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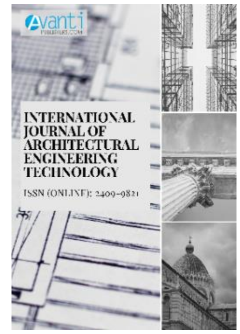

High Rise Buildings: Design, Analysis, and Safety – An Overview

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ABSTRACT

High-rise buildings have been rapidly increasing worldwide due to insufficient land availability in populated areas and their primary role as essential buildings in modern cities and capitals. However, high-rise buildings are very complicated due to the huge number of structural components and elements unlike low-rise buildings, as well as these high-rise buildings demand high structural stability for safety and design requirements. This paper aims to provide brief information about high-rise buildings regarding the basic definition, safety features, structural stability, and design challenges. A brief description of existing structural systems that are available in the literature is presented to articulate a technical issue that has been widely reported, named, adopting an effective structural system for resisting lateral loads resulting from wind and seismic activities. Consequently, a general overview is presented that covers the behavior of various structural systems for different heights of high-rise buildings by implementing a number of nonlinear static procedure analyses (pushover) and nonlinear dynamic procedure analyses (for wind and earthquake loading). Finally, a critical review of the available simplified model and seismic energy base design are also presented. This paper is intended to help in the development and application of construction systems for high-rise buildings in the future.

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1. Introduction

High-rise buildings investment projects (towers) reflect a component of the economic power of the country and a sign of its feature. A number of countries seek to achieve their progression by motivating the preparation of comprehensive plans to construct high-rise investment projects to enhance their prestige and economic power. In countries like Malaysia, Hong Kong, the USA, UK, Japan, etc funding such projects is a substantial component of their success. Varied and large investments are conducted after preparing serious feasibility studies to make sure that such projects accomplish the targeted gains at the state and economic levels for investors. These studies have been done through careful investigation of the architectural, planning, marketing, and financial aspects. Country's progression is effectuated through planning, economic and urban progress; It is the most significant reason that encourages technological advancement by seeking to utilize the latest systems and materials. All those factors assist in attracting capital sources into the country. With the end of the 20th century, numerous countries started to make progression by preparing comprehensive plans to construct high-rise investment projects with the developments of many principles and standards to guarantee the success of these plans. Most of the Arab Gulf states, Hong Kong, and Malaysia have begun such procedures in order to enhance the country at several levels where feasibility studies played an important role in investigating all elements and factors that affect the project and the success level of the investing companies. High-rise buildings began in old Rome with its four-story woody residence buildings. Then, such residence buildings have been built utilizing brick units. In the 19th century, in North America, the Monadnock Building has been built in Chicago in 1891 out of sixteen stories utilizing the load-bearing wall constructing method. As construction methods advanced, buildings ongoing to increase in high, reaching 60 stories in 1913 with the construction of the Woolworth Building in New York. High-rise buildings remain attractive for constructors throughout the time. Due to their extraordinary presence in the built environment, high-rise buildings have a particular importance and visible feature owing to their height, clearness and domination over other elements of the landscape [1]. Figure **1** shows the high-rise buildings worldwide.

Figure 1: High-rise buildings worldwide [2].

2. Basic Definition

Engineering Design Consultant (EDC) defines a tall building as a building having a height of 35 m or greater, divided at uniform intervals into accessible levels. To be count as a tall building, the tower should be constructed on solid flooring and fabricated over its entire height through a thoughtful process. High rise building (tower) can be defined as a building that has an overall height exceeding 36 m or more than 12 stories and its usage varying between administrative, residential or as a hotel. Except for height, it is always a relative issue and the building could not be defined utilizing the expression of height only, as the judgment of the building is based on the surrounding environmental conditions, so it is impossible to set an accurate definition of high-rise buildings. However, from a structural point of view, it could be known as the building whose height can be influenced by side loads resulting from wind and earthquake activities to the range that those loads would play a primary role in the design process [1].

Marsono [2] defined a Tall building as "A building in which tallness strongly influences planning, design and use" or "a building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period". A tall building can be defined as a high-rise building by the following guidelines:

- It should be divided into numerous floors, not less than 2 m high.
- In case it has less than twelve of these internal floors, the highest unpartitioned portion should not override 50% of the overall height.
- Unclear portions of levels like stairs may not be counted as floors for eligibility purposes in this definition.

