Title: **Damping Technologies for Tall Buildings**

Authors: Dario Trabucco, Research Manager, CTBUH
Alberto Lago, Research Assistant, CTBUH
Hadi Moghadasi Faridani, Research Assistant, CTBUH

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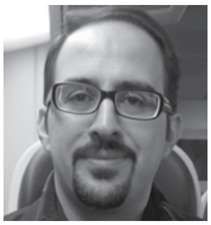
Damping Technologies for Tall Buildings

Alberto Lago



Hadi Moghadasi Faridani

Dario Trabucco

Authors

Alberto Lago, Research Assistant
Hadi Moghadasi Faridani, Research Assistant
Dario Trabucco, Research Manager
CTBUH Research Office, IUAV University of Venice
Dorsoduro 2206
30123 Venice, Italy
t: +39 41 257 1441
alago@ctbuh.org
www.ctbuh.org/tallbuildings/researchdivision

Alberto Lago is a researcher for CTBUH at IUAV University of Venice, Italy. He holds a Master's degree in Civil Engineering from the UCLA and in Architecture/Design from the University of Stuttgart. He also holds a PhD in Earthquake Engineering from the University of Pavia. He worked as a structural engineer at Skidmore, Owings and Merrill LLP in San Francisco before joining CTBUH. Lago is an accredited Professional Engineer in California and in Italy.

Hadi Moghadasi Faridani is a researcher for the CTBUH office at the IUAV University of Venice, Italy. He has a BSc in Civil Engineering and an MSc in Structural Engineering. Faridani also obtained a PhD in Structural engineering from Politecnico di Milano in 2015, with a dissertation entitled "Replacement Beam Methods for the Analysis of Tall Building Structural Systems." He is the author of several publications in international journals and conferences.

Dario Trabucco is the CTBUH Research Manager and researcher at the IUAV University of Venice, Italy. He is involved in teaching and research activities related to tall buildings, including the life-cycle analysis of tall buildings, service core design and issues pertaining the renovation/refurbishment of tall buildings. In 2009 he obtained a PhD in building technology with a thesis entitled "The Strategic Role of the Service Core in the Energy Balance of a Tall Building." From 2010 he has been the CTBUH Italy Country Representative.

Abstract

The scope of this paper is to review the possible solutions for modifying building motions through dampers. The three main categories of devices on the market for achieving this scope are "passive," "active," and "base isolation." The major solutions used by the tall building industry are reviewed here in relation to design principles, interaction with other building systems, testing, inspection and maintenance. Additionally, a study of the tall buildings over 250 meters constructed globally shows the wide utilization of these systems and the possible prominent applications they could have in the future.

CTBUH Research Project

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Keywords: Damping, Seismic, Wind

Introduction

The tall building industry is always looking to enhance performance from the safety, comfort and sustainability points of view. In 2015, after receiving a US$230,000 grant from Bouygues Construction, CTBUH began a review of how building performance goals under earthquakes and strong winds can be improved, by looking at the current utilization of dynamic modification devices. The main goal of this technological solution is to modify the dynamic behavior of a structure (mainly through energy dissipation) to reduce possible damage and create more efficient solutions from a structural and environmental perspective. The goal was to create a document that would bridge a needed gap in knowledge about the design and construction of tall buildings equipped with dynamic modification devices. The scope of this paper is to summarize the major aspects studied in the research; most importantly, the utilization of dynamic modification devices to enhance building performance in terms of safety and sustainability. The findings of this research project will be further explored in ***Damping Technologies for Tall Buildings: Theory, Design Guidance and Case Studies*** (see Figure 1).

