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Robotic High-Rise Construction of Pagoda Concept: innovative earthquake-proof Design for the Tokyo Sky Tree

Thomas Bock[1], Thomas Linner[2], Shino Miura[3]

[1]*Prof. Prof. h.c./ SRSTU Dr.-Ing./ Univ. Tokio, Technische Universität München (TUM), Germany,* *thomas.bock@br2.ar.tum.de*
[2]*Dipl.-Ing. Univ., Scientific Assistant, Technische Universität München (TUM), Germany,* *thomas.linner@br2.ar.tum.de*
[3]*Shino Miura, Researcher, The University of Tokyo, Japan,* shinomiura@gmail.com

Prof. Prof. h.c./ SRSTU Dr.-Ing./ Univ. Tokio Thomas Bock

Biography

Professor Bock (*1957) is Full Professor for Building Realization and Robotics at the Technische Universität München (TUM). His research focuses on automation and robotics in building construction, from planning over building production and utilization phase up to reorganization and deconstruction. After his academic studies in architecture at the University of Stuttgart and the IIT Chicago, he did his doctorate at the University of Tokyo. Among others, he is in the board of directors of the International Association for Automation and Robotics in Construction (IAARC), the Asian Habitat Society in Peking as well as the International Institute of Construction Information in Tokyo. He operates as a constultant at the Ministère de l'Emploi, de la Cohésion Sociale et du Logement in France and is committed as a member of the Academy of Architecture and Civil Engineering, the Petrovich Academy of Sciences as well as of the Academy of Informatics in White Russia. Beyond that, Prof. Bock is in the editorial board of top-journals as "Robotica", "Automation in Construction", and "International Journal of Construction Management". Recently he became coordinator of CIB's newly founded W119 (Customized Industrial Construction).

Abstract

More than 2,000 earthquakes or rather 60% of the earthquakes worldwide and 30% of Tsunamis happen in Japan. As it has been proved by the March 2011 earthquake (strength: 9,0) once more, Japan has developed highly advanced earthquake resistance technologies. Although the earthquake caused a devastating Tsunami, there was no damage by the earthquake at the sky tree site. Especially buildings in the Tokyo area have to endure several hundred smaller and larger shakings per annum without letting them cause damage to structure, sub-components and technical infills. With a height of 634 meters, the Tokyo Sky Tree is the world's second largest man-made structure on earth. However, the tower is one of the safest buildings ever built. Obayashi constructed the Tokyo Sky Tree by using techniques and components of its Automated Building Construction System (ABCS) which they have been developing since the 1980s. Ever since struck by frequent earthquake disasters, tsunamis, typhoons, fires and war destruction, Japan not only overcame those disasters but obviously used them as a reason to develop new technologies and advanced construction systems. Given that facts, it can be assumed that Japan again takes the March 2011 Disaster (earthquake, tsunami, nuclear incident) as a reason to advance state of the art disaster prevention technologies: In 2-5 years (after intensive R&D which usually follows disasters in Japan) it is highly possible that Japan will develope new cutting edge disaster prevention technologies.

Keywords: Robotic Construction, Earthquake Resistance Technology, Innovation Management

Introduction

With a height of 634 meters, the Tokyo Sky Tree is the world's second largest man-made structure on earth, only topped by Dubai's Burdsch Chalifa (830m) and followed by Gangzhou's Canton Tower (600m), Toronto's CN Tower (553m) and Moskow's Ostankino Tower. Other famous towers as Sears Tower (527m), Taipei 101 (508m) and the Petronas Towers (452 m) are significantly smaller. Despite being built in a seismically highly active area (in the Tokyo area 60-70 noticeable earthquakes are measured per annum), the tower is one of the safest buildings ever built. This has been enabled by a fusion of cutting edge structural design, advanced damper technology and high-quality ensuring construction technology. Additionally, after a two year design phase (2007/2008), the tower will have been completed within less than 3,5 years (July 2008-December 2011). In comparison: the construction of the only 150m high Munich Olympia Tower took more than three years and the construction of the Burdsch Chalifa even more than six years. The onward paper is organized as follows: In section one we analyze the design and engineering of the Tokyo Sky Tree. In section two we highlight the rise of earthquake resistance technology in Japan from traditional buildings and pagodas to new active and sensor controlled systems. Also, we show the adaptation of the pagoda's "shimbashira" principle to the needs of the Sky Tree project. In section three we outline how Obayashi constructed the Tokyo Sky Tree by using techniques and components of its Automated Building Construction System (ABCS). In section four we conclude our findings and show how frequent disasters in Japan affect innovation cycles in developing earthquake resistance technology.

