Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures

April 22nd, 2008

Agenda

Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures

April 22nd, 2008

8am PDT (Los Angeles) / 11am EDT (New York) / 4pm BST (London)

- Welcome & Introduction (Overview of NAFEMS Activities)
  - Matthew Ladzinski, NAFEMS North America
- Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures
  - Dr. Hatem Tagel-Din, Applied Science International, LLC
- Q&A Session
  - Panel
- Closing


Ladzinski


Tagel-Din

THE INTERNATIONAL ASSOCIATION
FOR THE ENGINEERING ANALYSIS
COMMUNITY

An Overview of NAFEMS NA Activities

Matthew Ladzinski
NAFEMS
North American Representative

Planned Activities in North America

➢ Webinars

- New topic each month!
  - Verification & Validation (V&V): Quantifying Prediction Uncertainty and Demonstrating Simulation Credibility (*May 15*)
  - Managing FEA in the Design Process (*June*)
- Recent webinars:
  - AUTOSIM: The Future of Simulation in the Automotive Industry
  - A Common Sense Approach to Stress Analysis and Finite Element Modeling
  - The Interfacing of FEA with Pressure Vessel Design Codes (CCOPPS Project)
  - Multiphysics Simulation using Directly Coupled-Field Element Technology
  - Methods and Technology for the Analysis of Composite Materials
  - Simulation Process Management
  - Simulation-supported Decision Making (Stochastics)
  - Simulation Driven Design (SDD) Findings

To register for upcoming webinars, or to view a past webinar, please visit: www.nafems.org/events/webinars

Planned Activities in North America

- Events
  - Practical Stress Analysis & Finite Element Methods *with* Bob Johnson
    - An opportunity to ensure that your organization gets maximum benefit from using FEA
    - Three-day Training Course
    - April 30th – May 2nd, 2008 in Troy, MI
    - Only a two seats left!
    - www.nafems.org/events

Planned Activities in North America

NAFEMS NA 2008 Regional Summit

NAFEMS 2020 Vision of Engineering Analysis and Simulation

- ***NAFEMS 2020*** will bring together the leading visionaries, developers, and practitioners of CAE-related technologies and business processes
- Goal: Provide attendees with the best "food for thought and action" to deploy CAE over the next several years
- Location: Embassy Suites Hotel & Convention Center, Hampton, Virginia
- Date: October 29-31, 2008

Call for Papers Now Open!

For more information, visit:

www.nafems.org/nafems2020

Other NAFEMS Activities

- NAFEMS Simulation Data Management Working Group (SDMWG) – name tbd
  - www.nafems.org/tech/sdmwg

- NAFEMS NA eNews Update
  - Monthly newsletter containing information on upcoming NAFEMS NA activities
  - Can be downloaded at: www.nafems.org/regional/north_america/enews

Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures

Hatem Tagel-Din

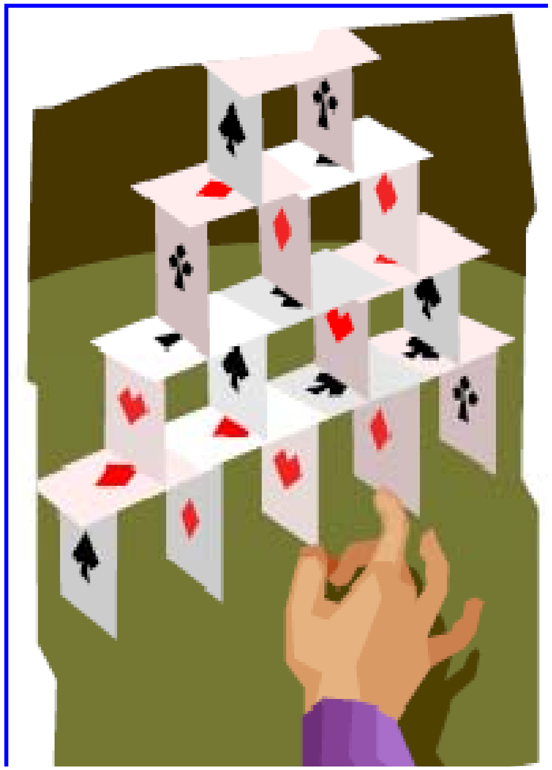
Applied Science International, LLC

Contents

- Definition of Progressive Collapse
- Problem Statement
- Why AEM?
- AEM Theory
- Modeling Advantages of AEM compared to FEM
- Analysis Advantages of AEM compared to FEM
- Practical Examples for Progressive Collapse Simulations

Definition of Progressive Collapse

"A collapse that is triggered by <u>localized damage</u> that can't be contained and leads to a chain of failures resulting in a partial or total structural collapse, where the final damage is <u>disproportionate</u> <u>to the local damage of the triggering event</u>"



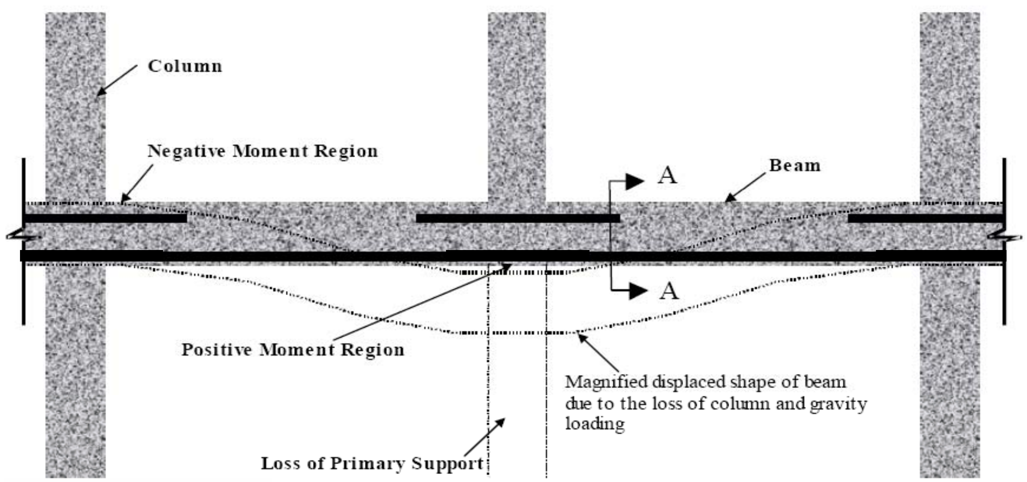
Definition of Progressive Collapse

GSA Code: Guidance

GSA: Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects.

Objective ➔ to reduce the potential for progressive collapse through:

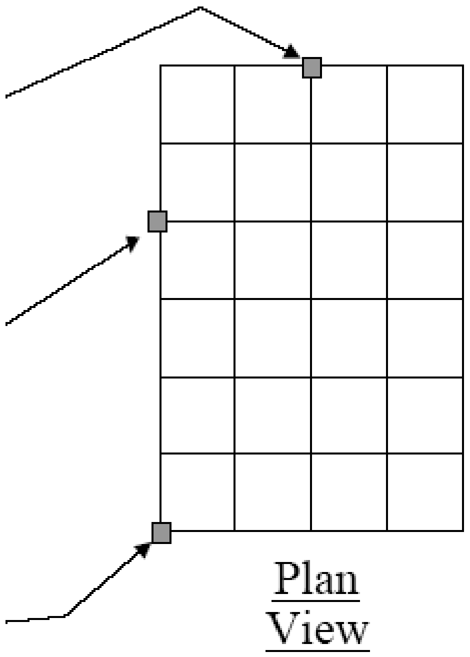
1) Redundancy for ensuring alternative load paths
2) Structural Continuity and Ductility
3) Capability of resisting load reversals
4) Capability of resisting shear failure



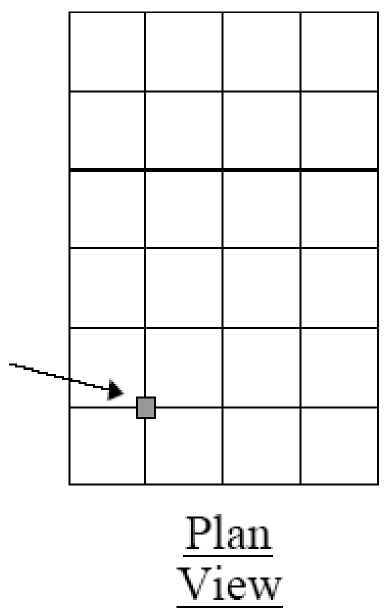
Definition of Progressive Collapse

GSA Code: Analysis

Remove a vertical supporting element from the **location being considered** (first floor only) and conduct a **static or dynamic analysis** for the structure.



Exterior consideration

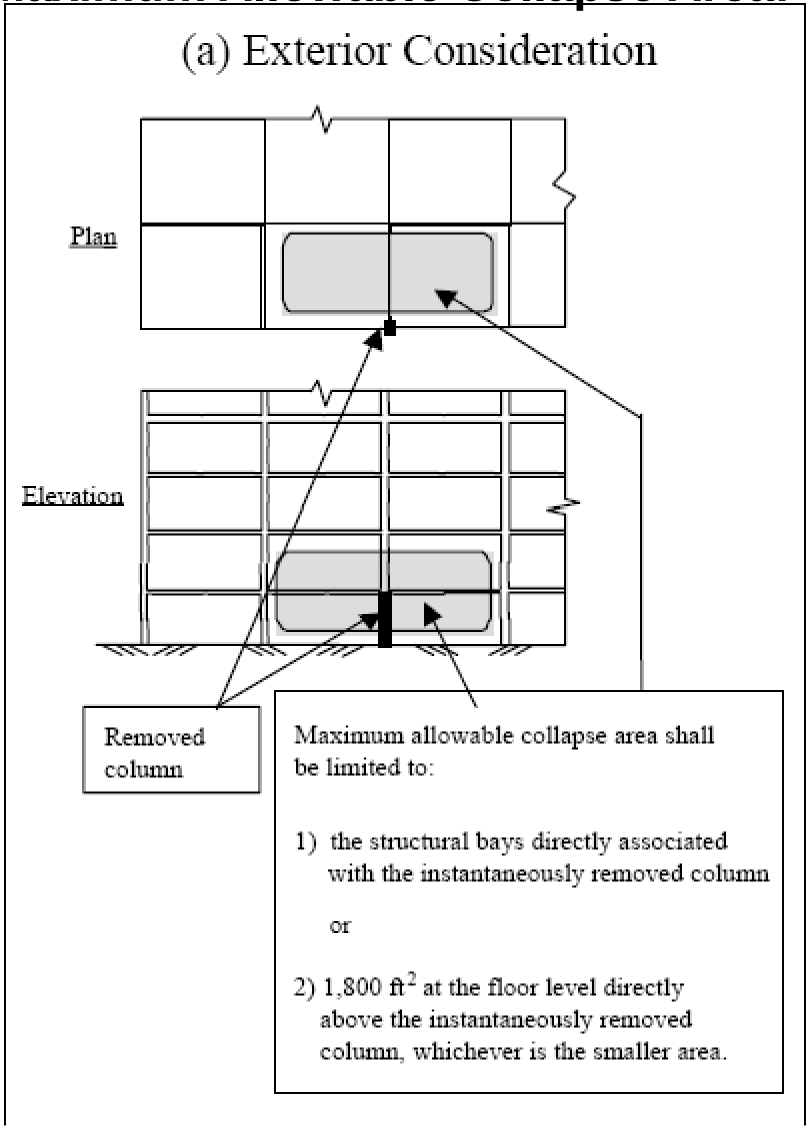


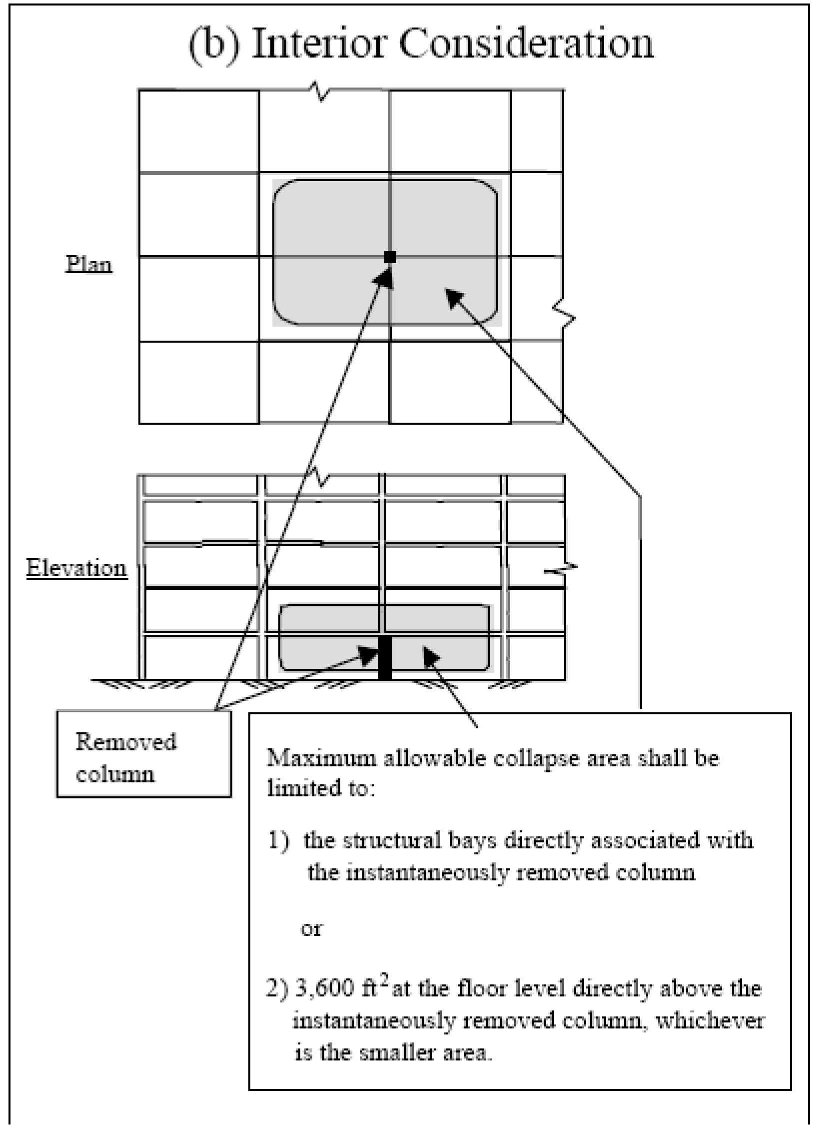
Interior consideration

Definition of Progressive Collapse

GSA Code: Analysis

1) Maximum Allowable Collapse Area:





Problem Statement

- **Given**:
  - Structural full geometry
  - Full reinforcement detailing
  - Material properties
  - Threat type (Bomb, car collision, fire, element removal.)
- **Questions**:
  - Will the structural collapse or not?
  - Is it partial or total collapse?
  - Which part will fail and how?
  - What is the footprint of the collapsed structures?
  - What are the effects of falling debris on adjacent structures?

Why AEM?

