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Design Optimization and Structural Performance Evaluation of High-Rise Buildings Using Braced Tube Systems

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Abstract
High-rise buildings present unique challenges in structural engineering due to increased lateral loads and stability concerns. This paper explores the design and structure performance study of high-rise buildings employing braced tube structures. The study investigates the behavior of braced tube systems under various load conditions, emphasizing their effectiveness to stay stable during wind and earthquake shaking. This work aims to explain how the structure works and holds up, design methodology & advantages of using braced tube systems in modern skyscrapers.

Overview
The rise of city development areas has driven the need for vertical construction, leading to the development of multistoried buildings. These structures require efficient systems to withstand Structural analysis of braced tube systems involves modeling complex interactions between axial loads, shear forces, and moments, typically using software like ETABS or SAP2000, in compliance with design codes. Braced tube structures, developed in the mid-20th century, offer a robust solution by integrating diagonal bracing within the exterior frame, enhancing stiffness and minimizing sway and for modern skyscrapers, combining engineering efficiency with architectural flexibility and aesthetic potential.
The structural performance of a G+20 storied building has been evaluated using ETABS 2015 software. The analysis incorporated various methods to assess the building's response to lateral loads, including static and dynamic earthquake forces, as well as wind forces. Dynamic earthquake analysis was conducted using the Response Spectrum method in accordance with IS 1893 (Part 1):2016 guidelines, which provides that offers a standardized approach for making structures safe from earthquakes in India. Wind load analysis followed the provisions of IS 875 (Part 3):2015, ensuring that the building's design accounts for wind pressures appropriate to its location and height. The structural design adhered to the specifications outlined in IS 800:2007, which governs the general construction and design of steel structures.
The main goal of this study is to find the best and most cost-effective way to protect buildings from side forces like wind and earthquakes particularly in regions susceptible to seismic and wind activities. By comparing different structural systems and their performance under specified loading conditions, the study aims to recommend a design approach that ensures both safety and cost-efficiency.

1. Advanced Structural Analysis and Optimization
Researchers employ advanced computational tools like Finite Element Analysis (FEA) to simulate and study how structures behave under various loads. Software such as MATLAB and ETABS enables

detailed modeling of tall and slender buildings, helping engineers identify potential weaknesses and optimize designs for improved performance and safety.

2. Optimizing Reinforced Concrete (RCC) Structures

Optimizing RCC structures involves iterative processes to achieve efficient and cost-effective designs. By understanding material properties and load distributions, engineers can minimize material usage while ensuring structural integrity. This approach leads to economical designs without compromising safety.

3. Enhancing Steel Structure Designs

Steel structures benefit from the material's strength and ductility, making them suitable for high-rise buildings. Optimization in steel structures focuses on exploring various design configurations and load-resisting mechanisms to enhance efficiency and safety. The inherent properties of steel allow for more straightforward optimization compared to RCC structures.

4. Seismic and Vibration Analysis

Understanding how structures respond to seismic activities and vibrations is crucial. Studies often focus on components like lead rubber bearing (LRB) isolators, which help take in and spread-out earthquake energy to lower the effect on buildings. Analyzing these effects ensures the development of structures that can withstand earthquakes and other dynamic forces.

5. Soil-Structure Interaction (SSI) Considerations

The interaction between a structure and the underlying soil significantly affects the building's performance, especially during seismic events. Research in this area examines how different soil types and conditions influence structural behavior. Incorporating SSI into design processes leads to more accurate assessments and safer structural designs.

Overview of Braced Tube Structures

Braced tube structures are an evolution of framed tube systems, incorporating diagonal braces to enhance structural integrity. The system forms a rigid three-dimensional structure by utilizing perimeter columns and closely spaced beams connected by diagonal bracing. This configuration allows the building to behave like a hollow tube, effectively resisting lateral loads through the exterior frame.