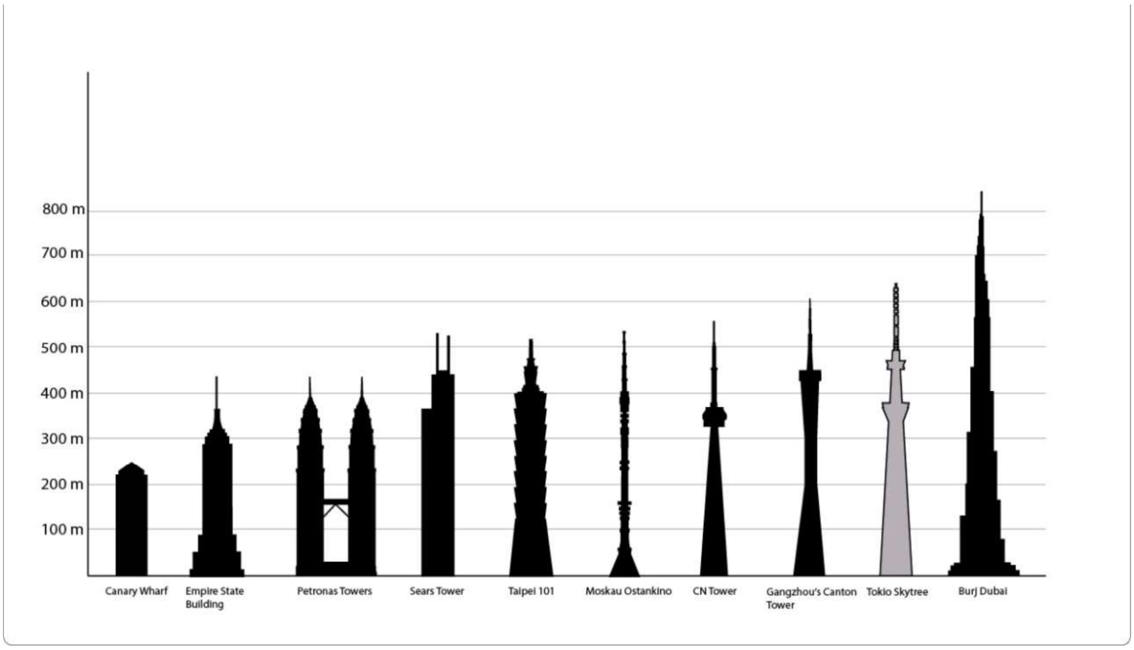

Figure 01: *The Tokyo Sky Tree is the world's second largest man-made structure on earth only topped by Dubai's Burdsch Chalifa (830m) and followed by Gangzhou's Canton Tower (600m), Toronto's CN Tower (553m) and Moskow's Ostankino Tower.*

1. Form follows technological Requirements

The form of the tower is the result of an overlay of several requirements concerning stability, use, production and appearance. This lead to a complex set of design parameters that had to be synchronized. From the bottom to the top, the tower changes its form several times; nevertheless, it appears as a well designed entity (Figure 02). Up to about 50 meters, the tower rests on a tripod like structure that allows inducing the forces of the structure in a concentrated and optimized way into the foundations. From 50 to about 200 meters, a triangular structure guarantees the stability of the tower against horizontal forces acting on the tower. Above 200 meters the triangular structure seamlessly changes into a round structure reducing the impact of horizontal wind forces on the tower. At the height of 350 meters and 450 meters, conically shaped rings are laid elegantly around the thinner tower structure. They not only contain restaurant and observatory functions but also enhance the towers stability and balance. Above all, the structural design allowed a modularization into highly stabile, factory made and large scale steel segments. In order to reduce the workload and enhance joining precision, major joining elements had been preinstalled to most components. The center of the tower is built by a concrete shaft containing supply services as elevators and ducts. Advanced hybrid damper technology, derived from the traditional building method “Shimbashira-Seishin“, ensures absorption of vibrations during several hundreds of earthquakes per annum in Tokyo.

