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STEEL STRUCTURE NONLINEAR FEA SIMULATION PROVIDES INSIGHT INTO WORLD TRADE CENTER COLLAPSE

Researchers Reconstructing Collapse of World Trade Center Rely on MSC.Dytran and MSC.Marc Nonlinear Software to Understand Factors Causing the Collapse and Facilitate Changes to Building Codes.

OVERVIEW

Had the World Trade Center (WTC) collapsed in two hours, there would have been few if any casualties. Which has raised the question: Why did the WTC collapse in just one hour? And what changes can be made to the building code for high-rise buildings and bridges to prevent another occurrence?

As part of a research study, funded by Federal Emergency Management Agency (FEMA), researches from academia, government and private industry investigated the cause of the collapse of WTC building, Dr. Abolhassan Astaneh-Asl, professor of civil and environmental engineering at the University of California, Berkeley, under the Directorate of Engineering of the National Science Foundation (NSF), investigated the collapse of the World Trade Center. He was one of five expert witnesses invited to testify before the Committee on Science of the U.S. House of Representatives at the March 6, 2002 hearing, Learning from 9/11 – Understanding the Collapse of the World Trade Center. Dr. Astaneh-Asl's presentation included a movie of a simulated crash of a passenger aircraft onto a generic steel structure created with MSC.Dytran and MSC.Marc by the MSC.Software nonlinear group.

INVESTIGATION

The collapse of the WTC was caused by a series of very complex events, involving tremendous impact to the structure, fire explosion and resulting heat. Simulation of these events requires an advanced technology to accurately predict the nonlinear impact dynamics, failure and thermal effects. Most civil engineering analysis software is tailored to perform a basic static and dynamic analyses in compliance with the building codes which places limitations on its element technology, material models, failure and nonlinearity. Basically, civil engineering analysis software provides linear static, frequency and normal modes (earthquake) analyses of building structures and therefore is unsuitable for simulating the complex events at the WTC.

To show the feasibility of simulating such a complex event, MSC.Dytran was selected to analyze the initial impact of a Boeing 747 on to a generic steel structure. MSC.Dytran, which is based on an explicit technology, is very well suited for short duration events such as crashes, impact dynamics and explosions. MSC.Marc was selected for the thermal analysis because of its powerful heat transfer and thermo-mechanical analysis capabilities. Both MSC.Dytran and MSC.Marc provide nonlinear analysis of many different types of applications and are limited only by the end user system resources.

CREATING THE MODEL

Because of the limited time available to provide an initial analysis, a search of MSC.Software's past projects turned up the public domain geometry of a Boeing 747 with partially meshed wings and engines. MSC.Patran was used to add the fuselage and stiffeners, tail section, flooring and other major components, completing the finite element model of the B747. Concentrated masses were added in specific locations along the aircraft to represent the cargo, passenger weight distribution and fuel. The total weight of the aircraft was 304,000 kg.

A full mockup of the building was unnecessary, because of

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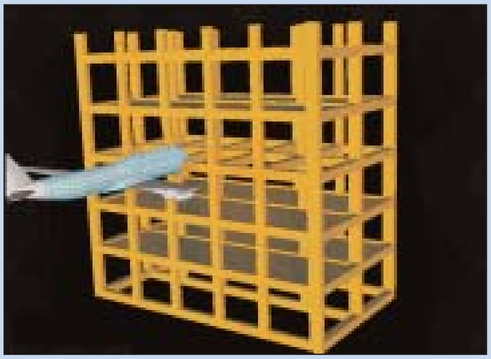
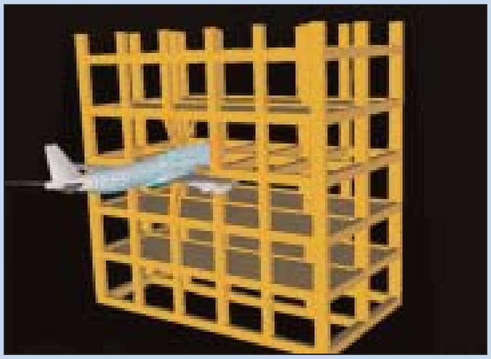
time limitations and the actual structural data had not yet been made available. Therefore, a generic six-story steel structure was constructed with tubular beams and columns. The gravity loading was applied to the entire structure and the dead weight of the building was added through the floorings located on the top-two and bottom-two floors of the structure. Floors were not added to the impact area, which facilitated the study of the failure pattern of both the aircraft and the beam-column connections. The foundation of the building was rigidly fixed. Approximately 61,000 elements were used to construct the entire model of the building and B747.

to complete 250 ms simulation time on an SGI dual processor (300Mhz).