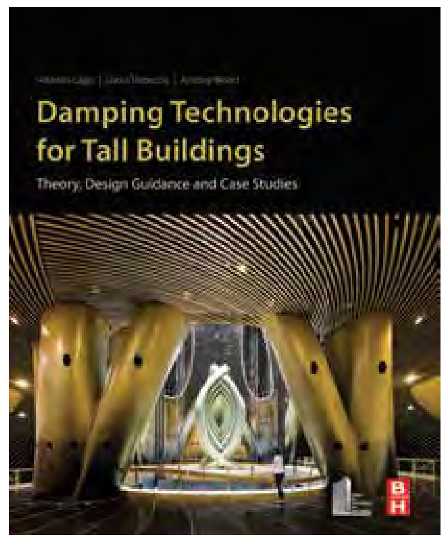

Figure 1. *Damping Technologies for Tall Buildings: Theory, Design Guidance and Case Studies*, will be available in October 2018. Find out more at: store.ctbuh.org/dampingtechnologies.

The paper explains in detail several different aspects, from understanding the basics of building dynamics to a review of the range of devices available on the market, evaluated against relevant design, installation and durability considerations. The basis of all these discussions is to reach a more reliable building performance goal for a given hazard level. This is considered one of the most prominent aspects of tall building design, as is evidenced by the requirements of the most recent national building codes.

After reviewing the major design criteria, the major steps involved in the design and construction process of tall buildings equipped with these technological solutions is discussed. Moreover, to comprehend the prominence of this topic in the tall building

Passive Systems	• Viscous Dampers • Oil Dampers • Viscoelastic Dampers • Hysteretic Dampers • Friction Dampers • Re-Centering Dampers	Material-Based (Distributed)
	• Tuned Mass Dampers (TMD) • Tuned Liquid Dampers (TLD) • Tuned Liquid Column Dampers (TLCD)	Mass-Based (Discrete)
Base Isolation	• Isolation Bearings • Sliding Bearings	
Active, Semi-Active & Hybrid	• Active Tuned Mass Dampers • Hysteretic Mass Dampers • Semi-Active Mass Dampers • Semi-Active Fluid Dampers • Semi-Active Stiffness Dampers • Semi-Active Control of Base Isolation Systems • Adaptive Tuned Mass Damper	

Table 1. Types of dynamic modification devices used in tall buildings.

industry, the authors provide an in-depth analysis of the CTBUH Skyscraper Center database, revealing worldwide trends for buildings above 250 meters in height with dynamic modification devices. The paper concludes with a description of potential areas of future research and development.

History of Dynamic Modification Devices

One of the first applications of a dynamic modification device in a tall building was the installation of 10,000 viscoelastic double-layer shear dampers at the World Trade Center in New York City (Mahmoodi 1969). Subsequently, major research studies in the utilization of passive dampers were carried out in New Zealand (Kelly, Skinner & Heine 1972; Robison & Greenbank 1976). However, the key trigger in the development of dampers was the occurrence of several earthquakes in the late 1980s and early 1990s, including Loma Prieta (1989) and Northridge in California, USA (1994), and Kobe, Japan (1995). Parallel development of wind-resistant design occurred in the late 20th century. In 1977, to counter wind forces, tuned mass dampers were installed in New York (601 Lexington, originally the Citicorp Center) and Boston (200 Clarendon, originally the John Hancock Tower). After the Kobe earthquake,base-isolated high-rise buildings started to appear, especially in Japan (Mele & Faiella 2018).

The other major category of dynamic modification, active structural control systems, has a more recent history compared with passive and base-isolation systems (Suhardjo, Spencer & Sain 1990; Inaudi, Kelly & To 1993). The major developments resulted from cooperative efforts between Japan and the US in 1989 (Soong & Spencer 2000).

Damping Considerations for Tall Buildings

Building dynamic motion is generally triggered by wind and seismic loads. This poses several problems in tall building design, chief among these being occupant comfort, as floor accelerations become prominent for the upper floors as the building height increases. To control the dynamic behavior of a building, a structural engineer can play with three major structural characteristics: mass, stiffness, and damping. It is common practice to work on stiffness and mass, but an alternative solution is to work on damping, or energy dissipation, in a dynamic system.