2. Advanced Earth Quake Resistance Technology

More than 2000 earthquakes or rather 60% of the earthquakes worldwide and 30% of Tsunamis happen in Japan. As it has been proved by the March 2011 earthquake (strength: 9,0) once more, Japan has developed highly advanced earthquake resistance technologies. Although the earthquake caused a devastating Tsunami, there was no damage by the earthquake at the sky tree site. Especially buildings in the Tokyo area have to endure several hundred smaller and larger shakings per annum without letting them cause damage to structure, sub-components and technical infills. Earthquakes can not only do damage to human beings but also to the equipment in office buildings or production facilities. The demand for mandatory and obligatory earthquake resistance methods especially make the construction of non-residential building expensive. Companies as Obayashi, Kajima, Shimizum, Takenaka and also smaller firms that have to do with engineering or construction of buildings spend enormous sums on research and development of new, and efficient earthquake resistance technologies. In a recent survey the authors have analyzed strategies and technologies that have been developed in Japan to guarantee safety in case of an earthquake. In this paper, we only focus on technologies used in case of the Tokyo Sky Tree. Outcomes of the survey describing, analyzing and finally categorizing disaster prevention strategies and technologies will be published in further papers. Nevertheless, chapter 6 already anticipates some of the findings of the survey.

Figure 02: *In order to achieve enhanced performance, the tower changes its form several times. Nevertheless, it appears as a well designed entity.*

2.1 Earthquake Resistance of the traditional Japanese House

Japan has a long history in developing earth quake resistant artificial structures. The traditional Japanese House already was built by a highly flexible kit system allowing the building to move and shake in a controlled way thus absorbing the vibrations. Therefore, the beams and columns of such a house were only plugged together (interlocking technology) and not joined in a fixed way or nailed. These joints allowed the joined elements to move within a certain scope (Figure 03a). The Japanese House originally also was not fixed with the columns on foundations. Yet, a middle column frame or a central pillar formed a kind of backbone on which the other columns were allowed to move in case of vibrations (Figure 04b). (1)

Figure 03: *Highly flexible kit system* ***Left:*** *Interlocking Technology: beams and columns of a traditional Japanese house were only plugged together and the joints allowed the joined elements to move within a certain scope. (1)* ***Right:*** *Backbone Technology: a middle column frame or a central pillar forming a kind of backbone of the house which was fixed to the ground and the other columns were allowed to move on the foundation in case of vibrations. (1)*

2.2 Earthquake Resistant Towers

Similar to the procedure of the companies Sekisui House, Daiwa House und Sekisui Heim, in the case of the Tokyo Sky Tree, traditional architectural know-how has been used, adjusted and finally improved, as well. The proven technology of “Shimbashira-Seishin” (Center Column Vibration Control) which had been used in five story pagodas has been applied to the Tokyo Sky Tree and improved by a combination with other passive and active control systems resulting in a new hybrid earthquake resistance technology making the Sky Tree as safe as no other building with a similar height.