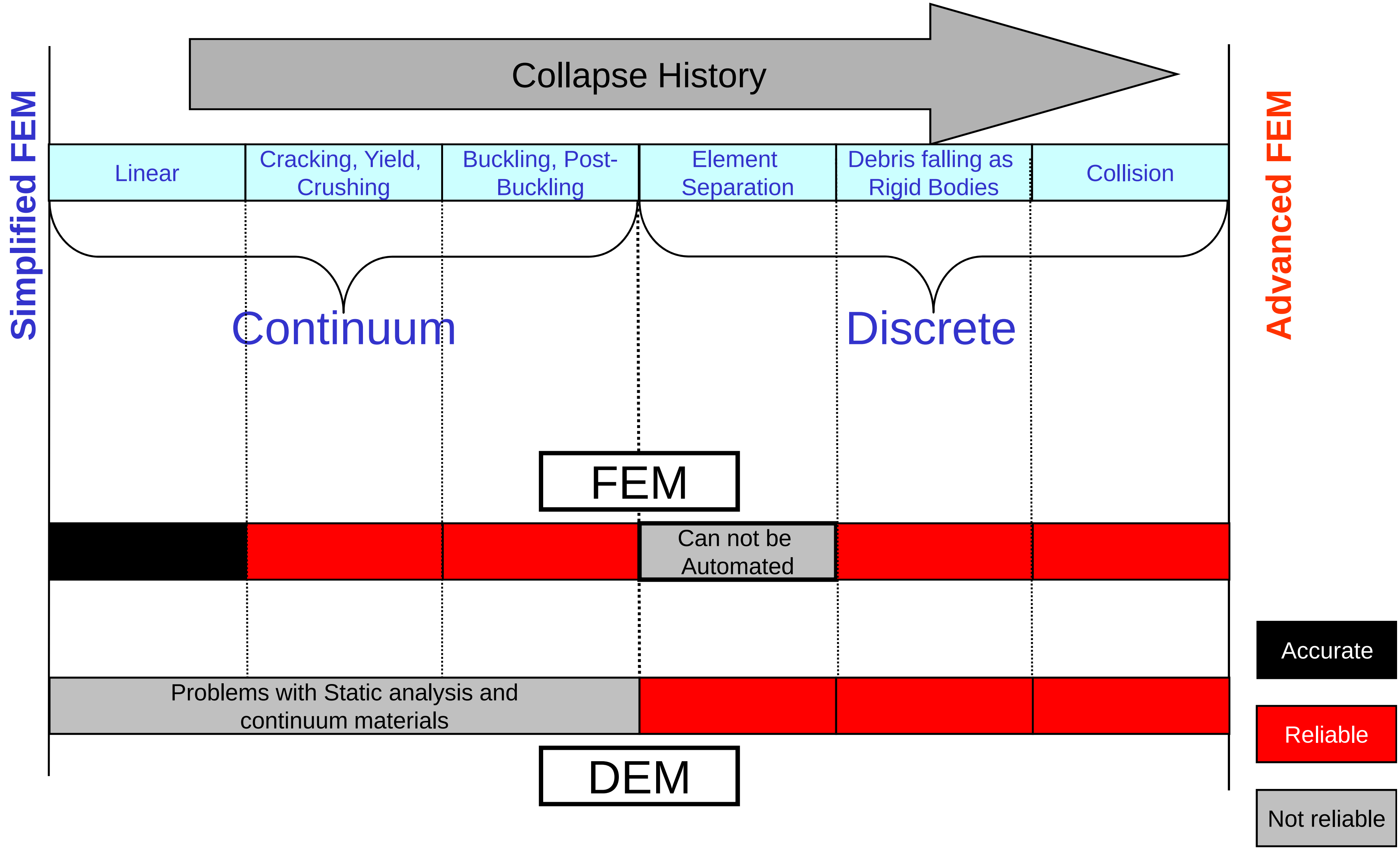
Why AEM?

Methods for Structural Analysis

- Finite Element Method (FEM)
- Boundary Element Method (BEM)
- Finite Difference Method
- Discrete Element Method (DEM)
- Discontinuous Deformation Analysis (DDA)
- Truss Method and Lattice Method
- Strut and Tie Method
- Spring Network Method
- Finite Section Method
- Rigid Body and Spring Method (RBSM)
- Mesh-Free Methods

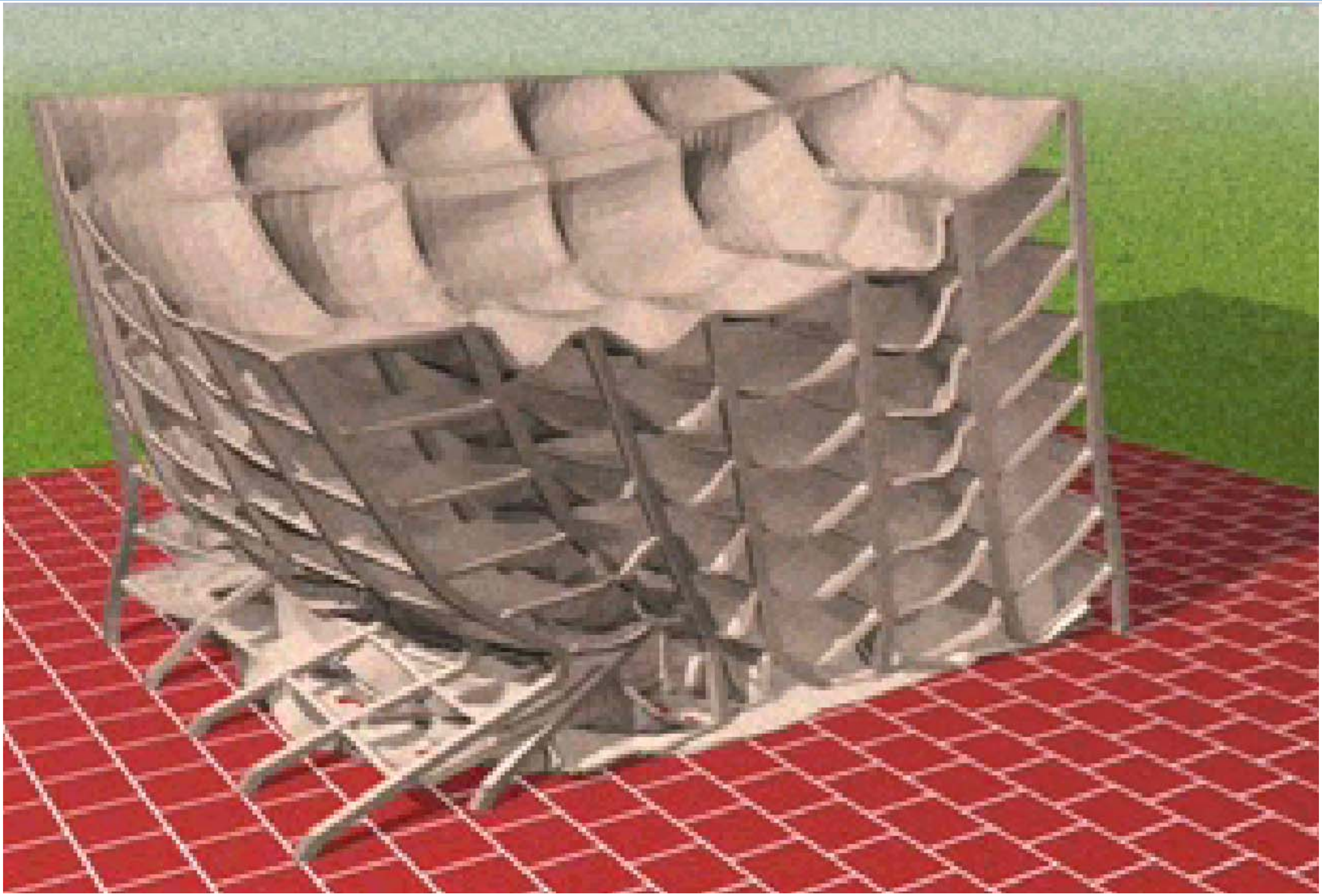
Why AEM?

FEM/DEM Comparison



Why AEM?

Analysis of Oklahoma City Building Using Advanced FEM

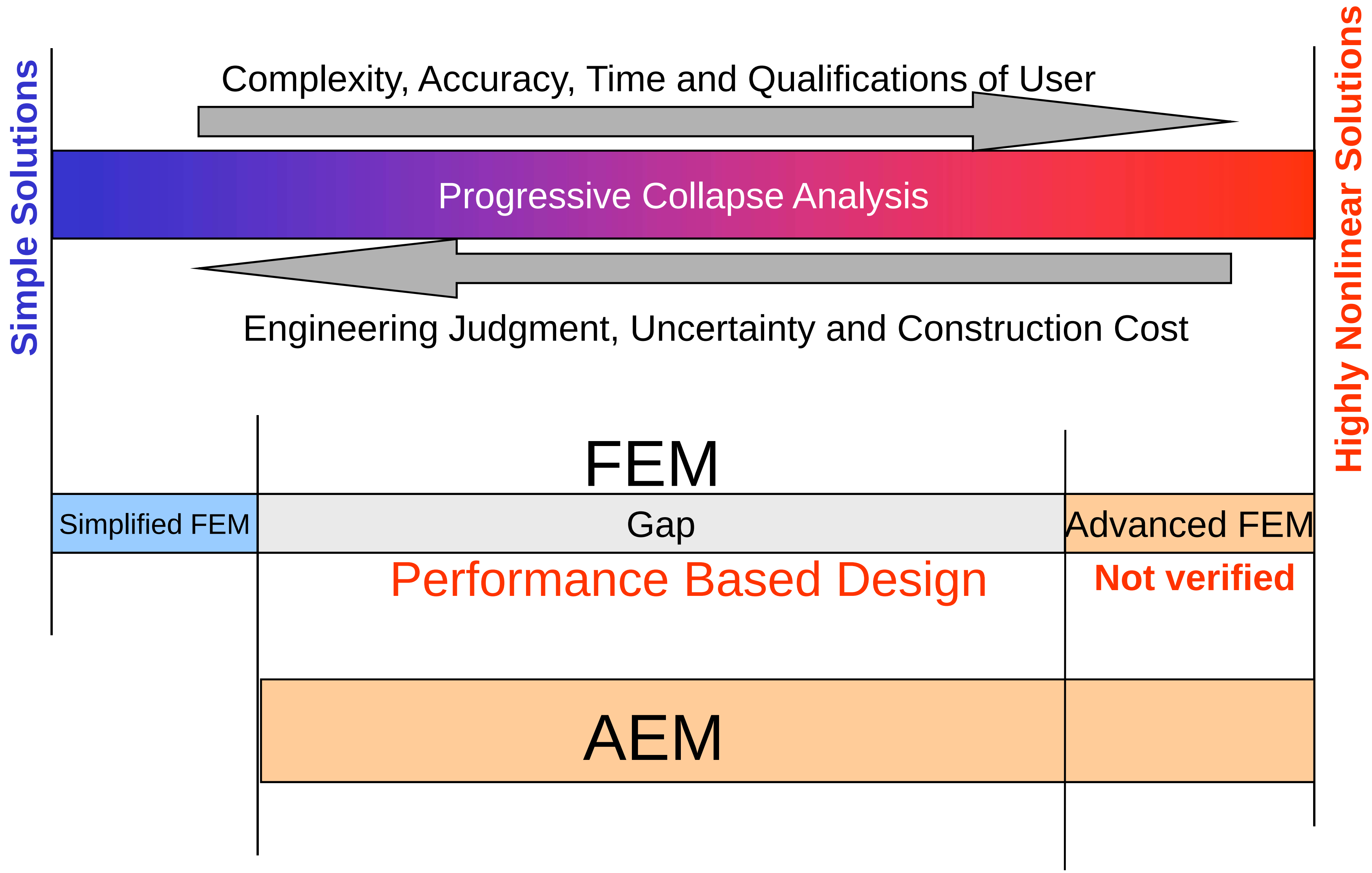


Why AEM?

Advantages of AEM compared to FEM

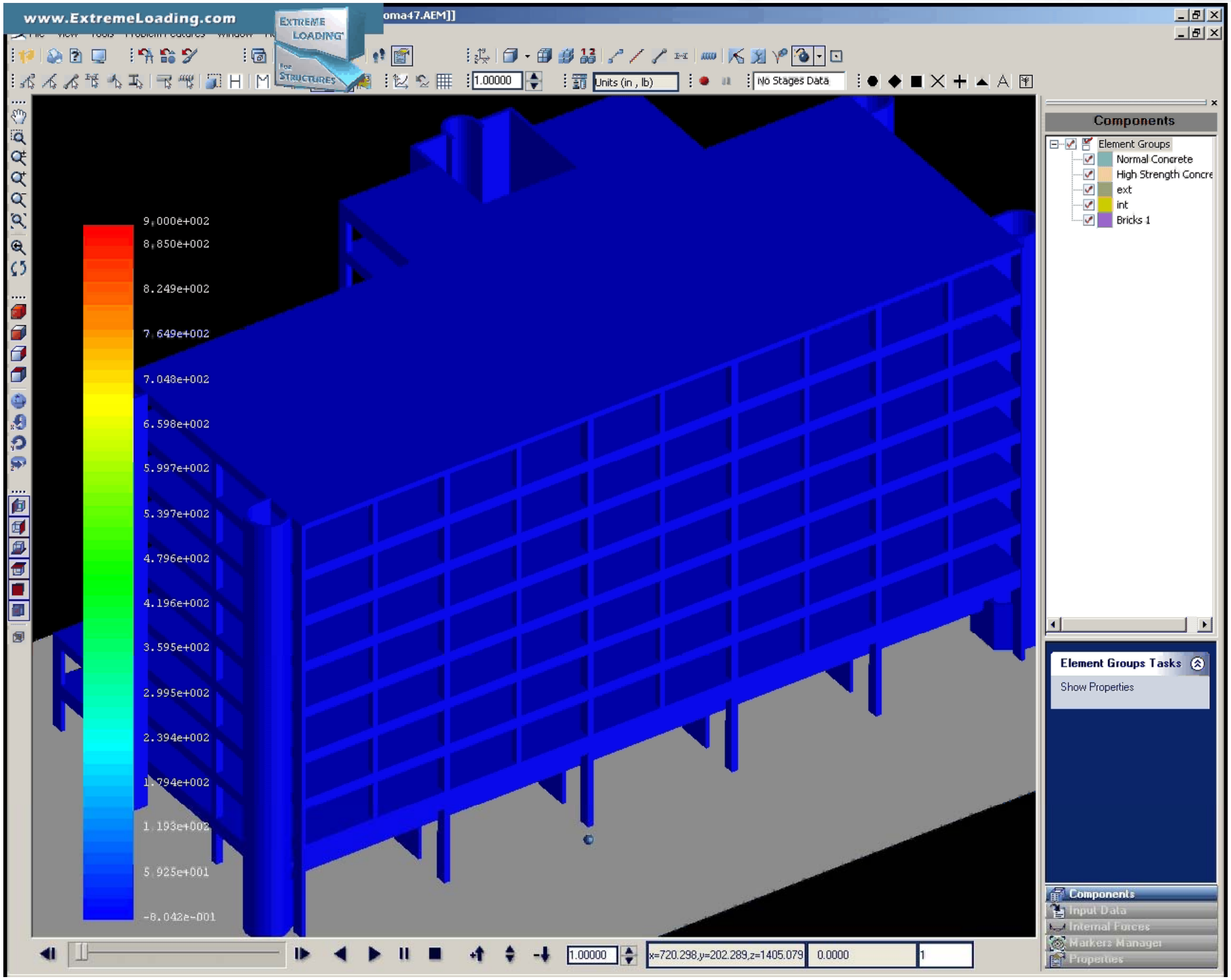
- Analysis Advantages
  - Analysis is as simple as the simplified FEM and as accurate as the advanced FEM.
  - Output includes stresses, strain and internal force diagrams
  - Automatic yield and cut of reinforcement bars
  - Automatic element separation and contact detection
  - Automatic plastic hinge formation
  - Automatic element collision
- Modeling Advantages
  - Physical elements
  - Much easier meshing
  - Easier modeling of reinforcement bars
  - Realistic and Easier modeling for Steel Structures

Why AEM?


Simple Solutions
Complexity, Accuracy, Time and Qualifications of User
Progressive Collapse Analysis
Engineering Judgment, Uncertainty and Construction Cost
Highly Nonlinear Solutions
FEM
Simplified FEM
Gap
Advanced FEM
Performance Based Design
Not verified
AEM

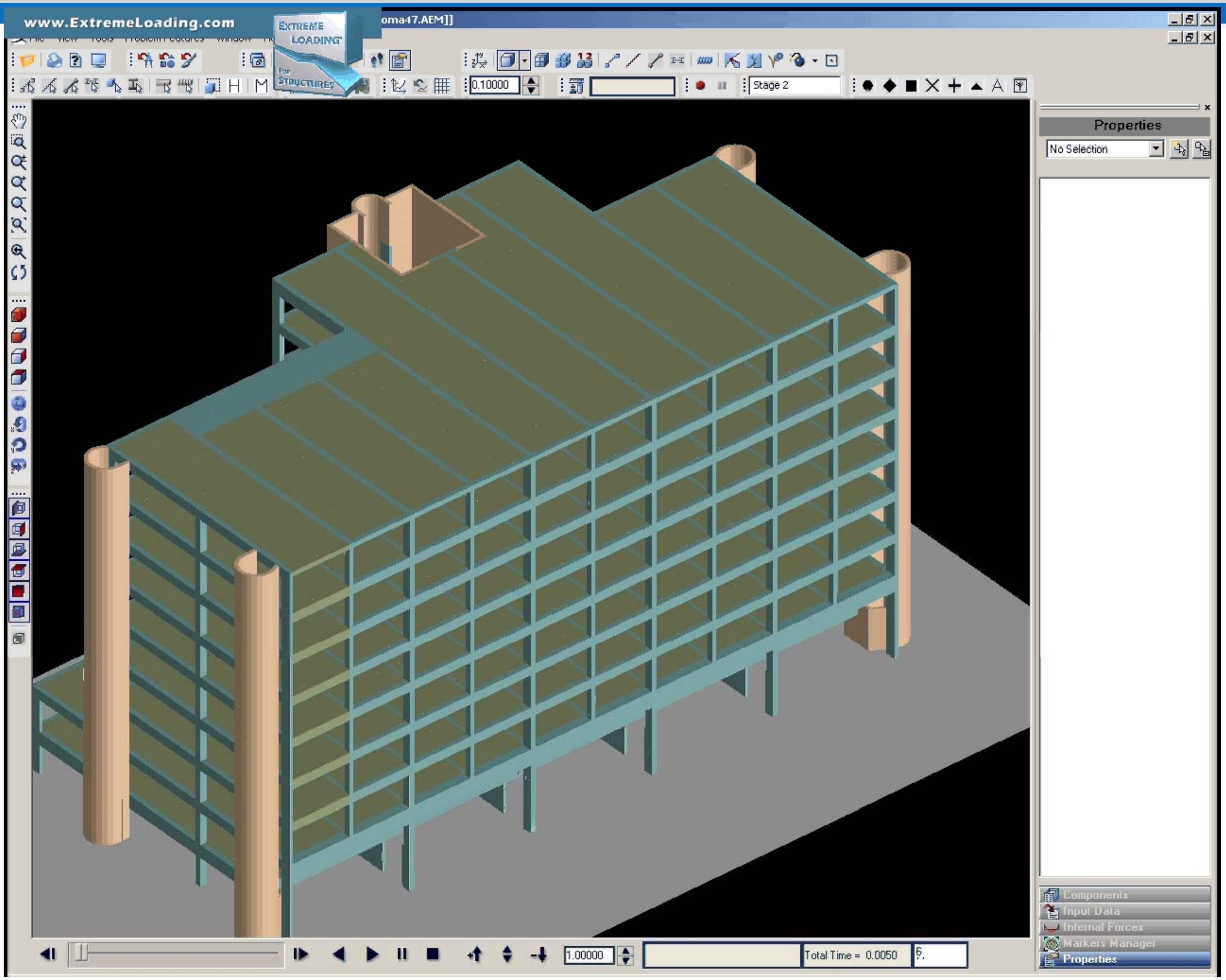
Why AEM?

