

Title: **Tall Buildings: Sustainable Design Opportunities**

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## Tall Buildings: Sustainable Design Opportunities

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### Biography

Mr. Akbar Tamboli has 34 years of experience in design, in both structural steel and concrete. He has been responsible for managing major projects including Tall high-rise buildings, office and residential developments, pharmaceutical research laboratories, hotels, and hospitals.

Mr. Tamboli's experience also includes providing technical expertise in solving complex construction problems related to structural design. His specialty includes design and management of large, fast-track projects.

In his professional career, Mr. Tamboli has participated in the design and management of projects in the U.S.A., Europe, Middle East and Asia.

Recently Mr. Tamboli has managed several high-profile institutional projects including the new John Edward Porter Neuroscience Research Center for the National Institutes of Health, in Bethesda, Maryland and the Janelia Farms Research Campus for Howard Hughes Medical Institute in Leesburg, Virginia. Another notable project was the Random House World Headquarters and Park Imperial high-rise building in New York City.

A resident of Princeton Junction, New Jersey, Mr. Tamboli received his Master of Science in Civil Engineering from Stanford University in 1967. He is active in various professional organizations, including the American Society of Civil Engineers. He has published two engineering handbooks:

Steel Design Handbook LRFD Method and Handbook of Structural Steel Connection Design and Details, both for McGraw Hill. Mr. Tamboli has also contributed to structural analysis chapters for Building Design Handbook and Civil Engineering Handbook, both for McGraw Hill.

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### Abstract

Tall buildings can serve several functions: providing occupiable floor space for rent or sale, providing instant recognition as an impressive architectural monument, and showcasing advanced technologies for building design and construction. This paper describes three major tall buildings focusing on their incorporation of sustainable structural designs. *Taipei 101, Taiwan*. This tall building stands at 1,667 ft (508 m) making it the world's tallest building according to the Council on Tall buildings and Urban Habitat (CTBUH). The stiff structure is designed for great strength to account for typhoon conditions. It consists of a fly-ash concrete mat with a structural frame of recycled steel. *Petronas Towers, Malaysia*. This "uniquely Malaysian" structure stands at 1,483 ft (452 m) making it the world's tallest twin-tower building according to the CTBUH. The structure is designed using high-strength fly-ash concrete and floor framing of recycled steel which offers the desired mass, stiffness, and damping properties to withstand windy conditions. *Random House Tower, New York*. This tall building which stands at 675 ft (206 m) is the first building in the U.S. to incorporate the use of tuned liquid column dampers (TLCD). The structural frame also utilizes both fly-ash concrete and recycled steel.

**Keywords:** tall buildings, sustainable structural design, fly-ash concrete, recycled steel, tuned liquid column dampers

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### Introduction

With increasing urbanization, high land prices in cities make ever-taller buildings economically viable. Technological advancements in architecture and engineering have also made tall, slender towers more practical from performance and constructability perspectives. In addition, there is the undeniable appeal that individual and grouped skyscrapers have in the public imagination, creating widely visible icons and enhancing local pride. According to Cesar Pelli, a classic skyscraper silhouette should have a shape that "directs the viewers' eyes towards the heavens."

Although one first considers tall buildings from atheistic and real estate perspectives, the demands of skyscrapers have pushed development of both architectural and innovative engineering principles. Of the numerous aspects of modern technology incorporated within these masterpieces of architecture and engineering, this paper will focus on one of their most noteworthy, but often overlooked features: their contributions toward sustainability.

### Sustainability

The concept of sustainability, commonly known as "green design," as defined by the US Green Buildings Council (USGBC) consists of three components: environmental, economic, and health & community benefits. All three of these components can benefit from choices made in the structural design of the building.

The following is a list of the environmental, economic, and health & community benefits, offered through sustainable structural design, as defined by the USGBC:

- Improvement and protection of the environment and biodiversity
- Decline of solid waste
- Conservation of natural resources
- Decrease in energy consumption with an increase in energy savings
- Savings in project life cycle costs
- Reduction in maintenance costs
- Improvement of occupant health and comfort

### Taipei 101, Taiwan

Taipei 101, displayed in Figure 1 below, is currently the tallest building in the world according to the CTBUH

In that role, this structure is widely admired for its architecture and engineering. Nevertheless, the sustainable structural design of this colossal skyscraper is often overlooked, but is just as significant as its exceptional height.