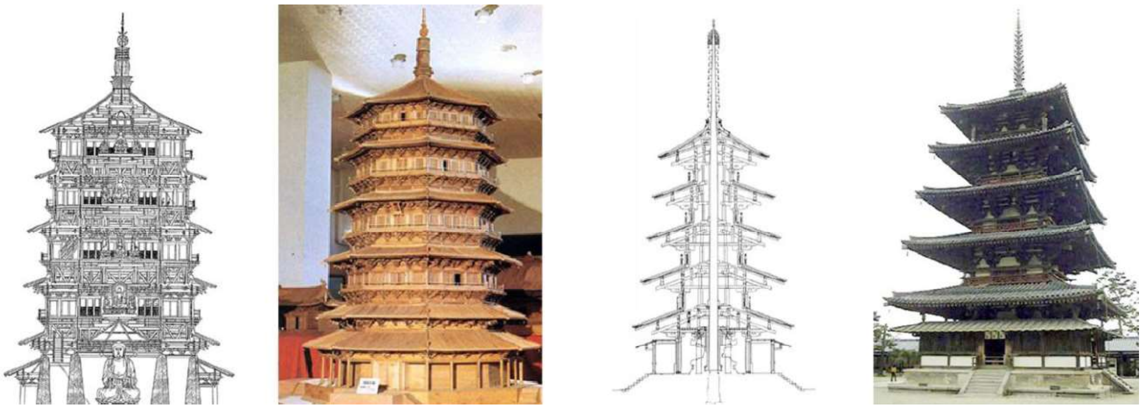

Figure 04: *Studies show that the “shimbashira” is a typical element of Japanese Pagodas facing earthquakes regularly, but cannot be found in China or Korea, which are not or at least not frequently hit by earthquakes.* ***Left:*** *Chinese Pagoda* ***Right:*** *Japanese Pagoda with “shimbashira”.*

Pagodas are multi-storey tower-like buildings, which can be found in Vietnam, China, Korea and Japan. At the beginning, they were mainly used for the safe-keeping of bones and other mortal remains of famous Buddhist monks. Later, they were used in a broader way and became part of architectural culture, especially in China. In Japan, the Pagoda is still a central element of temple and shrine areas. As studies show (2), the “shimbashira” is a typical element of Japanese Pagodas facing regular earthquakes, but cannot be found in China or Korea, which are not or at least not frequently hit by earthquakes (Figure 04). In 2002, Center Column Vibration Control based on the “shimbashira” technology was applied to the Marunouchi building, a 36 floors and 198 meter high building located near Tokyu Station. Mitsubishi developed the building as a mixed-use building complex containing shops and offices (Figure 05a) and the “shimbashira” as an integral element (Figure 05b). It is connected with each floor's structure (Figure 05c), thus serving both as a damper and a stiffening element.

***Figure 05**: In 2002, "Shimbashira-Seishin" (Center Column Vibration Control) was applied to the 198 meter Marunouchi building in Tokyo. **Left:** View of the building **Middle:** "Shimbashira" as a major element of the structure **Right:** Connection between the "shimbashira" and the steel structure of the building.*

2.3 Earthquake Resistance Technology Tokyo Sky Tree

The Tokyo Sky Tree is not an imitation of the pagoda's "shimbashira" principle, but a complex new interpretation that has been combined with a multitude of state of the art techniques. Generally, it is a multi-segment system that allows the individual segments to respond to the vibrations differently. At different parts of the building, a dissimilar reaction to the shakings is necessary. So, the inner concrete core (reinforced concrete) is decoupled from the outer steel structure and the antenna mast on the top is decoupled from the inner concrete core below. Thus basically three independent parts can be identified. Type and strength of the linking between the inner concrete core and outer steel structure change over the tower's height.From 0 to 125 meters both structures are firmly connected and form a stable base, which is fixed to the ground by an innovative system of foundation. Dispersed, wall-like plates are driven into the ground like the roots of a tree. The wall is spiked all over thus ensuring a safe grip of the foundation, also in case of extreme wind forces that might affect the 634 meter high tower structure. From 125 m to 375m meters, the inner concrete core and the outer steel structure are linked by oil dampers. If all parts of the tower would be fixed to each other, the shakings would be amplified over the building's height. The part above 375 meters can respond flexibly to the wind forces and counteract vibrations from the ground. Due to the applied decoupling strategy, the amount of seismic energy acting on the building in case of an earthquake can be reduced by 40%.

