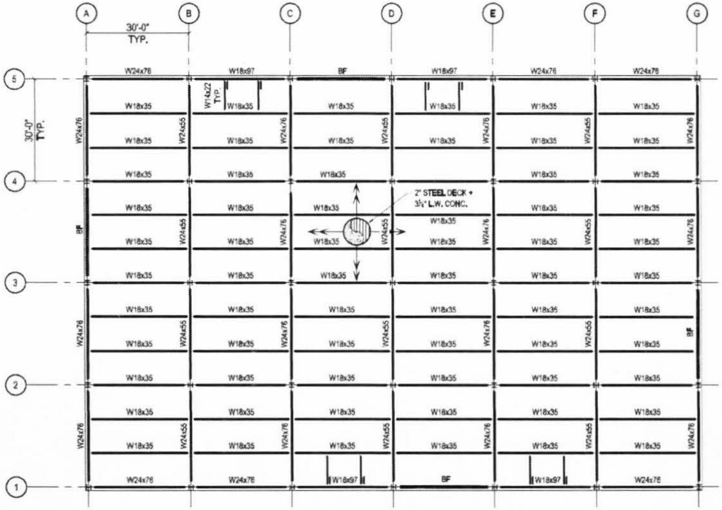
1"=20'

NEES - TIPS Research

3-STORY
SCBF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 1



STORY 1 & 2 PLAN

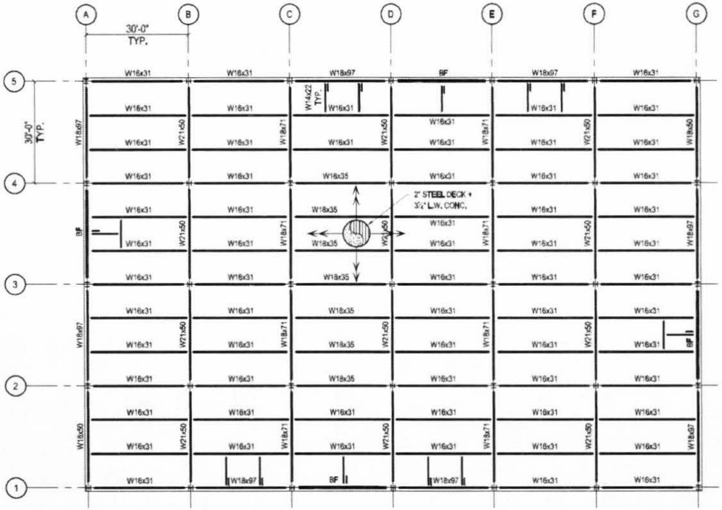
1"=20'

NEES - TIPS Research

3-STORY
SCBF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 2



ROOF PLAN

1"=20'

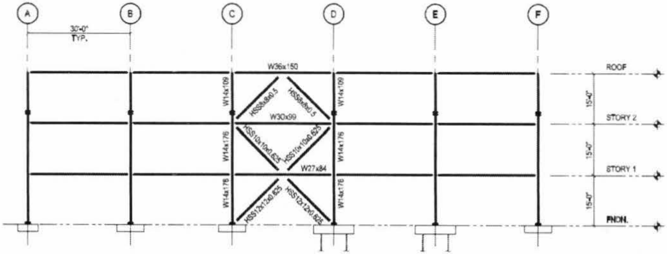
J:\Projects 2008\08.018 NEES TIPS Research\CAD\Figs SCBF.dwg, Fig 3 SCBF, 6/30/2008 2:20:45 PM
xrefs: FORELL/ELSESSER ENGINEERS, INC. - Structural Engineers

NEES - TIPS Research

3-STORY
SCBF
LOS ANGELES
DATE: JUNE 30, 2008

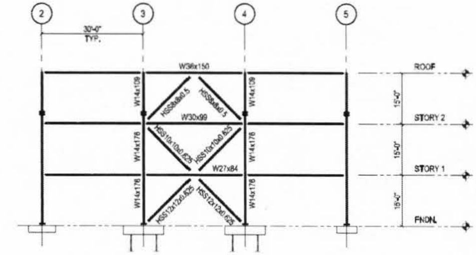
FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 3



BF ELEVATION ON LINE 1 (LINE 5 SIM.)

1"=20'



BF ON LINE A (LINE G SIM.)