The skyscraper Taipei 101 incorporates both environmental and economical benefits through the choice of its materials. This building is supported by an enormous 37,000 cubic yards and 16'-5" (5m) thick fly-ash concrete mat foundation supported by 380 4'-11"



Figure 1. Taipei 101

(1.5m) diameter concrete piles. These concrete piles are embedded with high-strength concrete and extend over 98ft (30m) into the bedrock. Above ground level, the building includes eight blocks of eight floors in the shape of opening flowers.

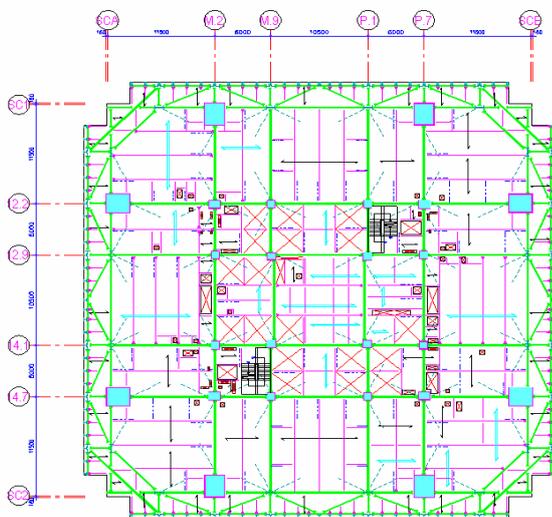


Figure 2. Level 50 Tower Framing Plan of Taipei 101

The Taipei 101 floor plan in Figure 2 consists of a square shape with saw-tooth corners, recycled steel floor framing, a square braced frame central core, and massive outrigger columns on each face.

The elevation view of Taipei 101 consists of a six story 71ft (21.5m) deep basement, a 25 story truncated pyramidal base, and eight 8-story flared modules, topped with an observation deck along with a spire. The structural components from an elevation view of Taipei 101 are exhibited in Figure 3. The building contains a braced core, lower multi-story outriggers, and single-story outriggers at the base of each module, which all consists of recycled steel. Figure 3 also displays the moment frames that work with the braced core to create a “dual system” which is very effective for seismic resistance.



Figure 3. Elevation View of Taipei 101

Furthermore, Taipei 101 also enhances its occupants’ health and comfort through the innovative structural design of incorporating “saw-tooth corners” into its perimeter design as exhibited in Figure 4.

Wind tunnel testing at RWDI, Guelph, Ontario, Canada was essential in considering typhoon conditions. It was concluded after the wind tunnel test that these “saw-toothed corners,” as displayed in Figure 5 below, dramatically reduce vortex shedding that generates wind sway. This, in turn, reduces the acceleration and inter-story drifts of the building, enhancing its occupants’ comfort and health.



Figure 4. "Saw-tooth corners" of Taipei 101



Figure 5: "Saw-tooth corners" used in the wind tests for Taipei 101

**Petronas Twin Towers, Malaysia**



Figure 6. Petronas Twin Towers

This building, displayed in Figure 6 below, was the tallest building in the world prior to the construction of Taipei 101 and is currently the tallest twin building in the world according to the CTBUH. Although quite different from Taipei 101, this structure also boasts sustainable structural designs.

As compared to Taipei 101, the Petronas Towers also consist of environmental and economical benefits in its sustainable structural design elements. The foundation as exhibited in Figure 7 below consists of a 14'-9" (4.5m) thick mat made of fly-ash concrete along with barrettes which act as friction elements. To avoid shear reinforcement, the mat form, incorporating 22 layers of 1 1/4in (31 3/4mm) diameter rebar made from recycled steel, had to be deep enough to fit a two story house. During the construction phase, a total volume of 17,000 cubic yards of fly-ash concrete was pumped into the job site for each tower's mat.

