Aircraft Impact Simulation of the WTC tower for Investigation on True Cause of the Total Collapse

Tragedy of World Trade Center
2001.9.11

○ Daigoro ISOBE
Zion SASAKI
Univ. of Tsukuba, Japan

筑波大学
University of Tsukuba

EME Department of Engineering Mechanics & Energy

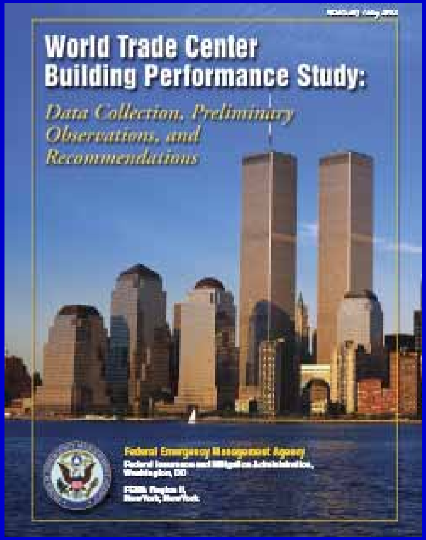
Background

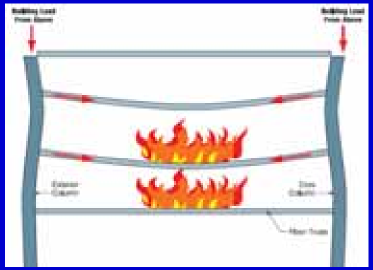
- 9/11 terrorist attack on the WTC towers caused an unprecedented tragedy in the history of architecture
- Twin towers stood in flames caused by jet fuel until finally, both collapsed totally to the ground
- Both towers collapsed at an unnaturally high speed
- Official statements given by FEMA in 2002 and NIST in 2005 stated that the main cause of the total collapse is the weakening of the core structures induced by the big fire

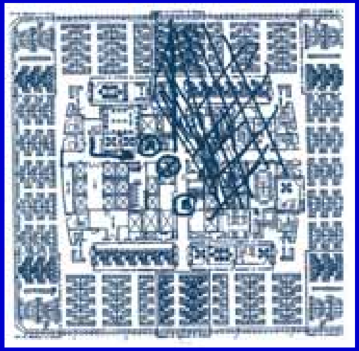
…but, was it really the main cause of the total collapse?

Total collapse of the WTC 2

Statements in the official reports





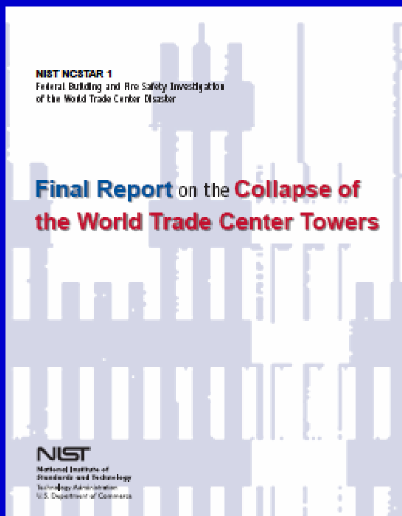


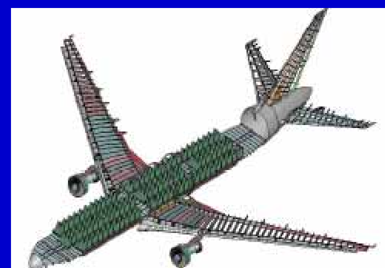
World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations, Federal Emergency Management Agency (FEMA), 2002

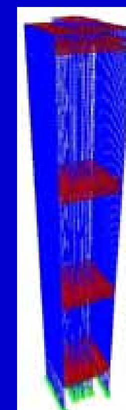
" …the fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely."

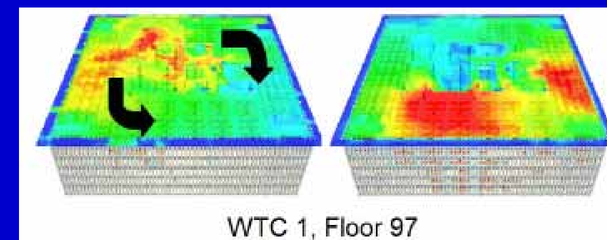
"…this heat (of burning jet fuel) induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and the resulting damage were sufficient to induce the collapse of both structures."

Statements in the official reports









Final Report on the Collapse of the World Trade Center Towers, National Institute of Standards and Technology (NIST), 2005

" …the WTC towers likely would not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact."

"…NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers."

Some emerging queries

- Did the fire really spread to such a wide range in the buildings to cause the total collapse?
- Was the heat high enough to reduce the strengths of all the structural members?

WTC 2 collapsing

… not likely.

Then, what was the real cause of the free-fall total collapse?

"The towers experienced an extreme dynamic load that no other high-rise building has ever experienced in history."

Objectives

Perform some aircraft impact analyses of a full-model WTC tower, to determine the possibility of the impact itself acting as a fatal cause of the collapse

Numerical code must be highly accurate, less-memory-consuming, member fracture and contact taken into account

Moment of impact

Applied a finite element code using the <u>ASI-Gauss technique</u>

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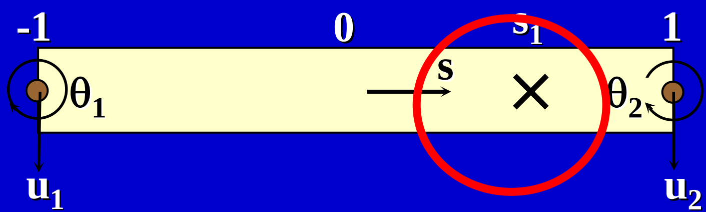
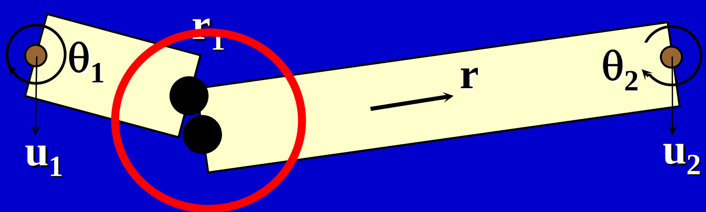
Adaptively Shifted Integration Technique



Linear Timoshenko beam element



Rigid Body Spring Model (RBSM)

× Numerical integration point

● Rotational and shear spring

(Location of plastic hinge)

(Location of stress evaluation point)