1"=20'

J:\-Projects 2008\08-018 NEES TIPS Research\CAD\Figs SCBF.dwg, Fig 4 SCBF, 6/30/2008 2:20:42 PM
keith FORELL/ELSESSER ENGINEERS, INC. - Structural Engineers

NEES - TIPS Research

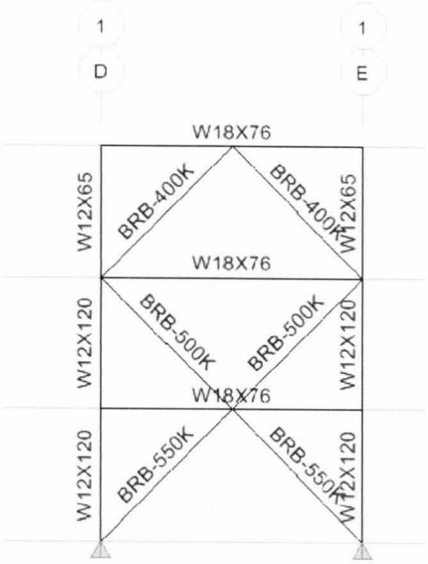
3-STORY
SCBF
LOS ANGELES
DATE: JUNE 30, 2008

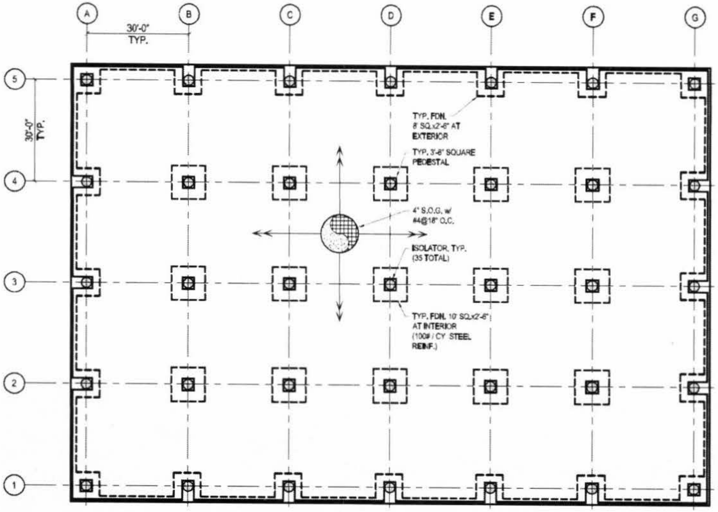
FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 4

Buckling Restrained Braced Frame Elevation view:

Brace Frame Elevation on Line 1 (Sim. on Lines 5, A, G)





FOUNDATION PLAN

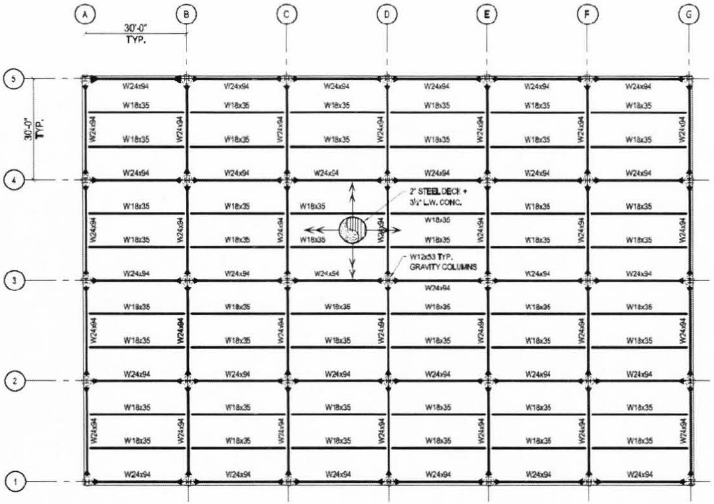
1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF
LOS ANGELES **DATE: JUNE 30, 2008**