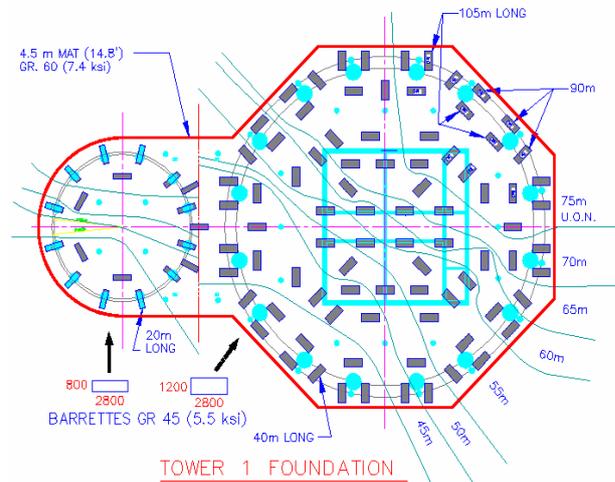


Figure 7. Tower 1 Foundation of One of the Petronas Twin Towers

Above the foundation, the structural systems highlight high strength fly-ash concrete which reduces the size and weight of the buildings' structural members. This translates into material and cost savings. Figure 8 below displays the concrete core of the structure.

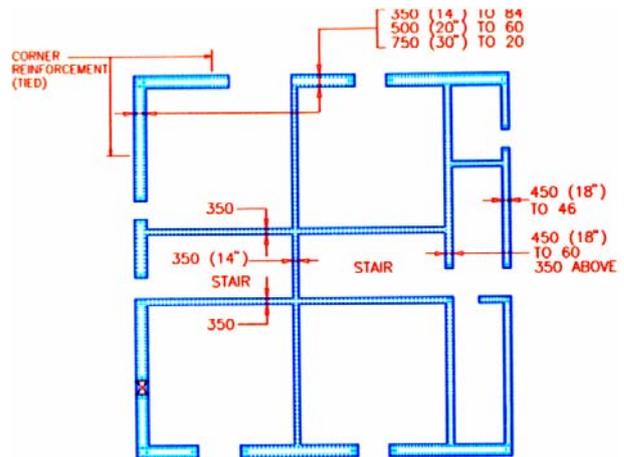


Figure 8. Lower Core Plan of the Petronas Twin Towers

The core consists of uninterrupted webs - two horizontal and one vertical which surround the stairs. With solid webs, the softening effect of openings in the outer walls is reduced. The concrete walls vary in thickness from 14in (355.6mm) to 30in (762mm). Furthermore, the lower levels consist of four layers of vertical rebar made from recycled steel.

Figure 9 below exhibits the perimeter “soft tubes” framing consisting of fly-ash concrete columns and “ring beams” which wrap the tower and the bustle. Each 4ft (1.2m) to 8ft (2.4m) diameter tower columns has the capacity to sustain 11,000 tons.

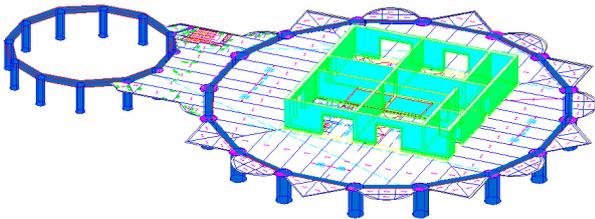


Figure 9. Typical Floor Plan of One of the Petronas Twin Towers

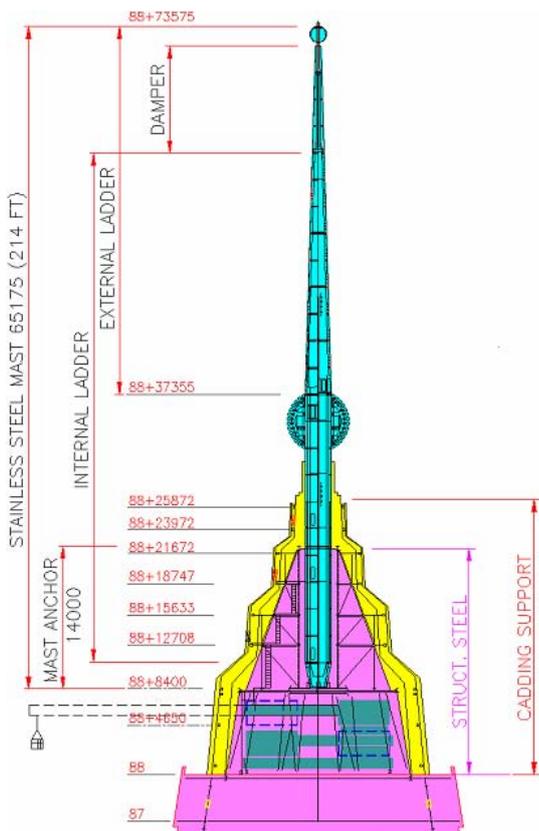


Figure 10. Pinnacle of Petronas Twin Towers

The pinnacle structure at the very top of these twin buildings, as displayed in Figure 10, not only makes the Petronas Towers the tallest twin buildings in the world, but it is also part of its sustainable structural design.