Relationship between the locations

$$s_1 = -r_1 , \quad r_1 = -s_1$$

Formation of fully plastic section

→ **Numerical integration point shifted**

→ **Precise location of plastic hinge expressed**

In elastic range

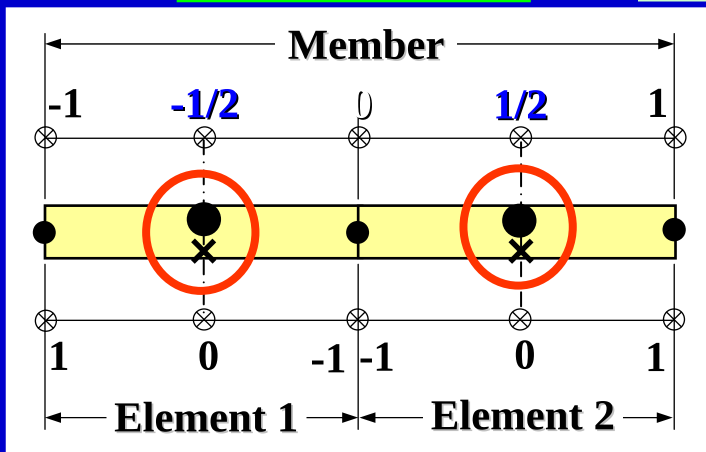
→ **One integration point located at midpoint**

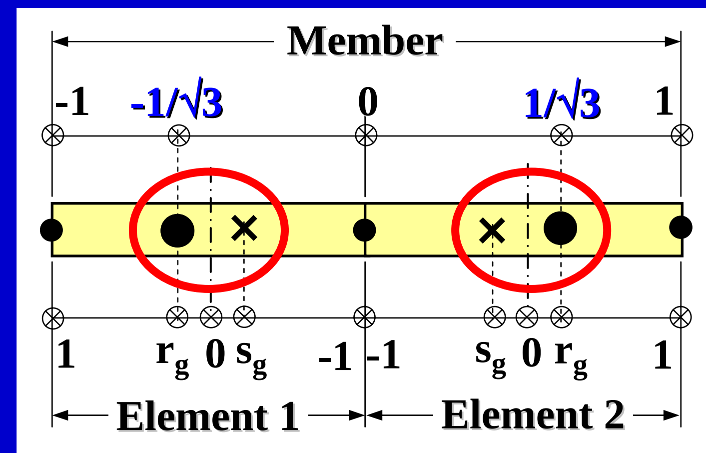
→ **Limitation of one-point integration**

→ **Accuracy fall in elastic solutions**

ASI-Gauss Technique

ASI technique | **Elastic range** | **ASI-Gauss technique**





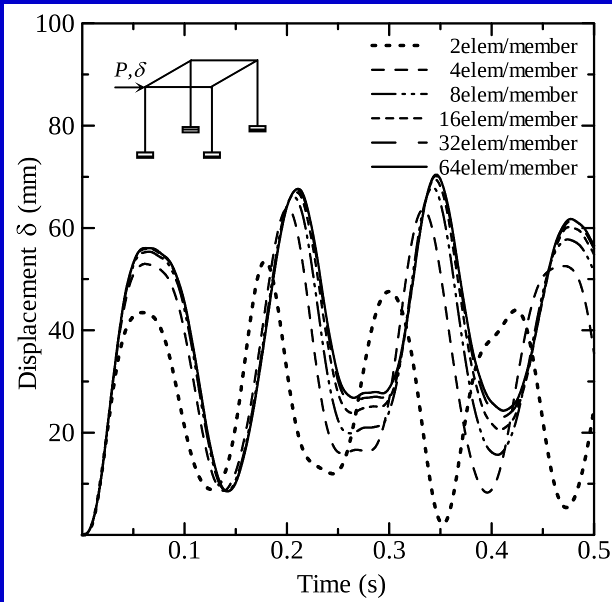
$s = 0$ × Numerical integration point $s_g = 1 - (2/\sqrt{3})$

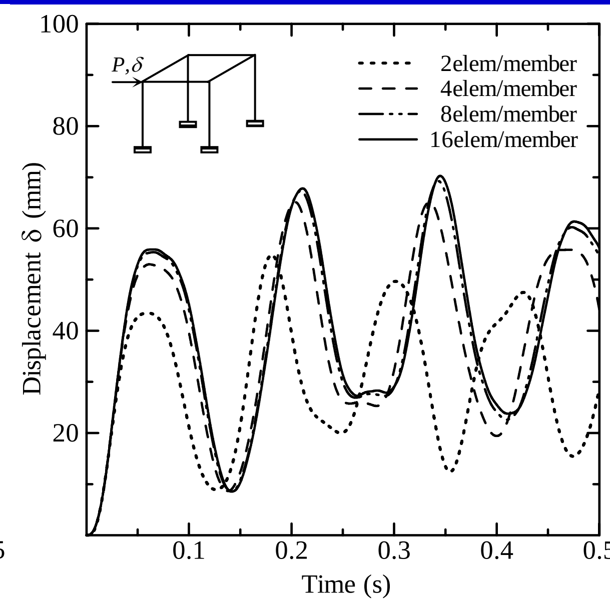
$r = 0$ ● Stress evaluation point $r_g = -1 + (2/\sqrt{3})$

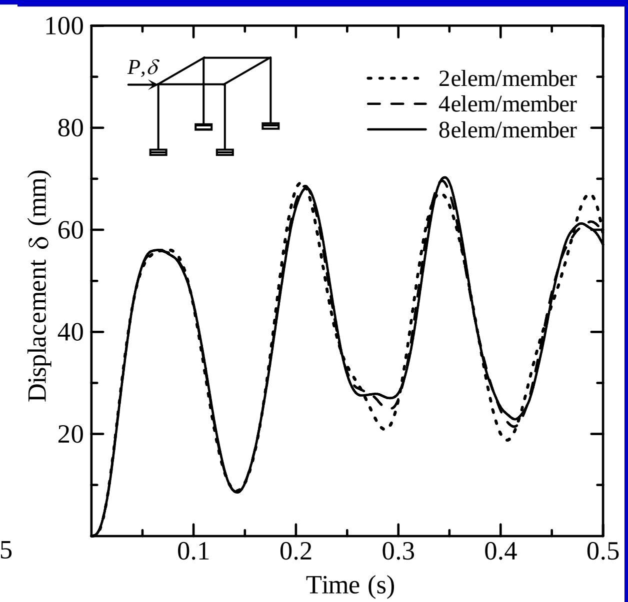
Improvement → **Place stress evaluation points of two consecutive elements at <u>Gaussian integration points</u>**