Every method of structural support that conforms to this definition is permissible, whether it is concrete, masonry, or metal frame [3].

2.1. Minimum Height

The cutoff between the tall building and other buildings is 35 m in height. This high has been specified relying on the original 12-story cutoff, utilized based on the following justifications:

- Typically, at least twelve stories are necessary to fulfill a physical existence that gains the term "high-rise".
- The twelve-story cutoff exemplifies an adjustment between the aspiration and manageability for the global database.

2.2. Safety Features of Tall Building

The safety of tall buildings is the most important problem in construction. All of the design codes and safety criteria should be practiced in construction. The unanticipated collapse of the World Trade Center towers has motivated to re-examine the way exit systems are designed for high-rise buildings. The current design designates a specific number, breadth and spacing of stairways that relied on the supposed occupant weight and building usage. The exit system on each story is sized for the number of occupants of that story, indicating the presumption that high-rise buildings will be vacated through partial or phased evacuation procedures. While discussing the demand for designing the simultaneous evacuation of tall buildings, concerns were raised about the sufficiency of depending just on stairways to vacate huge numbers of people from a great height. It is anticipated that if the design of future buildings is required for simultaneous evacuation under existing exit design procedures, there would be a building height beyond which stairways will occupy a significant portion of floor area that such buildings would be unpractical. Therefore, to achieve a safe tall structure, we should be careful about all problems in order to find out a perfect structure for design, construction, appearance, and architecture and to use it for constructing tall buildings in the future [4].

3. Design Issues

In structures that were constructed at the beginning of the twentieth century, structural elements were supposed to sustain mainly gravitational loading. Nowadays, owing to advances in structural systems/designs and high-strength materials, the weight of the building has been significantly reduced and slenderness is increased, necessitating that lateral loads such as earthquake and wind should be taken into account in the design processes. Lateral loading generated by earthquake and wind actions is yet predominant in design consideration. It must strictly control the lateral displacement of these buildings, not only for the safety and comfort of the occupants but furthermore to eliminate secondary structural impacts. Recently, there are several structural systems, like rigid frame [5], braced frame [6], shear-walled frame [7], frame-tube [8], braced-tube [9], bundled-tube [10] and outrigger [11] systems that have been utilized to improve the lateral resistance in high-rise buildings.

The effects of horizontal loads on a building rise exponentially with its high, in comparison to vertical loads. Designers have recently developed a variety of framing systems for tall buildings over the last four decades to reduce the use of materials. Generally, frame tube systems are quite acceptable in high-rise buildings as an economic framework through a wide variety of heights for buildings. [12-22]. In its simple design, the structure consisted of spaced outer columns over the perimeter connected via deep girders on each level. This results in a system of fixedly linked jointed orthogonal frame panels that form a rectangular tube that functions as a cantilever hollow box based on classic beam theory as shown in Figure **2**.

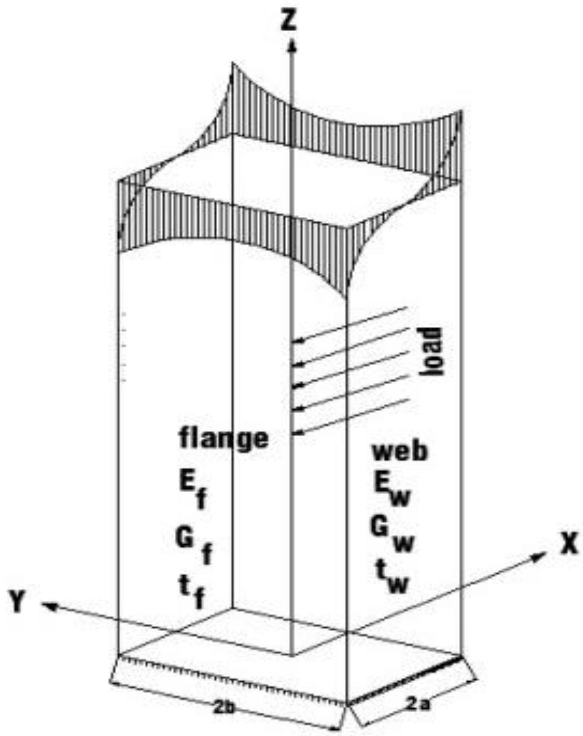
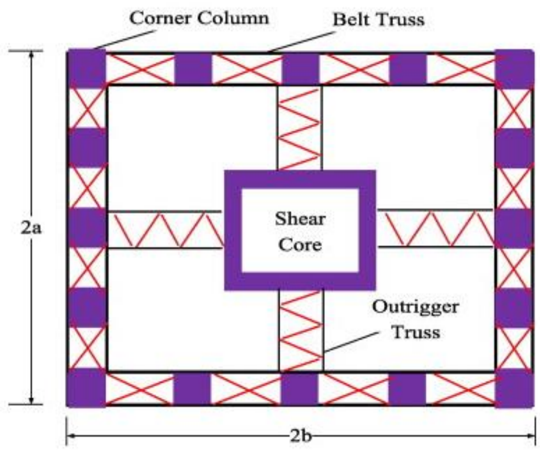