THERMAL SIMULATION

As the B747 deteriorated, it dispersed approximately 10,000 gallons of fuel inside the WTC, (allowing for fuel consumption during the flight). This was a massive amount of fuel and during the investigation of the WTC, fuel was even found in the elevator shafts and on the first floor. Based on the impact simulation created in MSC.Dytran, a heat transfer and thermal stress analysis was performed in MSC.Marc.





IMPACT SIMULATION

The B747 was run into a centralized location of the building exterior between the 3rd and 4th floors at 200 m/sec (about 450mph) at zero degree yaw and pitch angles. When the aircraft crashed into the WTC, the initial impact to the building resulted in massive structural failure and deterioration to both building and the aircraft. Then a fire explosion caused further weakness to the building structure. In order to visualize the massive rupture and structural failure emanating from the dramatic impact, “contact with erosion” were defined between the B747 and the steel structure.

The contact technology in MSC.Dytran allows the prediction of severe material failure such as rupture, perforation, cracking and shearing effects. In addition, “single surface contact” was defined for both the building and aircraft to account for buckling of structural beams and columns and the crushing of the internal components of the B747.

The failure criteria of the steel and aluminum material were defined based on their maximum plastic strains. For example, when an element reaches its maximum plastic strain limits it will no longer provide structural strength and is eliminated from the calculation..

The analysis showed that the impact of the crash substantially weakened the structure. However, because of redundancy in the structural design, the gravitational load was redistributed on the beams and columns that had not failed. Therefore, the impact of the B747 on the building by itself did not cause the WTC to collapse.

MSC.Dytran supports shared memory parallel capability, allowing the job to be submitted on multiple processors to reduce the CPU time. The impact simulation required 24 hours

The results of the impact simulation were brought into MSC.Patran for post processing, where the rigid floors were converted into deformable shell elements and element properties were associated with the beams, trusses and the floor. The analysis preference was switched to MSC.Marc and a new input file was written based on the deformed building.

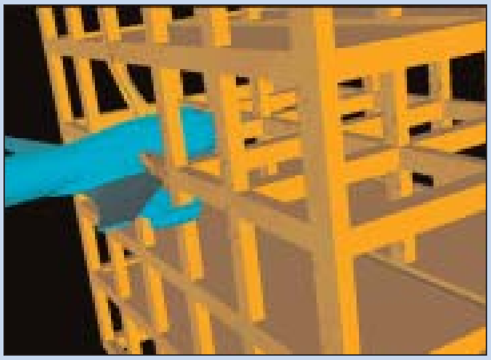
It was decided to run a nonlinear conduction/convection/radiation analysis with temperature dependent thermal and mechanical properties for the steel taken from the MSC.Marc database. In the temperature range to which many members were subjected the ultimate stress was reduced by a factor of five. The properties of the concrete were approximated.

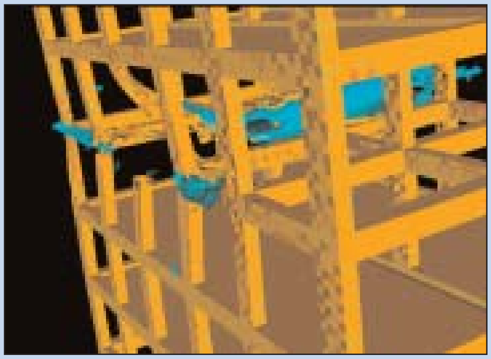
Because of time limitations, two strategies were pursued, including radiation on one model and not on the other. Radiation, where the energy travels from one surface to the next, plays a major role. To properly model radiation, it is necessary to compute the proportion of one surface visible from a second surface known as “view factor”. Because view factors must be calculated using an implicit procedure in MSC.Marc, it requires a large bandwidth and computing time. Selecting the radiating surfaces was a straightforward procedure because the model was constructed of shell elements instead of beam elements.