Optimal for two-point integration, accuracy mathematically guaranteed

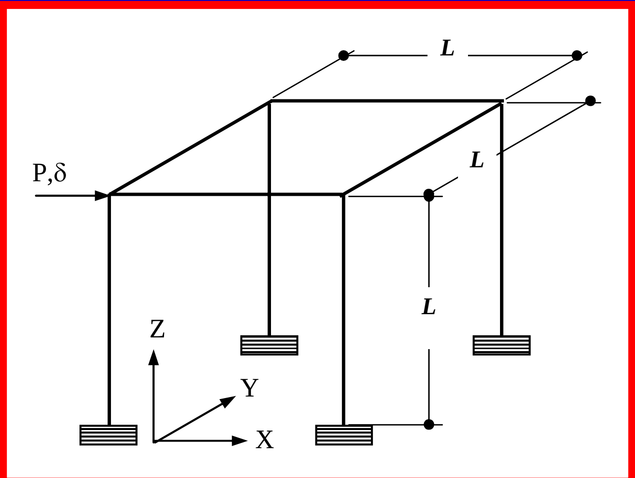
Estimation on ASI-Gauss Technique







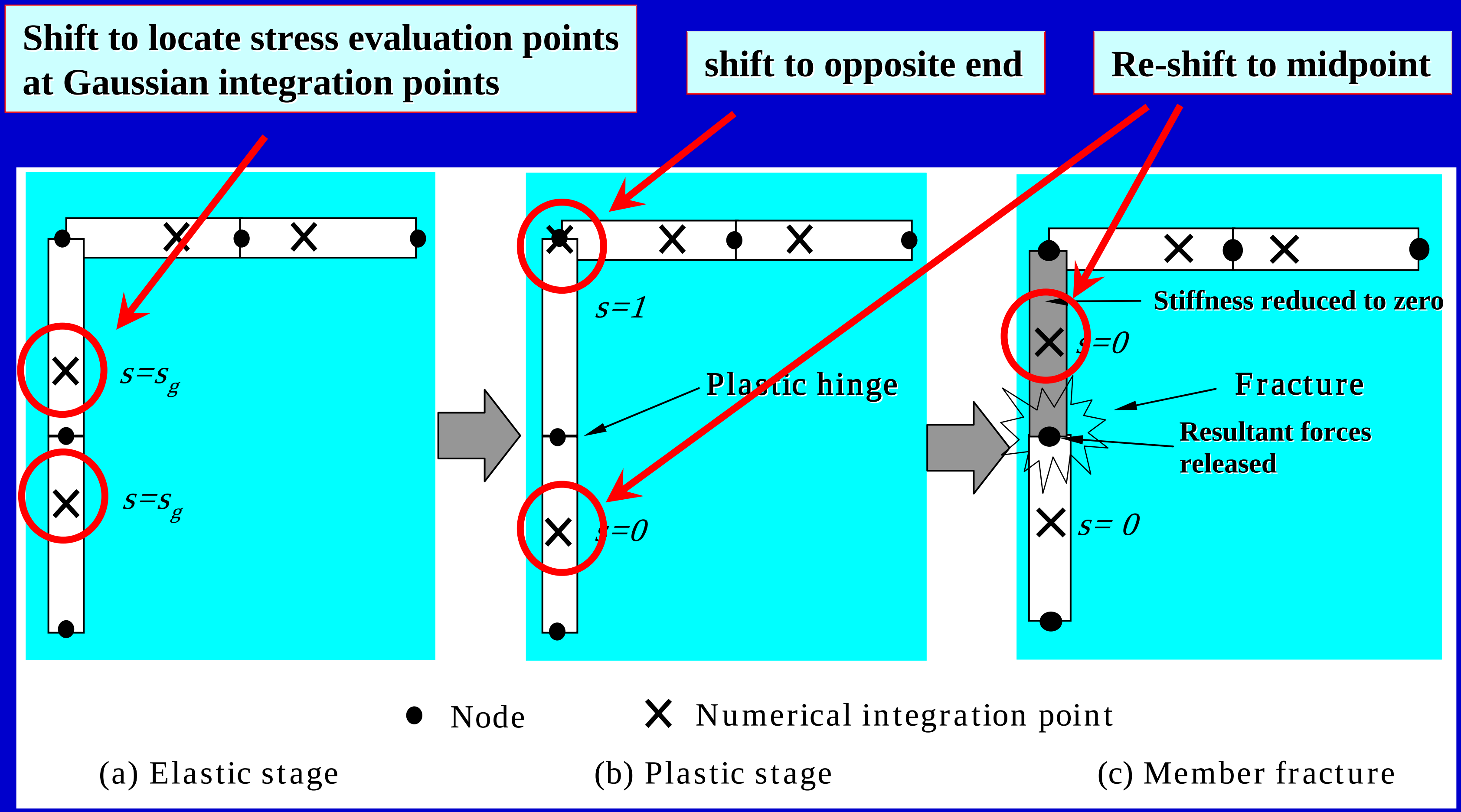
Conventional FEM | **ASI technique** | **ASI-Gauss technique**



Elasto-plastic response analysis of a space frame

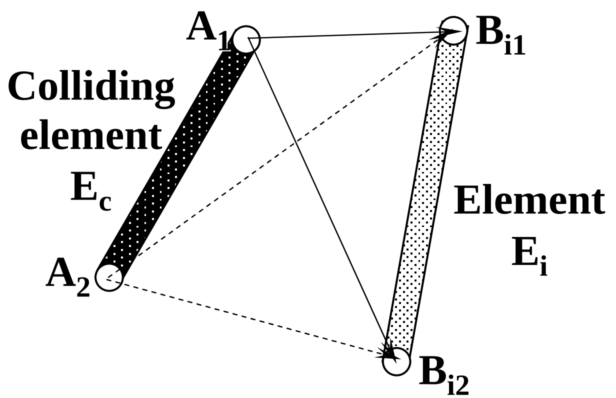
Achieved high accuracy in elastic range by using ASI-Gauss technique

