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Living Tall Buildings

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Abstract

This paper introduces a new approach to the structural design of buildings. The approach involves in-depth and sophisticated structural engineering analyses that provide reliable estimates of building performance during future severe winds and earthquakes. Credible scenarios of future severe winds and earthquakes are considered, and analyses are performed to calculate the expected monetary damage to the structural system and the building contents during the building's life. In addition, the lateral force resisting system is designed with the expectation that it will be modified to satisfy future requirements. The resulting Living Building is one with a structural system that satisfies current minimum code design criteria, meets the designers' original vision, and provides the owner with an optimized structure that continues to fulfill his or her needs well into the future.

Keywords: Living; Critical; Ductile; Damping;

1. Introduction

To the committed design professional, buildings are more than inanimate hunks of metal, glass and stone. Every building that he or she designs is like a child – a child that is conceived with a passionate vision of its form, structure and purpose; nurtured through the schematic design phase and the development of construction documents; and cared for during the labor pains of plan check corrections, requests for information, shop drawing review, and construction observation. Like children, our buildings mature, perform necessary functions during their lives, and eventually, grow old and die.

Unfortunately, the typical design process, as practiced with current codes, is incapable of providing the vehicle with which architects, engineers and building owners can consider a building's true life span and control the performance or *quality of life* that the building experiences during its existence. Building codes arbitrarily assign a design life of fifty years to tall and special buildings – a life span that is clearly insufficient for most tall and special buildings. In this predetermined period, the earthquake design goal is to prevent collapse during a major earthquake. There is only a passing consideration of the possible non-structural damage, and the true costs of repairs, disrupted operations, and demolition are never evaluated. In wind design, the goal is to prevent the yielding of a structural member in the lateral force resisting system. Optimal serviceability limit states such as human comfort are not addressed by the code. In addition, current structural design practice does not allow for the future structural modifications that are required to provide buildings with the ability to grow in a changing world and adapt to advances in technology and our improved understanding of earthquake and wind forces. As a result, the buildings we design today could become extinct during our lifetimes and turn into behemoths of a past age that are incapable of meeting the future needs of our communities.

A building, like a person, has a useful life with a finite ending point. When a building is designed to meet the minimum structural engineering code standards, which mandate that it not collapse in an earthquake, this ending point is intended to be demolition to build a new building or clear space for an alternate use. Like a person, the building will exist for a long time in a changing world, thus the role of the structural engineer must be to present the owner or developer with the option of a structural design that provides more than collapse prevention as mandated by the current building code. This optional structural design provides an improved *quality of life* for the building.

Discussed herein is a new building design scope of work that is particularly appropriate for the structural engineering design of new buildings including tall buildings, hospitals, laboratories and other special buildings. The scope is also appropriate for seismic and wind rehabilitation of existing buildings. The building that results from this new structural engineering design scope of work is called a *Living Building*. This new building design scope involves more in-depth and sophisticated structural engineering analyses so as to more accurately define the expected performance of the building during future earthquakes and severe winds.

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This extra effort will result in a reduction in the construction cost of the building as well as an increase in the confidence that the building will not collapse in a major earthquake or severe wind. These analyses consider credible scenarios of future earthquakes and severe winds, including hurricanes, during the building life and calculate for each the expected damage to the structural and nonstructural systems and the building contents. The results are used to optimize the design for a given level of acceptable damage within the available construction budget. In addition to the optimal design based on these advanced analyses, the building is also designed with the recognition that we are beginning a century of extreme technological advancement. This recognition is an essential part of the design of a *Living Building* because it expects that the building's lateral force resisting system will be modified during the life of the building. A *Living Building* design offers the owner or developer a structural system that meets current minimum code building design criteria with options for easily accommodating present or future structural modifications.

It is well understood that more detailed structural analyses will decrease construction costs by reducing unwarranted conservatism and at the same time increase confidence that the building will not collapse during a major earthquake or severe wind. The following discussion builds on this understanding by illustrating how the design of a *Living Building* improves the *quality of life* of the building by considering two important issues – future Technology Development and Nonstructural Damage caused by potential earthquakes during the expected lifetime of the building.