Design Considerations

- **Load Analysis:** Accurate estimation of dead loads, live loads, wind loads, and seismic loads is essential.
- **Material Selection:** High-strength steel and reinforced concrete are commonly used.
- **Bracing Configuration:** Different patterns such as X-bracing, K-bracing, and diagrid systems affect structural behavior.
- **Member Sizing:** Determined based on axial forces, bending moments, and buckling criteria.
- **Serviceability:** Drift limits, deflection, and human comfort are considered in design.

Structural Analysis Methodology

- **Modeling:** Structural modeling is conducted using software tools like ETABS, STAAD Pro, or SAP2000.
- **Load Application:** Loads are applied as per relevant codes (e.g., ASCE 7, Eurocode, IS 875).
- **Analysis Types:** Linear static, dynamic, and pushover analyses are performed.

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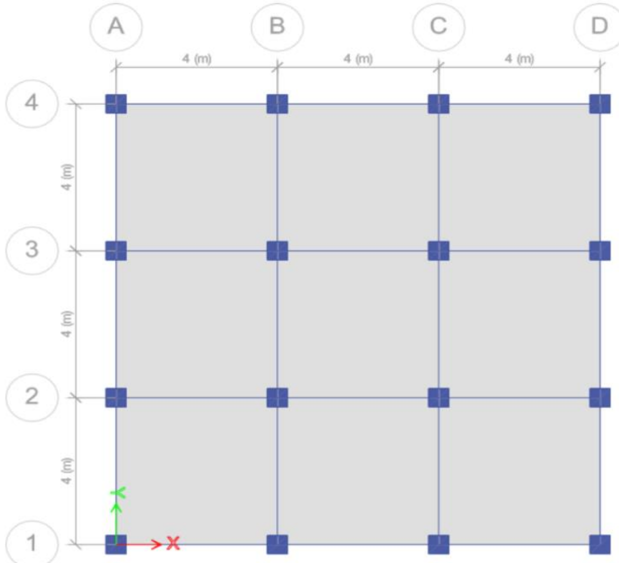


- **Performance Evaluation:** Key parameters like base force, movement, story shift and stress distribution are assessed.

Objective
This study aims to analyze and compare the performance of braced and bundled tube structural systems in a 21-story building subjected to wind and earthquake forces. Key parameters assessed include maximum displacement, Story shift, base force, and time duration and overall structural weight. The goal is to determine the most effective and economical System to resist side forces in tall buildings.

Numerical Study
In this paper, compares a 21-story building using X bracing systems with a building that has no bracing system. Here are some general data needed for the comparison.
General Data: -
Table -1 Properties and Data

Parameter	**Value**
Number of Stories	21
Height of each story	3m to all story
Plan Area	12m X 12m
Height of Structure	63m
Steel Grade	Fe 415
Concrete Grade	M30
Earthquake Load	As per IS:1893(Part-1) (Both Direction)
Slab Thickness	180 mm
Seismic Zone	V
Importance Factor	1.5
Response Reduction Factor	5
Type of Soil	2
Wind Load	IS:875(Part-3)-2015
Live Load	2 KN/M^2

Modeling of Building:-
This study uses ETABS software to analyze a building's response to earthquakes and wind. It examines key factors like how much each floor moves (story displacement), how much one floor moves relative to another (story drift), the total force at the base (base shear), the building's natural vibration time (time period), and the amount of steel used. Both static and dynamic methods are applied to identify weaknesses and improve the building's design for better safety and performance.

