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Review of Various Aspects of Seismically Safe Tall Buildings

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ABSTRACT

Tall building developments have been rapidly increasing worldwide. While the early design of tall buildings culminated with the dominance of the International Style, today's pluralism in architectural design has produced tall buildings of many different forms, including more complex forms, such as twisted, tilted, tapered and free forms. This paper reviews the evolution of tall building's structural systems. The use of "ductile seismic frames," whose proper seismic behavior largely depends upon construction details and specific design rules. . The superior structural properties of box-type wall structures with respect to conventional frame structures envisage a change of paradigm from actual "ductility-based" Earthquake Engineering (centered on frame structures) toward 100% safe buildings through a "strength-based" design exploiting the use of box-type wall-based structures. Finally, the future of structural developments in tall buildings is envisioned briefly.

Keywords: Damping systems, Tall buildings, seismic-proof buildings, developing countries, ductility based seismic design, RC Shear Wall.

I. INTRODUCTION

As science stands now, predicting the precise location, time and magnitude of earthquakes is not possible. However, the regions that are more vulnerable to quakes are well known. Much like the subduction zone off Sumatra, the Himalayan belt, in particular, is a seismically active region. As recently witnessed in Nepal and parts of India, the 7.8 magnitude **earthquake** ended up killing thousands of people. The culprit was unsafe buildings. After all, earthquakes do not kill, unsafe buildings do.

When an earthquake strikes, the ground shakes violently, depending on several factors like the magnitude, the depth of the focus and the nature of soil. In some rare cases involving sandy soils in the presence of ground water, the soil can suddenly behave like quick's and causing buildings to sink or tilt and collapse. In such regions, buildings should be either supported on pile foundations resting on hard strata or should be constructed after suitable ground improvement measures are undertaken. In hilly terrains (as in the Himalayan regions), landslides are likely to be triggered, bringing down buildings located on the unstable slopes. Slope stabilizing measures can help to some extent to arrest the damage.

Even if the soil and foundations in a structure are safe, collapse of a building can occur if it does not have adequate strength to resist the horizontal forces that are generated during an earthquake. Also, there should be adequate ductility, which is the ability of the structure to deform without collapsing during the earthquake. For this, it is important to ensure that the connections at the various interfaces of building components remain intact during the shaking. The seismic forces generated increase with the mass and the height of the building.

Unlike buildings that have a basement, those built on stilts — with no walls in the ground storey — are more likely to collapse, as evidenced during the 2001 Gujarat earthquake. The structural instability is triggered by yielding in the ground storey columns, causing the upper storeys to come crashing down. In this case, the vertical walls of the building do not reach the ground; they suddenly end at the first floor of the building. (AMLAN K. SENGUPTA and DEVDAS MENON, Professors, Department of Civil Engineering, IIT Madras)

Figure 1. Building raised on stilts-with no walls in the ground storey —collapsed.

II. SEISMIC-PROOF BUILDINGS IN DEVELOPING COUNTRIES

According to the World Bank—Global Facility for Disaster Reduction and Recovery, in the last decades, low- and middle-income countries have experienced 53% of all disasters globally but have accounted for 93% of disaster-related fatalities. Often, disasters such as earthquakes, tsunamis, cyclones, and flooding disproportionately impact poor populations living in unsafe buildings and areas more exposed to these natural hazards, which are likely to increase in frequency and intensity in the future (Moullier and Krimgold, 2015). Dramatic consequences in terms of human safety were caused by the collapse of numerous RC school buildings in China during the earthquakes that stroke the Sichuan region in 2008 (more than 10,000 students died for a total 69,000 lives lost) (Yin et al., 2009).

III. DAMPING TECHNOLOGIES FOR TALL BUILDINGS: NEW TRENDS

Tall buildings have become a prominent solution for increasing density in major cities around the world. The trend of the last so many years is to build taller, slimmer, and lighter structures. Indeed, the latest advancements in high-strength materials, with the same modulus of elasticity (i.e. less stiff structures) and construction methods have lead to more efficient solutions (Ali and Moon, 2007). However, these lighter systems could lead to structures more prone to vibrations, which can cause discomfort, damages, and eventually, structural failure.