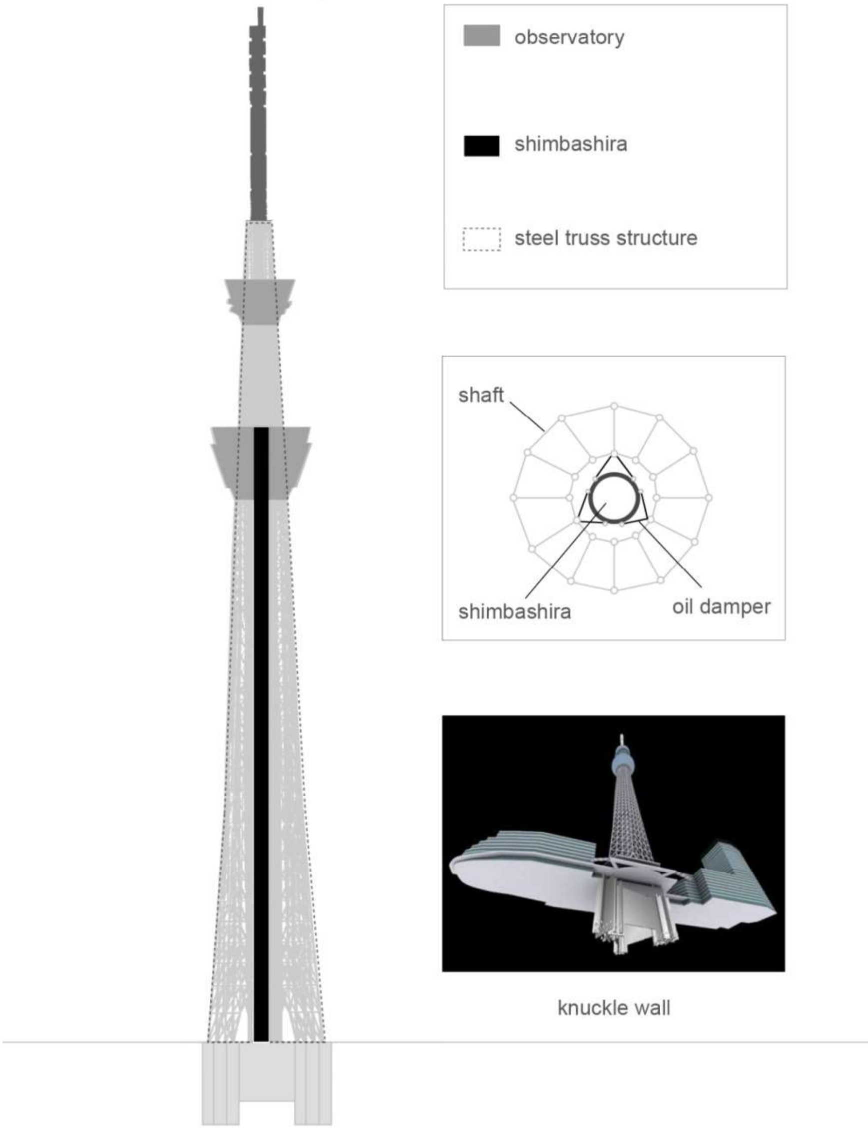

***Figure 06**: The Tokyo Sky Tree is a multi-segment system that allows the individual segments to respond differently to the vibrations. **Left:** Multi-Segment Structure **Top Right:** The inner concrete core and the outer steel structure are linked via oil dampers allowing both segments an individual movement. The Oil damper then absorbs the energy. **Down Right:** spiked, dispersed and wall-like foundation system that is driven into the ground like the roots of a tree.*

3. Advanced High-Precision Construction

Obayashi constructed the Tokyo Sky Tree by using techniques and components of its Automated Building Construction System (ABCS). This has been developed since the 1980s in order to automate assembly operations on-site to a high degree by installing an on-site factory, with automated logistics, automated column and beam positioning, automated welding and real-time process control. The ABCS's Super Construction Factory (SCF) sits on top of the construction and moves upward with the construction progress. A central element of the SCF is the Parallel Delivery System ensuring that materials are delivered upward from the ground in an automated way – on the one hand on the right floor (vertical PDS) and on the other hand to the right position. As the ABCS adjusts many processes, high precision construction is required from the very beginning. Therefore, Obayashi continuously controls the correct positioning of all assembled building parts by a laser scanning system. (3)