2. Technology Development

In many aspects of our lives when we purchase an item, we recognize that the item must be able to accommodate future changes. For example, the purchase of a watch or other expensive jewelry is usually dictated in part by the versatility of the item and its ability to accommodate fashion changes. Another example is that a computer is designed to have the memory capacity upgraded with newer and better cards. A third example is that a retirement plan must be designed to accommodate the uncertainty expected to occur in the typical 20-year retirement period.

A *Living Building* recognizes and incorporates in its design the anticipated changes in technology that are expected to occur in the design life of the building, whether it is 50 or 100 years. This technology development takes two forms: Research and New Products.

Research in the area of structural engineering continuously advances the basic accuracy with which structural engineer's model, using mathematical equations, the behavior of buildings under everyday loads and loads caused by extreme environmental events. As modeling techniques advance, structural design procedures become more accurate and optimal. This results in a cost savings not only in design fees but also in construction costs.

An example of research that has greatly benefited the structural engineering profession involves the data collected during strong earthquakes from seismic recording instruments on the ground and in buildings. This instrumentation, which began in the early 1970's, is continually increased in density with the goal of providing one or more measurements of ground shaking within one mile of most tall, hospital, or other special buildings. The seismic instrumentation network, primarily under the direction and support of the United States Geological Survey and regional organizations such as the California Integrated Seismic Network, provides valuable ground motion and building response measurements that enable structural engineers to develop more sophisticated and accurate analytical models of buildings to estimate structural performance in future earthquakes and severe wind events. Used in conjunction with post-event building damage survey data, these measurements also enable the validation of equations used to predict the structural and nonstructural damage in the building for the calculated building response.

Results from structural engineering research are continuously improving our knowledge about the seismic and wind behavior of buildings and advancing our analytical modeling methods. Transfer of these improvements into the practicing structural engineering field has been fostered through organizations such as the Applied Technology Council, the Earthquake Engineering Research Institute, the American Association of Wind Engineering, the American Society of Civil Engineers, and the Structural Engineers Associations in many states. The ever increasing number of scholarly journals, focused seminars, annual conferences, and guideline documents has dramatically increased our knowledge about structural engineering materials, building systems, and the nature of extreme loading conditions such as seismic and wind. Accompanying this increase in knowledge have been rapid advances in computer technology, facilitating the development of commercially available structural analysis and design software tools capable of addressing extremely large and complicated buildings in a relatively short time frame.

Improved knowledge and technology sometimes highlight key mistakes in the way structural engineers had been designing buildings, necessitating design code changes and an admission that we did not fully understand the behavior of certain types of building systems or components. Two recent examples of building design mistake discovery are the lack of life safety provided by non-ductile concrete frames during the 1971 San Fernando earthquake and the cracked welded connections in steel moment frames during the 1994 Northridge earthquake. A *Living Building* design incorporates the recognition that research conducted during the 50- to 100-year lifetime of a new building will likely identify mistakes we are now making in structural design or analysis. With this recognition, the *Living Building* design utilizes the most innovative lateral force resisting system type for the building that best meets the project's architectural and cost constraints but it is also adaptable to future design improvements.

Research is only one part of technology development. The other part is the increase in new commercial products that have been arriving for building applications at an unprecedented pace. This increase is a result of government-funded research of new product development in non-building, but technically similar, applications. It is also the result of imagination and creativity of individuals in a cost conscious building market. To illustrate this consider the three new products shown in Figure 1. These different products were rarely discussed twenty years ago and now are all important products in building design. Since the 1980's, starting with base isolation technology, new product development for building applications has occurred every few years. For example, base isolators were followed by viscous dampers, then most recently, by unbonded steel braces. Figure 2 shows a schematic of a building with a braced frame concept where the braces can be (a) conventional steel braces, (b) braces with viscous dampers, or (c) unbonded braces. The *Living Building* vision of design offers the owner these three options at different initial costs and different future life cycle costs, but all with the initial design approach that the braces are able to be changed in the future and "upgraded" with future new products such as active dampers.