Analysis of Oklahoma City Building Using AEM



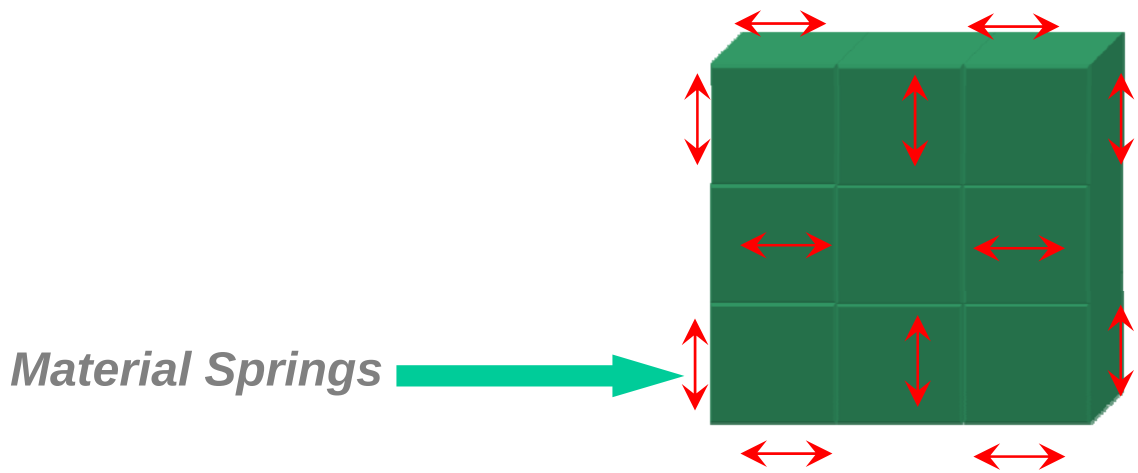
Why AEM?

Analysis of Oklahoma City Building Using AEM



AEM Theoretical Background

Element Discretization

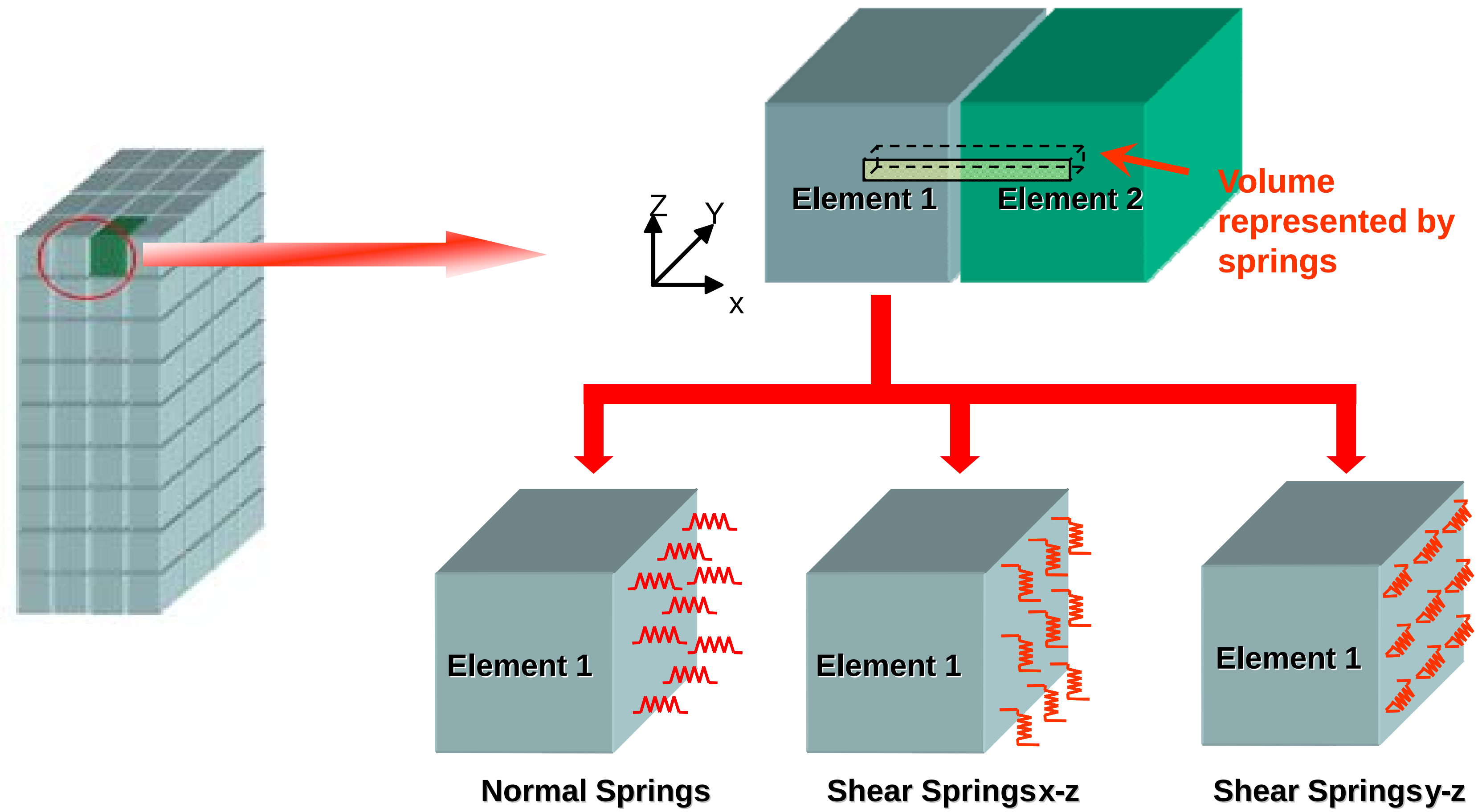


The continuum is discretized into elements connected together with nonlinear springs that represent the material behavior

The springs represent axial deformations as well as shear deformations

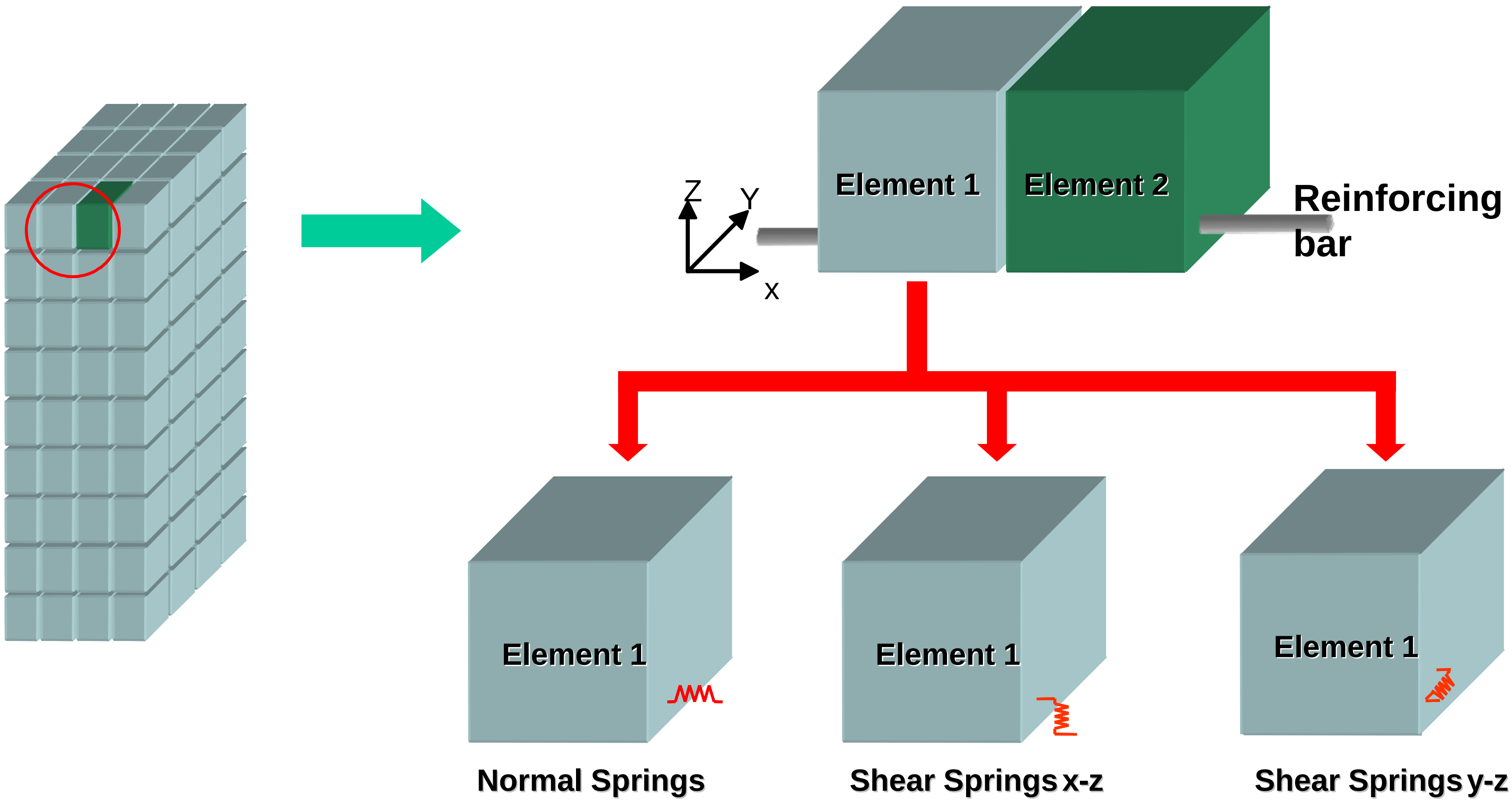
AEM Theoretical Background

Connectivity (Matrix Springs)



AEM Theoretical Background

Connectivity (Reinforcement Springs)

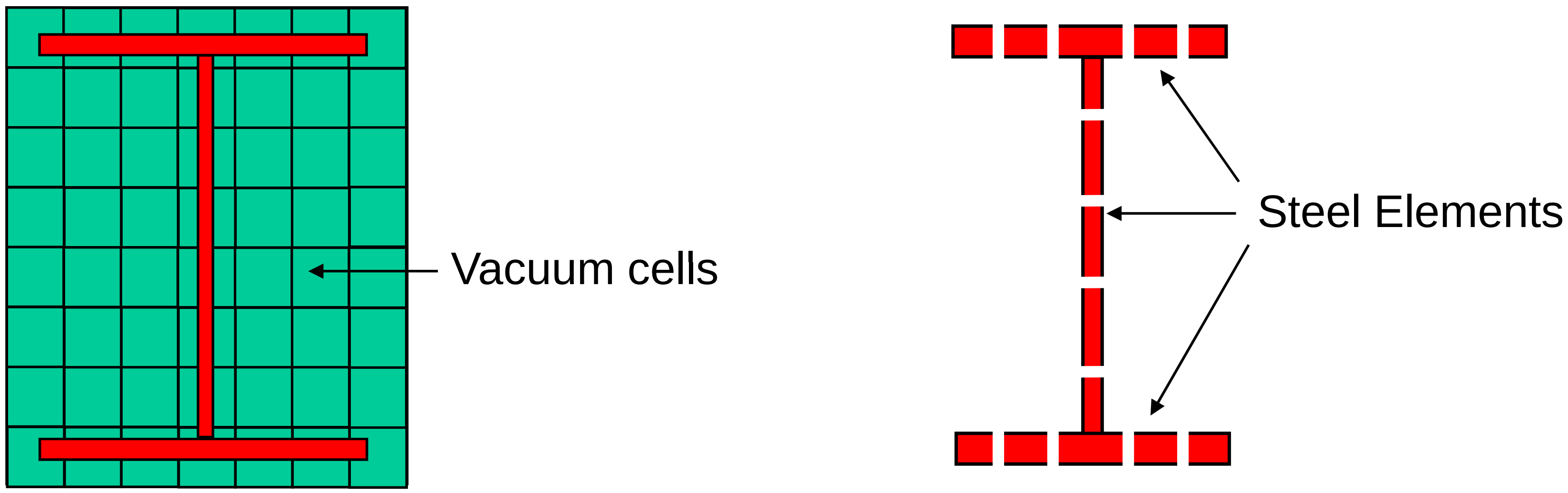


AEM Theoretical Background

Connectivity (Steel Sections)