In a building, the primary source of damping is the so called inherent/intrinsic damping that comes from many different sources: material, structural joints, soil-structure interaction, and non-structural elements. This makes it difficult to reliably estimate its value. Moreover, intrinsic damping exhibits complex behavior due to an amplitude of motion dependency (Jeary 1986) and a building frequency correlation (Smith, Merello & Willford 2010). Given these difficulties, intrinsic damping estimation relationships are frequently based on full-scale measurements. Several databases are available, and one of the most prominent is provided by Satake et al. (2003). However, given the wide frequency spectrum of possible excitation, there is a high variability in damping estimations when different data sets are used (Bernal et al. 2012).

This great uncertainty is reflected in the building code and guideline recommendations, since they do not provide prescriptive theoretical models, but only recommended values for structural analysis (which in most cases are valid only for low-rise buildings) (Tamura 2005).

In addition, for intrinsic damping in a building, there could be other sources of energy dissipation:

- Aerodynamic: due to building movement in a fluid (air).
- Hysteretic: from inelastic behavior of structural members.
- Supplemental/Additional: damping provided by external devices added to the structure.

When a designer decides to control the dynamic behavior through damping, the predominant method is to add an external device. This solution helps in reducing uncertainties in intrinsic damping estimation and meets structural performance criteria, both from a wind and seismic point of view.

Dynamic Modification Device Types

There are several dynamic modification devices on the market, and they are classified based on the controlling mechanism they utilize. There are three major categories defined as follows (see Table 1):

> "Among 525 buildings of 250 meters or greater height (under construction or to be completed by 2020), 18% (97) are equipped with dynamic modification technologies."

- Passive
- Base isolation
- Active, semi-active, and hybrid

Passive systems have constant properties, while active, semi-active, and hybrid systems change their properties based on load demands, and in most cases require an external energy source to be functional. Isolation systems are considered independent from the other two categories, since the main function is to decouple the structural response of the building portion above the isolation level.

Passive Systems

Passive systems can be divided in four sub-categories, depending on the energy dissipation behavior they utilize (see Table 2):

- *Displacement-dependent:* dissipates energy as a function of the differential displacement between device ends. Consequently, the forces generated are in-phase with the building inertia forces.
- *Velocity-dependent:* dissipates energy as a function of the differential velocity between device ends. Consequently, the forces generated are out-of-phase with the building inertia forces.
- *Mixed systems:* two devices belong to this category – viscoelastic and friction. Viscoelastic dampers dissipate energy as a function of both displacement and velocity; friction devices do so almost independently of the frequency of the system.
- *Motion-dependent:* consists of a large mass (or a combination of a discrete number of smaller masses), which, through large differential motion (i.e., tuned mass dampers) or turbulence (e.g., tuned liquid dampers), converts input building motion into other forms of energy (such as heat).

Passive devices can be further grouped in relation to their position in within a building:

- *Distributed.* Displacement-dependent, velocity-dependent and mixed systems are utilized within the building structure, with different possible geometrical configurations (see Figure 2), and usually in multiple locations along the building height.
- *Discrete.* Mass damping approaches are usually applied only in a few locations in a structure. The major categories are tuned-mass, tuned liquid and tuned column liquid dampers (see Figure 3).

Isolation Systems

Isolation systems (e.g., rubber bearings, sliding systems) are considered in a different category than passive devices, even if they do not require any external energy input to function. The main goal is to uncouple the building motion of the structure above the