A *Living Building* design recognizes the future benefit that new building products will provide by planning for the inclusion of these new products now and/or in the future. For example, if budgets are limited during the initial building construction phase, a somewhat standard eccentric-braced frame system can be used now but include design features to accommodate future modification. The number and location of bays with the braced frames can not only satisfy architectural constraints now, but also allow for future uncovering and modification. The future upgrade would be, for example, the introduction of either unbonded braces or dampers in the building at the pre-determined locations identified in the initial design.

3. Nonstructural Damage

None of us likes to be sick. In a similar way, a building does not like to suffer damage when an earthquake or severe wind occurs. Unfortunately, the realities of life are that we will be sick, and a building will experience levels of earthquake ground motion or severe winds that produce damage. For example, during its design life, a building can be expected to experience various sized earthquakes, depending on the seismicity of the region in which it is located. When these earthquake forces occur, the building can expect damage; however, collapse of the structure is not expected because collapse prevention is a basic mandatory design criterion. Most often building damage is to the nonstructural system; damage to the structural lateral force resisting system typically occurs only during severe ground shaking.

Nonstructural damage is damage to building elements, such as ceilings, walls, light fixtures, partition walls, contents, and HVAC systems. Considerable documentation of nonstructural damage during earthquakes has been made, dating back to the 1971 San Fernando earthquake. The 1994 Northridge earthquake showed clearly the extent and significant economic impact of this damage. Many buildings experienced little or no damage to their structural systems, but were forced to remain closed for several weeks following the earthquake due to nonstructural damage.

Nonstructural damage is the result of two fundamentally different types of building motion. One type of nonstructural damage (e.g. partition wall cracking) is a function of the relative lateral displacement between the floors of the building. Structural engineers refer to this as the interstory drift. The other and more significant type of nonstructural damage is caused by the horizontal motion of the building elements, or the acceleration of the floors. Floor acceleration, essentially how fast the building is moving back and forth, causes damage to the contents, including equipment anchored to the floors or ceilings.

A *Living Building* design considers the nonstructural damage that would be expected to occur with different lateral force resisting systems. The owner or developer is presented with several structural design options, each with an associated cost of construction as well as an expected lifetime cost associated with nonstructural damage in future earthquakes. For illustration, Table 1 shows for a 50,000 square foot hospital located in Pasadena, California the expected loss due to nonstructural damage for three different types of lateral force resisting systems, each subjected to three different levels of earthquake shaking characterized by the probability of occurring in the next 50 years. Note the magnitude of the nonstructural loss compared to the structural loss shown in the table. Note also that structural and nonstructural damage depend on both the probability of earthquake shaking and the lateral force resisting system. Thus the results in Table 1 can be used to weight the benefits in reduced expected losses over the next 50 years against the initial costs associated with each structural design option. A similar analysis can easily be done to estimate losses over time periods shorter than 50 years, for example, the next 10 or 30 years for decisions related to real estate investment.

To illustrate why nonstructural damage depends on the building's lateral force resisting system, consider Figure 3, which shows cartoons of two structures, (a) brittle and (b) ductile, being pulled by three giants. These cartoons illustrate a fundamental structural design concept that is a critical consideration for a Living Building. It is important to evaluate, for each considered lateral force resisting system, its Force - Displacement behavior, that is the relationship between the force applied to the structure and the resultant horizontal displacement of the top of the structure as shown in Figure 3(c). Note in this figure the sudden drop in the load (measured in terms of the giant's pull) that the brittle unreinforced concrete tower can carry in contrast to the much greater horizontal displacements that the ductile palm tree can experience.

Figure 4 shows the force-displacement curves for the three lateral force resisting systems included in Table 1. The existing concrete frame building can carry the lateral load imposed by an earthquake only up to the horizontal displacement that causes collapse. Thus, damage to the nonstructural components in the existing concrete frame building would be more severe in those components sensitive to interstory drift. The seismic upgrade designs using conventional braces and unbonded braces both increase the stiffness of the building, meaning that for the same applied force, the displacement is less. The conventional brace design can carry more load but with a lower threshold for maximum displacement, thus we would expect the building with the conventional brace upgrade to experience more severe nonstructural damage in components sensitive to floor accelerations, which directly relate to applied force.