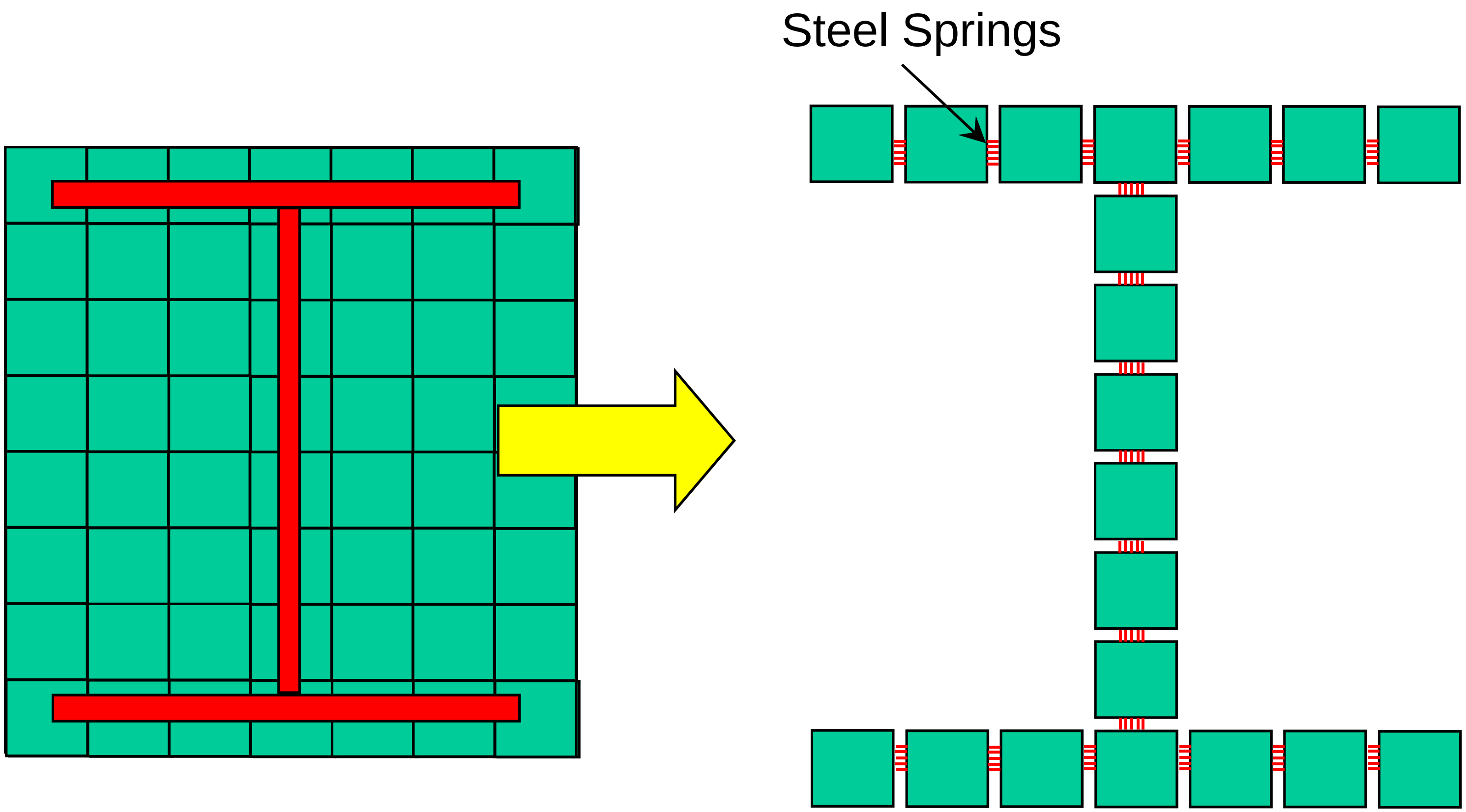
2 ways for modeling a steel section

- Implicit Steel section
- Explicit Steel section



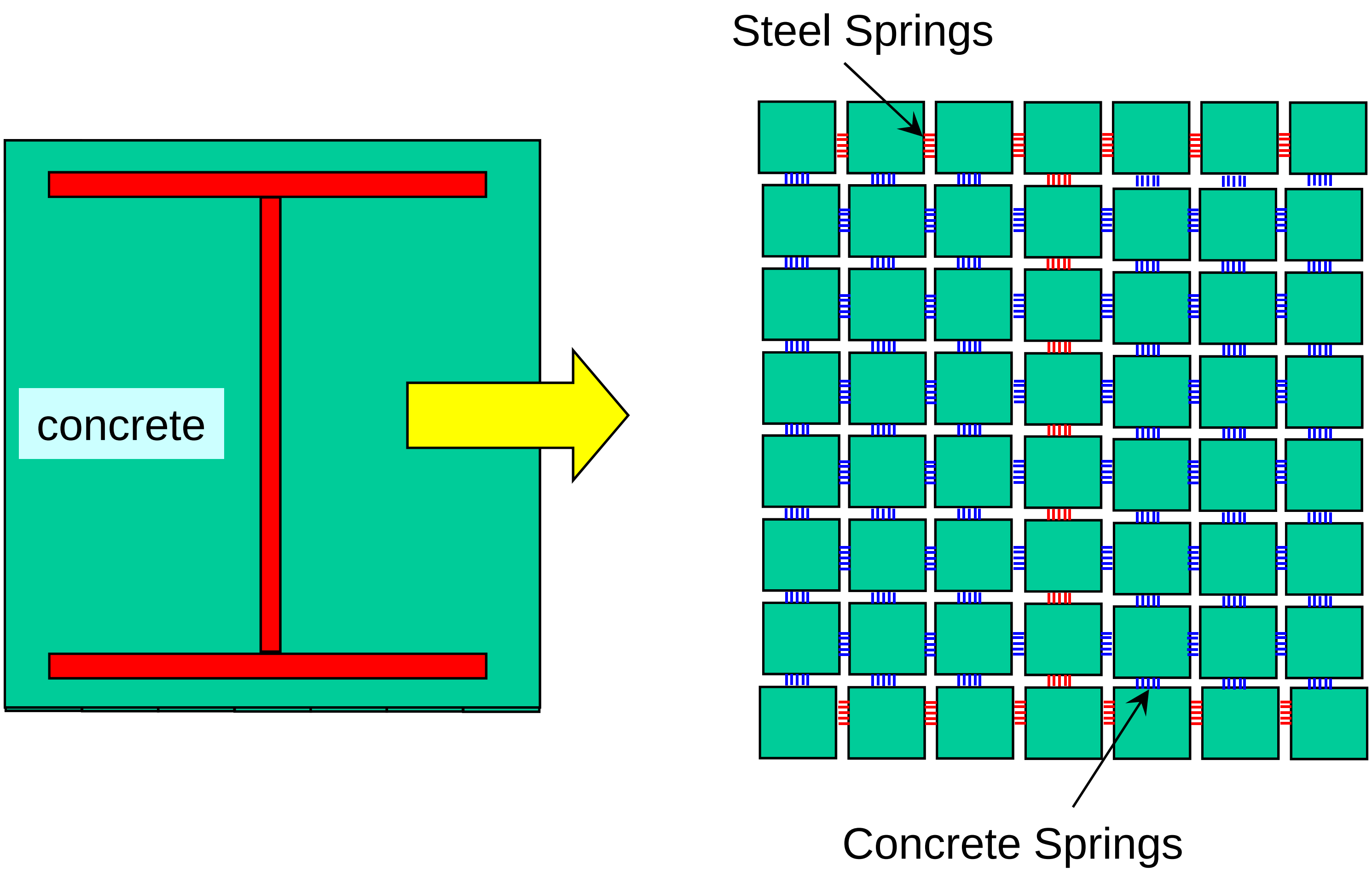
AEM Theoretical Background

Connectivity (Matrix Springs)



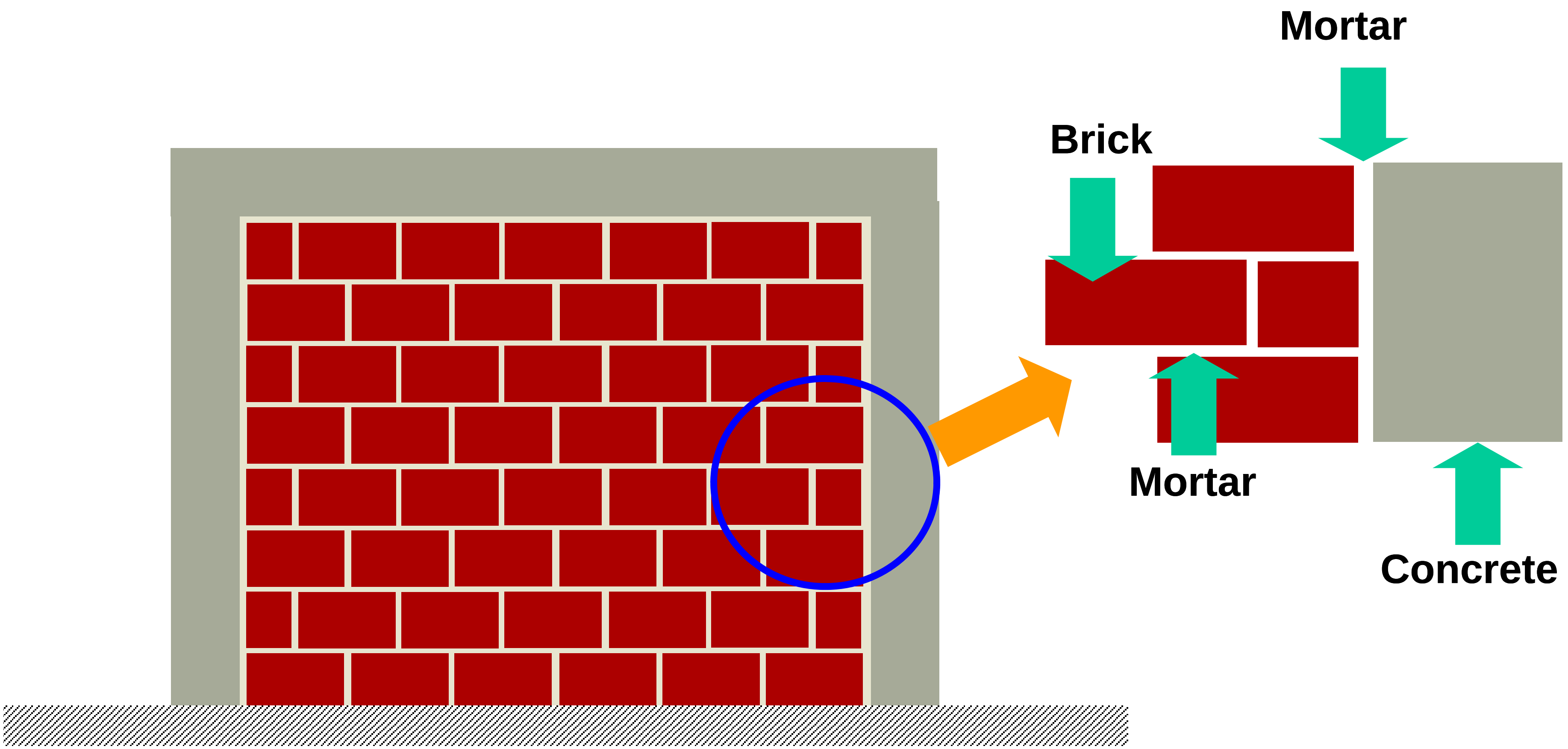
AEM Theoretical Background

Connectivity (Matrix Springs)