Figure 2: Framed tube: Orthotropic membrane tube and axial stresses distribution [23].

The overturning moment of the lateral load is withstood by the axial stress in the four framed panel columns, while the shear forces caused by the horizontal load are withstood by in-plane bending of the columns and beam of two side frames. In case that frame elements are extremely rigid, it is possible to count the axial stresses in the columns resulting from the overturning moment employing the accepted presumption "plane sections remain plane". Due to the shear lag phenomenon, having the influence of raising the axial stresses in corner columns and reducing axial stresses in inner columns whilst decreasing the structure lateral stiffness, shear and flexural flexibility of frame elements complicates the bending action of the basic beam for the framed tube [16].

There have been developments in a variety of simplified methods of analysis. Khan and Amin [19] indicated that the effects of shear lag can be approximated for very elementary design purposes through considering the framed tube structure as a couple of equivalent channels, each with an efficient flange breadth of no greater than half width of web panel or greater than 10 percent of structure high. Chan *et al.* [12] suggested evaluating the effects of shear lag in cantilever systems with solid shear walls as web panels and fixedly connected beam-column frames as flange panels by considering the distributions of axial deformations as parabolic or hyperbolic cosine form over the width of flange panels. Coull *et al.* [14, 15] established an orthotropic membrane analogy to transform the framework panels into equivalent orthotropic membranes each with flexible characteristics selected for representing the shear and axial behaviors of the real frame. Khan and Smith [18] also established an orthotropic membrane analogy for a simplified analysis of framework panels through performing FEM for determining the membrane's equivalent elastic characteristics. Later, Ha *et al.* [17] furthermore established an orthotropic membrane analogy for incorporation of shearing deformations of frame elements and beam-column joint deformations in deriving equivalent elastic characteristics. Their analogy seems to be more sophisticated and thus more concise than others.

The outrigger system as a novel and efficacious structural system consists of a centric core, inclusive of either shear walls or braced frames, with horizontal “outrigger” girders or trusses connecting the core to the outer columns as shown in Figures **3** and **4**. Moreover, in most conditions, outer columns are connected to each other via an external belt girder. To achieve sufficient rigidity, the outriggers and belt girders must be at least one and sometimes two floors deep. Hence, they are normally placed at factory levels to minimize the impediment they create [23]. A comprehensive survey about outrigger and belt-truss systems in skyscrapers can be found elsewhere in the literature [24].



Figures 3: Schematic plan of combined system [23].

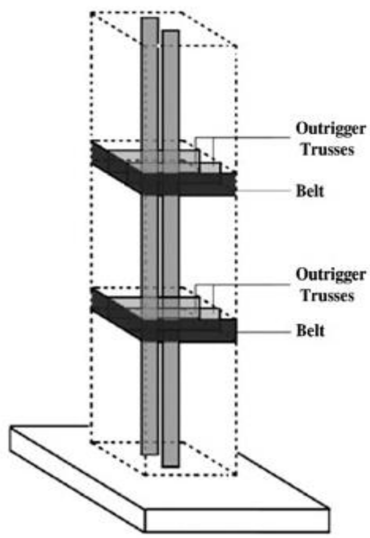


Figure 4: Outriggers system [23].