Fig 1 Plan of 21 story X Bracing Tube System

Fig 2 Elevation of X Bracing System

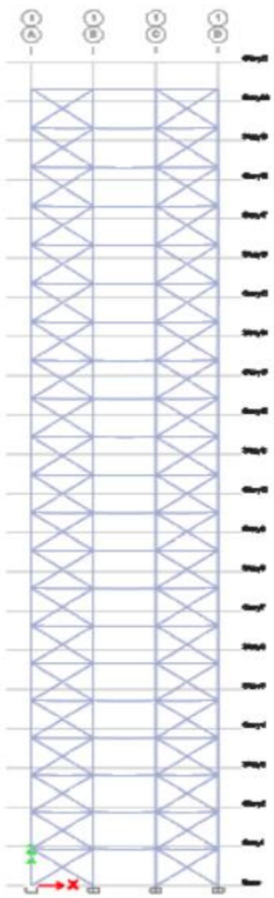
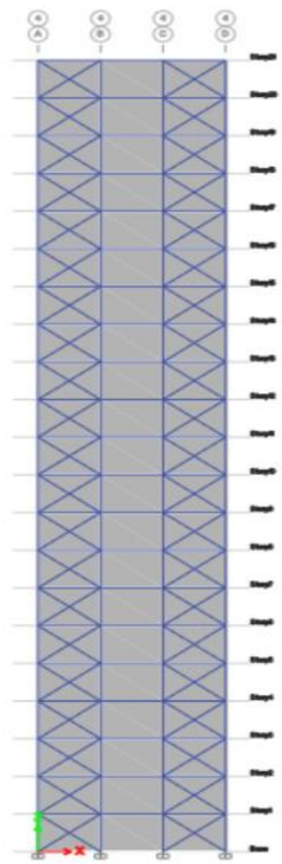


