WTC Towers: Innovative Design Features and Structural Modeling

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Abstract

The National Institute of Standards and Technology (NIST) is undertaking the federal building and fire safety investigation of the World Trade Center (WTC) disaster. The objectives of this investigation are to: (1) determine why and how the World Trade Center Towers collapsed following the initial impacts of the aircraft and subsequent fires; (2) determine why the injuries and fatalities were so high or low depending on location including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response; (3) determine what procedures and practices were used in the design, construction, operation, and maintenance of the buildings; and (4) identify areas in current building and fire codes, standards, and practices that warrant revision. This paper presents innovative features that were incorporated in the design of the WTC towers and how the towers are modeled for structural analysis.

Keywords: Buildings; collapse; modeling; structures; World Trade Center

Introduction

The 110-story World Trade Center (WTC) towers were designed in the mid 1960's. Figure 1 shows the towers which were located at lower Manhattan, New York City. Although the towers were similar, they were not identical. The height of the north tower (WTC 1) at the roof level was 417 m above grade and the height of south tower (WTC 2) was 415 m. The north tower also supported a 110 m tall antenna. Both towers were approximately 63 m x 63 m square in plan (Fig. 2). On September 11, 2001, the WTC towers were attacked by hijacked Being 767 aircraft. The first aircraft struck WTC 1 at 8:46 a.m. (EDT) and the second aircraft struck WTC 2 at 9:03 a.m. (EDT). The impact of the airplanes caused severe damage to the buildings and significant fires. WTC 1 collapsed at 9:59 a.m. and WTC 2 at 10:29 a.m.

The structural design of the towers incorporated a number of innovative features to meet both architectural and structural demands. These features as well as techniques used to model the towers are presented below.

Innovative Structural Features

Several innovative structural concepts were incorporated in the design of the towers. They are presented below.

The design of high-rise buildings (over 40 stories) is generally controlled by wind loads. Since the early 1960's, a vertical tube-like structural system has been used for super high-rise buildings to resist lateral loads in any direction by cantilevering from the foundation. The tube system may be a framed tube with moment resisting frames where the columns are closely spaced, a three-dimensional diagonally braced tube, or a shear wall tube wherein shear walls are joined along their edges to form a tube-like structure. In the WTC towers, a framed-tube system was used. For a square framed tube, the columns in the windward side are in tension and the columns in the leeward side are in compression. The columns in the side walls function analogous to the web of a beam, in which the columns closer to the windward side are in tension where as the columns closer to the leeward side are in compression. Thus, the wind load on a framed-tubular building is resisted entirely by the columns. Although, in 1965, this structural system was used for a 43-story concrete building in Chicago prior to the WTC towers, the WTC towers were the first super high-rise steel buildings that incorporated the framed-tube concept.

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The perimeter structure consisted of closely spaced, built-up box columns. These columns extended from floor 9 to floor 107. Below floor 9 to the foundation the exterior columns change in size as well as geometry. From floor 9 and above, each building face consisted of 59 columns spaced at 1.02 m (see Fig 2). The columns were fabricated by welding plates of steel to form an approximately 0.36 m square section (see Fig. 3). Adjacent columns were interconnected at each floor level by deep spandrel plates, typically 1.32 m deep. In order to maintain the width of the exterior columns uniform, 14 different grades of steel ranging from 250 MPa to 690 MPa were specified, which is an innovative approach for a very tall building. Typical buildings use 2 or 3 different grades of steel for columns.

For the floor framing outside of the core area (Fig. 2), a composite long-span steel-truss system was used. This provided a large floor space uninterrupted with interior columns. Indeed, column-free space of 2875 m^2 was available for each floor. The composite trusses spanned 10.7 m in the short direction and 18.3 m in the long direction. Instead of using individual shear stud connectors, the web bar extending above the top chord and into the concrete slab (shear kneuckle) provided the shear connection between the concrete slab and the steel trusses (sees Fig. 4).

For the WTC towers, the design wind loads were based on model tests in a boundary-layer wind tunnel. In order to reduce wind-induced vibration, viscoelastic dampers were installed between the bottom chord of steel trusses and exterior wall columns (see Fig. 4).