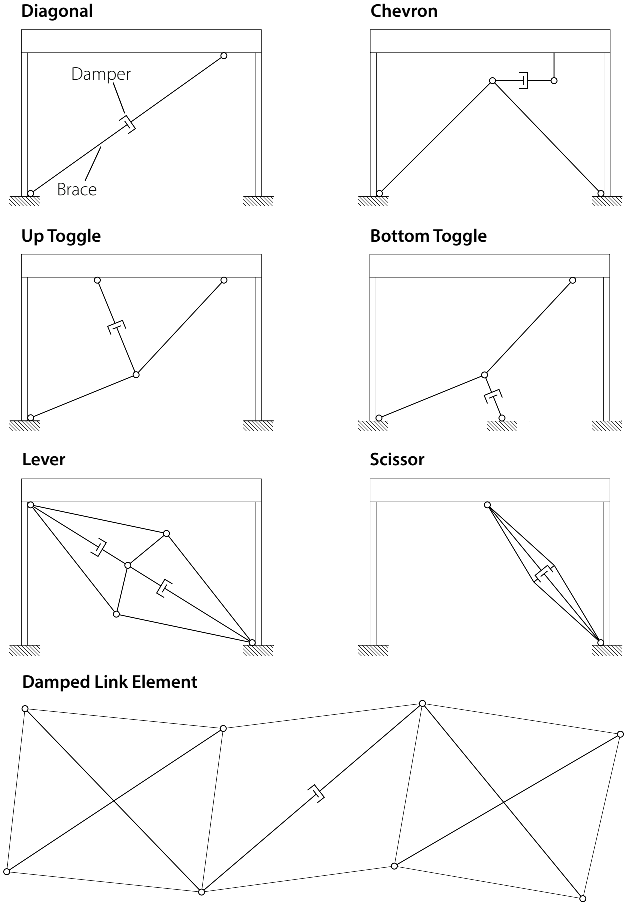

Figure 2. Possible geometric configurations of distributed damping devices.

Displacement-Dependent	Velocity- Dependent	Mixed Systems	Motion-Dependent
Metallic	Viscous	Friction	Tuned Mass
Self-Centering		Viscoelastic	Tuned Liquid
			Tuned Liquid Column

Table 2. Categories of passive added damping devices.

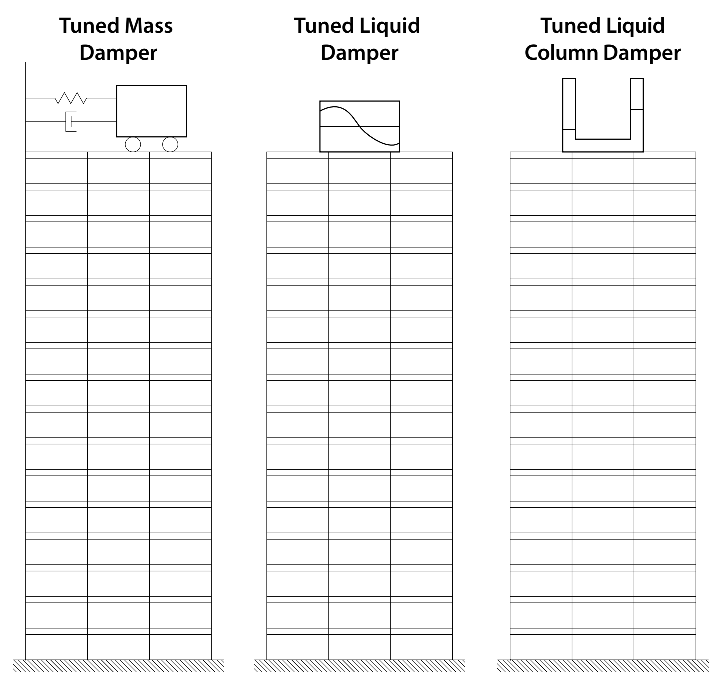

Figure 3. Simplified diagram of mass-damping system types.

isolation point from the input ground motion (see Figure 4). In addition, dissipation devices can be added at the isolation level to reduce the horizontal displacement, especially when the seismicity is very high.

The general rule for seismic isolation systems is to have a ratio of three between the period of the isolated building and the period of the fixed-base building, which presents difficulties when applied to tall buildings. However, in the last decade, several tall buildings have been equipped with isolation devices, such as the 199-meter Nakanoshima Festival Tower in Osaka, Japan.

Active, Semi-Active, and Hybrid Systems

This category of dynamic modification devices has variable properties that adjust based on the structure's properties and on the level of external excitation, in order to accommodate uncertainties in the design. Therefore, devices in this category require energy input to be functional. "Active" systems are defined as a combination of the following elements (see Figure 5):

- Sensor: measures the displacement along the degree of freedom.
- Controller: determines the appropriate response to be applied.
- Actuator: applies the required force.