Fig 3 Elevation of X Bracing System



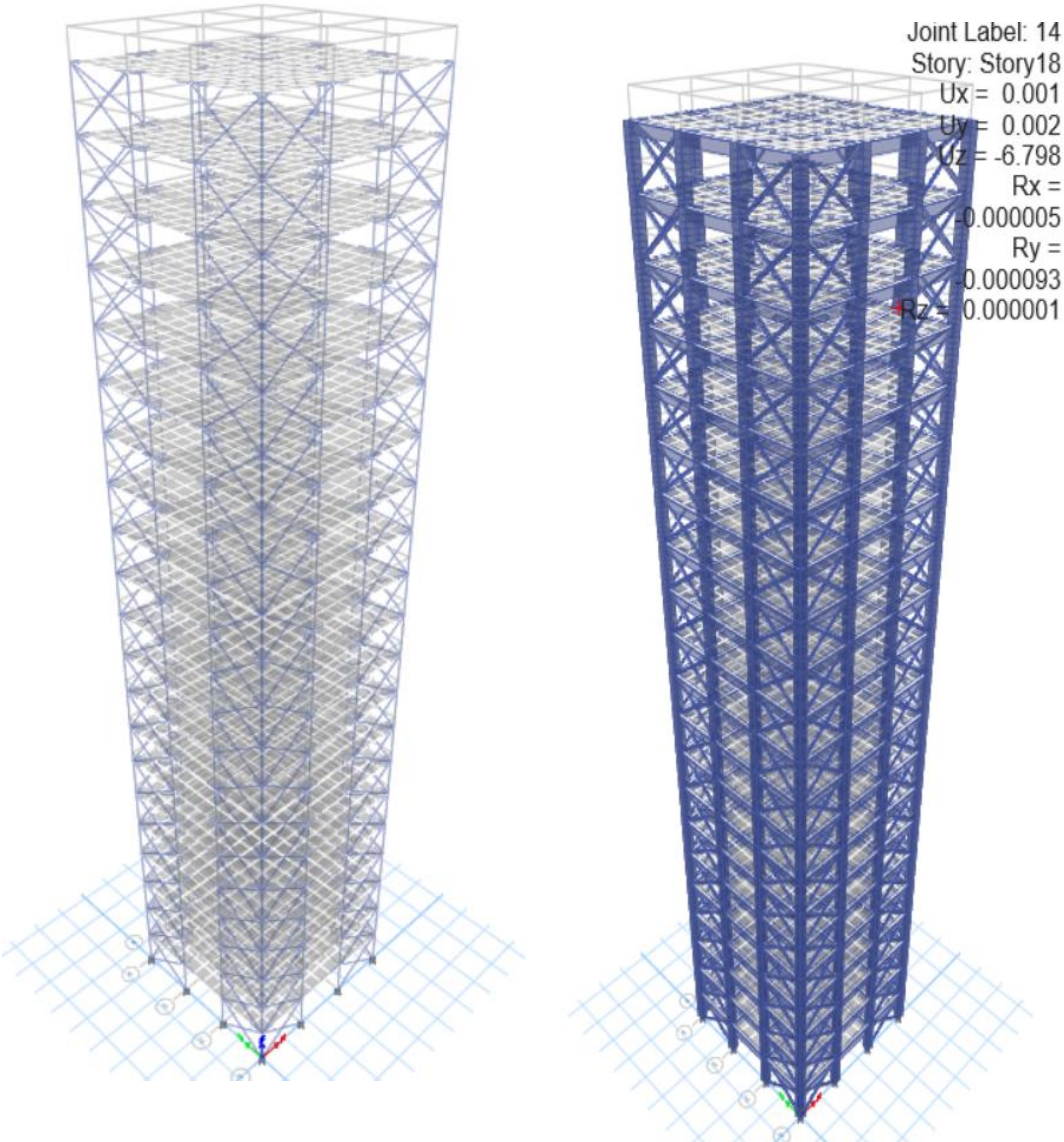


Fig 4. Dead Load Displacement

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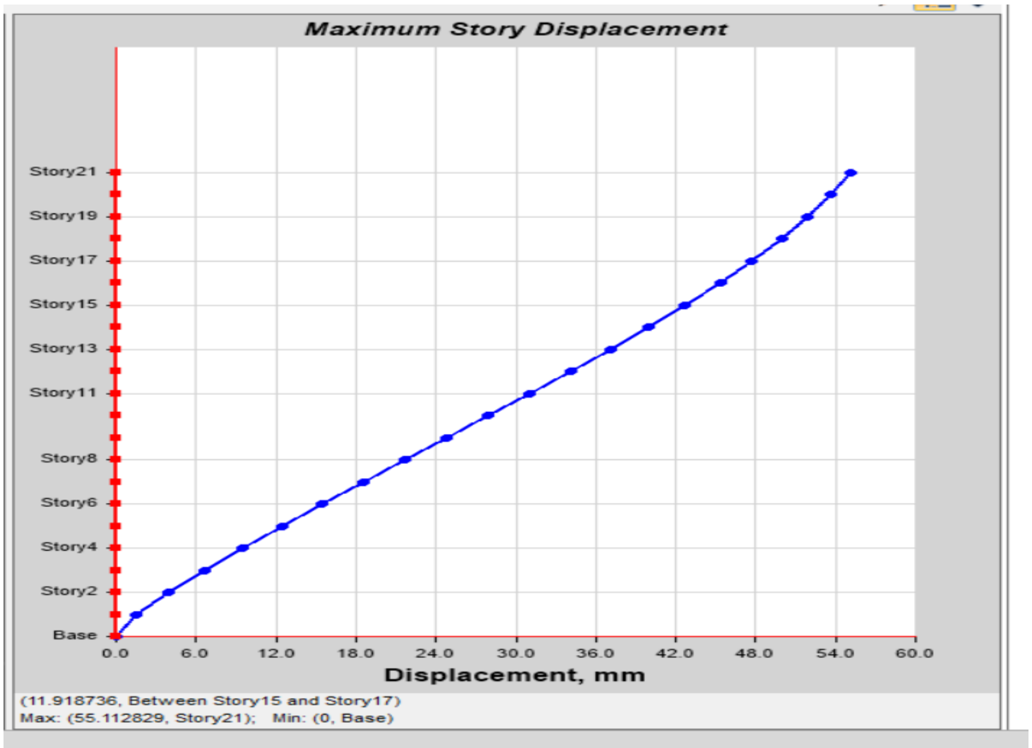
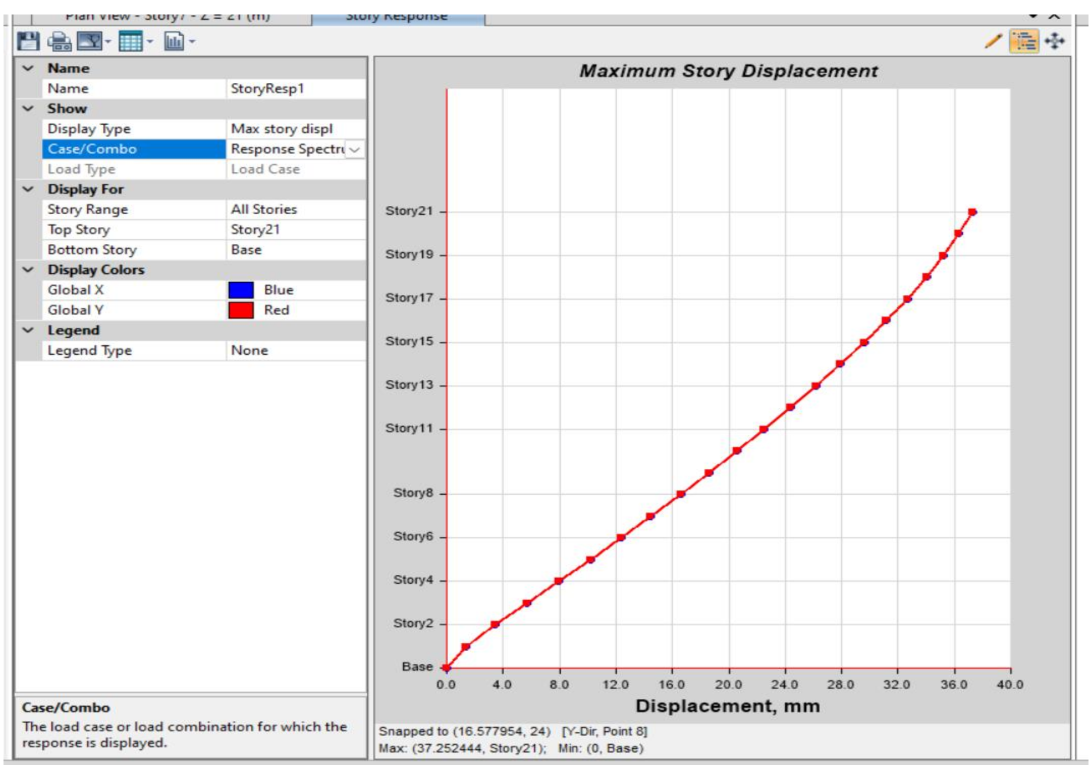
Result and Discussion