Table 1. Expected Damage for 50,000SF Hospital Building in Pasadena, California

Earthquake Level (probability of occurring in next 50 years)	Loss ($x1000) due to Structural (S) and Non-structural (NS) Damage								
	Existing Concrete Frame Building			Upgraded Building (Conventional Braces)			Upgraded Building (Unbonded Braces)		
	S	NS	S+NS	S	NS	S+N	S	NS	S+NS
Occasional (50%)	283	825	1,108	59	1,308	1,367	20	276	296
Design (10%)	921	2,216	3,137	328	2,097	2,425	274	1,327	1,601
Rare (2%)	building collapses			1,043	3,923	4,966	1,000	3,301	4,301

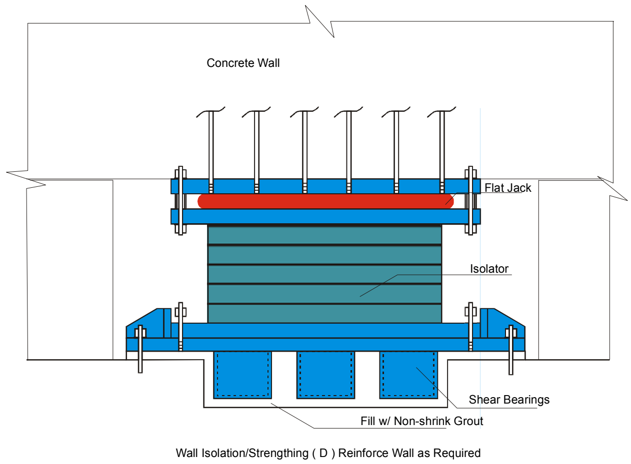


Fig. 1 (a). Base Isolator.

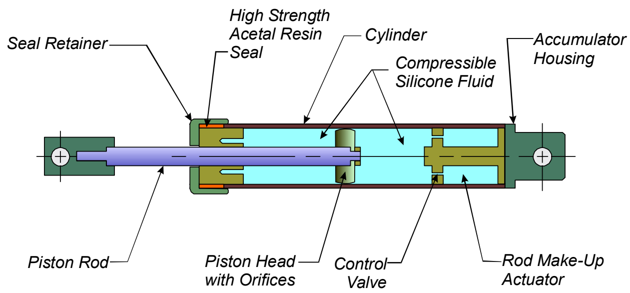


Fig. 1 (b). Viscous Damper.

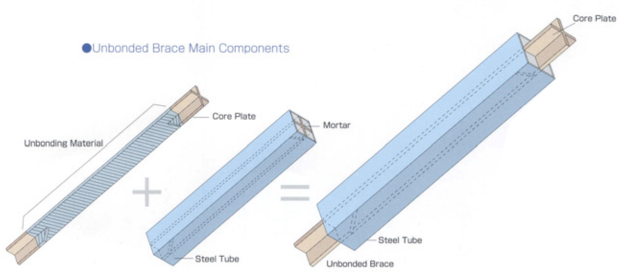


Fig. 1 (c). Buckling Reduced Braces.

Fig.1. Illustrations of New Building Products

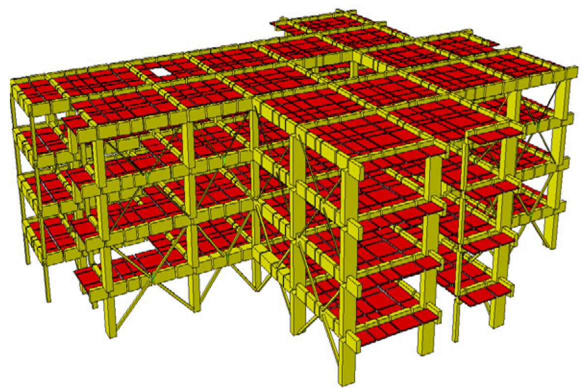


Fig.2. Schematic of Living Building design with several bracing options.