Member Fracture Algorithm



Locations of numerical integration points in each stage

Elemental Contact Algorithm



$A_1(x_{c1},y_{c1},z_{c1})$, $A_2(x_{c2},y_{c2},z_{c2})$

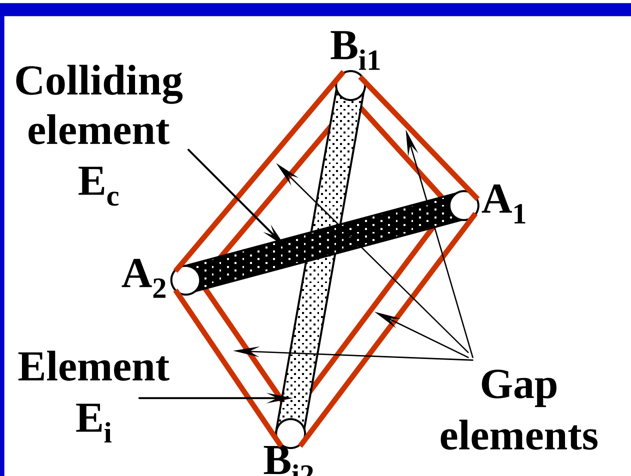
$B_1(x_{i1},y_{i1},z_{i1})$, $B_2(x_{i2},y_{i2},z_{i2})$

Lie on the same plane
OR
Nearly form a plane

AND

Exist in a specific distance

Determination of contact

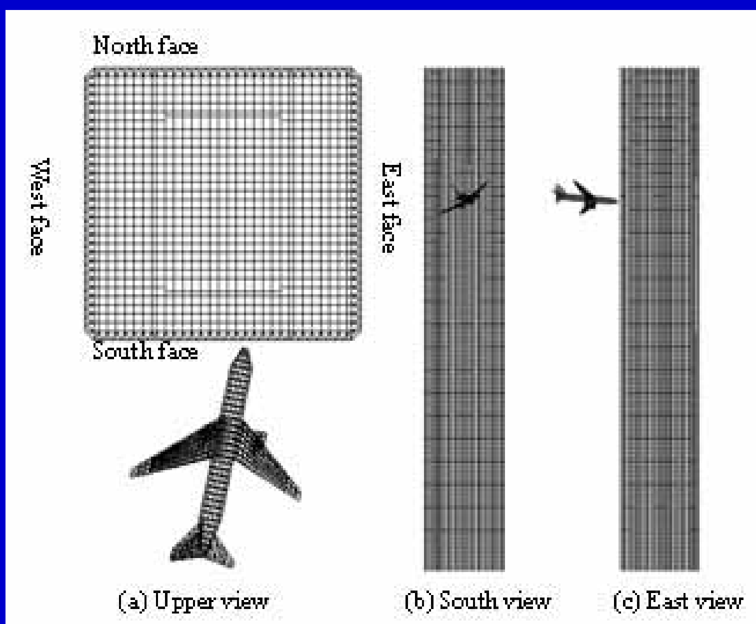


- ✧ **4 gap elements connecting 2 elements after determination of contact**
- ✧ **Gap elements automatically eliminated after certain time of contact**

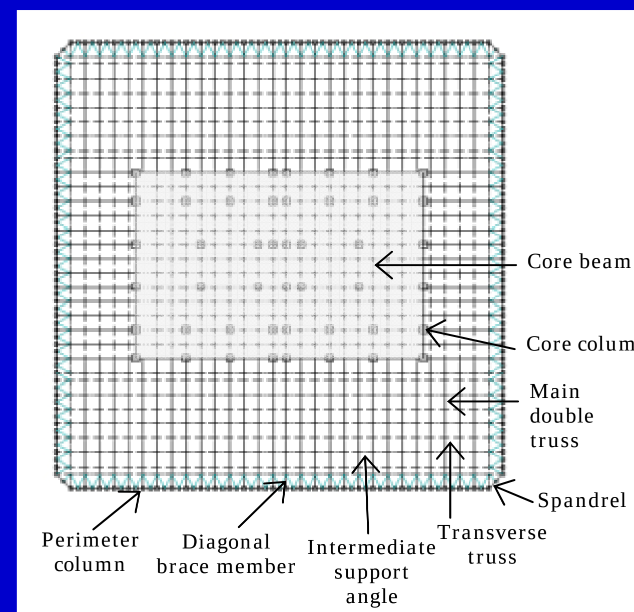
Connection of elements in contact

Numerical Model and Analytical Conditions

- Initial velocity of aircraft = 262 m/s, mass = 142.5 t
- Implicit scheme (Newmark's β method)
- Numerical damping (δ=5/6, β=4/9)
- Updated Lagrangian Formulation
- Conjugate Gradient solver
- Strain rate effect on yield strength
- Time increment = 0.2 ms (actual time 0.8 s)
- ASI-Gauss technique



Analyzed model



Cross section of the WTC towers

Other Analytical Conditions

Yield condition

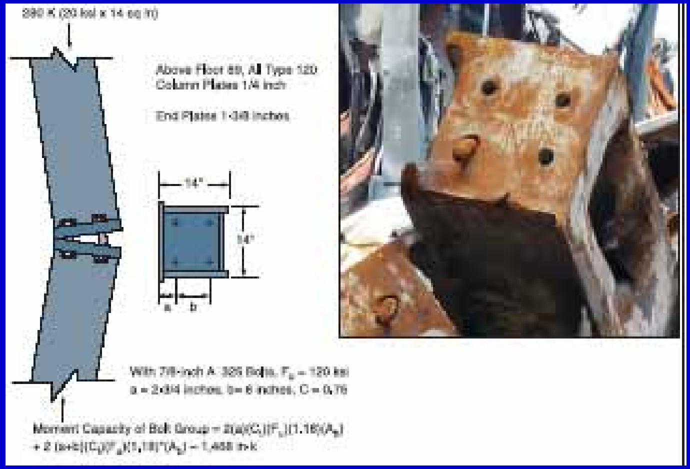
$$f_y = \left(\frac{M_x}{M_{x0}}\right)^2 + \left(\frac{M_y}{M_{y0}}\right)^2 + \left(\frac{N}{N_0}\right)^2 + \left(\frac{M_z}{M_{z0}}\right)^2 = 1$$

M_x, M_y : bending moments around the x- and y-axes, N : axial force,
M_z : torsional moment, M_{x0}, M_{y0}, N, M_{z0} : fully plastic values

