Seismic Design of High-rise Buildings

by Akira Wada, Professor Emeritus, Tokyo Institute of Technology; Chairman of CTBUH Japanese Group

Development of Seismic Engineering in Japan

In 1924, one year after the Great Kanto Earthquake that devastated Tokyo, Professor Toshikata Sano (1880-1956) added to the Urban Building Law a new requirement: the static horizontal seismic factor should be set as 0.1 or more. Ten years later, Professor Ryo Tanabashi (1907-1974) published an article in July 1934 stating that the seismic resistance of a structure cannot be adequately assessed simply by providing ample strength against a static horizontal force; he contended that the seismic impact should be expressed using the energy squared by the maximum ground velocity and that the resisting capacity of a structure should be assessed using the strain energy absorbed by the structure itself. In March of the same year, he suggested that research should be started on the construction, even in earthquake-prone Japan, of super high-rise buildings like those seen in New York.

In the postwar period, Professor Tanabashi insisted through his article published in April 1963 that high-rise building should be possible in Japan in light of the following examples: given that seismic motion works on small and large structures with identical amplitudes, a flower vase might fall over in an earthquake, but a large high-rise building would not, even if both objects were proportionally identical. In other words, contrary to small boats, large ships are resistant to capsizing in rough seas.

Around the same time, Professor Kiyoshi Muto (1903-1989) promoted research on a high-rise building for the Tokyo Station. While his effort in this case was not rewarded, the Hotel New Otani was completed in Tokyo in 1964 with a building height surpassing 45 meters. In 1968, the Mitsui-Kasumigaseki Building designed by Prof. Muto, was completed as Japan's first high-rise building to surpass 100 meters in height. On every story of the building frame, precast concrete walls with many vertical slits were incorporated to maintain their initial structural stiffness while absorbing energy during a strong earthquake. Accordingly, it can be said that the concept of passive-controlled structures was already being applied at the initial stage of high-rise building in Japan.

Introduction of Advanced Seismic Design

Entering the 1970s, most high-rise buildings were constructed using a seismic design method that relied on the plastic rotation capacity of steel-frame beam ends to provide energy absorption. However, several structural designers believed such designs would leave these buildings with residual deformation in frames subjected to large plastic deformation, thereby making restoration difficult. In response to this, the concept of damage-controlled design began to grow (refer to the figure below). The Northridge Earthquake of January 1994 and the Great Hanshin Earthquake of January 1995 caused fracture phenomena in many steel-structure beam-ends, resulting in considerable concern about the feasibility of restoring damaged buildings.

In Japan, following implementation of the New Seismic Design Codes in June 1981, extensive research has been conducted on seismic-isolation structures. In 1995 a seismic-isolation structure was put into practical use that adopted energy-absorption members such as steel and lead dampers along with employing laminated rubber bearings as elastic supporting members. Since then, another concept has been increasingly applied whereby the beam-column frames of high-rise buildings bear vertical loads in a manner similar to the laminated rubber bearings in seismic-isolation structures. This design produces mainly elastic behavior during an earthquake so that the seismic energy is absorbed by the energy absorbing members incorporated in the framing of each floor.

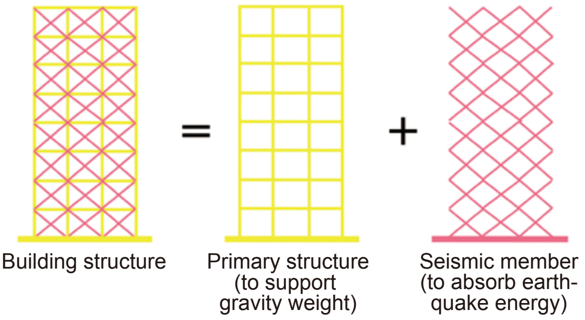
Enhanced Seismic Resistance

In addition to the seismic designs mentioned above, the seismic safety of high-rise steel structures is steadily being enhanced due to following factors: higher strength and sufficient ductility of steel materials, the provision of upper and lower limits for yield stresses, progress in welding technology and the adoption of haunches to prevent the plasticization of beam-end welds. Another contributing factor is the utilization of column members with stiffness and strength that are made possible by the use of concrete-filled tubular columns manufactured by filling square or circular steel tubes with concrete.

In addition, remarkable progress in computer-aided structural analysis technology makes it possible to use dynamic response analysis that can accurately treat the dynamic behavior of columns, beams, shear walls and various dampers. This, in turn, has resulted in the construction of high-rise buildings with complex framing and super high-rise buildings with heights reaching 300 meters.