Taller and slimmer buildings need to withstand a variety of external forces that are different from those of low-rise constructions, and, as a consequence, different structural solutions need to be used. Moreover, many major cities are threatened by a variety of extreme events such as earthquakes and strong winds. Motion control of tall buildings, therefore, should take into consideration both static and dynamic loads. This can be accomplished by increasing the structural stiffness and damping while keeping the material amount at a minimum.. Increasing damping, instead, can mainly be achieved by installing auxiliary damping devices, since the damping characteristics of the main structural system (i.e. inherent damping) is quite uncertain until the building is complete (Smith et al., 2010)

There are also several examples of innovative solutions adopted only for tall buildings, and among all, the most relevant are:

- Inclusion of dampers in outrigger systems. (Ahn et al. 2004; Smith and Willford, 2007; Joung and Kim, 2011; and Asai et al., 2013).
- Dampers in shear walls. The paper by Madsen et al. (2003) introduces dampers in shear walls, even though this solution was already proposed for low-rise building. In recent years, several papers have discussed their application for tall buildings (e.g. Pant et al., 2015).

- Adjacent buildings equipped with dampers (Bharti et al., 2010). These are utilized to reduce and avoid the possible pounding between abjection buildings.
- Double skin façade as mass damper (Lago et al., 2010; Moon, 2011; and Fu, 2013). Double skin façades can be utilized as a structural motion control device in tall buildings. Two different strategies have been developed (Moon, 2011): one with low connection stiffness between inner and outer skins together with a damping mechanism, and one with inserting additional masses in the cavities of the double skin façade that could act as distributed tuned mass dampers.
- Self Mass Damper (SMD; Kidokoro, 2008). Based on a project completed in Tokyo in 2007, and inspired by the pendulum movement of an antique clock, this system utilizes the existing mass of the building to act as a mass damper without adding any additional mass. The author explains how the system is created by disconnecting the upper floors via a system of sliders and high-damping rubber bearings.

Another important feature, peculiar to tall buildings, is higher modes of vibration contribution. These frequency characteristics of tall buildings can be very relevant for the design of passive damping systems (Lago, 2010; and Au et al., 2012). This is particularly true for mass damper systems since they are tuned to the building's first mode of vibration.

In addition to these innovative damping solutions, auxiliary damping has also been used quite extensively in the retrofit of existing tall buildings. As an example, the 54-story Shinjuku Center Building in Tokyo has been retrofitted with deformation dependent oil dampers to overcome problems in the existing building's structural capacity under long-period ground motions (Aono et al., 2011).

Seismic retrofit of high-rise building with deformation-dependent oil-dampers (Aono et al., 2011) treats the problem of long-period ground motion on existing high-rise buildings in Japan. To overcome this problem the authors suggest that the most advantageous solution is to utilize a deformation-dependent oil damper that eliminates the requirements of additional reinforcement in those areas where these devices are installed (which is typical when other devices are utilized). Indeed, this damper limits its force when the frame deformation comes close to its limit. The proposed solution has been utilized in a 54-story office building in Japan (Shinjuku Center Building). Dynamic analyses under long-period earthquakes were conducted and compared with the observed response during the 2011 earthquake off the Pacific coast of Tohoku. The results show the good agreement between the model and the real response.

IV. FRAME STRUCTURES: DUCTILITY-BASED SEISMIC DESIGN

Masonry-wall constructions have been used for at least 10,000 years to build a variety of constructions such as dwellings, public buildings, and monuments. Up to the mid nineteenth century, masonry constructions were the most used construction system all over the world, until the introduction, with the Industrial Revolution, of new construction materials such as steel and concrete, which allowed the development of a new construction system: the frame. The first frame building structures were realized during the reconstruction of the city of Chicago after the "Great Fire" of 1871. The new tall steel buildings made the city be known as the "Skyscraper City." These first frame structures were realized using steel frames braced by diagonal elements providing the required strength and stiffness against wind loads. Figure 2 shows the "Unity" building, a steel frame built in Chicago in 1892, as well as the "Monadnock" Building, the tallest masonry building ever constructed, which was also built in Chicago.