Modeling of the WTC Towers

The primary structural systems in the global modeling of the towers includes exterior columns, spandrel beams, and bracing in the basement floors, core columns, core bracing at the mechanical floors, core bracing at the main lobby atrium levels, hat trusses, and the floor systems.

Global Models of the Towers

Three-dimensional structural analysis computer models of the 110-story above grade structure and 6-story below grade structure for each of the two towers were developed. The global models were used to establish the baseline performance of the towers under gravity and wind loads.

In establishing the modeling techniques for the global models, parametric studies were performed to evaluate the behavior of typical portions of the structure. In addition, once the models were completed, order-of-magnitude checks were performed for gravity load, wind load, and eigenvalue results to check the accuracy of the models.

The size of the global model is as follows:
Number of joints: 53,700
Degrees of freedom: 218,700
Number of frame elements: 73,900
Number of shell elements: 10,000.

The global model of WTC 1 is shown in Fig. 5.

Core Column Modeling

The core columns were modeled as frame members spanning from node to node at the representative floor elevations. The core column model is comprised of over 5000 nodes.

Exterior Wall Modeling

The global model of the towers is comprised of frame elements for the exterior columns and spandrel beams. In order to ensure that the global model properly captures the intended behavior of the exterior walls, a detailed shell element model was also developed of typical exterior panels to calibrate the results of the frame model. For that purpose, each plate of each column or spandrel was specifically modeled for the detailed shell element model. A simplified frame model was also developed (see Fig. 6). A parametric study of typical three-column, three-spandrel exterior wall panels from the face of the towers (floors 9 to 106) was performed using the two modeling methods. The objectives of the study were to (1) match the axial stiffness of the frame model with the detailed shell model under gravity load and (2) match the inter-story drift of the two models by modifying the rigidity of the column/spandrel intersections in the frame model. The parametric study assumed that the shell model best represents the as-built panel performance, and therefore, it was used to tune the performance of the frame model, which was used throughout the global model. In the study, the top of the three columns were loaded via a rigid link and displacements around the column- spandrel panel zone were compared. The study found that 50 % column rigidity and 100 % rigidity of the panel zone of the frame model produced displacement results consistent with the shell model.

Floor Framing Modeling

For the majority of floors in the global models, the rigid diaphragm model provided a sufficiently accurate representation of the flow of forces and deformations while keeping manageable the model's computational requirements.

For the beam-framed floors 3, 4, 5, 6, 7, 9, 41, 42, 43, 75, 76, 77, 107, 108, 109, 110, and roof, flexible diaphragms were inserted in the global model. Similar to the exterior wall modeling, a parametric study was used to develop a simplified model of the flexible floor diaphragm by comparing the performance of this simplified model against a detailed model of the floor. The detailed model of the floor includes all primary structural members of the floor, while the simplified model is a shell element representation of the floor. The material properties of the shell model matched the properties of the concrete floor outside the core in the respective floor model.

The flexible shell element model was calibrated against the truss-framed floor model. Both models are shown in Fig. 7. The models were subjected to an in-plane load on the windward and leeward faces. The column base supports were released for the exterior wall columns along the loaded faces and for all core columns to allow lateral translation only in the direction of loading.

The relative displacements between the windward and leeward sides were compared between the two models. The shell thickness was modified to match the in-plane stiffness determined by the detailed floor models.

Summary

This paper presented several innovative features that were incorporated in the design of the World Trade Center towers, and how the simplified structural models were developed to analyze the global behavior of the towers. These models were used to establish the structural capacity of the towers prior to the impact of aircrafts.

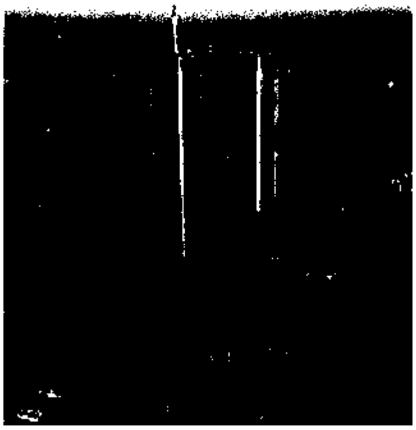


Fig.1. World Trade Center Towers.