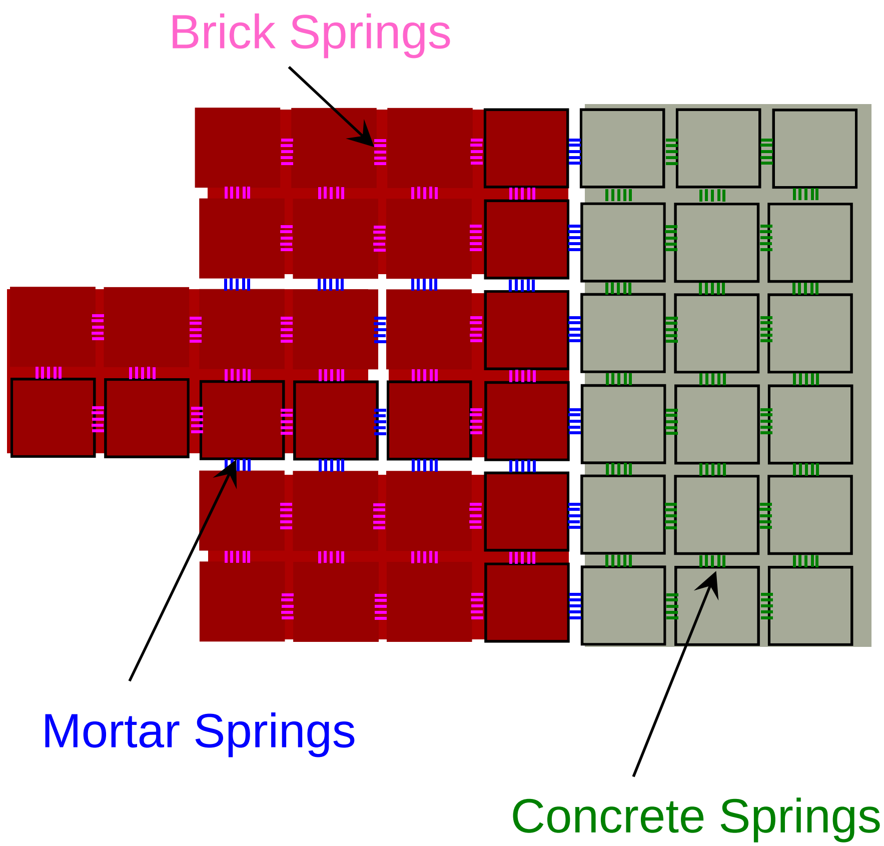
AEM Theoretical Background

Masonry Walls Modeling



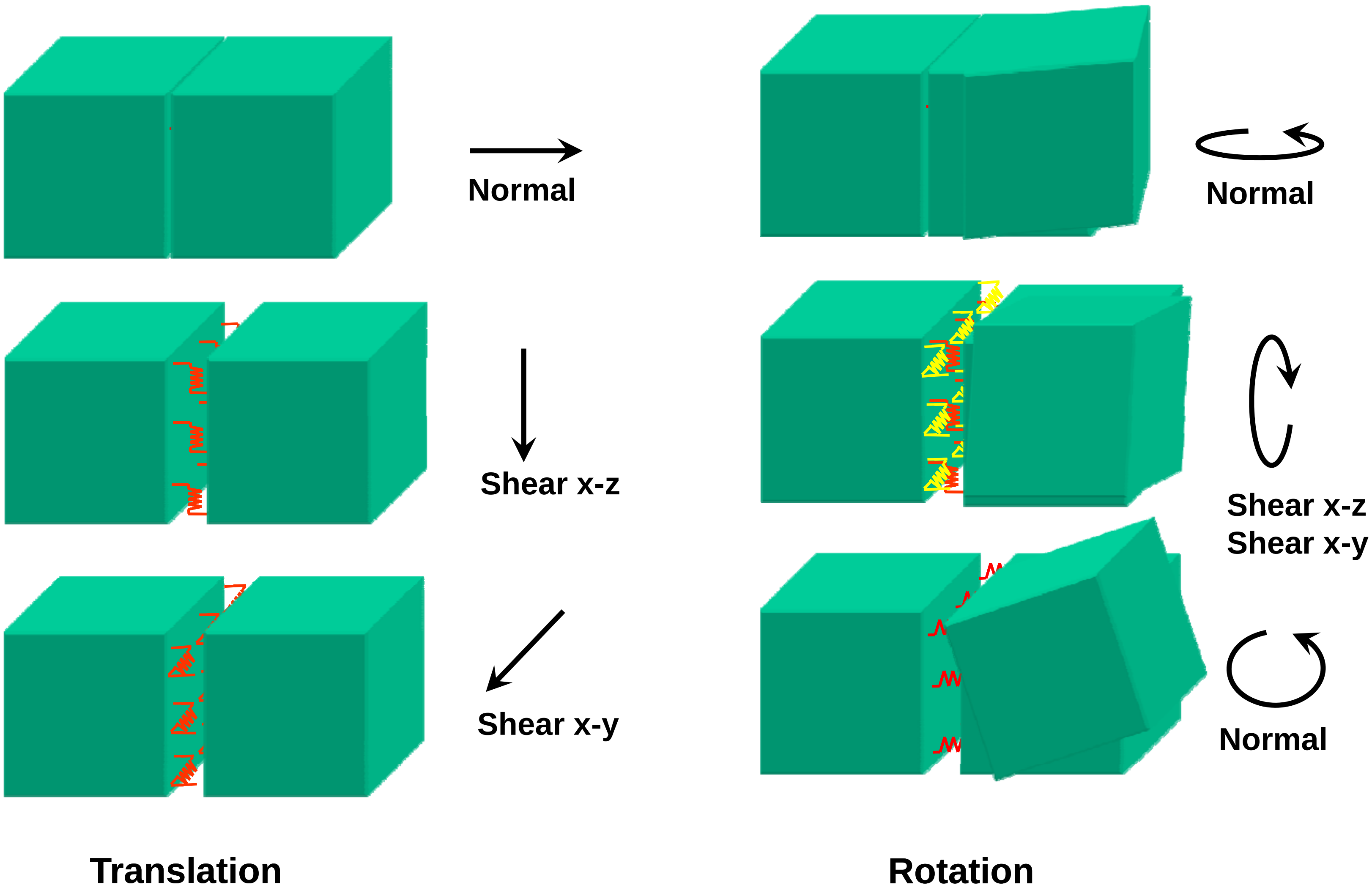
AEM Theoretical Background

Masonry Walls Modeling



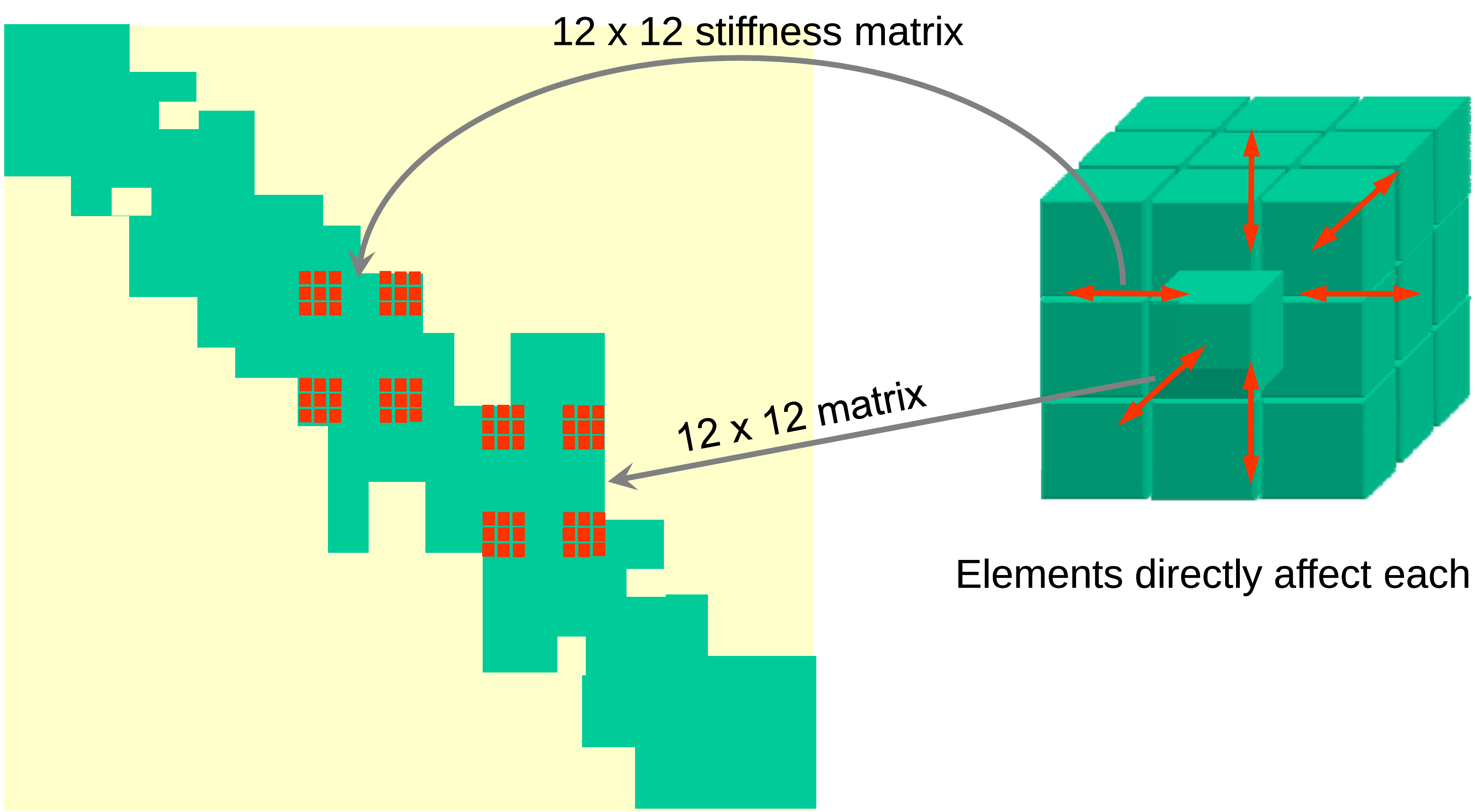
AEM Theoretical Background

Degrees of Freedom



AEM Theoretical Background

Assembly of Overall Stiffness Matrix



Elements directly affect each other

Overall Stiffness Matrix

AEM Theoretical Background

Equation of Motion

$$[M]\{\Delta \ddot{y}_i\} + [C_i]\{\Delta \dot{y}_i\} + [K_i]\{\Delta y_i\} = \{\Delta F_i\}$$

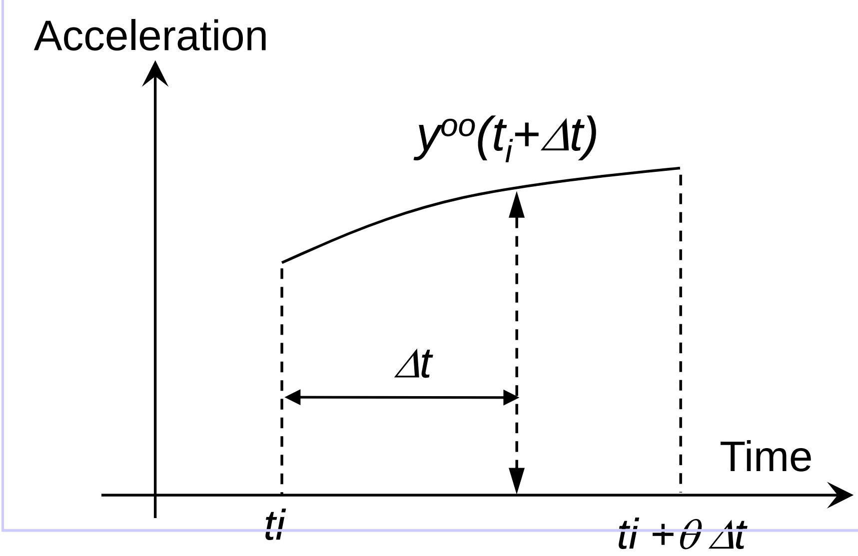
Incremental Equation of Motion

requested

Step-by-step integration (Newmark-beta) method

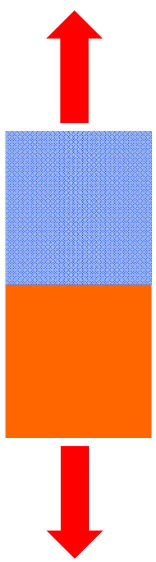
$$\{\Delta \dot{y}_i\} = \{\ddot{y}_i\}\Delta t + \gamma\{\Delta \ddot{y}_i\}\Delta t$$

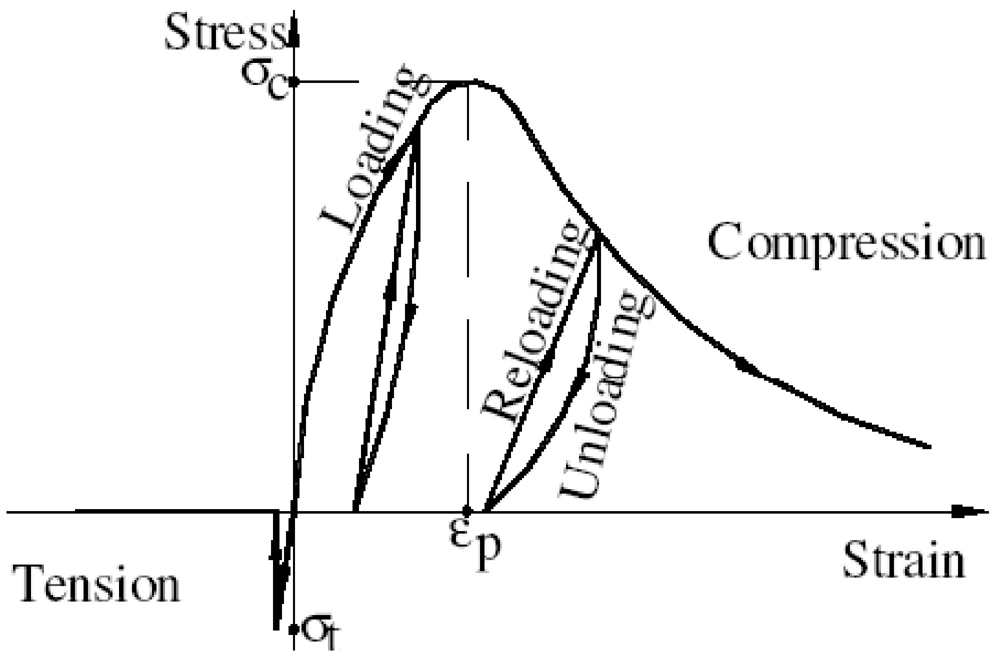
$$\{\Delta y_i\} = \{\dot{y}_i\}\Delta t + \frac{1}{2}\{\ddot{y}_i\}\Delta t^2 + \beta\{\Delta \ddot{y}_i\}\Delta t^2$$

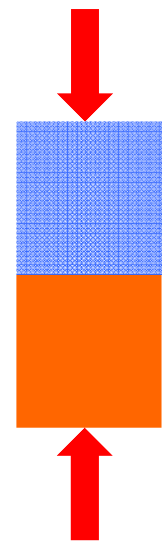


AEM Theoretical Background

Material Models (Concrete under axial stresses)







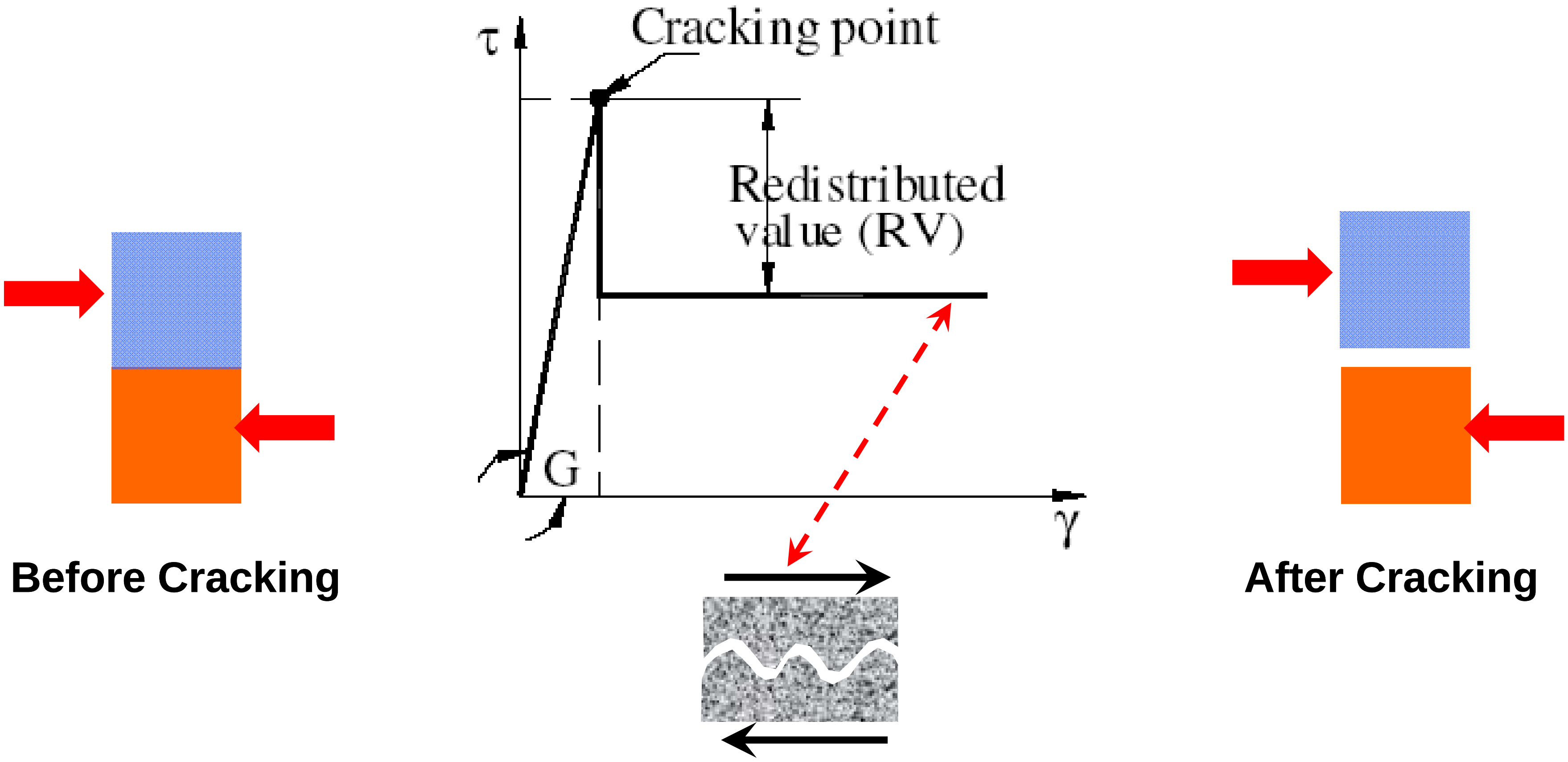
Tension

Fully path-dependent model for concrete
(Okamura and Maekawa, 1991)

Compression

AEM Theoretical Background

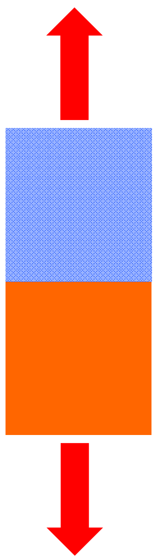
Material Models (Concrete under Shear Stresses)



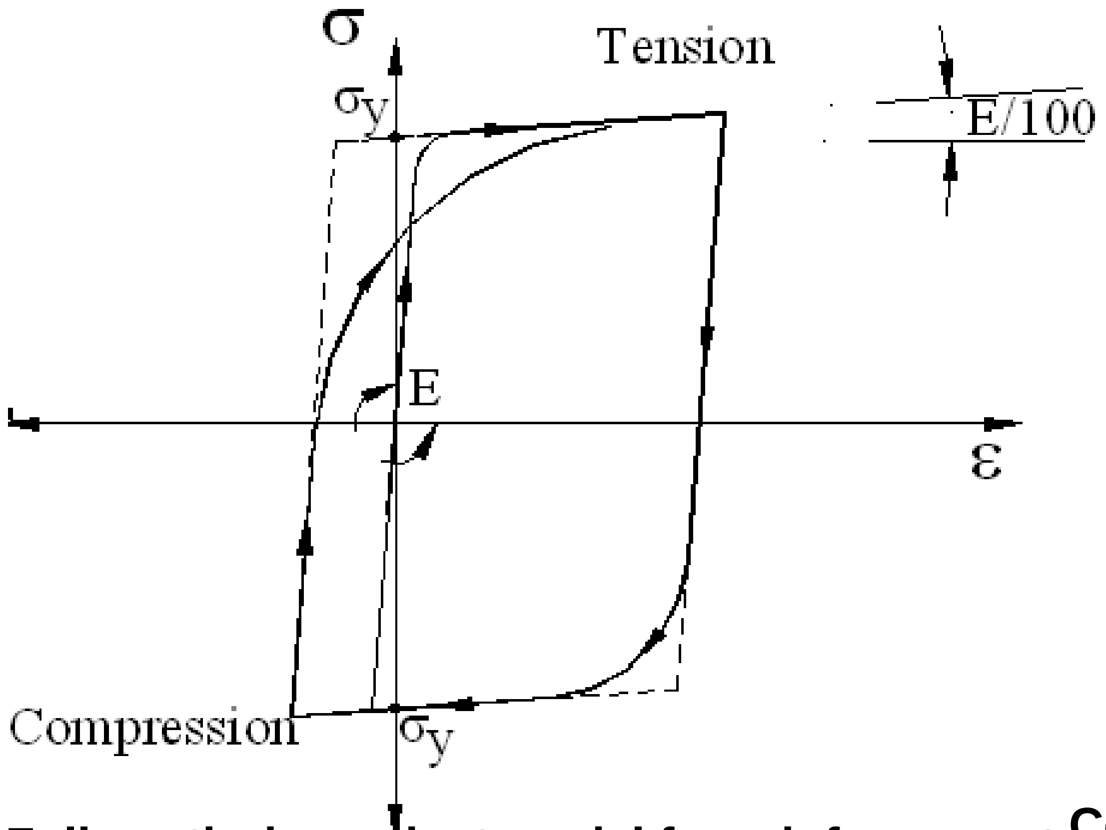
Friction and interlocking

AEM Theoretical Background

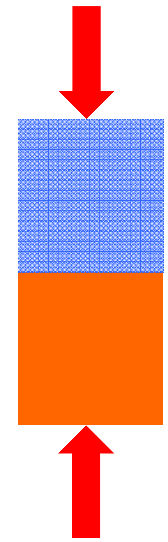
Material Models (Steel under axial stresses)



Tension



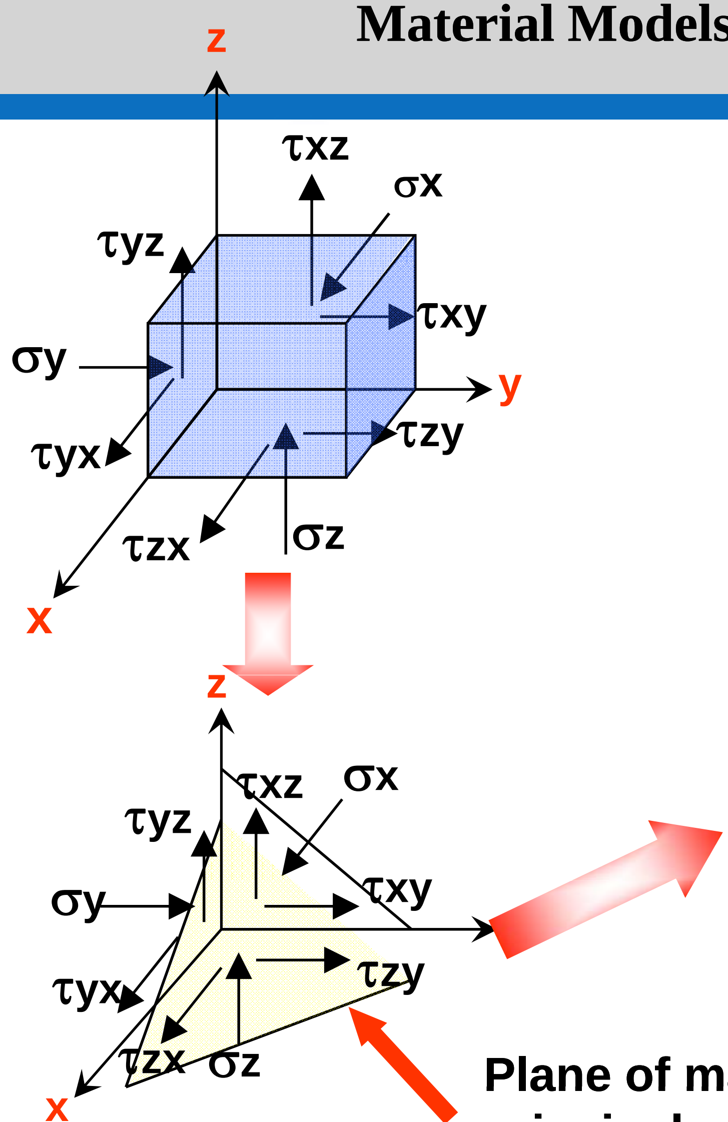
Fully path-dependent model for reinforcement
(Ristic et al, 1986)