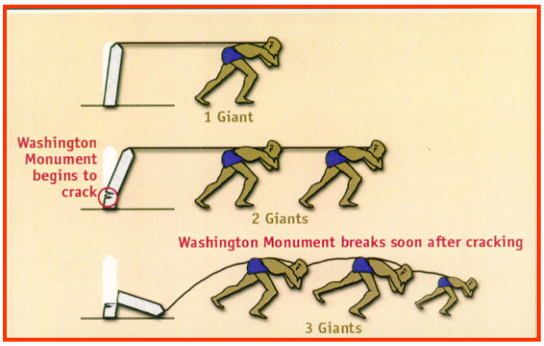


Fig.3(a). Brittle Structure

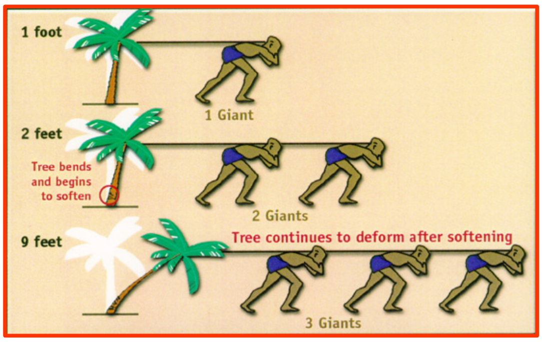


Fig. 3(b). Ductile Structure

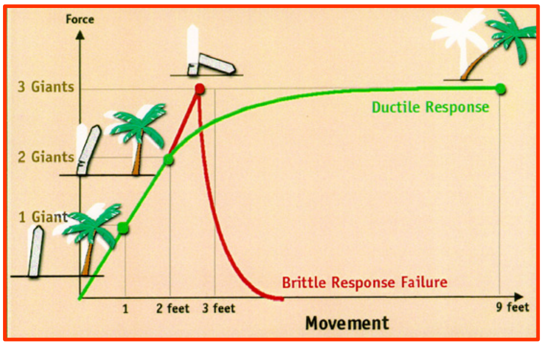


Fig. 3(c). Plot of Force Versus Displacement

Fig. (3) Illustrations of Force Displacment Behavior

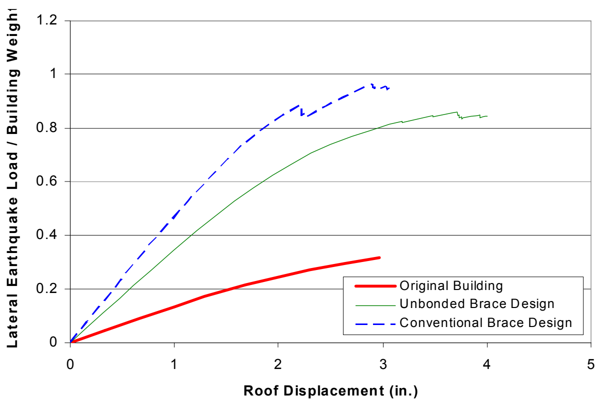


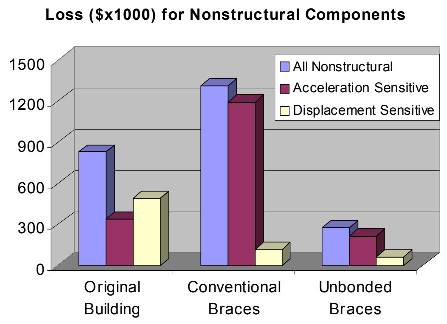
Fig.4. Force-displacement curves for three lateral force resisting systems.

4. Example Living Building Design – Tall Building

A tall building typically has a life that is at least 100 years, therefore tall buildings are especially well suited to the Living Building design approach. Significant technology changes have occurred over the past 100 years, and the same can be expected to occur over the next 100 years. For example, 100 years ago the steel moment frame was the most advanced structural system. As another example, compare the state of electronics 100 years ago to the earthquake and hurricane measurements being made today using ground and satellite instruments that help us better understand the loading on buildings. Technologies such as active dampers that are able to sense the building motion and make real time adjustments to the damping of the building to reduce the motions that the building and its occupants experience in earthquakes and severe winds are likely to become commonplace in tall buildings of the future. From an architectural standpoint, today's tall building designs must incorporate creative solutions for providing flexible space planning. For all of these reasons, tall buildings (and their occupants) are expected to benefit more than any other type of structure from a *Living Building* Design.