The controlling algorithm is the main element that is derived from the measured information using the following general formats (Soong & Spencer 2000): (a) feedback control or closed-loop control system (sensors measure structural response only), (b) feed-forward control (sensors measure excitation only), and (c) feedback and feed-forward control (sensors measure both structural response and excitation).

In addition to active systems, another category is "semi-active," in which the control actuators do not add mechanical energy directly to the structure. Alternatively, when active and passive devices are combined, the system is called a "hybrid."

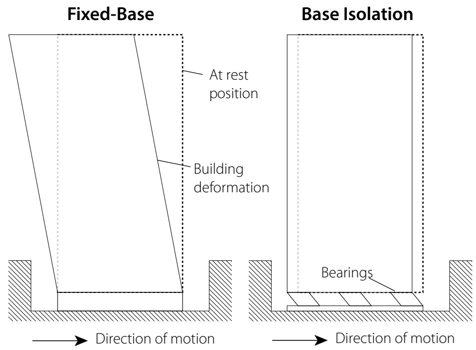

Figure 4. Schematic concept diagram of base isolation.

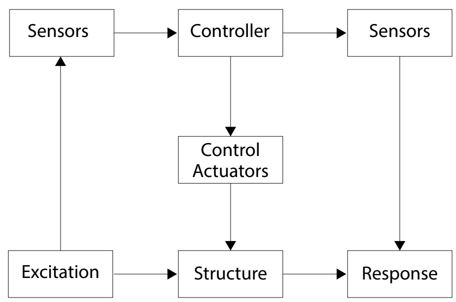

Figure 5. Diagram of a structure using active dynamic-response modification systems. Adapted from Soong & Spencer (2000).

Practical Design Aspects

Dynamic modification system installation in tall buildings is a straightforward process. The involvement of each stakeholder (e.g., wind consultants, wind tunnel laboratory, damper manufacturer, owner, and architect), is necessary at the earliest possible point in the design process, in order to understand the system as a whole. Consistent interaction among the stakeholders plays a vital role in the success of project.

Despite the volume of research and range of applications of dynamic modification technologies, standards have not been developed accordingly. Major national codes, such as: US (ASCE/SEI 7–16), Europe (EN 1998-1), China (GB50011–2001), Japan Building Standard Law, and New Zealand (NZS 3101); usually provide basic recommendations for structures with passive and isolation systems, without providing a general design procedure. Moreover, mass damping approaches and active, semi-active and hybrid systems are not addressed by any of the available standards.

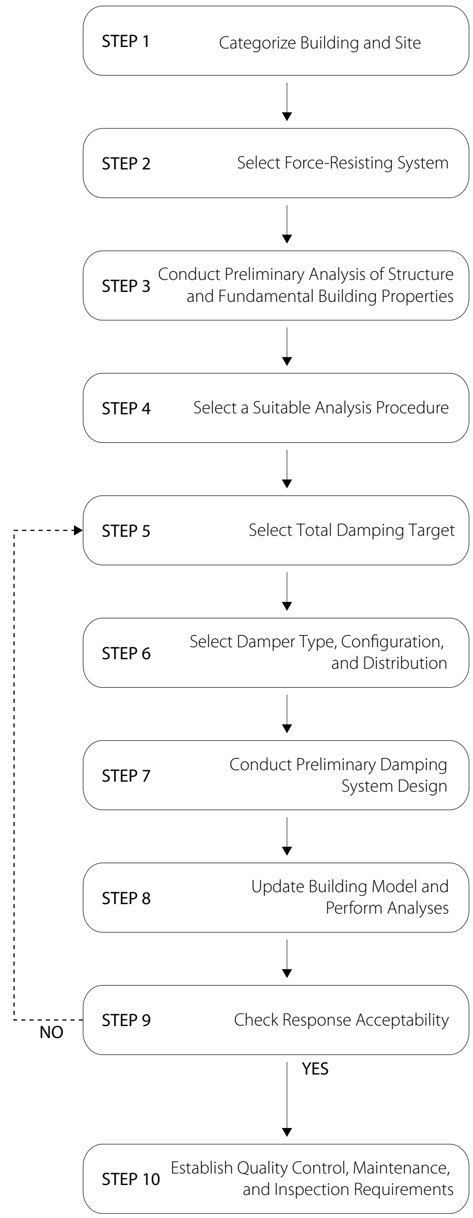

Figure 6. Step-by-step procedure for selecting and implementing a passive damping system design.