This pinnacle acts like a mast with 46ft embedment and a 168ft projection. A conventional steel framing skeleton and separate cladding skin would have

required considerable ongoing maintenance and inspection at all locations where cladding connects to the skeleton which is a difficult challenge. However the pinnacle structure of the Petronas Towers is made from stainless steel that act as both the skin and the structural framing. This translates into a reduction in maintenance costs.

### Random House Tower, New York

This project, displayed in Figure 11 below, integrates one of the most innovative technologies available in its sustainable structural design as the first tall building in the U.S. to utilize TLCDs.



Figure 11. Random House Tower

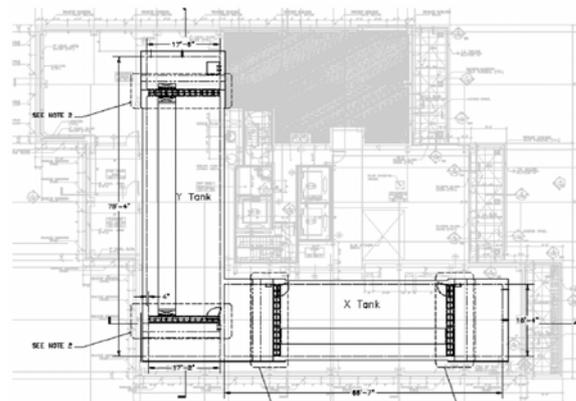


Figure 12. 50<sup>th</sup> Floor Plan of Random House

This passive damping system is a variation of the tuned mass damper (TMD). The TLCD creates the same effect as the TMD while substituting the mass block, spring and damper, system of the TMD with the motion of water or another liquid. All the water in the TLCD ‘U’ serves as the mass block. Water, rising and falling in opposition in the upstanding legs of the tank, serves as restoring springs to produce the desired natural frequency

of water motion, which is tuned to the sway rate of the building. Damping is provided through a gate, or set of louver blades, or other similar device, placed in the path of the motion of the water, to dissipate energy as turbulence in the moving water. The plan and sections of the TLCD installed in the Random House Project are shown in Figures 12 through 14.

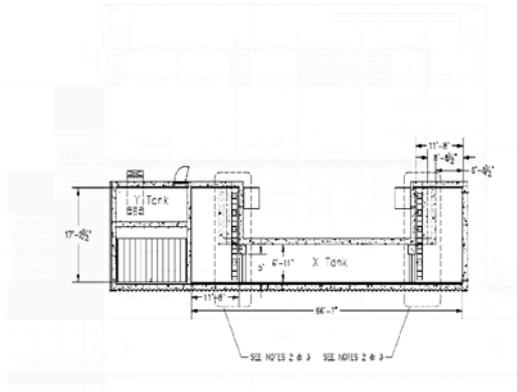


Figure 13. East-West Section through Building Top of Random House

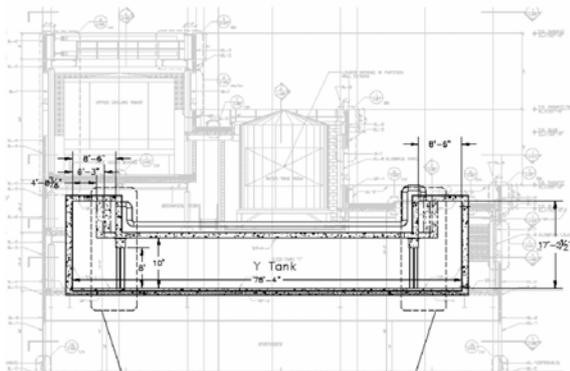


Figure 14. North-South Section through Building Top of Random House

Without a damping device, the deflections and accelerations at the top floors of the building would have been high enough to cause discomfort to the building's occupants. However, the use of TLCD results in restricting the inter-story deflections to less than  $H/350$  or  $1/2''$  in the case of the Random House building. Additionally, according to the comparison study of a wind sensitive 76-story 1004ft (306m) concrete office tower, with a height to width ratio of 7 to 3, the concrete tower achieved a much better structural response with the utilization of a TLCD as opposed to without a TLCD (Yang, 2000). The following graphs in Figures 15 through 18 display the reduction in structural response with the utilization of TLCDs.