4. Structural Stability

An essential consideration in structural design is to ensure the stability subject to any kind of load conditions. All structures undergo several shape changes under loading. In a stable structure, the deformations caused by a loading are usually small, and internal forces are produced by load action that tends to return the structure to its original shape after the load is removed. In an unstable structure, the deformations generated by loading are massive and usually tend to increase continually as long as the loads are applied. In contrast, an unstable structure will not induce internal forces that tend to return the structure to its original shape. Unstable structures oftentimes collapse instantly and completely when subjected to loading. It is the primary responsibility of the structural designer to ensure that the proposed structure in fact constitutes a stable configuration. Figure **5** could be a good example of the frame structure instability undergoing horizontal loading. Any horizontal loading can result in deformation and it is obviously shown that the structure does not have the capacity to withstand the horizontal loading and does not have any mechanism that tends to return it to its original configuration shape after removing the horizontal loading [25]. There are a few existing methods to improve structural stability. The methods are steel plates shear walls, strip model, and steel bracing model.

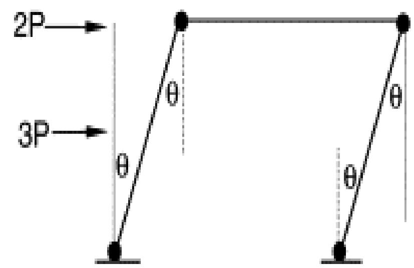


Figure 5: Instability of frame structure under horizontal loads [26].

4.1. Steel Plate Shear Walls

A "steel plate shear wall" consists of thin steel sheets confined by steel beams and columns that could be multi-story in height and width of one or more bays, with either simple shear or moment-resisting beam-to-column connection. This system is an economical and effective way to resist horizontal loads on structures under earthquake and wind activities [27]. Steel plate shear walls were utilized for buildings in Japan and the United States. The steel plate shear wall system has also been used instead of a moment-resistant frame when the alternative is RC walls as the steel plate-system provides low foundation cost. "Steel plate shear walls" provide the upcoming further features; the speed of erection and increasing the usable area [28]. In the current practice of design, the wall capacity is restricted to the elastic buckling strength of its plate panels [29].

4.2. Strip Model

The strip model is shown in Figure **6**. It was developed for steel plate shear walls by Thorburn *et al.* [30], who realized that the infill plate buckling does not reflect the ultimate capacity for the system and that the inclined tension field controls the post-buckling behaviors. The tensile yield strength for plate material is perceived to be the limiting stress and the pre-buckling shear strength of the infill plate will be ignored. The boundary beams are infinitely rigid that indicates the existence of opposing tension fields below and above the modeled panels. The strip model has been utilized as an accurate analytical tool to compare predicted results from the model with the experimental result [28].

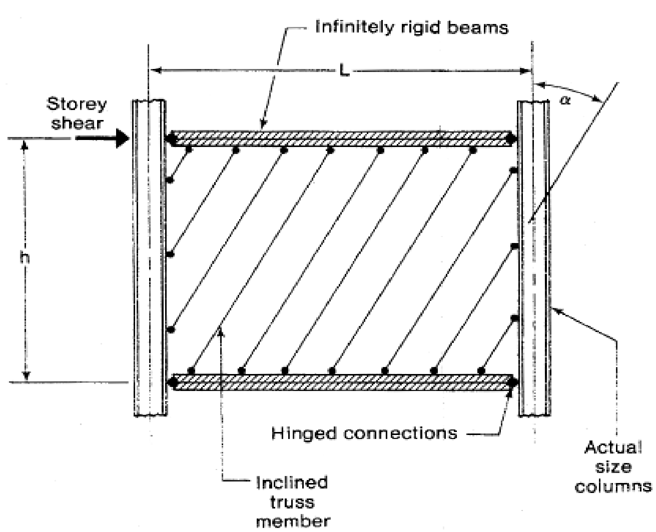


Figure 6: Strip model as shear wall [30].