This is why the authors are developing general design procedures for each of the previously defined categories. Step-by-step procedures are developed based on the available code requirements and from extensive review of available literature (see Figure 6). The goal of the proposed procedures is to provide the designer with a possible workflow for the design of tall buildings with dynamic modification devices, starting from the definition of the building site, progressing to the selection of the main structural systems, and proceeding to the preliminary design of the dynamic modification devices. The procedure also provides recommendations for quality control and maintenance of these devices.

Testing, Inspection, and Maintenance

Testing represents the most important tool to validate design assumptions and to understand device reliability and performance. Moreover, inspection and maintenance are other important practices for achieving long-term performance objectives and the expected device life. Serving this scope, quality control procedures, consisting of pre-installation tests and inspections, are usually performed. Pre-installation tests serve to verify assumed properties and acceptance criteria used in the design phase. In addition, long-term periodic inspection and maintenance programs are required to assure the expected life of some damping systems. Basic principles can be gathered from national codes and standards requirements (ASCE 2017, CEN 2003 and 2009, JSSI 2003, MOHURD 2012, MOHURD 2013, Nakagawa 2000), which provide general recommendations only for distributed and isolation devices. For mass damping and active, semi-active and hybrid systems, recommendations can be found in the available literature.

Trends in Damping Systems

The worldwide distribution of dynamic modification devices across tall buildings of 250 meters or higher is shown in ***Tall Buildings in Numbers*** (page 48). Among a total number of 525 buildings (under construction or to be completed by 2020), 18% (97) are equipped with dynamic modification technologies. Regionally, North America and Middle East have 33% of the tall building stock of 250-meter-plus buildings equipped with damping systems, while portions are lower in Asia (12%) and in Australia (23%).

Possible reasons for these differences could be:

- Differences in performance levels that each building needs to satisfy based on its location and hazard level.
- Location of damping manufacturers in the world, with the major ones being located in United States and Europe.
- Practitioners' level of awareness of damping technologies.

In addition, 31 case studies were reviewed and described by the stakeholders involved in the building design (architects, structural engineers, and other consultants) (see Figure 7).

Future of Damping Systems

As seen above, there is a great variety of technological solutions available, drawing from the extensive research carried out in the last 40 years. As seen in the literature, the current research investigations are pushing for the development of new technological systems that can resist both wind and earthquakes, for example through the integration of different damping technologies in the same building (such as combining tuned mass dampers with viscous dampers), or with devices that have variable properties (such as viscous dampers). Furthermore, the worldwide utilization of dampers can be increased through the development of standards and codes that will guide the design process, utilization, testing and maintenance of these systems. Therefore, it is clear that the main goal for future development is spreading the knowledge among the related professions about damping technologies that can enhance building performance, as well as make more resilient and sustainable tall buildings.

> “National codes provide basic recommendations for damping without providing a general design procedure. Moreover, many damping approaches and systems are not addressed by any of the available standards.”

Conclusions

The research overviewed in this paper has shown the state-of-the-art in the design and installation of dynamic modification devices in tall buildings. The effort conducted for this research project intends to underline the premises of the evolution of this technological system and the possibilities of enhanced design of more performant and efficient tall buildings.

A deep review on the different devices available has shown the great importance that damping systems have gained in the tall building community (especially in the last 30 years). Indeed, given the great amount of research and experimental tests conducted, the reliability of these devices is increasing.