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 1



BASE PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
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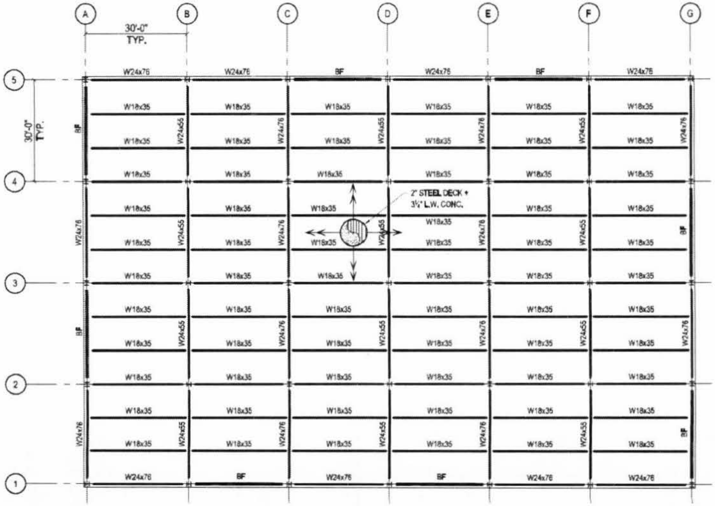
FIG. 2

J:\Projects 2008\08 018 NEES TIPS Research\CAD\Figs OCBF.dwg, Fig 2 OCBF, 6/30/2008 2:11:02 PM
karin, FORELL/ELSESSER ENGINEERS, INC. - Structural Engineers



STORY 1 & 2 PLAN

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
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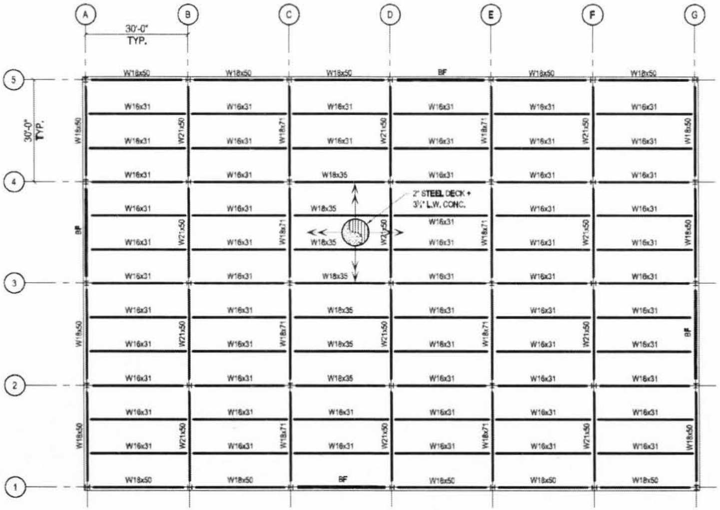
Troy Morgan, Ph.D, P.E.

FIG. 3



ROOF PLAN

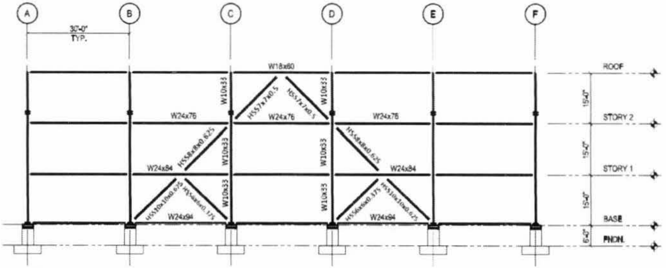
1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF
LOS ANGELES
DATE: JUNE 30, 2008

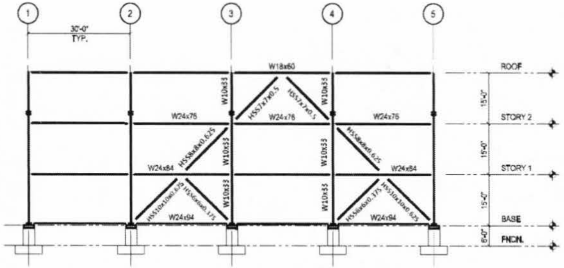
FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 4



BF ELEVATION ON LINE 1 (LINE 5 SIM.)

1"=20'



BF ON LINE A (LINE G SIM.)

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF
LOS ANGELES **DATE: JUNE 30, 2008**

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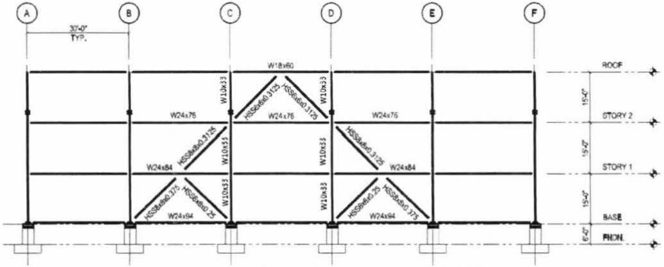
In Collaboration With
Troy Morgan, Ph.D, P.E.