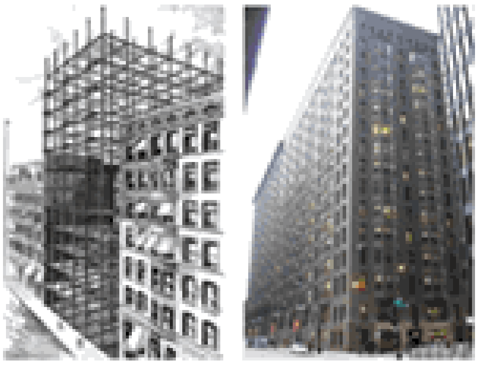

Figure 2. From the left: Unity Building, Chicago (courtesy of Chicago History Museum); Monadnock Building, Chicago (courtesy of David K. Staub).

During the 1971 San Fernando Earthquake, RC frame structures experienced large inelastic responses and severe damages, thus highlighting their inherent insufficient strength capabilities and the need of large ductility to ensure a good seismic behavior. The conceptual breakthrough that paved the way toward current trends in Earthquake Engineering is represented by the design approach proposed by the SEAOC Vision 2000 Committee (1995), known under the name of Performance-Based Seismic Design (PBSD), followed by actual research trends in Direct Displacement-Based Design procedures (Bertero and Bertero, 2002; Priestley et al., 2007). The new design philosophies are grounded on the full exploitation of the non-linear deformation capacities, thus requiring a complete knowledge of structural and non-structural components behaviors. Furthermore, these issues appear even more relevant when dealing with buildings to be designed and constructed in developing countries.

V. SEISMIC BEHAVIOR OF RC SHEAR WALL STRUCTURES

Since the use of shear wall buildings is not predominant in most earthquake-prone countries (USA, Europe), researchers did not pay too much attention in the study of the seismic response of RC wall structures, especially for the case of low-rise buildings, realized with squat RC walls (Hidalgo et al., 2002). Despite the low amount of research works devoted to wall structures, buildings made by shear walls showed quite superior performances during strong earthquakes, such as the ones which stroke Chile on March 3rd, 1985 (Wood, 1991) and February 27th, 2010 (Carpenter et al., 2011).

Shear walls are typically designed to exhibit a ductile behavior (Synge et al., 1980; Paulay et al., 1982) by ensuring the ultimate shear strength being higher than the shear corresponding to develop flexural yielding in the vertical boundary reinforcement of the walls. In such a case, the shear walls would develop a ductile flexural mode of failure, thus even ensuring inelastic resources in the case of severe earthquakes.

VI. RC SANDWICH WALL BUILDINGS DESIGNED IN INDIA

In 2016, a residential complex made of 4-storey buildings to be realized in Mumbai (India) has been designed by a local company in partnership with Nidyon Costruzioni srl using the sandwich panel technology presented in the previous section. The typical building is made of eight apartments per floor for a total number of 32 apartments per building. Each apartment has a total surface of 47 m^2 as shown in Figure 3.The construction cost of the building can be estimated around 6500Rs/m^2 and is in line with that of conventional residential buildings: the average construction cost to build a residential house including materials and labor cost with average finishes and bathroom/electrical accessories is around 20000 Rs./m^2 (Approx.).

Figure 3. Typical apartment and typical floor of the residential buildings designed in Mumbai

VII. CONCLUSION

This paper has presented a general review of structural systems for tall buildings. There is much we can do to protect our buildings and thus save lives. It is possible today to assess the vulnerability of any building to earthquake, and, wherever possible, to undertake retrofit measures to make it safe.

A box-type wall structures envisage a change of paradigm from the actual “ductility-based” Earthquake Engineering (centered on frame structures) toward a “strength-based” design, exploiting the use of box-type wall-based structures even for the case of low-rise buildings. Indeed, the use of this solution can easily yield to almost 100% safe buildings against earthquake, e.g., earthquake proof buildings. A stiffer building can be achieved with a proper selection of the structural configuration. Tubes, diagrids, and core-supported outrigger structures could be considered more optimal solutions than others.

The extent of damage to buildings depends not only on the magnitude of the earthquake, but also on the type of construction practice followed in a particular region or country. By 2050, it is expected that one billion new dwelling units will be required to house the world’s growing population, thus the issue of making safe and regulated building practices is one of the main challenges for the next future.

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