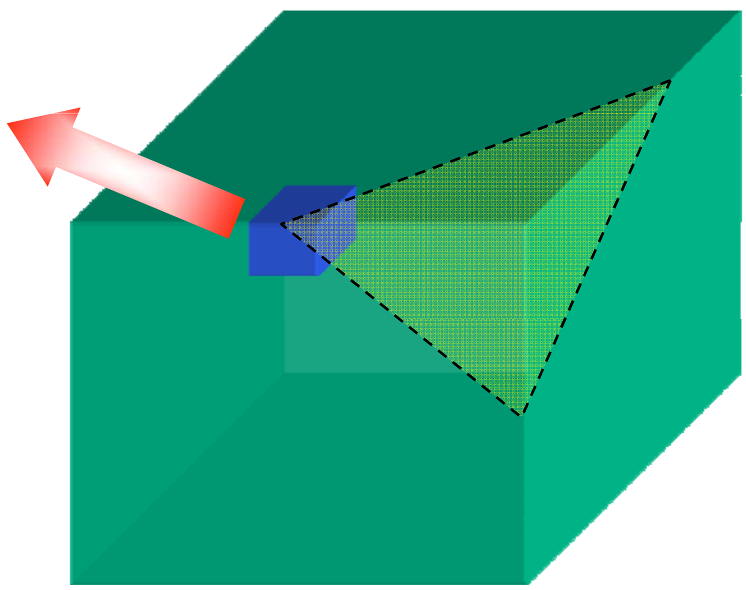
Compression

AEM Theoretical Background

Material Models (Cracking Criteria)

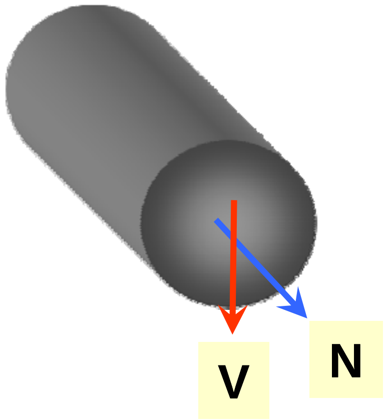


Plane of major principal stress



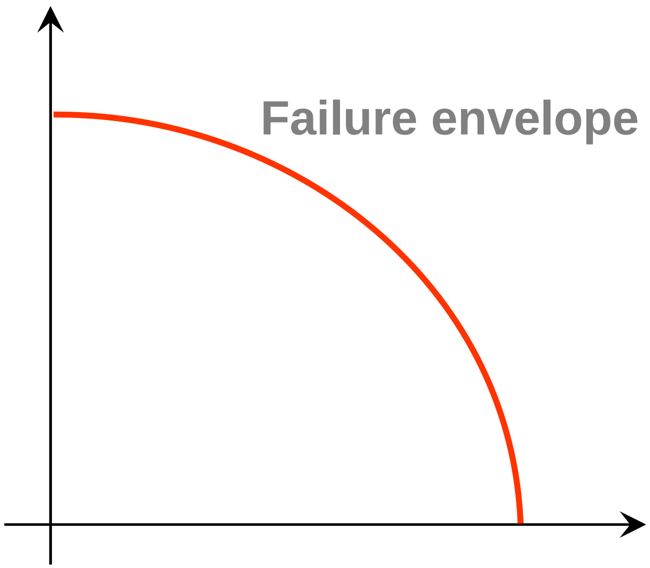
AEM Theoretical Background

Cut of Rebar



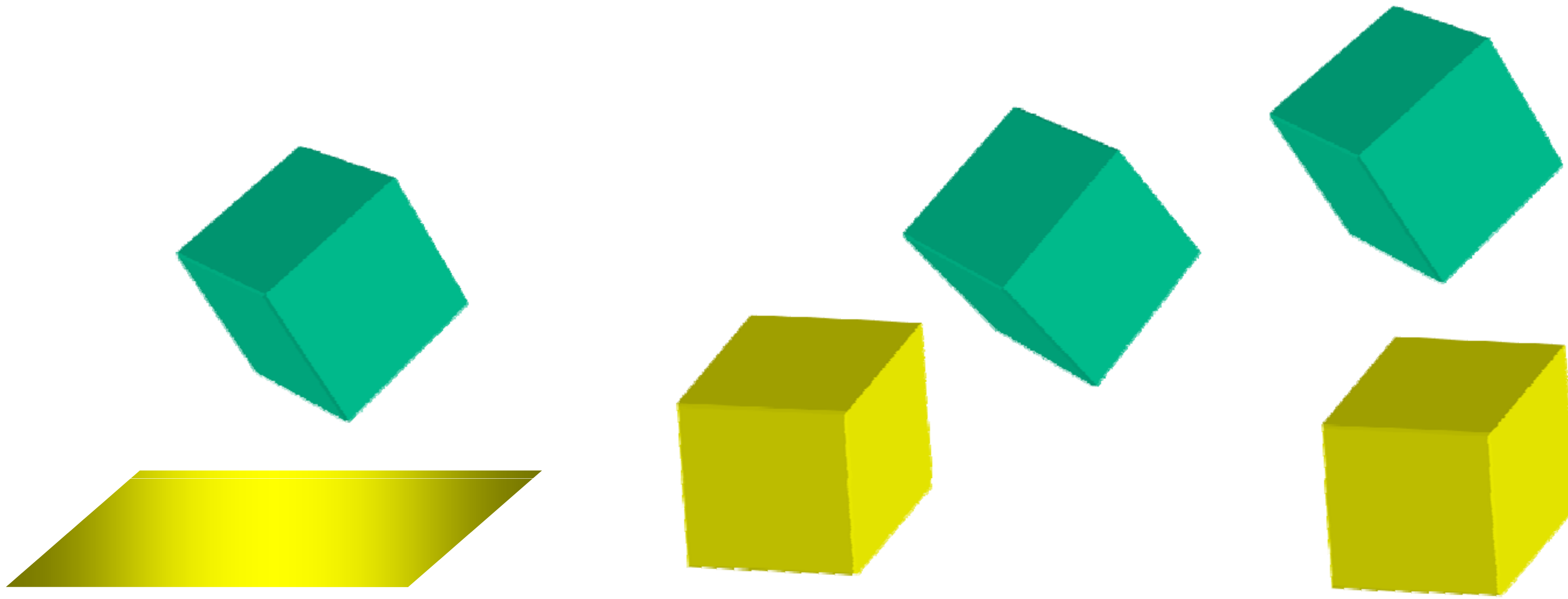
Von-Misses Criteria applied for Ultimate Strength
Bar resists only Normal and shear forces
No Flexural rigidity at the time-being

$$\left(\frac{N}{N_P}\right)^2 + \left(\frac{V}{V_P}\right)^2 + \left(\frac{M}{M_P}\right)^2 = 1$$