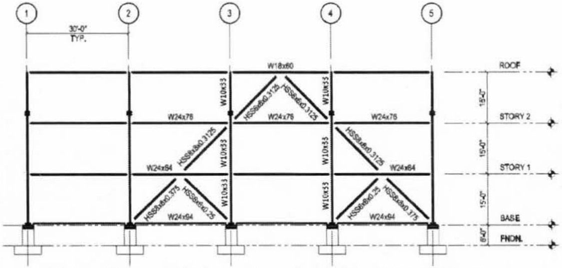
FIG. 5

Z:\Projects 2008\08.018 NEES TIPS Research\CAD\Figs OCBF.dwg, Fig 6 OCBF, 6/30/2008 2:10:54 PM
[illegible] FORELL/ELSESSER ENGINEERS, INC. - Structural Engineers



BF ELEVATION ON LINE 1 (LINE 5 SIM.)

1"=20'



BF ON LINE A (LINE G SIM.)

1"=20'

NEES - TIPS Research

3-STORY
BASE ISOLATED OCBF 2
LOS ANGELES
DATE: JUNE 30, 2008

FORELL/ELSESSER ENGINEERS, Inc.
In Collaboration With
Troy Morgan, Ph.D, P.E.

FIG. 5

Appendix B: IMRF cost estimates sample

	Quantity	Unit	Rate	Total
1. Foundations				
Basement excavation				
Mass excavation	5,700	CY	12	68,400
Shoring		SF	45.00	0
Structural backfill	400	CY	20.00	8,000
Dispose off site, avg 20 miles	5,300	CY	15.00	79,500
Reinforced concrete spread footings				
Excavation	319	CY	30.00	9,570
Formwork	5,300	SF	12.00	63,600
Concrete	319	CY	350.00	111,650
Reinforcing	31,900	LB	1.20	38,280
Base isolator pedestals				
Formwork	980	SF	12.00	11,760
Concrete	32	CY	350.00	11,200
Reinforcing	4,800	LB	1.20	5,760
Base isolator				
Isolators	35	EA	15000	525,000
Slab on grade (mud slab)	24,064	SF	4.5	108,288
Moat cover (sacrificial)	632	LF	75	47,400
				1,088,408
2. Vertical Structure				
Columns				
WF steel columns	100	TN	4000	400,000
Moment connections	236	EA	350	82,600
Fireproofing to steel	100	TN	450	45,000
Reinforced concrete walls				
Moat retaining wall, 8"	3,792	SF	45	170,640
				698,240
3. Floor and Roof Structure				
Floor at lowest level				
WF Structural steel	107	TN	4000	428,000
Metal deck with concrete fill	22,204	SF	8	177,632
Fireproofing to steel	107	TN	600	64,200

Elevated floor structure				
WF Structural steel	161	TN	4000	644,000
Metal deck with concrete fill	44,408	SF	8	355,264
Fireproofing to steel	161	TN	450	72,450
Roof structure				
WF Structural steel	68	TN	4000	272,000
Metal deck with concrete fill	22,204	SF	8	177,632
Fireproofing to steel	68	TN	450	30,600
				2,221,778

4. Exterior Cladding

Exterior wall framing				
Metal stud, 6"	27,360	SF	6	164,160
Batt insulation	27,360	SF	1.1	30,096
Exterior finish to exterior wall				
Metal panel/rain screen	27,360	SF	75	2,052,000
Interior finish to exterior walls				
Gypsum board, taped and sanded	27,360	SF	4	109,440
Glass & glazing				
Aluminum framed windows	8,208	SF	70	574,560
Doors, frames & hardware				
Entry doors	4	EA	3000	12,000
Soffits, trim & fascias				
Sunshading			0	0
				2,942,256

5. Roofing, Waterproofing & Skylights

Roofing				
Single ply roof with insulation	24,064	SF	13	312,832
				312,832

6. Interior Partitions, Doors & Glazing

Interior partitions				
Metal stud and drywall framing	86,630	SF	15	1,299,456
Doors, frames & hardware				
Interior doors	230	EA	2000	460,000
Glazing				
Allowance for interior glazing (3%)	2,600	SF	45	117,000
				1,876,456