Because of the complexity of the structural model, the radiation matrix became excessive. The view factor calculation using the Monte Carlo method in MSC.Mentat required 19 hours of processing time. Since this simulation, a new algorithm has been developed that reduces processing time to two hours. The radiation procedure was dropped because of time limitations. However, at the temperatures involved, radiation played an important part and, because of the combustion, modeling of this effect is nontrivial.

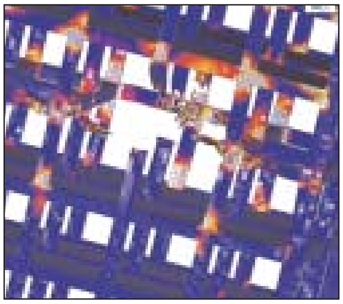
Very little information was available regarding the heat source, so it was assumed to be 1500∞ C, acting in the area of the structure carved out by the plane. Convective boundary conditions were applied to nearby members in the center of the structure. A thermal analysis using an adaptive time stepping procedure was performed for one hour. It illustrates that the temperatures would have reached over 500∞ C even on adjacent floors (even if more radiation was included). The thermal analysis required 2,300 seconds on a workstation. The thermal results were then incorporated into MSC.Marc to perform an elastic-plastic dynamic analysis. MSC.Marc used an implicit procedure for this.

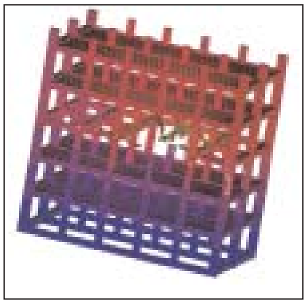
While dynamics would normally not be included in this type of analysis, part of the structure obtained from MSC.Dytran was disconnected. In a static analysis, this would normally result in rigid body modes. But gravity loads and the thermal loads were driving this analysis. The thermal stress analysis showed little deflection for the first 30 minutes and then a large plastic strain occurred which resulted in instability. This is reflected in the large plastic strains that are shown in the joists. The model with close to 56,000 shell elements required 12 hours of processing time.





While the impact of the crash substantially weakened the structure, the remaining steel beams and columns melted because of the extreme temperatures. Also buckling in the trusses was possible, especially after the damaged crossbeams were unable to provide lateral support. As a result, the load could no longer be distributed and the building collapsed.





RECOMMENDATIONS

What-if studies need to be conducted on many other thermal parameters, including the insulation and thickness of the walls, and insulation of steel beams and columns. Analysis of structural parameters, including spacing of beams and columns and radiation on beams and columns should be factored into the simulation. In addition, an analysis should be undertaken of the difference between material used in the staircases and drywall, which has a much higher tolerance for temperature, as well as an analysis of what caused the fire sprinkler system to fail within a few minutes of the impact.

CONCLUSION

“Understanding how and why the World Trade Center buildings collapsed will help us prevent this type of building collapse in the future”, said Dr. Abolhassan Astaneh-Asl, PhD, professor of Civil and Environmental Engineering at the University of California, Berkeley, who testified before the committee. “To simulate the very complex issues and non-linearities involved in analyzing the impact of an airplane and the ensuing fire you need the most powerful and advanced software, such as MSC.Software’s simulation tools. The contributions of MSC.Software to our research program have been invaluable. We will continue to use these tools in our investigation to gain insight to what might have caused collapse and to learn valuable lessons that can be applied in the future to prevent such catastrophic collapses.”

The design and construction of a building to withstand the impact and heat of a passenger plane may be too costly. However, by using nonlinear analysis the amount of redundancy required to mitigate the problem and to predict the time before a full collapse occurs would save lives. For example, if the WTC had not collapsed until two hours elapsed, then even as massive as the destruction was, there would have been time to evacuate and minimal if any deaths would have occurred.

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