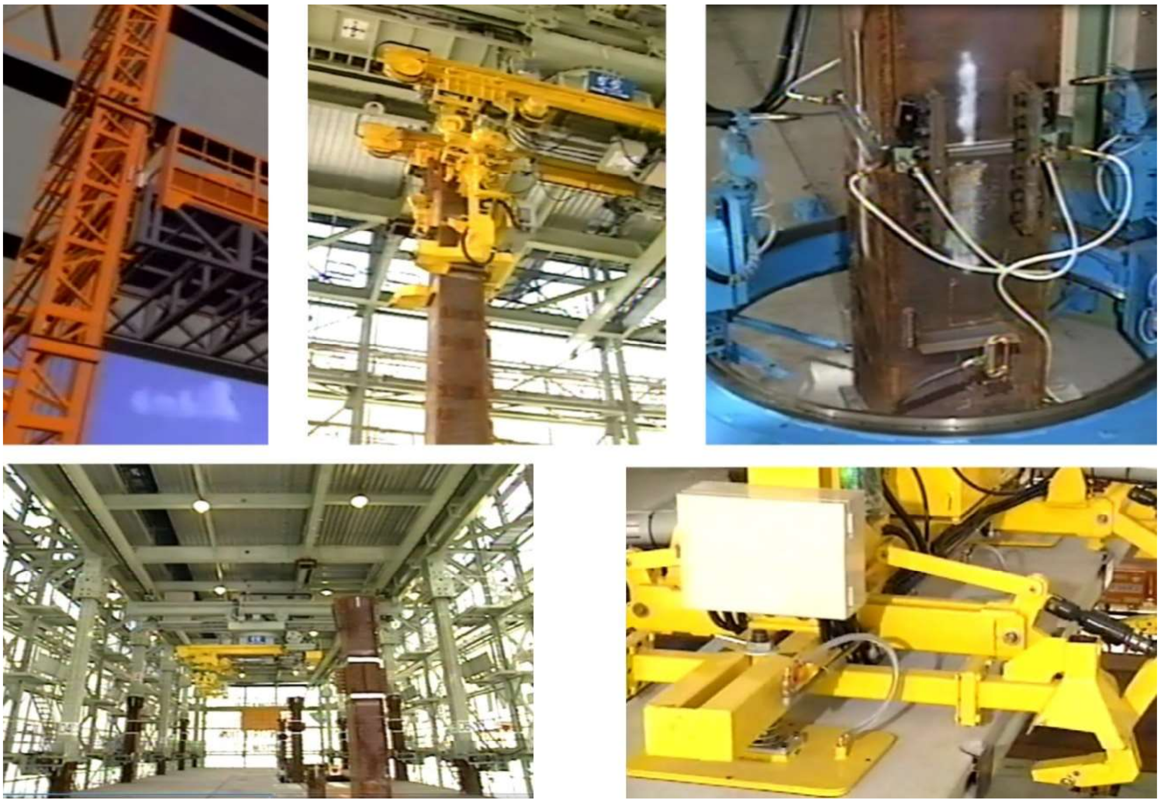

***Figure 07**: Obayashi's Automated Building Construction System (ABCS)*
***Top Left:** Automated Vertical Delivery System **Top Middle:** Automated Column Positioning **Top Right:** Automated Welding Robots **Bottom Left:** Super Construction Factory (SCF) **Bottom Right:** Automated Positioning of Floor Elements*

Using and adjusting ABCS Sub-systems was in the case of the Tokyo Sky Tree highly efficient, as the 634 meter tall structure is an extreme project requiring high precision and technical support. Following ABCS-Subsystems have been used during the construction process of the Sky Tree in a modified way:

- Sub-System 1: Automated Logistics and Positioning
- Sub-System 2: Automated Welding
- Sub-System 3: Automated Column Alignment

4. Disaster as a trigger for Innovation

Ever since struck by frequent earthquake disasters, tsunamis, taifuns, fires and war destruction, Japan not only overcame those disasters but obviously used them as a reason to develop new technologies and strategies. Frequent disasters are surely one reason why Japans construction industry is so advanced today. So it is scientifically proven, that war destruction and earth quake destruction supported the progress of Japans advanced and highly automated prefabrication industry. Further, the high quality homes that home makers as Sekisui House, Daiwa House and Sekisui Heim offer are the outcome of a demand for safe taifun and earthquake resistant homes. After each major disaster in Japan the time span between disaster and Innovations that enter the market (Law Changes and Technical Innovations) became shorter (Figure 08). This means Japan has learned to react on disasters and to bring necessary innovations into market.