7. Floor, Wall & Ceiling Finishes

Floor				
Lobby & primary circulation	2,000	SF	20	40,000
Ceramic tile	1,800	SF	15	27,000
Carpet/VCT	68,392	SF	5	341,960
Walls				
Lobby & primary circulation	1	LS	10000	10,000
Ceramic tile	2,700	SF	15	40,500
Paint	200,621	SF	1.2	240,745
Ceiling				
Lobby & primary circulation	2,000	SF	25	50,000
Gypsum board, taped and sanded	1,800	SF	20	36,000
Lay in acoustic tile	68,392	SF	5	341,960
				1,128,165

8. Function Equipment & Specialties

Built in fittings	72,192	SF	3	216,576
				216,576

9. Stairs & Vertical Transportation

Stairs				
Primary circulation stairs, fully finished	2	FL	40000	80,000
Exit stairs	4	FL	25000	100,000
Elevators				
Pitless traction elevators	2	EA	120000	240,000
Premium for suspended shaft at isolator plane	2	EA	50000	100,000
				520,000

10. Plumbing Systems

Plumbing fixtures, including supply and waste piping				
Domestic fixtures	80	EA	6500	520,000
Surface water drainage				
Roof drainage	24,064	SF	5	120,320
Basement drainage	24,064	SF	3	72,192
Premium for flexible connections at isolator plane	1	LS	45000	45,000
				757,512

11. Heating, Ventilation & Air Conditioning

HVAC system, standard VAV, Chiller/Cooling tower	72,192	SF	45	3,248,640
				3,248,640

12. Electrical Lighting, Power & Communication

Electrical systems	72,192	SF	35	2,526,720
Premium for flexible connections at isolator plane	1	LS	50000	50,000
Lighting for isolator crawl space	24,064	SF	2	48,128
				2,624,848

13. Fire Protection Systems

Fully automatic fire sprinkler system	72,192	SF	6	433,152
Premium for flexible connections at isolator plane	1	LS	20000	20,000
				453,152

14. Site Preparation & Building Demolition

0

15. Site Paving, Structures & Landscaping

0

16. Utilities on Site

0

SECTION 1 TITLE COMPONENT SUMMARY

Gross Area: 72,192 SF

		$/SF	
1.	Foundations	15.08	1,088
2.	Vertical Structure	9.67	698
3.	Floor & Roof Structures	30.78	2,222
4.	Exterior Cladding	40.76	2,942
5.	Roofing, Waterproofing & Skylights	4.33	313
Shell (1-5)		100.61	7,264
6.	Interior Partitions, Doors & Glazing	25.99	1,876
7.	Floor, Wall & Ceiling Finishes	15.63	1,128
Interiors (6-7)		41.62	3,005
8.	Function Equipment & Specialties	3.00	217
9.	Stairs & Vertical Transportation	7.20	520
Equipment & Vertical Transportation (8-9)		10.20	737
10.	Plumbing Systems	10.49	758
11.	Heating, Ventilating & Air Conditioning	45.00	3,249
12.	Electric Lighting, Power & Communications	36.36	2,625
13.	Fire Protection Systems	6.28	453
Mechanical & Electrical (10-13)		98.13	7,084
Total Building Construction (1-13)		**250.57**	**18,089**
14.	Site Preparation & Demolition	0.00	0
15.	Site Paving, Structures & Landscaping	0.00	0
16.	Utilities on Site	0.00	0
Total Site Construction (14-16)		**0.00**	**0**

TOTAL BUILDING & SITE (1-16)		**250.57**	**18,089**
General Conditions	9.00%	22.55	1,628
Contractor's Overhead & Profit or Fee	5.00%	13.66	986
PLANNED CONSTRUCTION COST	***June 2008***	**286.78**	**20,703**
Contingency for Development of Design	10.00%	28.67	2,070
Escalation is excluded	0.00%	0.00	0
RECOMMENDED BUDGET	***July 1 2008***	**315.45**	**22,773**
Architect Fee	8.00%	25.24	1,822
Structural Engineer Fee	2.00%	6.30	455
Change Order Contingency	5.00%	15.78	1,139
Testing and Inspection	2.00%	6.30	455
Owner Project Management	2.00%	6.30	455
Move In and Commission	2.00%	6.30	455
TOTAL SOFT COST PACKAGE	***July 1 2008***	**66.23**	**4,781**
TOTAL BUDGET	***July 1 2008***	**381.67**	**27,554**