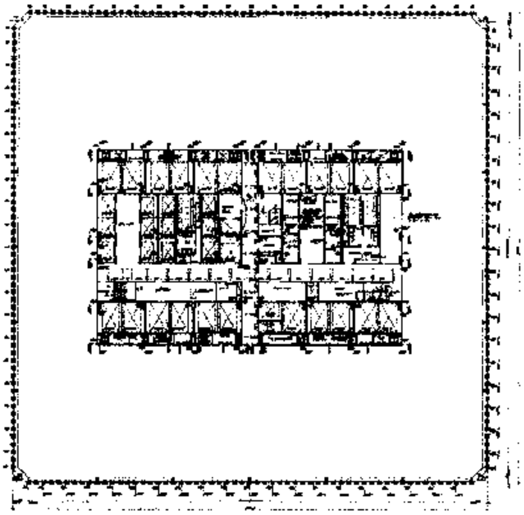
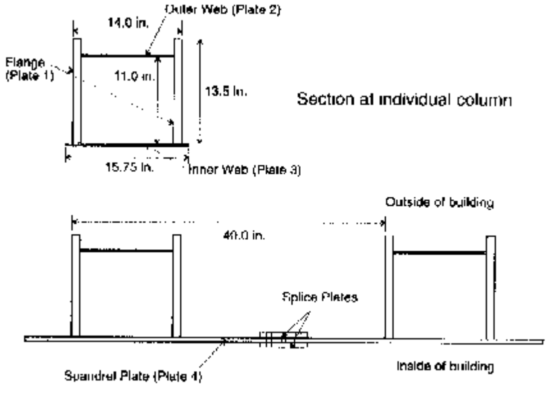


Figure 2 Typical floor plan



Section at individual column

Section at spandrel

Figure 3 Cross section of exterior column

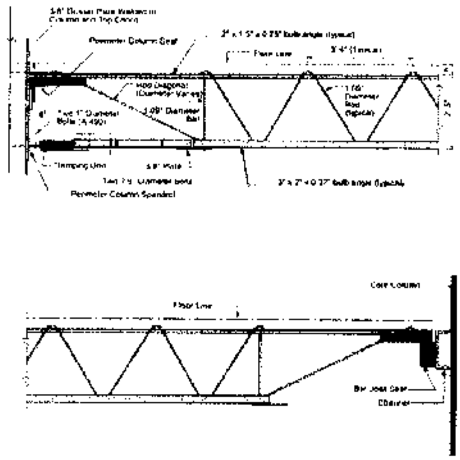


Figure 4 Steel truss details

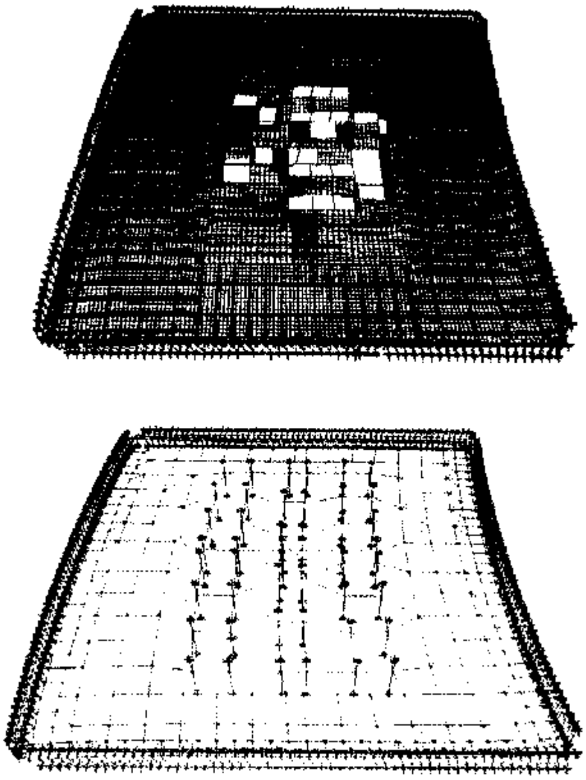


Figure 7 Deflections of trussed-framed model (top) and equivalent floor model (bottom)