One of the major goals of this research was to provide a reference tool for engineers, architects, consultants and contractors to design and implement damping technologies in tall buildings. Therefore, the authors hope that this document could become an important reference for the tall building industry. ■

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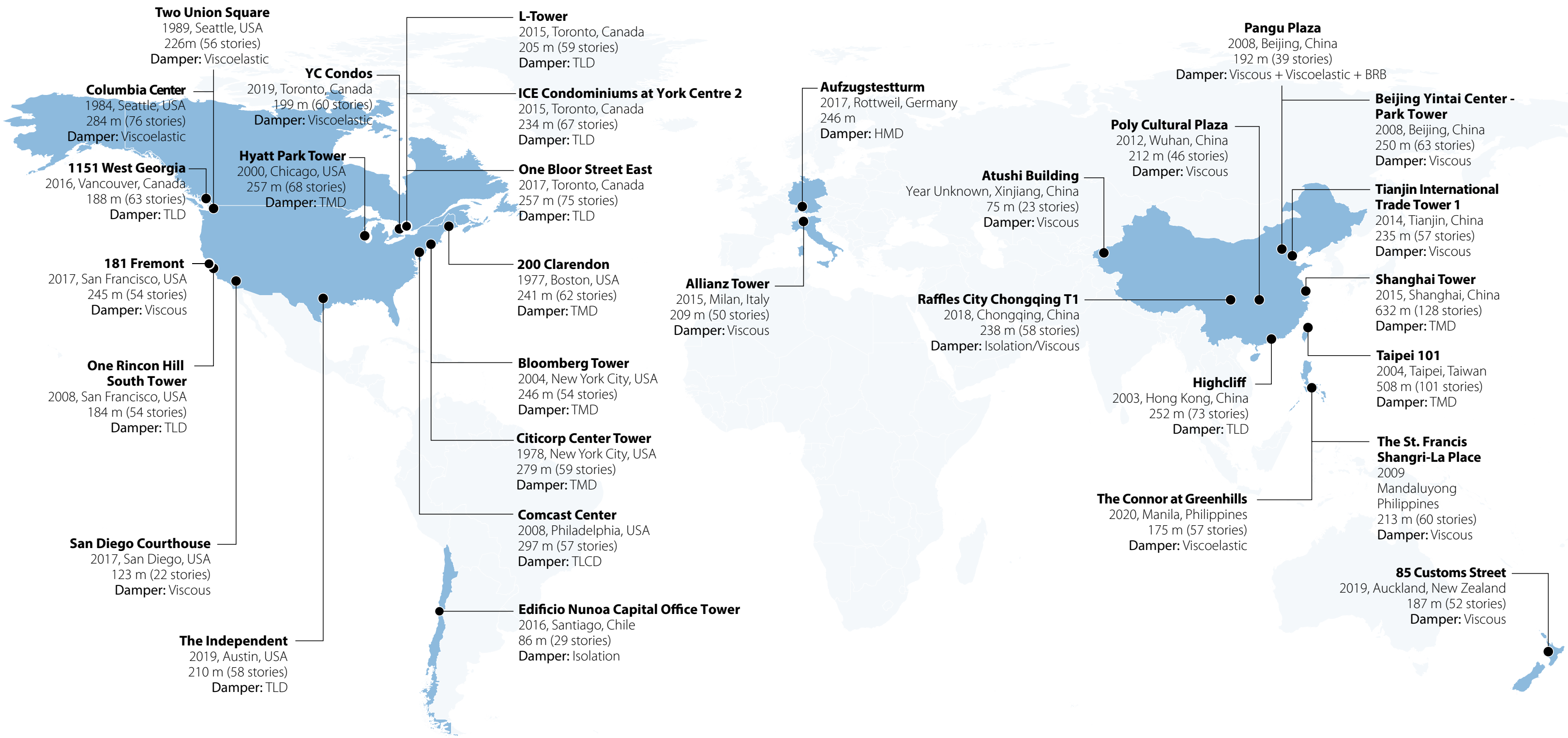

Figure 7. Locations and statistics of tall buildings with damping systems reviewed by the researchers.

US$230,000 grant from Bouygues Construction in 2015, and has been made possible through the contribution of many experts in the field.

Unless otherwise noted, all image credits in this paper are to the authors.

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