This section illustrates an example of a tall building *Living Building* design for a tower planned for residential space, at least in the short term. Figures 6 and 7 show plan and elevation views of this 60-story reinforced concrete building located at a site with moderate seismic risk and a potential for severe hurricane loading. The building site's natural hazard environment for earthquakes and wind is similar to the environment in Boston. The basic building design is a reinforced concrete building with shear walls resisting the lateral loads and columns and shear walls carrying the vertical loads. The floor system is a flat slab design.

A critical design consideration is the yield limit state for earthquake and wind loads. Figures 8 and 9 show the force versus displacement response of the building for the loading in the longitudinal and transverse directions for the building design with the lateral earthquake and wind loads resisted only by the shear walls. In the longitudinal direction (Figure 8) the 475-year lateral earthquake force with an R-factor of 1.0, meaning there is no reduction in the force via the R-factor to account for inelastic behavior of the lateral force-resisting system, produces a load of 3.45% of the building weight, exceeding the 500-year lateral wind force of 2.04% of the building weight. When the typical R-factor of 3.5 for a reinforced concrete shear wall system is applied to the lateral earthquake load, the force is reduced to 0.99% of the building weight and the design of the building is controlled by the wind force. In the transverse direction (Figure 9), the wind load controls the building design as the 500-year wind force always exceeds the 475-year earthquake force, even with no R-factor reduction in the earthquake load.



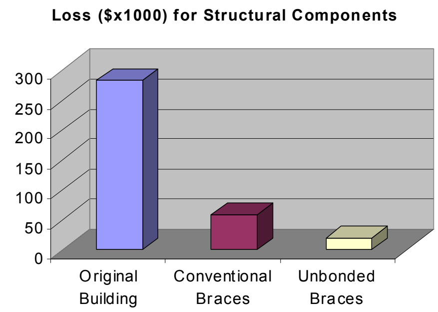


Fig. 5(a) Nonstructural Damage

Fig. 5(b) Structural Damage

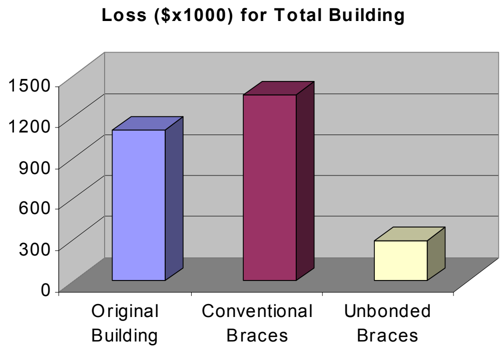


Fig. 5(c) Combined Structural & Nonstructural Damage

Fig. 5. Expected Loss for 50,000 ft2 Hospital Building in Pasadena, CA During Occasional Earthquake

This design is considered a *Living Building* design because of the intentional variation from the basic concrete shear wall building design by adding viscous dampers at the top of the building. As illustrated in Figure 7 and in more detail in Figure 10, the *Living Building* design replaces the concrete shear walls above the 50th floor with a concrete frame with steel braced frames with dampers. Viscous dampers in a "Toggle Brace" configuration can be effectively used to amplify the inter-story drift necessary to activate the dampers (McNamara 2003).

In tall building design one of the most important parameters in the design is the damping in the building. For more than 30 years, the importance of having realistic design values for damping has fostered a considerable amount of research around the world. Based on results of this research, damping values for the 60-story concrete shear wall building for the wind design limit states have been computed and are given in Table 2. The damping is relatively small for the basic concrete shear wall design and is based on research by Tamura (2000). Figure 11 shows the damping values recommended by Tamura (2000) as a function of roof drift.