This innovative design approach offers many benefits for the Random House building. The immediate advantage to using TLCDs is the decrease in both the inter-story deflections and building accelerations; additionally the TLCD set acts in multiple directions simultaneously. Several studies have shown that

maximum wind responses can be reduced to 40% through the utilization of the TLCDs. (Yang, 2000)

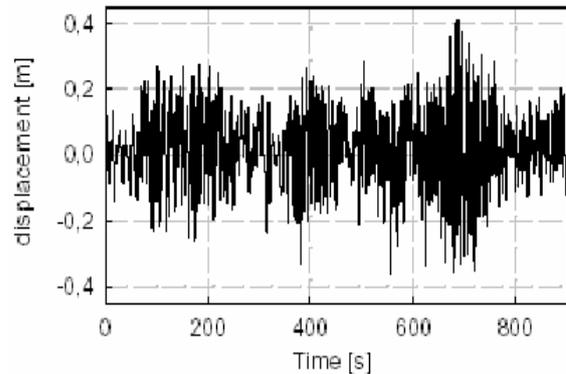


Figure 15. Top Floor Displacement of the Original Building

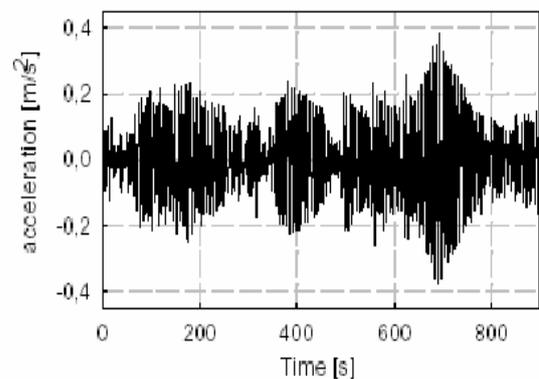


Figure 16. Top Floor Acceleration of the Original Building

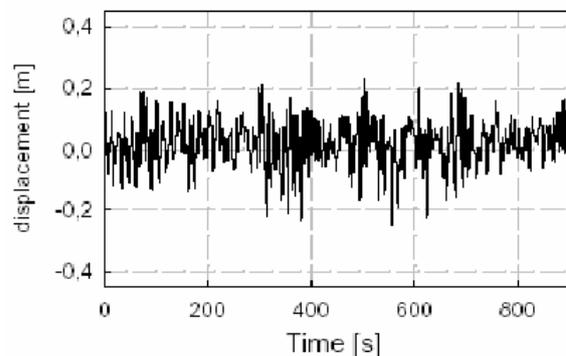


Figure 17. Top Floor Displacement of the Building with a Passive TLCD

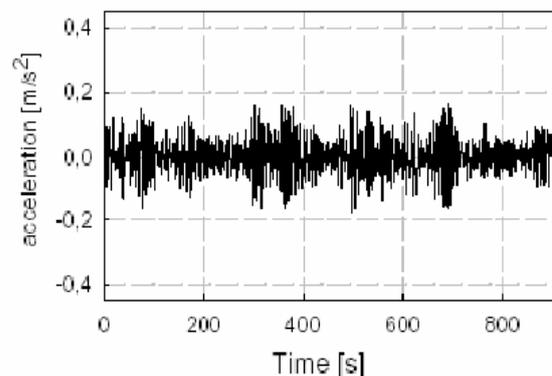


Figure 18. Top Floor Acceleration of the Building with a Passive TLCD

In addition to providing structural capabilities, the TLCD also offers sustainability advantages. In terms of environmental benefits, the water in the tanks of the TLCDs can also be used for fire fighting purposes as well as chilled water storage. Moreover the TLCD system conserves natural resources by substituting water for the additional concrete, steel, or other structural materials needed to assist in controlling the movement of the building.