Fracture condition

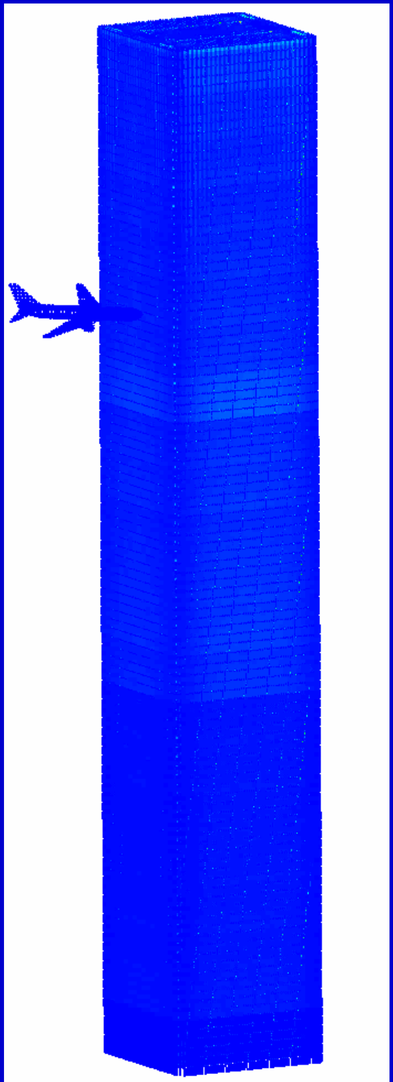
$$\left|\frac{\kappa_x}{\kappa_{fx}}\right| - 1 \geq 0 \;\; or \;\; \left|\frac{\kappa_y}{\kappa_{fy}}\right| - 1 \geq 0 \;\; or \;\; \left(\frac{\epsilon_z}{\epsilon_{fz}}\right) - 1 \geq 0$$

κ_x, κ_y : bending strains around the x- and y-axes,
ε_z : axial tensile strain,
κ_{fx}, κ_{fy}, ε_{fz} : critical values