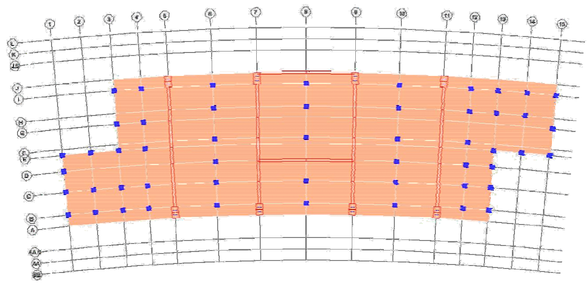


Fig. 6. Typical Floor Plan of Example Building

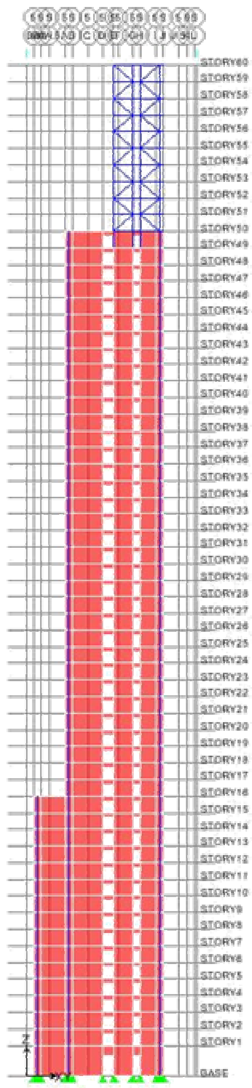


Fig. 7. Frame Line 5 of Example Tall Building

The most obvious benefit of a *Living Building* design, e.g., the addition of dampers during the initial construction phase, is the ability of the design to increase the damping in the building. An increase in damping has two major benefits. It reduces the total wind and earthquake forces on the building and it reduces the levels of motion in the building response thus providing better human comfort. Figure 12 shows how the total building forces will decrease with damping. Note that even a small increase in damping from 1% to 2% has a significant (almost 40%) impact on the floor accelerations and the human comforts limit states.

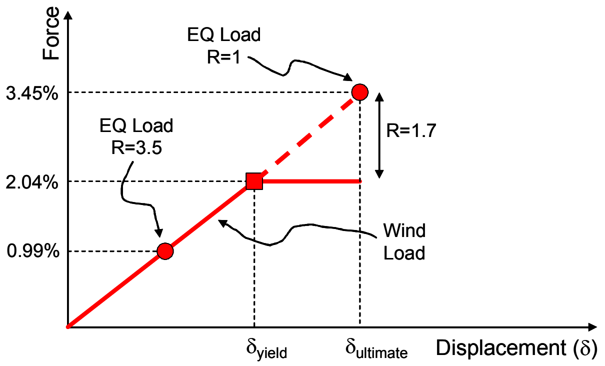


Fig. 8. Force-Displacement Response of Building in Longitudinal Direction.

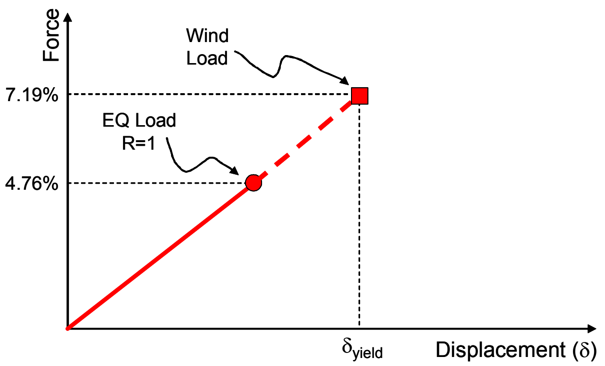


Fig. 9. Force-Displacement Response of Building in Transverse Direction.

The benefits of the *Living Building* design for this tall building are:

1. The lateral force resisting system below the 50th floor is a reinforced concrete coupled shear wall design with the same dimensions and lay-out approved by the client prior to the introduction of the *Living Building* approach.
2. The viscous-damped steel braces added above the 50th floor are in the same locations as the original shear wall locations, thus the concrete design remains a flat plate design.
3. The lateral floor acceleration level for the 10-year return period wind is significantly reduced because the viscous dampers system in the *Living Building* design can more than triple the damping of the building.
4. The base shear and overturning moment in the 100-year wind and ultimate design level wind can be significantly reduced with the *Living Building* design because it can more than double the damping in the building.
5. The seismic shear force and overturning moment are significantly reduced because of the reduction in the dead weight at the top of the building with the *Living Building* design.
6. One area of uncertainty in the wind design of the building is the potentially damaging shedding vortices that may occur due to future construction of buildings adjacent to the site. The dampers utilized in the *Living Building* can be fine-tuned in the future to address this problem if it occurs.
7. The Living Building design plans for future advances in damper technology with reduction in costs enabling the upgrade from the current viscous dampers to new active dampers at some point during the life of the building.