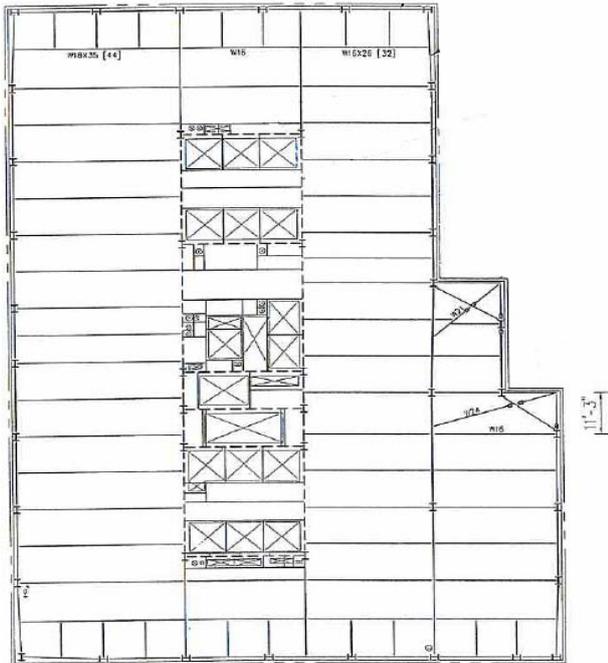


Figure 19. Typical Steel Framing of Random House

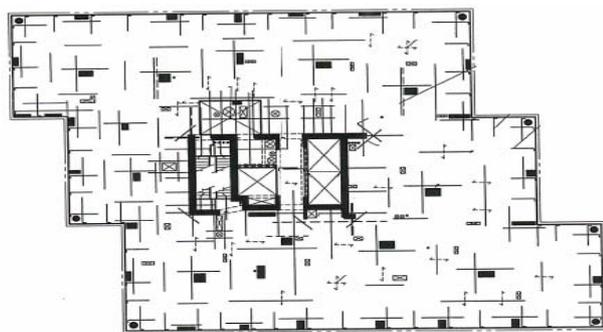


Figure 20. Typical Concrete Framing of Random House

In terms of economic benefits, the TLCD system imposes minimal maintenance requirements on the management of the Random House building. Furthermore, the effectiveness of TLCDs actually increases as the building becomes less stiff due to the inevitable cracking of the concrete or wear and tear of the non-structural elements over time. More important, the traditional method to decrease building inter-story drifts and accelerations, providing the building with more mass and stiffness through the use of additional structural

material, has proven to be extremely costly. Using TLCDs to address acceleration and drift requirements while the building frame addresses just strength and safety requirements is both cost effective and environmentally friendly.

Lastly, the health benefits include the enhancement of the occupants' wellbeing and comfort by decreasing the acceleration and inter-story drifts of the building. This in turn provides a better working environment that helps to increase productivity, and a better living environment for better health.

The Random House building also incorporates sustainable structural design features similar to those found in the Taipei 101 building and the Petronas Towers. Recycled steel is used in the structural framing systems which support the office space on the bottom 25 floors as well as the transition trusses halfway up, while fly-ash concrete is used in the structural columns and floors of the condominium levels above. These recycled steel and fly-ash concrete framing systems are shown in Figures 19 and 20 respectively.

This decision to split the use of materials was to best accommodate the very different floor layout requirements of residential and commercial office spaces in the building. The fly-ash concrete allows for variations in residential arrangements, while the recycled steel frame provides clear spans for office spaces as well as easier future modifications for risers and convenience stairs. This in turn helps reduce future maintenance and renovation costs.

## Conclusion

Sustainable structural design is an integral part of tall buildings through the utilization of recycled steel, fly-ash concrete, and TLCDs. These sustainable structural design decisions provide economic, environmental, and health benefits directly to the occupants of the building as well as to the community as a whole.

## References

- FAIRWEATHER, V. (2004). *Expressing Structure: The Technology of Large-Scale Buildings*. Birkhäuser. Germany.
- TAMBOLI, A. (1996). *Steel Design Handbook LRF Method*. McGraw Hill. New York.
- TAMBOLI, A. (1999). *Handbook of Structural Steel Connections*. McGraw Hill. New York.
- TAMBOLI, A. (2004). *Form, Structure for Taipei 101 and Petronas Twin Towers*. Stanford University Lecture.
- TAMBOLI, A. et. al (2005). *Manhattan's Mixed Construction Skyscrapers with Tuned Liquid and Mass Dampers*. CTBUH 7<sup>th</sup> World Congress. New York.
- YANG, J.N. et. al (2000). *A Benchmark Problem For Response Control of Wind-Excited Tall Buildings*. 2<sup>nd</sup> European Conference on Structural Control. Paris.