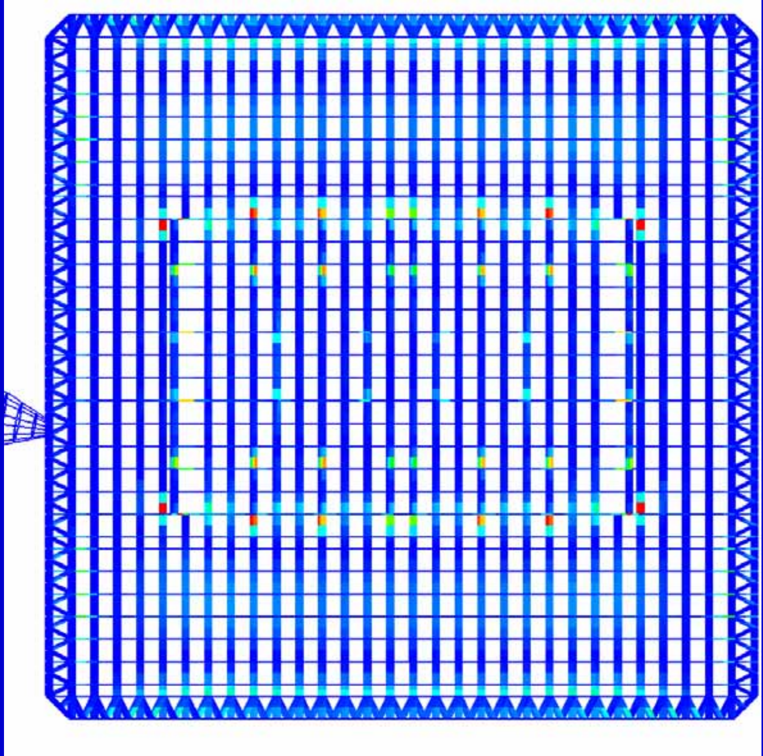


Typical WTC column joints, FEMA

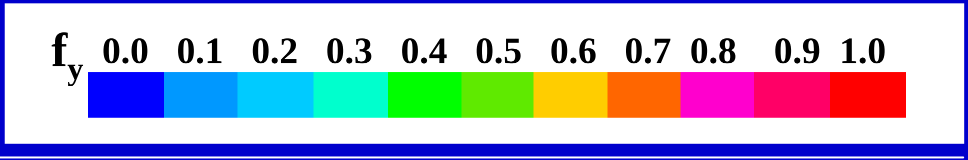
Aircraft Impact Analysis of WTC2



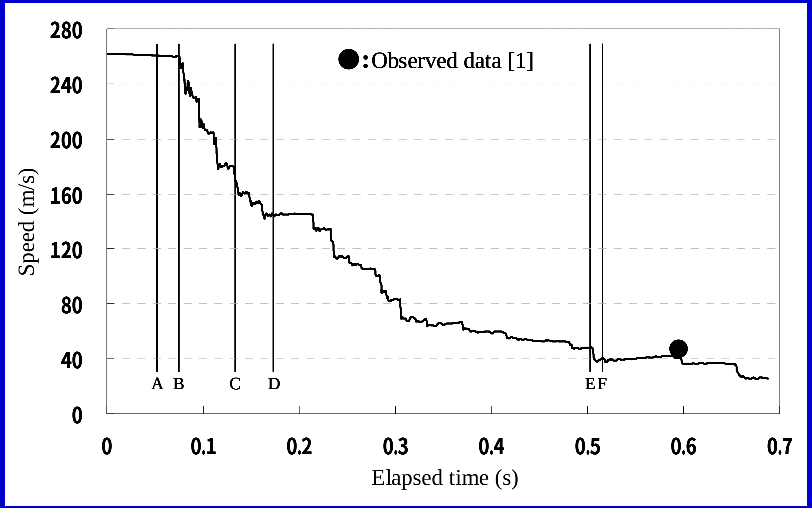
Global view



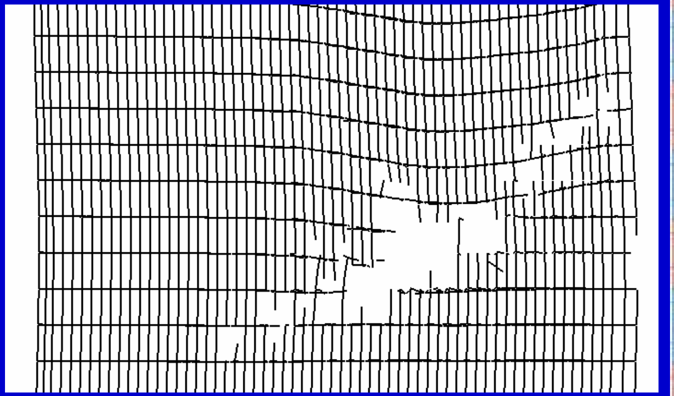
Upper view



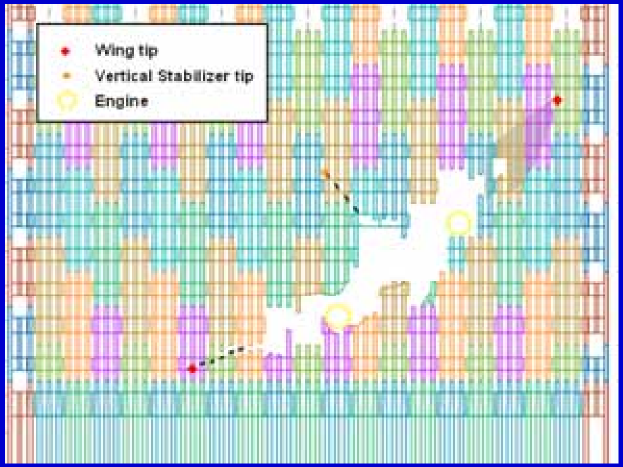
Aircraft Impact Analysis of WTC2



Velocity curve of the right engine



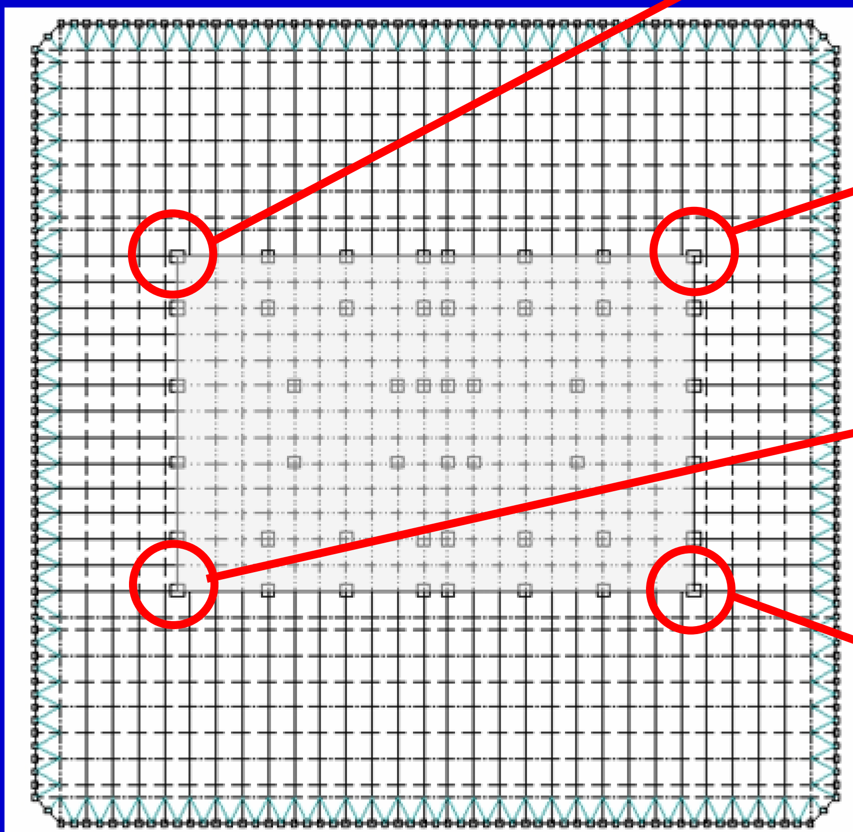
(a) Numerical result

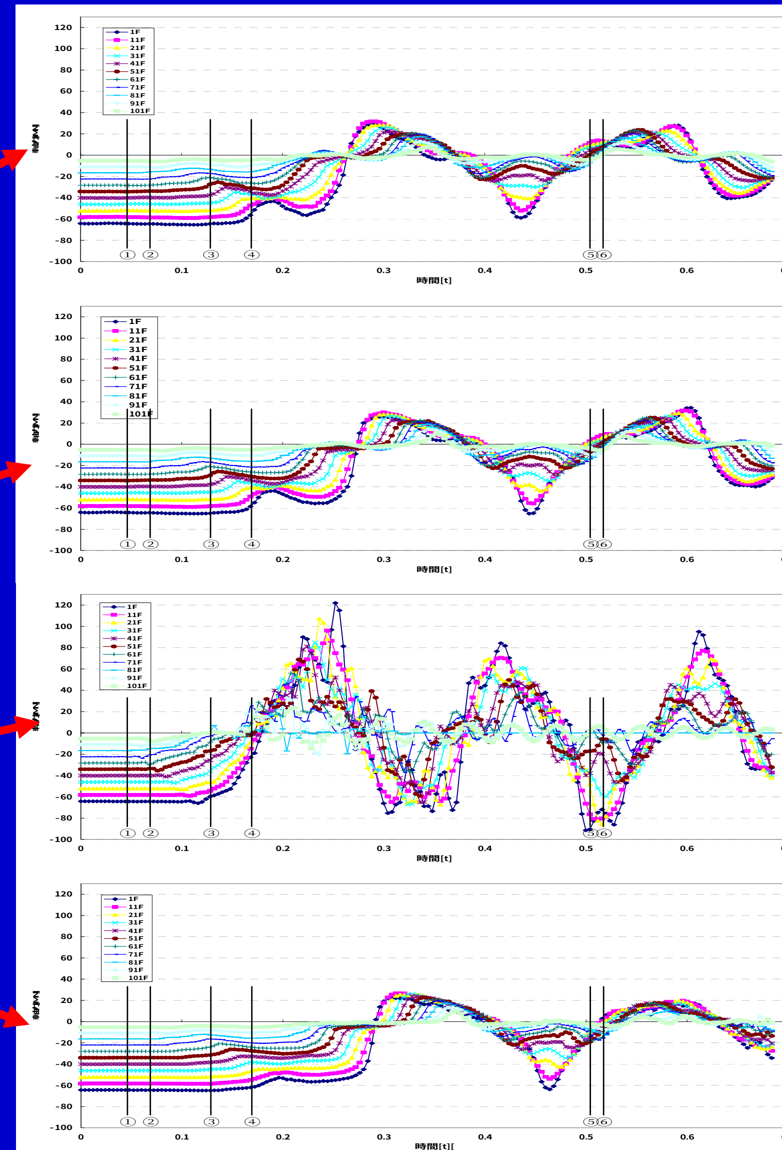


(b) Observed data (NIST)