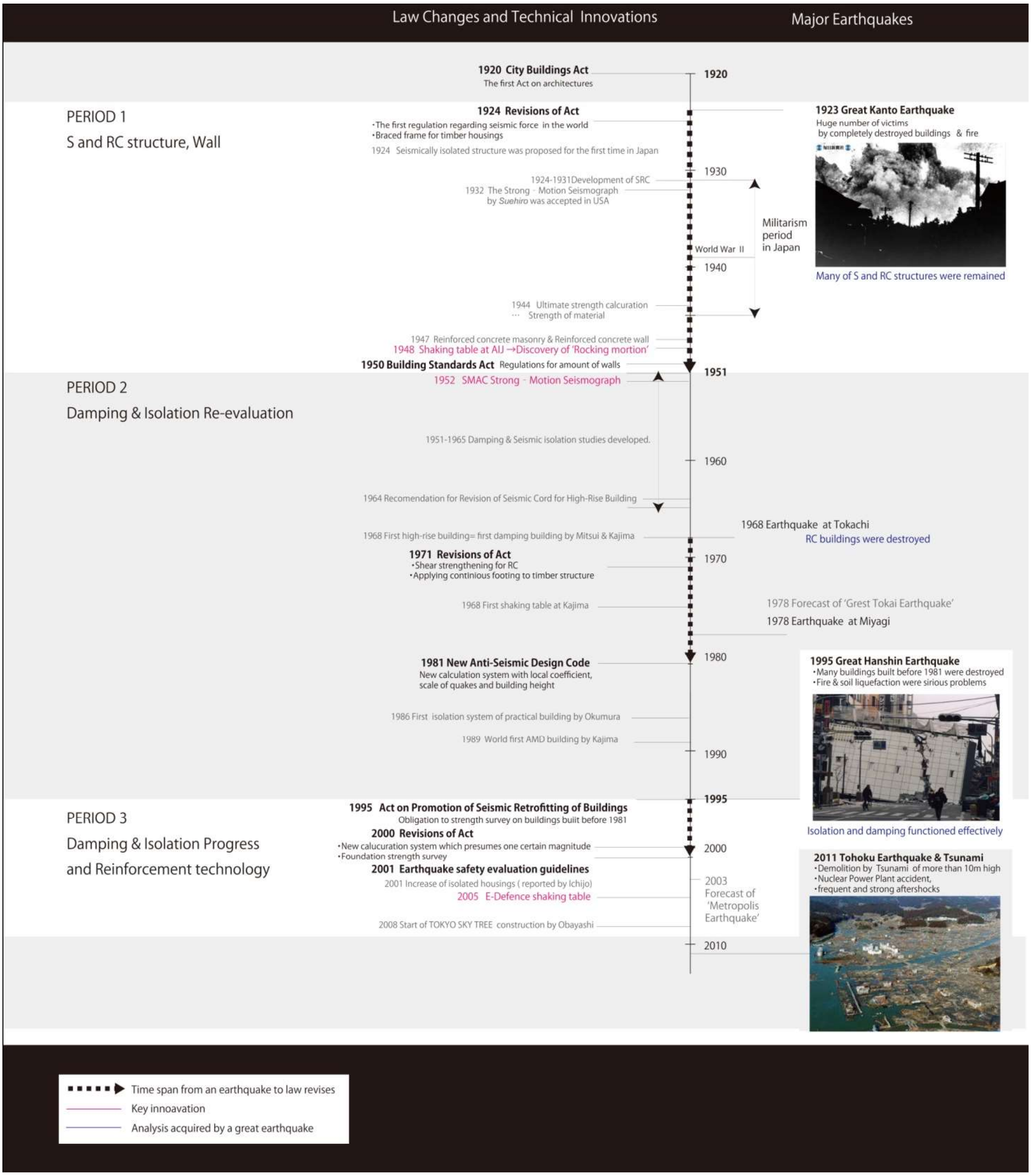

Figure 08: *After each major disaster in Japan the time span between disaster and Innovations that enter the market (Law Changes and Technical Innovations) became shorter.*