Story Maximum Displacement with “No Bracing”



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Maximum Story Displacement with "X Bracing"
Fig. 6 & 7 indicates that adding bracing reduces the maximum story displacement by approximately **32.41%**, enhancing the building's lateral stability.

Conclusion:
Implementing bracing in a 21-storey structure reduces the lateral displacement due to seismic forces by approximately **32.4%**, significantly enhancing the building's structural performance and stability.

Strength Comparison of Tube Structures (With Actual Values)

Type of Tube Structure	Lateral Stiffness (kN/m)	Torsional Rigidity (kNm/deg)	Axial Load Capacity (MN)	Max Drift (%)	Base Shear Capacity (kN)
Framed Tube	100,000 – 150,000	50,000 – 80,000	120 – 180	1.0 – 1.5	10,000 – 14,000
Braced Tube (X-Braced)	180,000 – 250,000	90,000 – 120,000	180 – 250	0.6 – 0.8	15,000 – 20,000
Diagrid Tube	250,000 – 350,000	140,000 – 180,000	200 – 300	0.3 – 0.5	18,000 – 25,000
Bundled Tube	220,000 – 300,000	100,000 – 150,000	250 – 400	0.4 – 0.7	16,000 – 22,000
Outrigger Tube	280,000 – 360,000	160,000 – 200,000	300 – 450	0.3 – 0.6	20,000 – 28,000

Standard specifications and IS codes for Braced tubes
(i) Material Specifications

Code	Title
IS 2062	Hot Rolled Low, Medium and High Tensile Structural Steel – Specification
IS 1161	Steel Tubes for Structural Purposes – Specification
IS 1786	High Strength Deformed Steel Bars for Concrete Reinforcement

(ii) Design and Structural Analysis

Code	Title
IS 800:2007	General Construction in Steel – Code of Practice
IS 456:2000	Plain and Reinforced Concrete – Code of Practice
IS 875 (Part 1 to 5)	Code of Practice for Design Loads (Dead, Live, Wind, Snow, etc.)
IS 1893 (Part 1): 2016	Guideline for Earthquake Resistant Design of Structures