Appendix C: Cost information of non-structural components and utilities

Non-structural components

1. Exterior Cladding

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Exterior wall framing								
Metal stud, 6"	27,360	SF	6	$164,160	27,360	SF	6	$164,160
Batt insulation	27,360	SF	1.1	$30,096	27,360	SF	1.1	$30,096
Exterior finish to exterior wall								
Metal panel/rain screen	27,360	SF	75	$2,052,000	27,360	SF	75	$2,052,000
Interior finish to exterior walls								
Gypsum board, taped and sanded	27,360	SF	4	$109,440	27,360	SF	4	$109,440
Glass & glazing								
Aluminum framed windows	8,208	SF	70	$574,560	8,208	SF	70	$574,560
Doors, frames & hardware								
Entry doors	4	EA	3000	$12,000	4	EA	3000	$12,000
Soffits, trim & fascias								
Sunshading			0	$0			0	$0

2. Roofing, Waterproofing & Skylights

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Roofing								
Single ply roof with insulation	24,064	SF	13	$312,832	24,064	SF	13	$312,832

3. Interior Partitions, Doors & Glazing

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Interior partitions								
Metal stud and drywall framing	86,630	SF	15	$1,299,456	86,630	SF	15	$1,299,456
Doors, frames & hardware								
Interior doors	230	EA	2000	$460,000	230	EA	2000	$460,000
Glazing								
Allowance for interior glazing (3%)	2,600	SF	45	$117,000	2,600	SF	45	$117,000

4. Floor, Wall & Ceiling Finishes

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Floor								
Lobby & primary circulation	2,000	SF	20	$40,000	2,000	SF	20	$40,000
Ceramic tile	1,800	SF	15	$27,000	1,800	SF	15	$27,000
Carpet/VCT	68,392	SF	5	$341,960	68,392	SF	5	$341,960
Walls								
Lobby & primary circulation	1	LS	10000	$10,000	1	LS	10000	$10,000
Ceramic tile	2,700	SF	15	$40,500	2,700	SF	15	$40,500
Paint	200,621	SF	1.2	$240,745	200,621	SF	1.2	$240,745
Ceiling								
Lobby & primary circulation	2,000	SF	25	$50,000	2,000	SF	25	$50,000
Gypsum board, taped and sanded	1,800	SF	20	$36,000	1,800	SF	20	$36,000
Lay in acoustic tile	68,392	SF	5	$341,960	68,392	SF	5	$341,960

5. Function Equipment & Specialties

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Built in fittings	72,192	SF	3	$216,576	72192	SF	3	$216,576

6. Stairs & Vertical Transportation

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Stairs								
Primary circulation stairs, fully finished	2	FL	40000	$80,000	2	FL	40000	$80,000
Exit stairs	4	FL	25000	$100,000	4	FL	25000	$100,000
Elevators								
Pitless traction elevators	2	EA	120000	$240,000	2	EA	120000	$240,000

Isolated building cost for non-structural elements $6,896,285
Fixed building cost for non-structural elements $6,896,285

Utilities

7. Plumbing Systems

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Plumbing fixtures, including supply and waste piping								
Domestic fixtures	80	EA	6500	$520,000	80	EA	6500	$520,000
Surface water drainage								
Roof drainage	24,064	SF	5	$120,320	24,064	SF	5	$120,320

8. Heating, Ventilation & Air Conditioning

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
HVAC system, standard VAV, Chiller/Cooling tower	72,192	SF	45	$3,248,640	72192	SF	45	$3,248,640

9. Electrical Lighting, Power & Communication

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Electrical systems	72,192	SF	35	$2,526,720	72192	SF	35	$2,526,720

10. Fire Protection Systems

	Isolated				Fixed			
	Quantity	Unit	Rate	Total	Quantity	Unit	Rate	Total
Fully automatic fire sprinkler system	72,192	SF	6	$433,152	72192	SF	6	$433,152

Isolated building cost for utilities $6,848,832
Fixed building cost for utilities $6,848,832