The Great East Japan Earthquake that occurred on March 31, 2011, produced large amplitudes and long-duration vibrations in high-rise buildings not only in Sendai near the epicenter but also in Tokyo, Osaka and Nagoya. Earthquake ground motion is recorded by means of acceleration, and response analysis for seismic design is conducted by inputting the recorded ground motion. However, because the acceleration of the long-period component included in ground motion is much lower than that of the short-period component, certain problems have emerged *vis-à-vis* the occurrence of unexpected large vibrations in buildings located far from an epicenter. These large vibrations are due to the following two reasons: 1) the earthquake ground motion is not accurately included in the acceleration records applied in conventional design; and 2) Earthquake ground motion is commonly applied for 30 seconds duration in the response calculation. However, tall structures with limited damping capacity that are subjected to long-term ground motion with a period of 4 seconds or more exhibit synchronized large vibrations after this 30 seconds until 600 seconds. To cope with this problem, existing high-rise buildings have been retrofitted with seismic energy absorption members. ■

Damage-controlled Structure



Advanced High-rise Building Technologies in Japan

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By Akira Wada, Emeritus Professor, Tokyo Institute of Technology

日本の超高層建築／耐震設計

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関東大震災起きた次の1924年に、その数年前から施行されていた市街地建築物法の規則に、佐野利器は静的水平震度を0.1以上とすべきと書き加えた。これから10年が過ぎ、棚橋　諒は、構造物の耐震性は静的水平力に対して構造物の強度を確保することだけでは不十分であり、地震力を最大速度の二乗のエネルギーで表し、構造物の抵抗力は構造物の持つ靭性が吸収する歪エネルギーで評価すべきであると「建築学研究」（1934年7月号）に書いている。同じ年の「建築と社会」の3月号には、地震国の日本においてもニューヨークのような超高層建築を建設することについて、研究を始めるべきであると訴えている。戦後になり「カラム」（1963年4月号）において、地震動は小さなものにも大きなものにも同じ振幅で作用するから、花瓶のような小さなものは倒れるが、同じプロポーションであっても大きな超高層建築が花瓶のように倒れることは無い、小さなボートは荒海で転覆するが、大きな船は耐えられることを例に挙げ、超高層建築は日本でも建設できることを主張している。

同じころ、武藤　清は東京駅ビルの超高層化に関する研究を推進しており、これは実現しなかったが、東京オリンピック（1964年10月）の開催に合わせて建設された四谷のニューオータニホテルが高さ45mを越える建築として竣工した。1968年には三井霞が関ビルが日本で初めて100mを越える超高層建築として竣工し、この骨組の各層には、縦方向に多くのスリットを前もって入れたプレキャストコンクリート壁が初期剛性の確保と地震時のエネルギー吸収部材として組み込まれた。このように、初期の超高層建築には、制振構造の考え方が取り入れられていたといえる。

1970年代に入り、鉄骨梁の材端の塑性回転能力によるエネルギー吸収に期待した耐震設計法を使った超高層建築が普及し、骨組にエネルギー吸収部材を組み込むことはあまり行われなくなった。ただ、この設計法で作られた超高層建築の場合、大地震動を受けると大きな塑性変形を受けた骨組に残留変形が残り、その後の修復は難しいであろうと考える設計者が現れ、損傷制御設計の考え方が芽生えてきた。1994年1月のノースリッジ地震、1995年1月の兵庫県南部地震において、多くの鉄骨構造物の梁端に破断現象が生じ、この心配が現実になった。

我国では1981年6月に施行された新耐震設計法以降、免震構造への研究が盛んになり、1995年には弾性支持部材としての積層ゴム支承と鋼材や鉛を利用したエネルギー吸収部材を用いた免震構造が実用化していた。超高層建築の柱・梁の骨組は、免震構造の積層ゴム支承のように鉛直荷重を受け持ち地震時には弾性挙動を主とし、各層の骨組に組込んだエネルギー吸収部材に地震時のエネルギーを吸収させようとする考え方が多く使われるようになってきた。

このような設計法の進歩とともに、鋼材の高強度化と靭性の確保、降伏点に上下限を持たせたこと、溶接技術の進歩、梁の材端の溶接部を塑性化させないための水平ハンチの活用などにより、鋼構造による超高層建築の安全性は高まっている。角形鋼管や円形鋼管の内部にコンクリートを流し込むCFTの実用化により、剛性と強度を高めた柱部材が活用されるようになったことも大きな進歩である。

これらに加え、コンピュータによる構造解析技術の進歩も目覚ましく、柱・梁・耐震壁・各種のダンパーの力学的挙動を正確に扱った動的応答解析が可能になり、複雑な骨組の超高層建築、高さが300mにも達する超高層建築が実現してきている。

2011年3月11日に起きた東北地方太平洋沖地震では、震源地に近い仙台だけでなく東京・名古屋・大阪などに建つ超高層建築に大きな振幅かつ長い時間の揺れが起きた。地震動は加速度で記録し、これらを入力として耐震設計のための応答解析を行うが、地震動に含まれる長周期成分の加速度は短周期成分の加速度に比べて非常に小さいため、従来の設計に用いられていた加速度記録には正しく含まれていないこと、さらに、応答計算に用いる地震動の継続時間が30秒程度では、周期が4秒以上で減衰が小さな構造物が長周期成分の加速度により同調振動を起こすまでには至らないことなどが原因となり、思いのほかの揺れが生じたことが問題となっている。これらに対処するために、既存の超高層建築に地震時のエネルギー吸収部材を組込むことが必要になっている。