4.3. Steel Bracing Model

Steel bracing system as diagonal bracing for seismically inadequate steel frame or reinforced concrete frame is examined to provide stiffening and strengthening to existing buildings against lateral loading due to seismic activities and sometimes the building could be braced as a preventative measure or as part of repairing construction after seismic damage. A steel braced frame is an effective structural system for structures subjected to lateral seismic or wind loading. In steel braced frames, columns and beams with steel braces act the same as vertical and horizontal truss elements [31].

5. Linear and Non-Linear Analysis

In the linear analysis, the material is presumed to be unyielding and there is no load movement because it is based on an undeformed formation and has no iteration process. The calculation for obtaining the results is further not as intricate as the 2nd order analysis. Linear analysis is also known as 1st order analysis. In the nonlinear analysis, effects of finite deformation and displacement of the system are computed to formulate the equilibrium equations. Figure **7** shows a straight elastic bar with vertical and horizontal loading at the bar edge. The axial force (P) acting on top of the bar was moved following the displacement in the deformed shape that was used for next iteration process due to the presence of lateral force (αP). Distance from b to b' represents the displacement, L refers to the length of the bar. This only happens in nonlinear analysis which is also called 2nd order analysis [32].

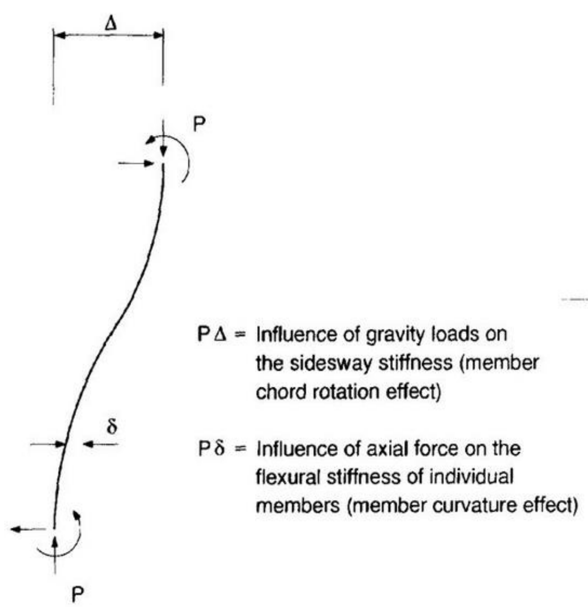


Figure 7: Schematic drawing of the bar with 2nd order effects [33].

According to Cook *et al*. [34], in structural mechanics, the kinds of nonlinearity involve the following criteria:

- Material nonlinearity, in which the properties of materials are functions of the state of strain or stress. Examples involve nonlinear elasticity, creep, and plasticity.
- Geometric nonlinearity or second-order effect, in which the deformation is large enough that the equilibrium equation must be written regarding the deformed structural geometry. Furthermore, the load may shift the position as it increases.

6. Wind Loading

There are several instances where structures have failed owing to an instability that needs second-order analysis (P-Delta). One of the problems resulted from wind loading. The wind induces outward and inward pressures that act on the surfaces of buildings, relying on the surface orientation like the flat. This pressure increases elevation in parts of the building, obligating the building to isolate if it is too weak to withstand wind loading. Thus, the most essential thing for overcoming this issue is that the connection between column and beam in a frame that is rigid or pin-ended must be taken into account for a rational design. It will be structural instability, which means losing some situation and approaching failure like swaying and buckling if the structure could not bear a certain loading, whether from imposed, dead, or wind loading, and further natural hazards like earthquakes [35]. According to Ankireddi and Yang [36], wind load is assumed to be increased gradually along building height as shown in Figure **8**. Whereas BS EN 1991-1-4:2005 [37] allows 50% reduction and acts at the center of the building to simplify the analysis. The load is assumed to be static load which makes the structure simple to evaluate even most software have the capability to analyze the structure due to dynamic load. These two different ways of calculating the lateral load comes from wind effect and would give a significant difference in P–Delta analysis outcomes.