AEM Theoretical Background

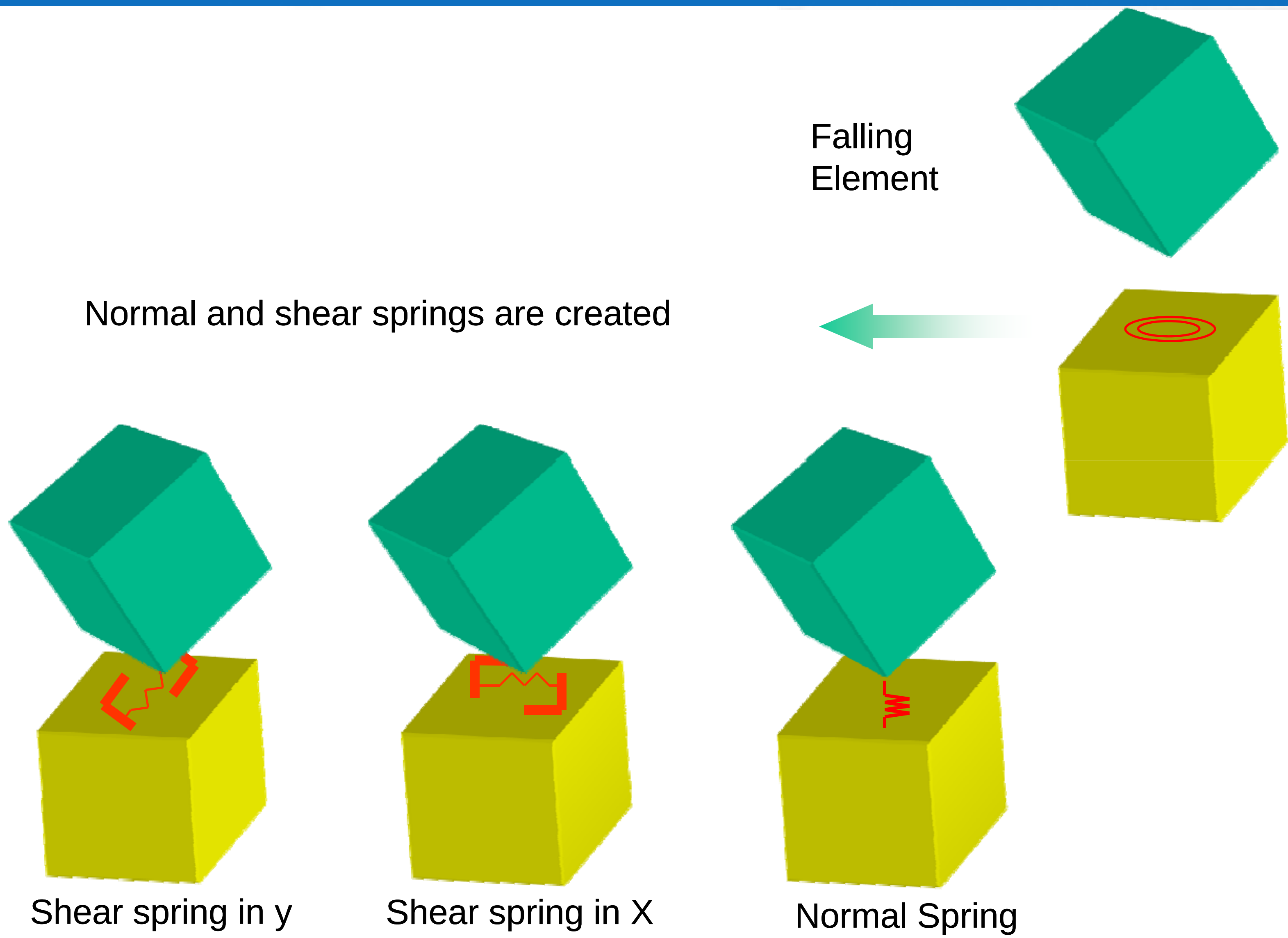
Types of Contact



Corner-Ground Type   Edge-Edge Type   Corner-Face Type

AEM Theoretical Background

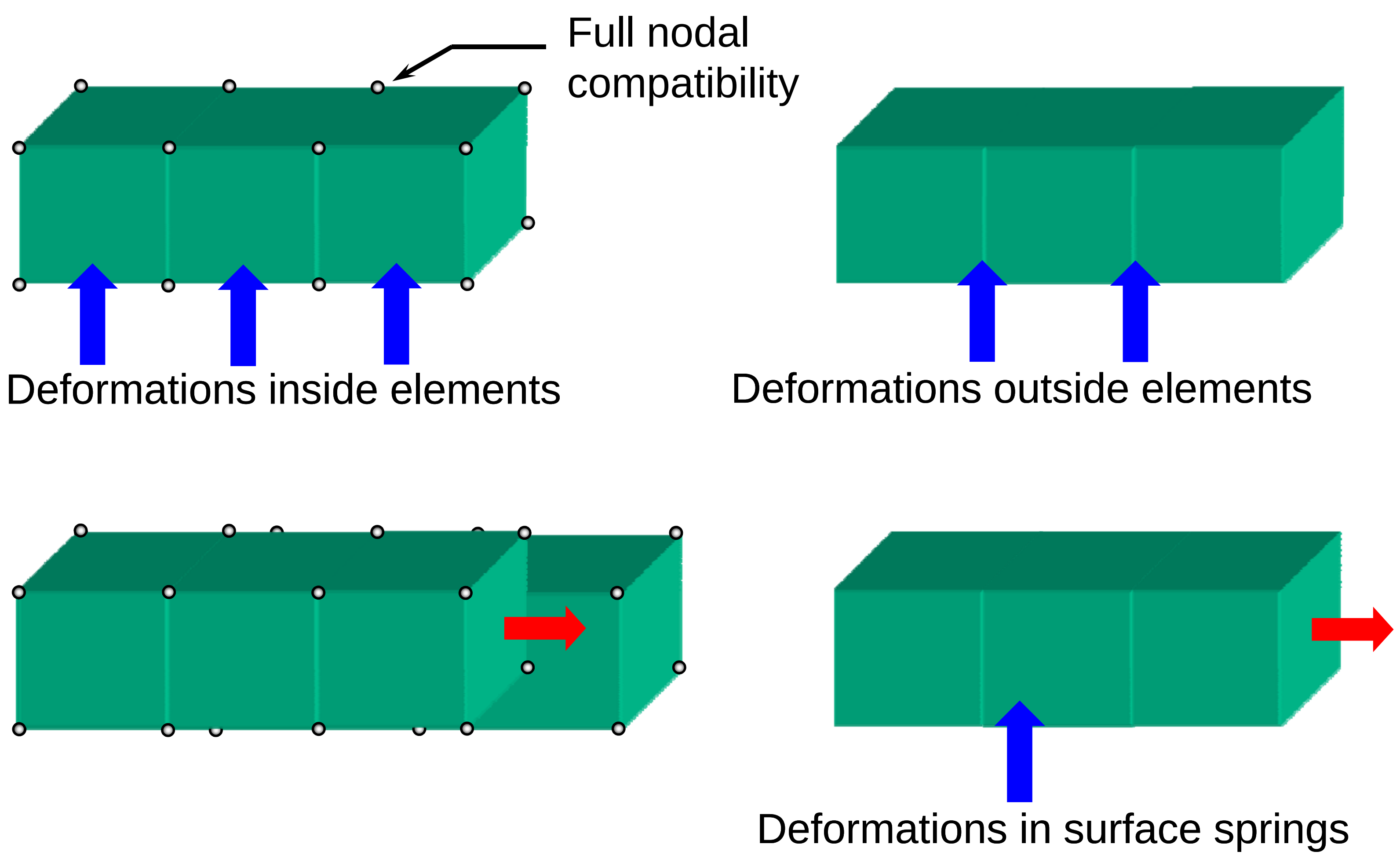
Collision Springs



AEM Theoretical Background

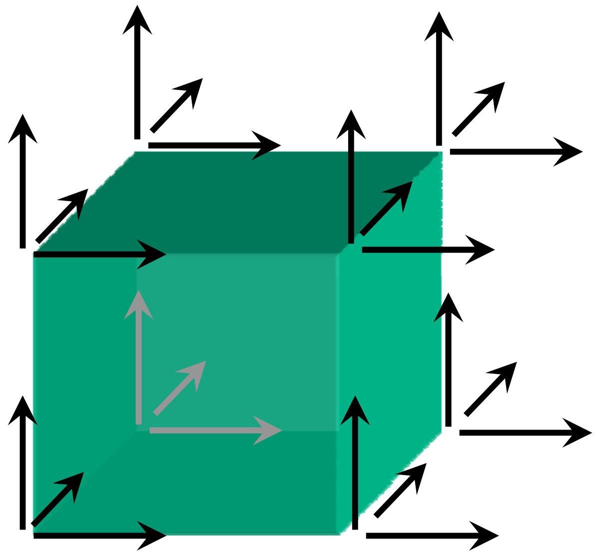
FEM/AEM Comparison

FEM | **AEM**

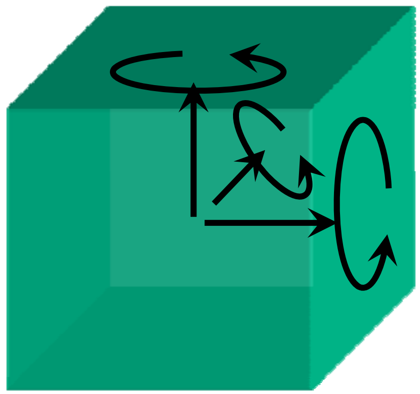


AEM Theoretical Background

FEM/AEM Comparison



FEM



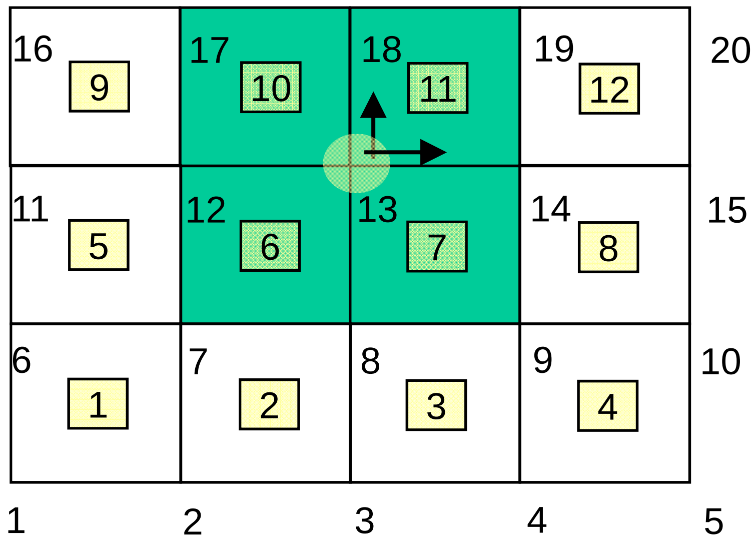
AEM

8 nodes x 3 DOF → 24 DOF/ Element

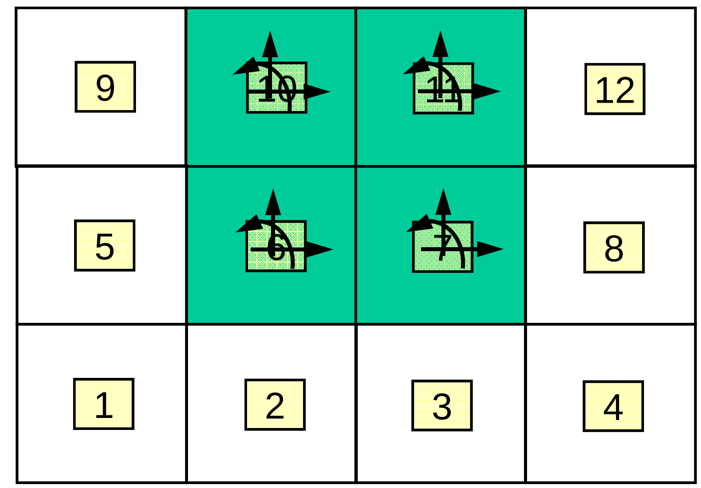
6 DOF/ Element

AEM Theoretical Background

FEM/AEM Comparison



FEM



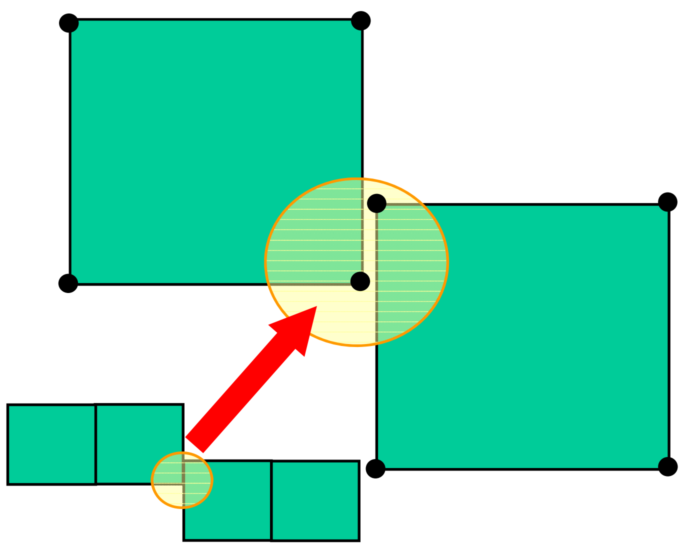
AEM

- Elements compatible at nodes (moves together there)
- For example Node 13 connects Elements 6,7,10,11
- Deformations are inside the elements

- Elements are connected through their faces
- For example elements 6,7,10,11 are not compatible in deformations
- Deformations are localized at the faces of the elements

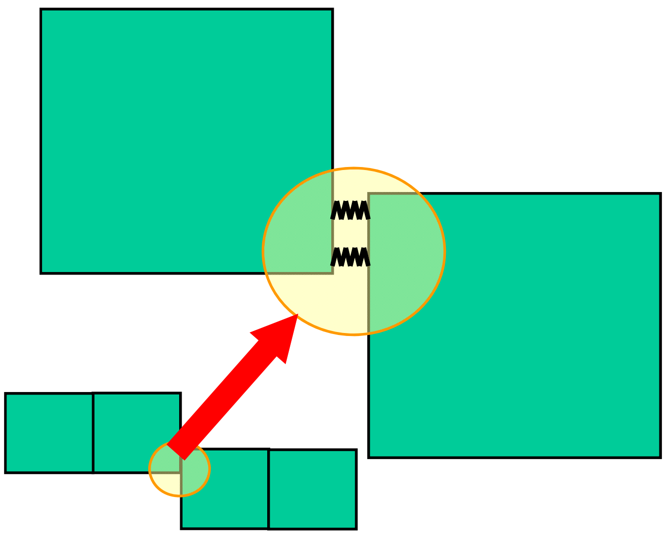
AEM Theoretical Background

FEM/AEM Comparison



FEM

No Connectivity

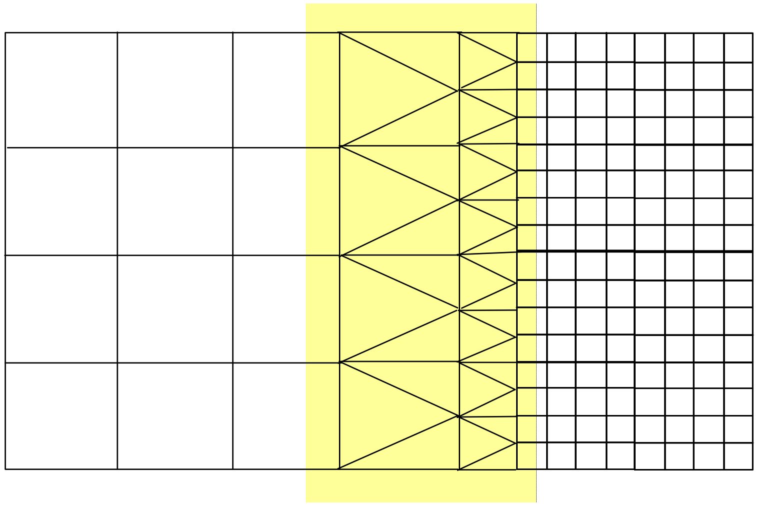


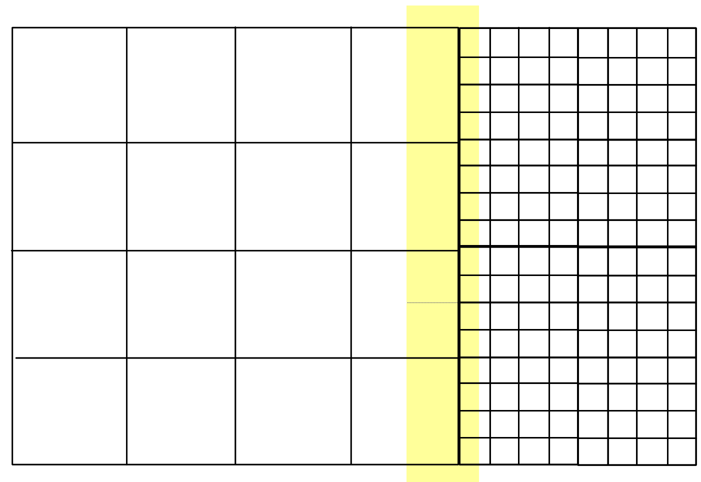
AEM

Connectivity included

AEM Theoretical Background

FEM/AEM Comparison (Transition Elements)





FEM

AEM

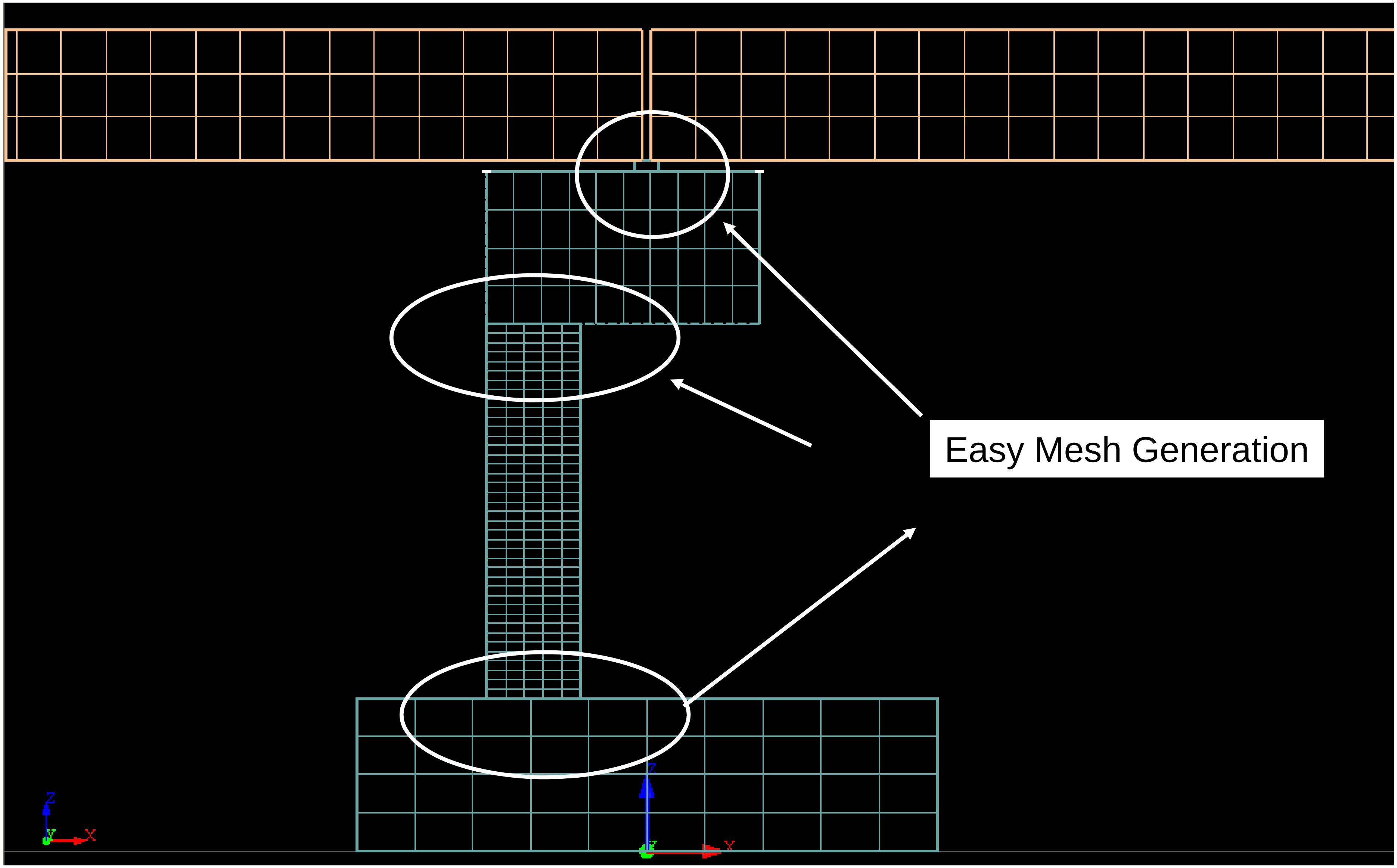
There should be transition elements between large elements and small elements

There is no need for the transition elements between large elements and small elements

Modeling Advantages of AEM compared to FEM

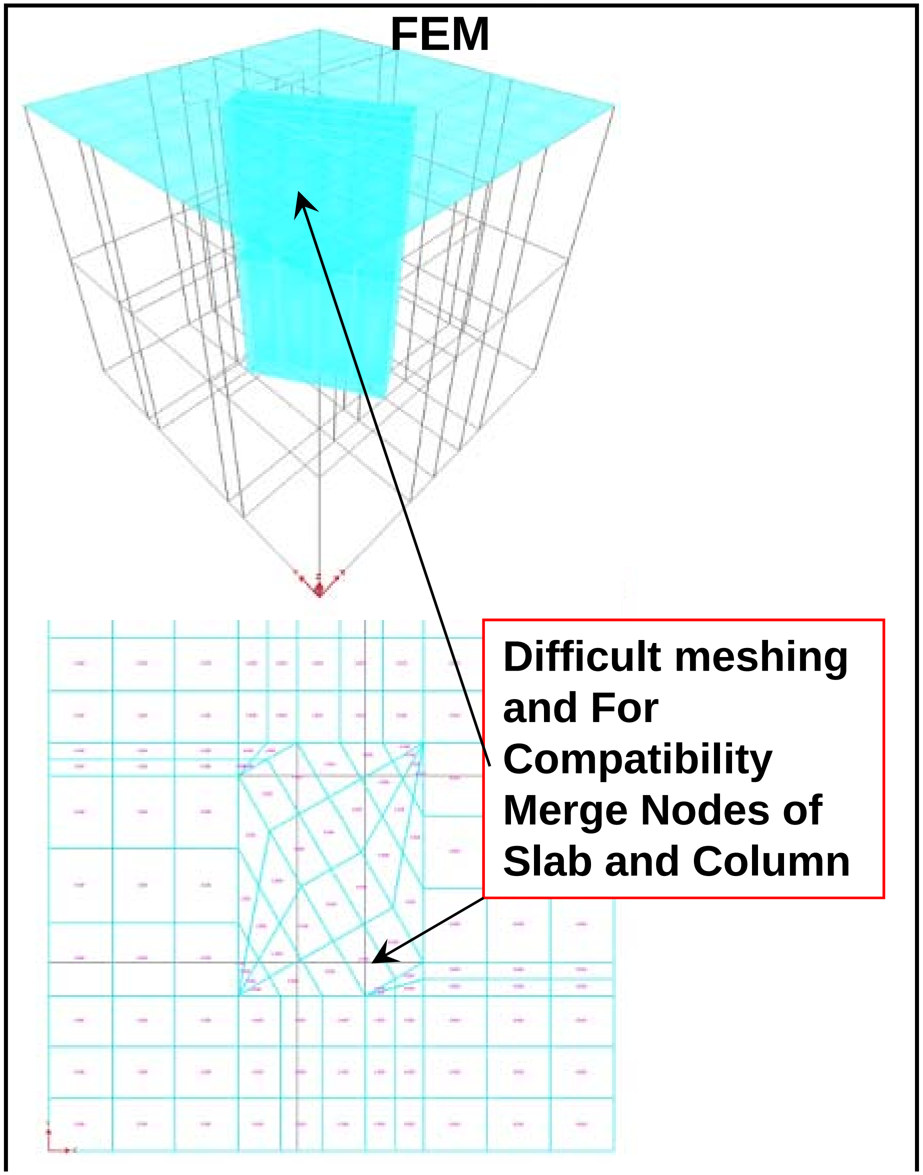
Modeling Advantages of AEM compared to FEM