In case of the periods whose triggers are great earthquakes, the existing technologies which have survived are immediately and strongly supported to widespread by Acts. Period 2 was distinguished from others in the point of that the trigger was the new key technologies. It can shorten the re-evaluation cycle of existing technologies without waiting next disasters and even poses subjects that researchers have never expected. It means the technological paradigm brought by key technologies has more possibilities to invent brand-new ways and to step up from stereotype technologies. In addition, mature researches are to reflect them to Act revises. The time table shows:

- Act changes related to earthquake technologies (Figure 8, Left Side)
- Major earthquakes since 1920 (Figure 8, Right Side)

It sorts the Japanese the history of earthquake resistance technologies into three innovation periods:

- **Period 1 (1923-1950):** S and RC structure, wall brought by Great Kanto Earthquake.
- **Period 2 (1951-1994):** Damping & Isolation Re-evaluation brought by two key technologies for experimental and basic studies, Shaking table and SMAC strong-motion seismograph.
- **Period 3 (1995-2010):** Damping & Isolation Progress and Reinforcement technology brought by Great Hanshin Earthquake.

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5. Conclusion

Despite being built in a seismically highly active area, the Tokyo Sky Tree is one of the safest buildings ever built. This has been enabled by integration along the value chain and a fusion of intelligent land development, cutting edge performance, clever structural design, advanced damper technology and high-quality. The investment into the tower was enabled by intelligent value creation through multi-use development. Further, the form of the tower is the result of a complex performance oriented overlay of several requirements concerning stability, use, production requirements and appearance. Traditional architectural know-how known from Pagodas (“Shimbashira-Seishin”) has been used, adjusted and finally been merged with new technologies. In order to ensure precision and and efficient embedding of the development and design parameters into the real building, Obayashi constructed the Tokyo Sky Tree by using sub-systems of its Automated Building Construction System (ABCS). The Tokyo Sky Tree thus not only is a landmark but also a symbol for Japan being able to apply advanced technologies not only in the building itself but also during the construction process. Further, the project shows how to re-use and evolve traditional principles as the “shimbashira” principle and conjoin it with cutting edge damper technology. Ever since struck by frequent earthquake disasters, tsunamis, taifuns, fires and war destruction, Japan not only overcame those disasters but obviously used them as a reason to develop new technologies and strategies (chapter 6). Frequent disasters are surely one reason why Japans construction industry is so advanced today. So it is scientifically proven, that war destruction and earth quake destruction supported the progress of Japans advanced and highly automated prefabrication industry. Further, the high quality homes that home makers as Sekisui House, Daiwa House and Sekisui Heim offer are the outcome of a demand for safe taifun and earthquake resistant homes. The demand for obligatory earthquake resistance makes especially the construction of non-residential building expensive. Companies as Obayashi, Kajima, Shimizum, Takenaka and also smaller firms that have to do with engineering or construction of buildings spend enormous sums on research and development of new, and efficient earthquake resistance technologies. Given that facts, it can be assumed that Japan again takes the March 2011 disaster (earthquake, tsunami, nuclear incident) as a reason to advance traditional as well as the state-of-the-art technologies for disaster prevention: In 2-5 years, after intensive research and development which usually follows disasters in Japan, it is highly possible that Japan produces new cutting edge disaster prevention technologies.

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- **Figure 01:** Self-created graphic
- **Figure 02:** Photo Prof. Bock
- **Figure 03:** Left: taken from Desho-sha Website: http://www.densho-sha.co.jp/kiritsuma.html, last visited 06/04/2011, Right: http://science.discovery.com/videos/what-the-ancients-knew-ii-shorts-japanese-construction.html, last visited 22/06/2011
- **Figure 04 & 05:** Prof. Suematsu, Nagoya and Prof. Atstushi Ueda Book (ISBN 4-10-600491-7) (by courtesy of Prof. Suematsu and Prof. Atstushi)
- **Figure 06:** Self-created graphic according to http://www.skytree-obayashi.com/, last visited 22/07/2011
- **Figure 07:** Figures taken from, “The ABCS System” Video, Riverside Sumida Bachelor Dormitory, Tokyo, 1993