Damages on the south face

Axial force produced in core columns



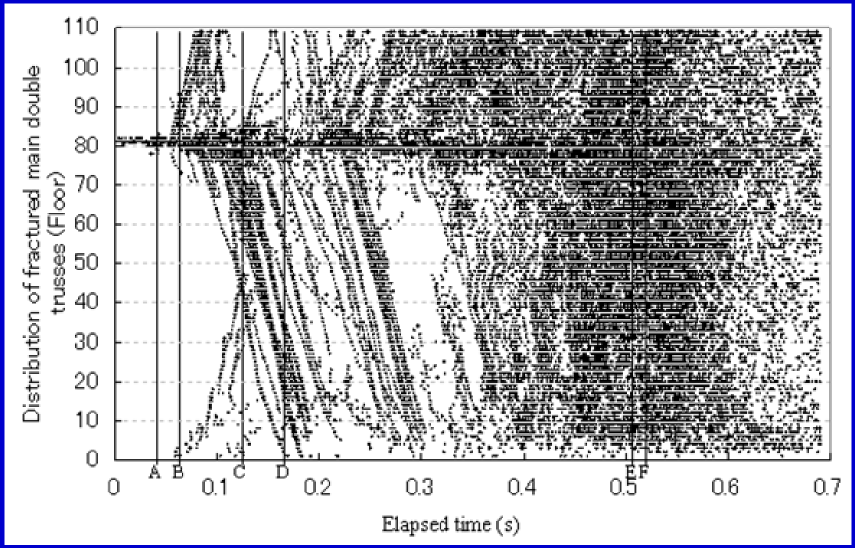


Locations of core columns

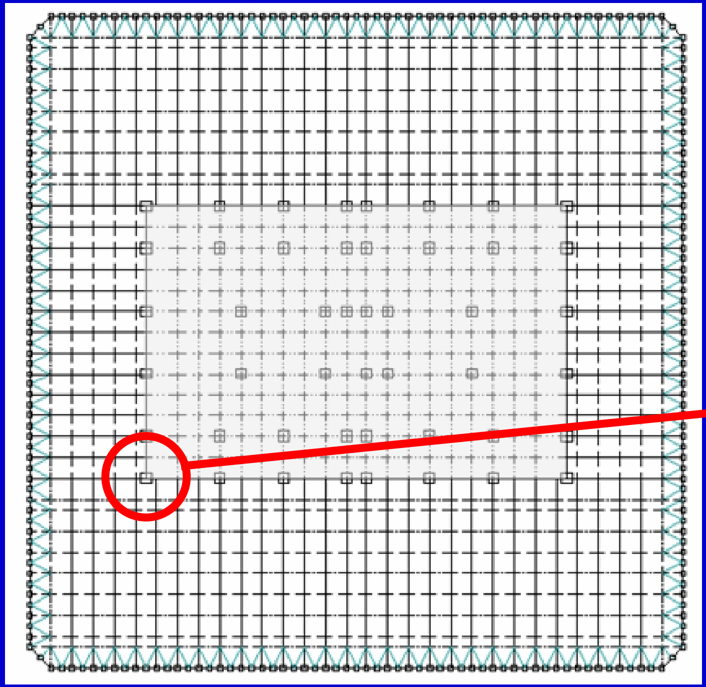
Time histories of axial forces

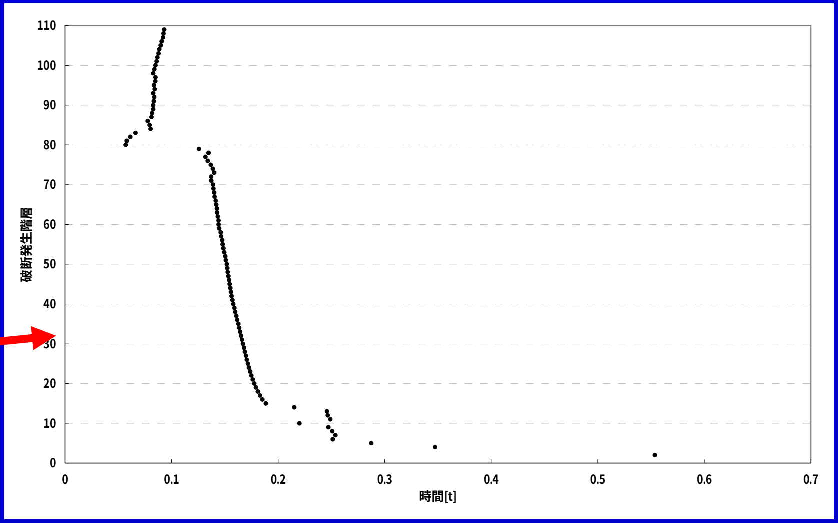
What produced the gigantic tensile force?

Instant disconnections between the core columns and the main double trusses during the impact is observed.



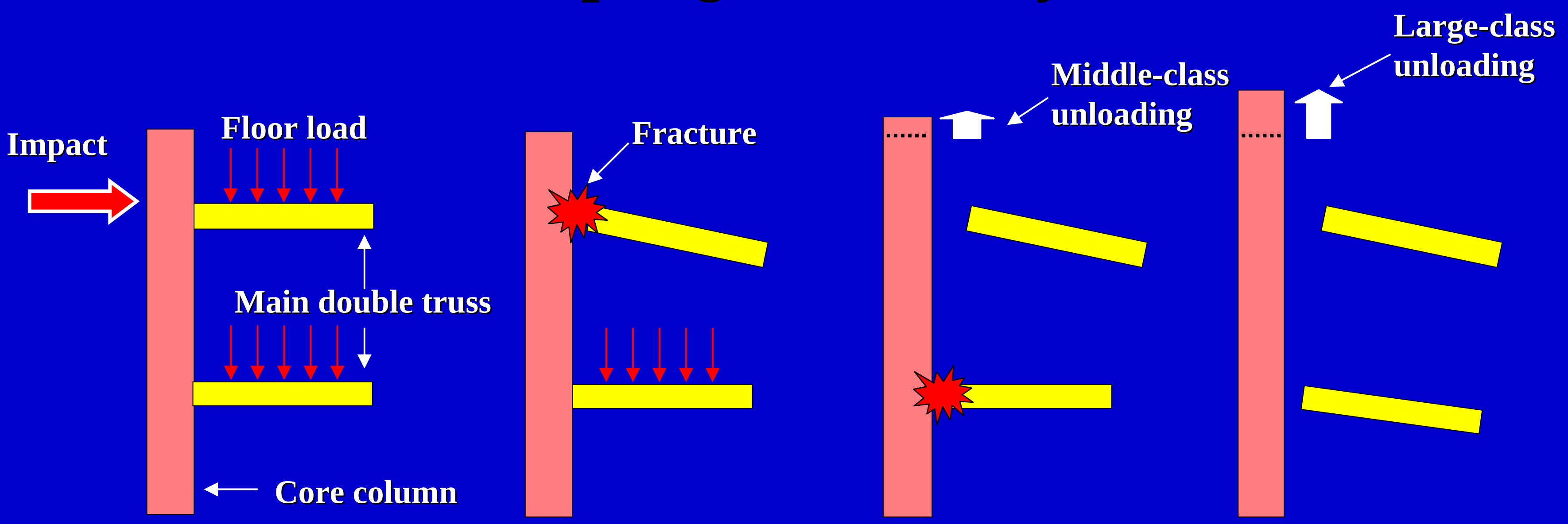
Distribution of fractured main double trusses