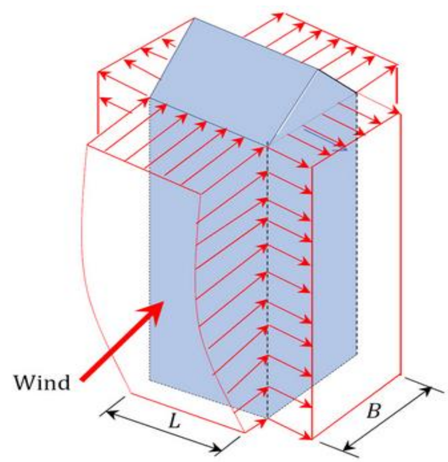


Figure 8: Wind loads act on the surface of the building [38].

Wind direction is also important and could not be predicted on a structure during its lifetime. Wen [39] believes that doubt in wind direction still has not been seriously studied until now. Wind direction should be considered especially for structures that are critical to wind direction like high-rise buildings and suspension bridges. The impact of wind direction should be investigated to determine the perfect direction for the building to be constructed so as to reduce the horizontal load and at the same time, the deflection to the structure will be reduced.

The wind speed on the construction site could not be ignored owing to the fact that it will affect in the long or short term without any warning such as collapse if the structure is very weak. This already happened in Hurricane Frederic east of Pascagoula, Mississippi on September 12, 1979. This incident resulted in damages to buildings, power lines, and trees in communities located in coastal areas. High wind speed can also result in the breaking of windows and other glass products which may endanger human health. According to Mehta *et al.* [40], wind speed estimate was based largely on an indirect approach. An alternate approach and convenient equipment have to be conducted to obtain comprehensive wind data. Both studies previously discussed provide evidence that wind speed and wind direction contribute greatly to deflection in tall building structures. This is due to the width and length of the building, and the wind speed could also increase the horizontal load amount.

7. Pushover Analysis

Since past decades, pushover or nonlinear static analysis has gained much interest within seismic engineering society [41]. However, utilizing this method for unsymmetrical-plan or high-rise buildings has a significant disadvantage since it is restricted to a single-mode response. Improved pushover methods have been extended to effectively deal with this limitation. Over the past two decades, modal pushover analysis (MPA) [42] , incremental response spectrum analysis (IRSA) [43], upper-bound push over analysis [44], adaptive modal combination (AMC) procedure [45], and the extended N2 method [46] have been suggested for including higher-modes effects in estimation of seismic behaviors of high-rise buildings. The consecutive modal pushover (CMP) procedure [47] has been proposed employing the single- and multi-stage nonlinear static analysis as well. Seismic responses have been gained via envelope peak responses obtained from single- and multi-stage pushover analysis as long as it is conceivable to implement various pushover analyses and enveloping the outcomes. In the procedure of CMP, multi-stage pushover analysis controls seismic responses on the middle and top floors of high-rise buildings, while responses are controlled in the lower floors by single-stage pushover analyses. The CMP procedure has been demonstrated to be effective in estimating the seismic requirements for tall buildings, especially plastic hinges rotation. In another study, multi-modal pushover approaches including the modal pushover with elastic higher modes and the consecutive modal pushover (CMP) and single-mode pushover approaches involving N2 (2004) and ASCE 41 [48] coefficient methods have been assessed for a diversity of buildings kinds [49]. In the case of short buildings, it should be well known that the CMP procedure only involves a single-stage pushover analyses, and multi-stage pushover analysis is not performed. Moreover, buildings with an unsymmetrical-plan with an irregular distribution of stiffness or mass, undergo seismic activity and probably encounter torsional rotations coupled with translational [50].

8. Simplified Model and Seismic Energy

By the meaning of increasing growth of super-tall buildings ("super-tall is defined as a building over 300 meters in height by the Council on Tall Buildings and Urban Habitat" (CTBUH Height Criteria)), the seismic design for these buildings has turned into a serious research matter in earthquake community. Various investigations were carried out recently employing FEM modeling of super-tall buildings for simulating nonlinear and linear seismic responses and identifying the possible collapse progress. Lu *et al.* [51] developed a simplified FEM model for Shanghai World Financial Center (its overall height is roughly 492 meters) by utilizing ANSYS software. They investigated the seismic responses subjected to various earthquake excitements and contrasted the calculated responses with the experimental data of a shaking table test having a 1:50 scale. Fan *et al.* [52] also developed the FEM model for Taipei 101 Building (overall height is about 508 meters) using ANSYS and investigated the seismic behavior subjected to different intensity seismic loads. Lu *et al.* [53] generated a simplified FEM model for Shanghai Tower (its overall height is about 632 meters) using MARC software [54] and anticipated the possible collapse progress and failure modes due to severe earthquake excitements. Jiang *et al.* [55] further established the FEM model for Shanghai Tower by ABAQUS software, investigated the structural responses and the distribution of structural damage subjected to frequented earthquake, design level earthquake, and maximum considered earthquake (MCE) in an Intensity 7 Region designated in Chinese Code for the Seismic Design of Buildings (GB50011-2010) [56]. In a similar way, Poon *et al.* [21] developed a FEM model for Shanghai Tower using Perform 3D and implemented the time-history analysis subjected to 7 ground motion records, representing the 2,475-year return period of earthquakes.