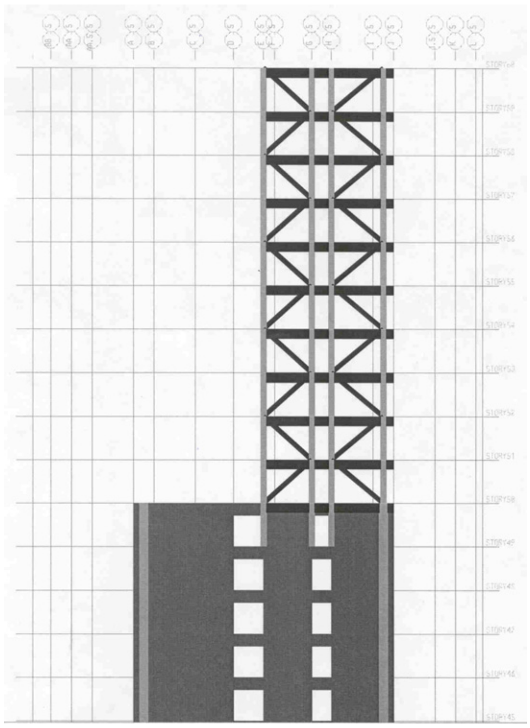


Fig. 10. Elevation of the Example Tall Building Above Floor 50

5. Conclusions

A Living Building is a new concept – a structural engineering design for tall buildings, hospitals, laboratories, and other special buildings that involves more in-depth and sophisticated structural engineering analyses so as to more accurately define the expected performance of the building during its lifetime. The design scope will result in a reduction in the construction cost of the building as well as an increase in the confidence that the building will not collapse in a major earthquake or extreme wind event. The design is optimized for a give level of acceptable damage within the available construction budget. In addition, the building is also designed with the recognition that we are beginning a century of extreme technological advancement and are continuously improving our knowledge of building behavior through focused research and development. This recognition is an essential part of the design of a Living Building because the design offers the owner or developer a cost-effective structural system that meets current minimum code building design criteria with options for easily accommodating present or future structural modifications.

Table 2. Fundamental Mode Damping for Reinforced Concrete Building for Wind Limit States.

Limit State	Wind Load Return Period (yr)	Damping (%)
Ultimate – No Yielding	500	2.00
Servicability – Interstory Drift (Skin Damage)	50	1.50
Servicability – Floor Acceleration (Human Comfort)	10	0.75

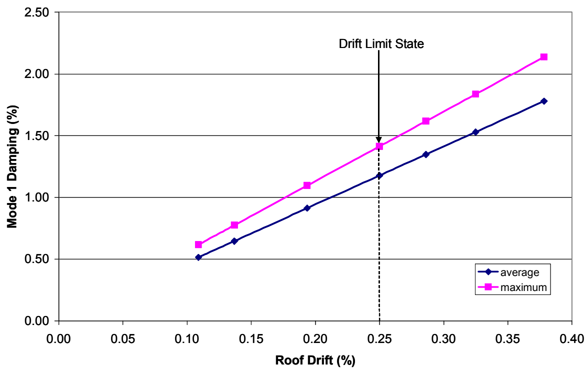


Fig. 11. Damping in Concrete Shear Wall Building as a Function of Roof Drift

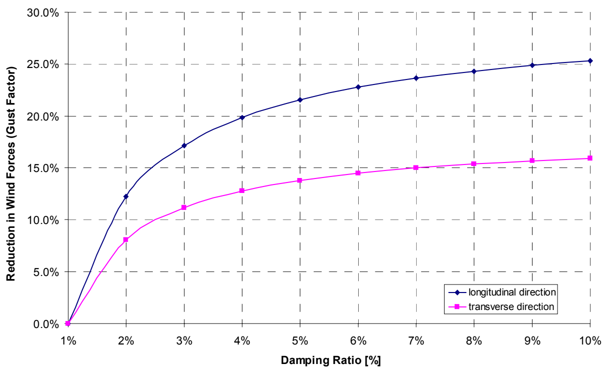


Fig. 12. Reduction in Wind Forces (gust factor with respect to 1% damping ratio) as a Function of Damping Ratio

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