Main double trusses disconnected from core column No. 1001

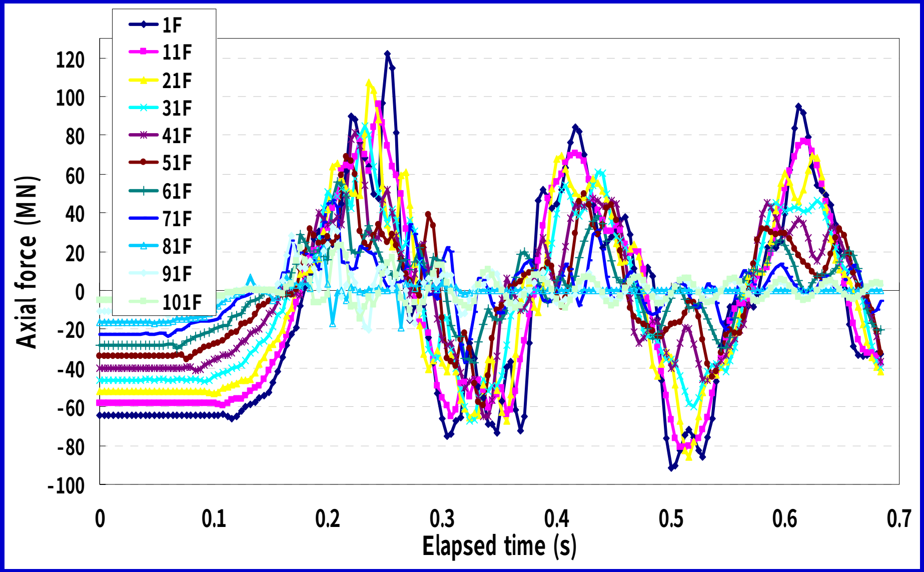
“Spring-back theory”



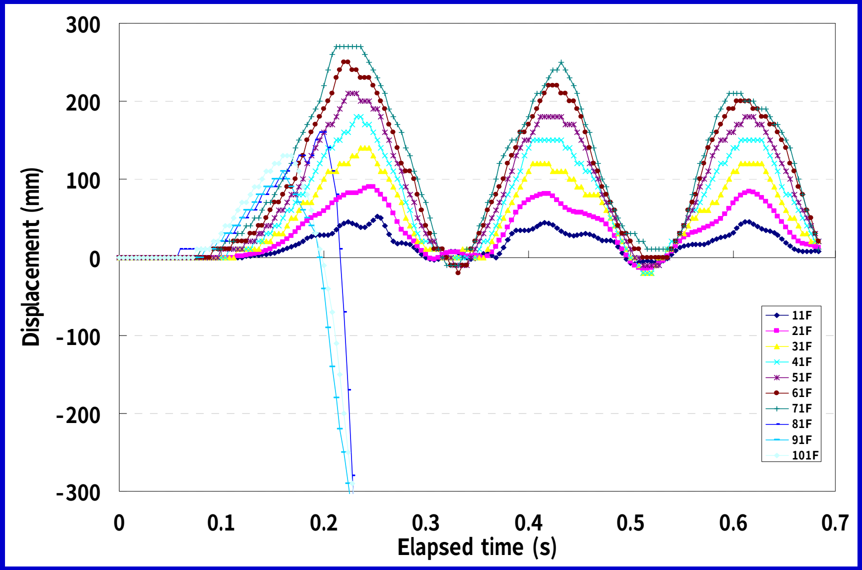
Disconnect-and-release chain reaction

A spring-back phenomenon of the core columns due to a very rapid unloading is observed. The spring-back phenomenon is fatal enough to produce gigantic tensile force to the columns. This might have triggered some connections to become totally fractured, and thus, eventually, have led to a total collapse of the towers.

“Spring-back theory”



Time histories of axial forces (core column No. 1001)

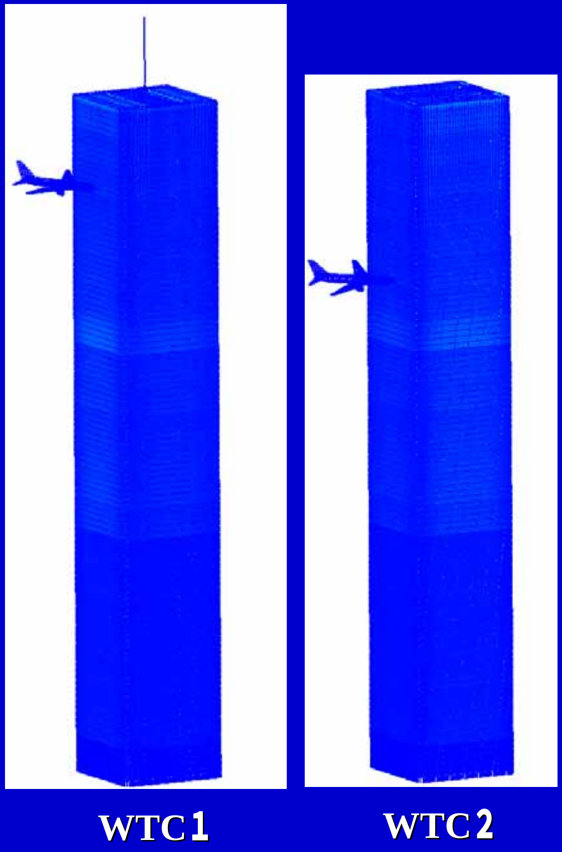


Axial displacement due to spring-back phenomena (core column No. 1001)

A spring-back phenomenon of the core columns due to a very rapid unloading is observed. The spring-back phenomenon is fatal enough to produce gigantic tensile force to the columns. This might have triggered some connections to become totally fractured, and thus, eventually, have led to a total collapse of the towers.

Conclusion

Spring-back phenomenon → fatal cause of the total collapse?



<u>Future works</u>

Re-investigate behaviors of member joints

Run parametric simulations