Currently, it is a quite acceptable practice to utilize FEM modeling for super-tall buildings for estimating their seismic responses and identifying a possible collapse progress. Nevertheless, super-tall buildings contain several components that result in a huge number of elements in FEM modeling. The required computational workload for generating a refined FEM model and implementing the sequent time-history analyses, parametric analyses, or dynamic incremental analyses (IDA) is overwhelming. Thus, it is mandatory to create simplified models which could present main nonlinear properties for super-tall buildings as well as could successfully minimize modeling and computational efforts. Despite the fact that few studies have been reported on developing simplified models for super-tall buildings, numerous investigators have carried out researches to develop simplified models for traditional tall buildings. For instance, Connor and Pouangare [13] suggested a simplified model for designing and analyzing elastic responses of a framed tube structure under lateral static loading. Encina and de la Llera [57] presented a wide-column model for simulating both time-history and modal responses for shear wall structures having free plan layouts. Meftah *et al.* [58] introduced a simplified model for seismical analyses of an asymmetrical building having regular features over its height, and simplified formulas for internal forces and circular frequencies under earthquake excitations were gained depending on the D'Alembert principles.

Furthermore, the energy-based design method was vastly utilized in seismic structural design [59-61]. One of the main aims of seismic design is effectually dissipating energy in target structural elements for ensuring the entire building's safety. Recently, a great deal of investigations has been done on the plastic energy dissipating capabilities for frame, shear wall, and frame-shear wall structures. For instance, in order to evaluate the energy dissipating capabilities of a set of multiple degree of freedom structures (MDOF) with various stress stiffness ratios, strength levels and damping ratios, Leger and Dussault [62] utilized analogous viscous dampers for representing the seismic energy dissipation via hysterical behavior and other non-yielding mechanisms. Lee and Bruneau [63] investigated the energy dissipating capability of compression elements in concentrically braced frames using the experimental data. Plastic energy dissipating capabilities of steel beams suffer ductile fracture subjected to different loading dates have been assessed by Jiao *et al.* [64]. In a similar manner, Miao *et al.* [65] investigated the mechanism of energy dissipation in RC frame-coupled shear wall structures with various span/depth ratios in coupling beams. Regarding boom super-tall buildings, the mega system is mostly accepted and commonly the dimensions for those elements are unusually large. Accordingly, the mechanical properties of this system, the plastic energy dissipation of those quite large structural elements, and the trends of plastic energy distribution over buildings heights are yet not distinctly understood. Few studies were found on plastic energy dissipation of large structural elements in super-tall buildings [66].

9. Conclusion

This paper has presented a general overview of high-rise buildings regarding basic definition, safety features, design issues, structural stability, linear and nonlinear analysis for both static and dynamic procedures resulting from wind and seismic activities. Brief descriptions of various structural systems that are available in both literature and the public domain are reported. In addition, a critical review of available simplified models and seismic energy base design are also presented. Moreover, this review could avail as a massive foundation for future works. Taking into consideration the growing attention in sustainable architecture that involves energy-efficient design, research on this design direction is expected to become quite significant to both practice and academia. The innovative and emerging systems could be frequently upgraded for the benefit of researchers and professional practitioners. As high-rise buildings are increasingly developed using lighter members, serviceability issues such as floor vibration, lateral sway, and occupant comfort must be paid greater attention by researchers. Innovative structural systems must be developed for the next generation of sustainable megastructures and ultra-high tall buildings.

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