(iii) 3. Wind and Seismic Loads

Code	Description
IS 875 Part 3:2015	Wind Loads – Method of calculation for buildings and structures
IS 1893:2016 (Part 1)	Seismic Load Calculation for General Buildings
IS 16700:2017	Criteria for Structural Safety of Tall Concrete Buildings (Important for >50 m)

Manufacturing of Braced Tube Structures for Tall Buildings

Manufacturing of braced tube structures for multistoried buildings involves a detailed and standardized process aimed at ensuring structural stability, durability, and precision. These structures rely on a combination of steel fabrication, welding, and assembly techniques to create diagonal bracing and perimeter frames, forming a stiff and load-resistant "tube" system.

Material selection is the first step, involving steel sections that are shaped through a hot-rolling process. (as per IS 2062), hollow structural sections (IS 4923), and reinforcing steel (IS 1786). Steel grades such as E250 and E350 are commonly chosen based on strength requirements. Structural shapes include H-beams, angles, channels, and circular or rectangular tubes.

The **fabrication process** includes CNC plasma or laser cutting of steel components, followed by drilling or slotting for bolted or welded connections. Diagonal braces are attached using MIG/MAG or arc welding, adhering to IS 816 and IS 9595. For efficiency, prefabricated braced panels are often assembled off-site and transported as modules.

Quality control measures include non-destructive testing (Ultrasonic and Radiographic) to verify weld integrity, along with dimensional checks to ensure compliance with design specifications. Steel components are coated with anti-corrosion and fire-resistant materials to extend their service life.

In the **site assembly phase**, prefabricated braced panels are transported to the construction site and lifted into position using cranes. Final connections are completed through on-site bolting (as per IS 3757 and IS 800) or welding.

Relevant IS codes that guide this process include **IS 2062, IS 800, IS 816, IS 9595, IS 4923, and IS 4759**, which cover material properties, fabrication, welding practices, and protective coatings. The braced tube system's modular approach ensures faster construction, cost-effectiveness, and high structural performance for modern skyscrapers.

Benefits of Braced Tubes over Other types of Tubes

Feature	**Braced Tube**	**Framed Tube**	**Tube-in-Tube**	**Bundled Tube**
Basic Concept	Exterior columns + diagonal bracing	Closely spaced exterior columns + deep spandrel beams	Inner core + outer frame both act as tubes	Several tubes bundled together
Lateral Load Resistance	High (due to diagonal bracing)	Moderate to high	High (core + frame share lateral loads)	Very high (multiple tubes increase stiffness)

Efficiency	Very efficient for wind and seismic loads	Less efficient compared to braced tube	Efficient, but depends on core design	Highly efficient; used for supertalls
Complexity of Construction	Moderate	Low to moderate	Moderate	High (irregular geometry & connections)
Material Usage	Less material due to efficient bracing	More materials (heavier frames)	Moderate	Depends on number of tubes used
Typical Height Range	Up to ~300 m (practical)	40–70 stories	40–80 stories	80+ stories (used in iconic towers like Willis Tower)
Examples	John Hancock Center, Chicago	DeWitt-Chestnut Apartments, Chicago	One Shell Plaza, Houston	Willis (Sears) Tower, Chicago

Examples where Braced Tubes used

John Hancock Center (875 North Michigan Avenue), Chicago, USA

- **Height:** 344 meters (1,128 ft)
- **Type:** X-braced tube structure
- **Significance:** One of the first buildings to use **exterior diagonal bracing** as a structural and architectural feature. A classic example of a **trussed tube system**.

Willis Tower (formerly Sears Tower), Chicago, USA

- **Height:** 442 meters (1,450 ft)
- **Type:** Bundled tube structure (closely related to braced tube)
- **Structural Concept:** Nine square tubes bundled together; some include internal bracing
- **Significance:** It was one of the tallest buildings on the planet back then.; revolutionized high-rise construction.

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