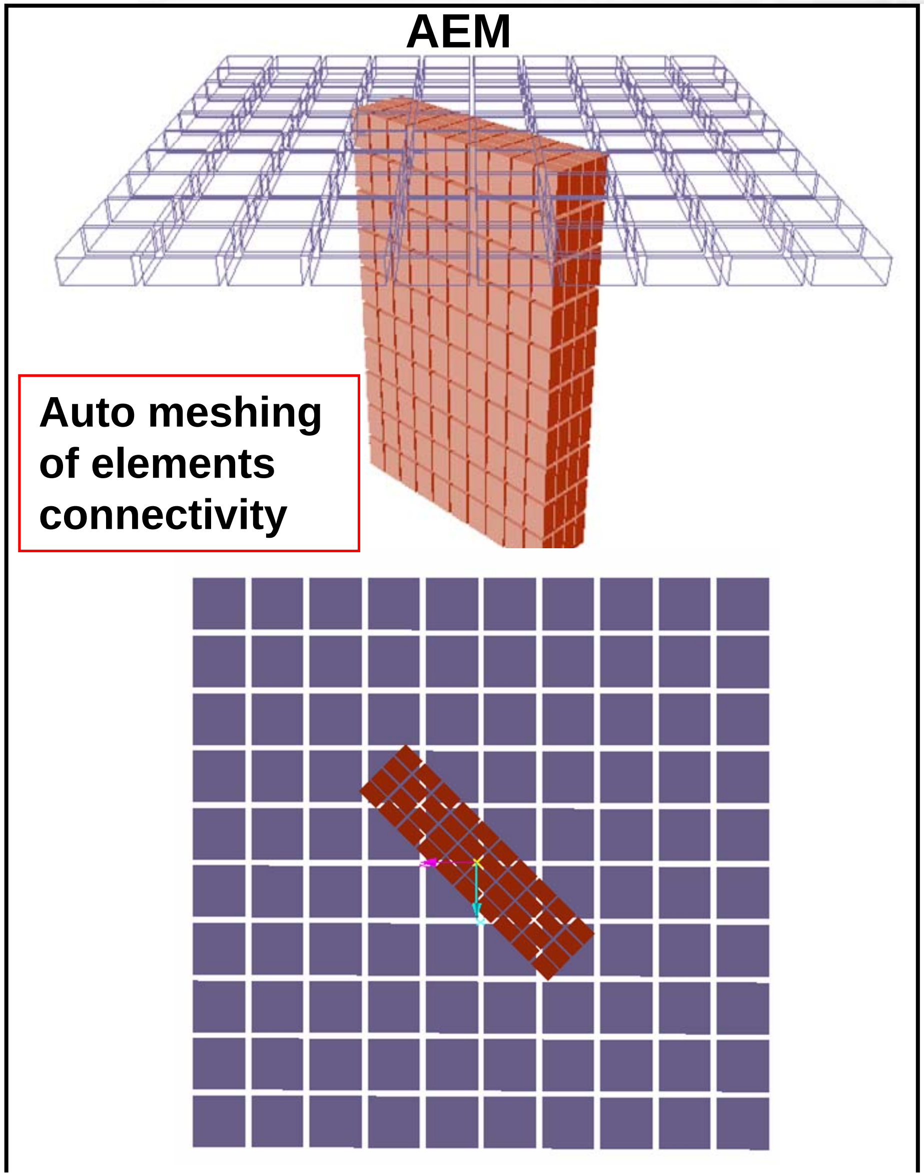
Easy Element Connectivity



Modeling Advantages of AEM compared to FEM

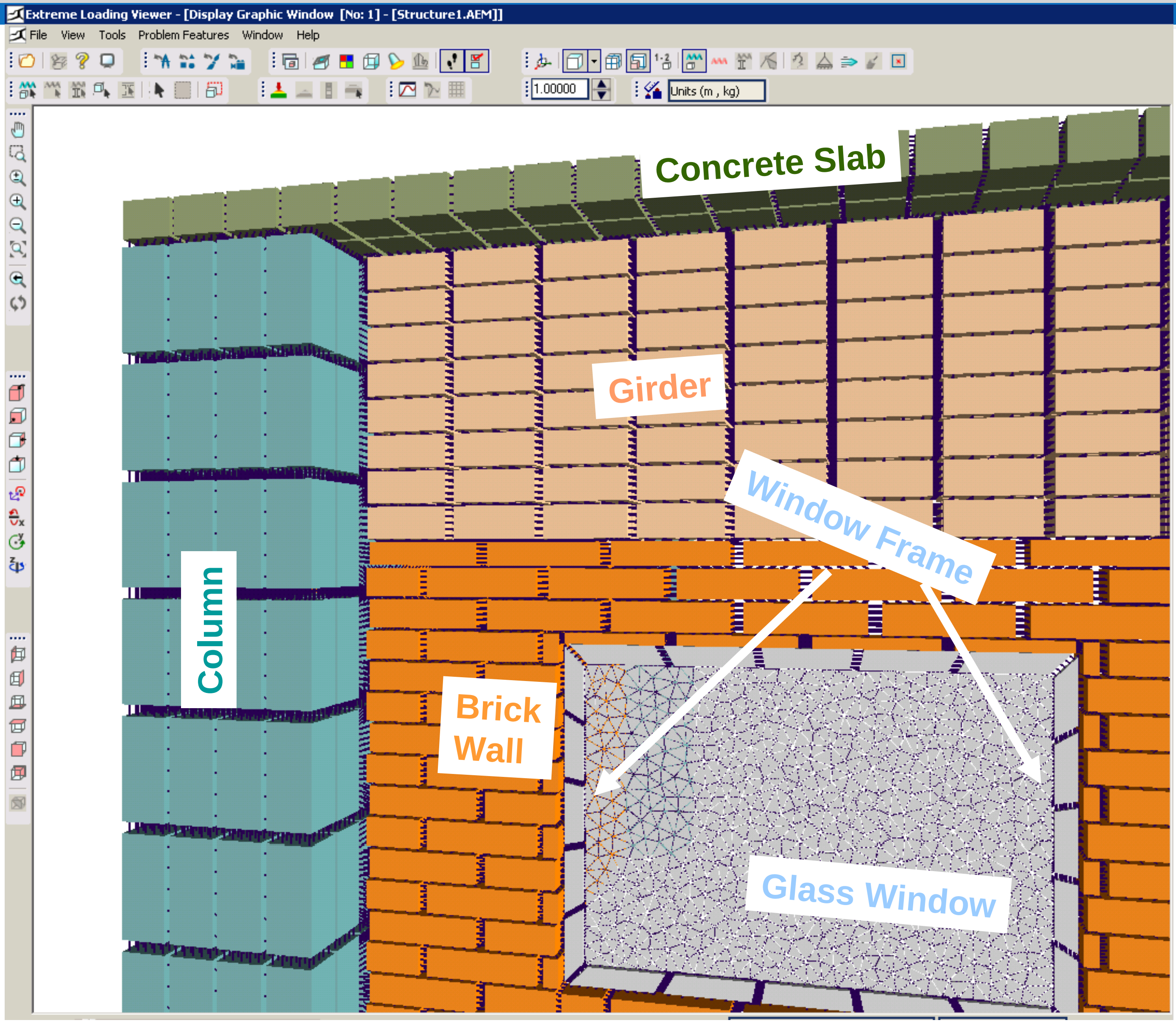
Easy Element Connectivity





Modeling Advantages of AEM compared to FEM

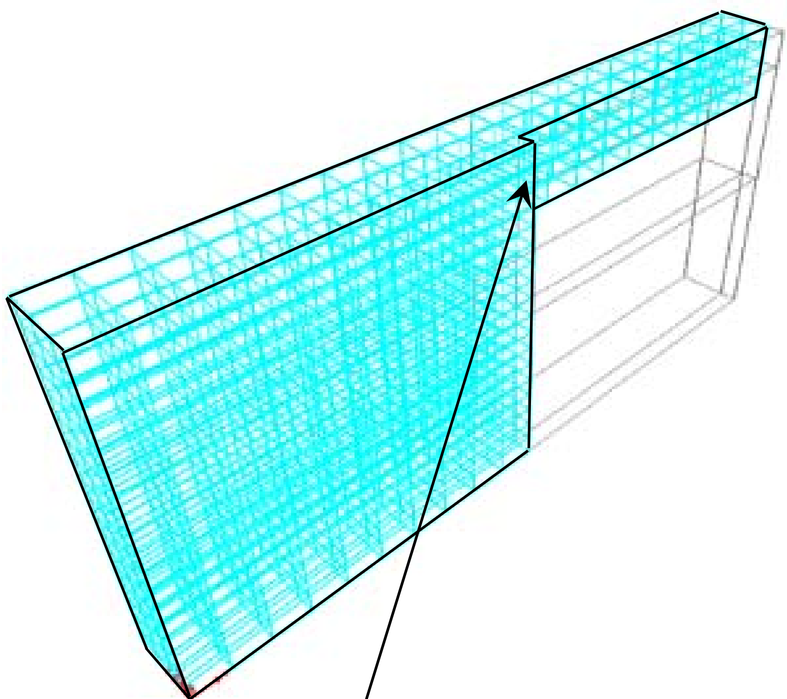
Easy Element Connectivity



Modeling Advantages of AEM compared to FEM

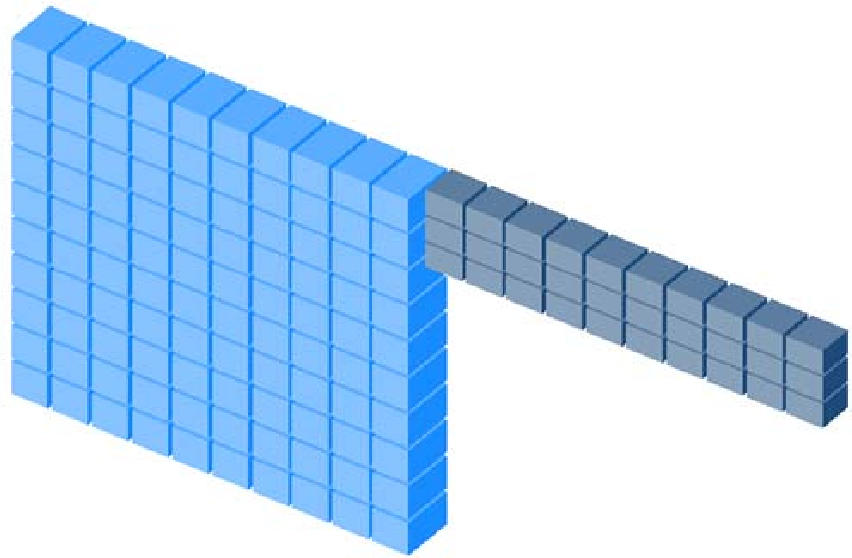
Easy Element Connectivity

FEM



Difficult meshing Between wide and thin elements

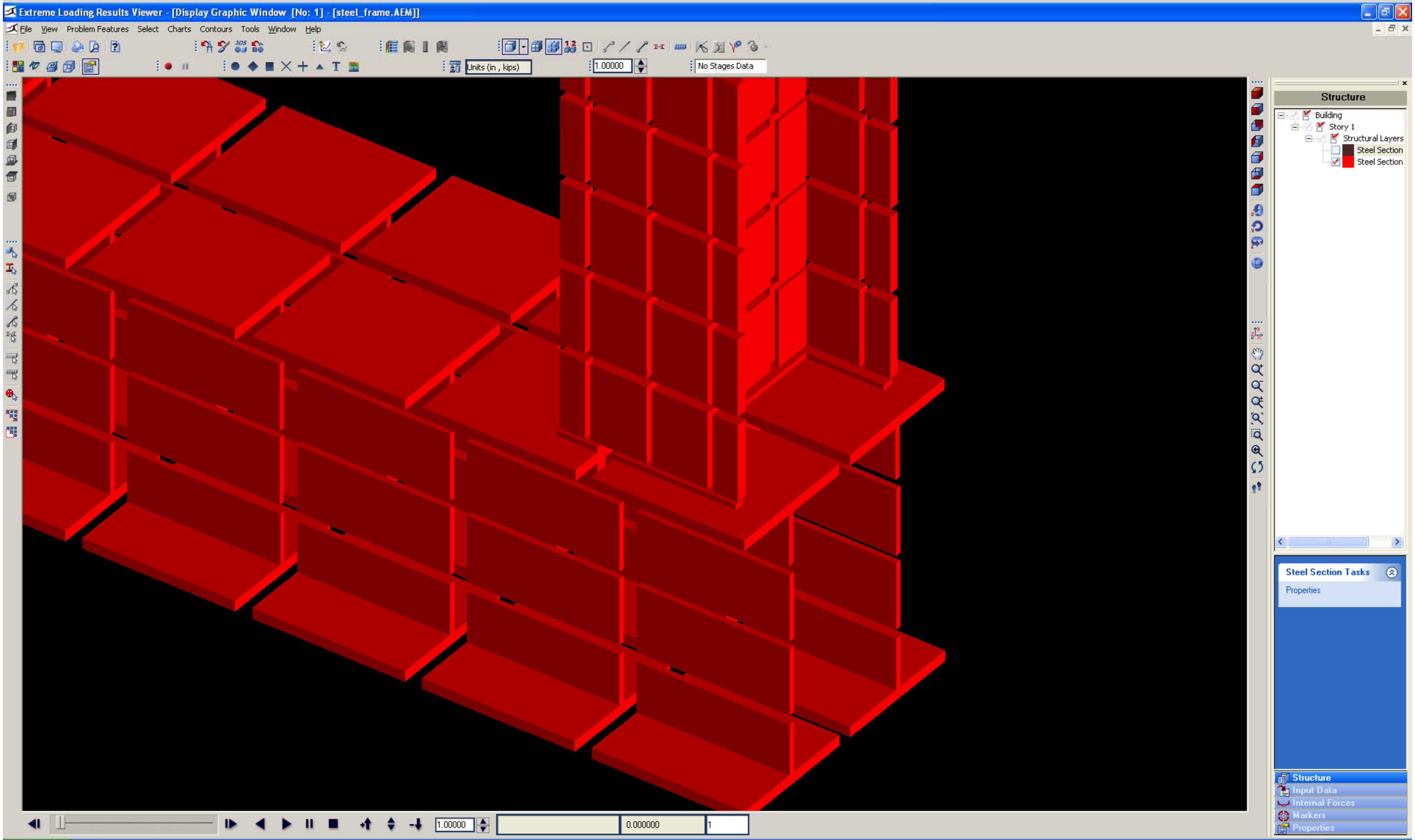
AEM



Connection of Elements Through Interfaces

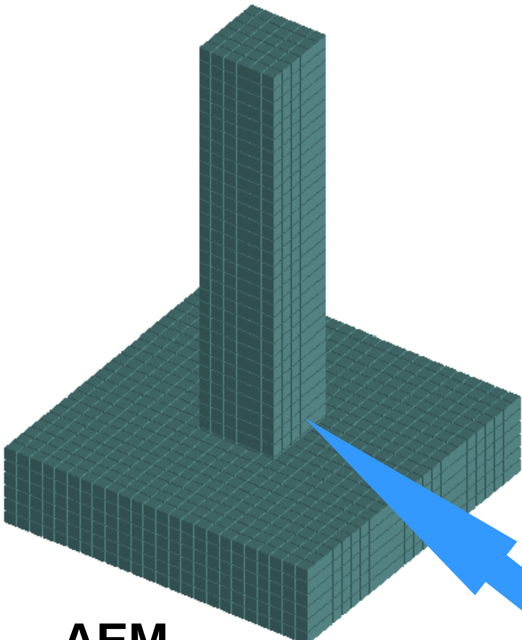
Modeling Advantages of AEM compared to FEM

Easy Modeling of Steel Structures

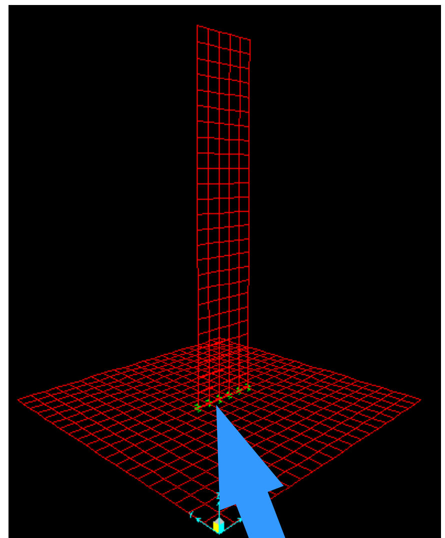


Modeling Advantages of AEM compared to FEM

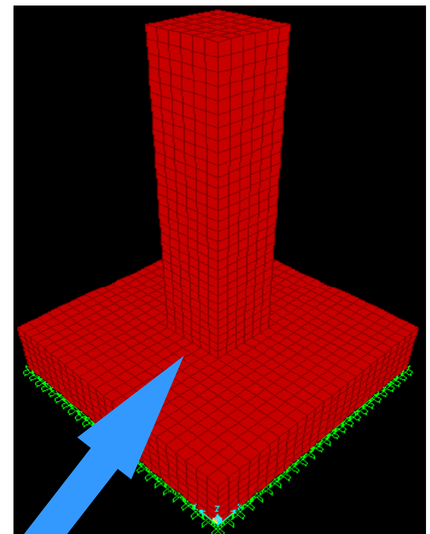
No Need for Gap Elements



AEM



Shell Elements



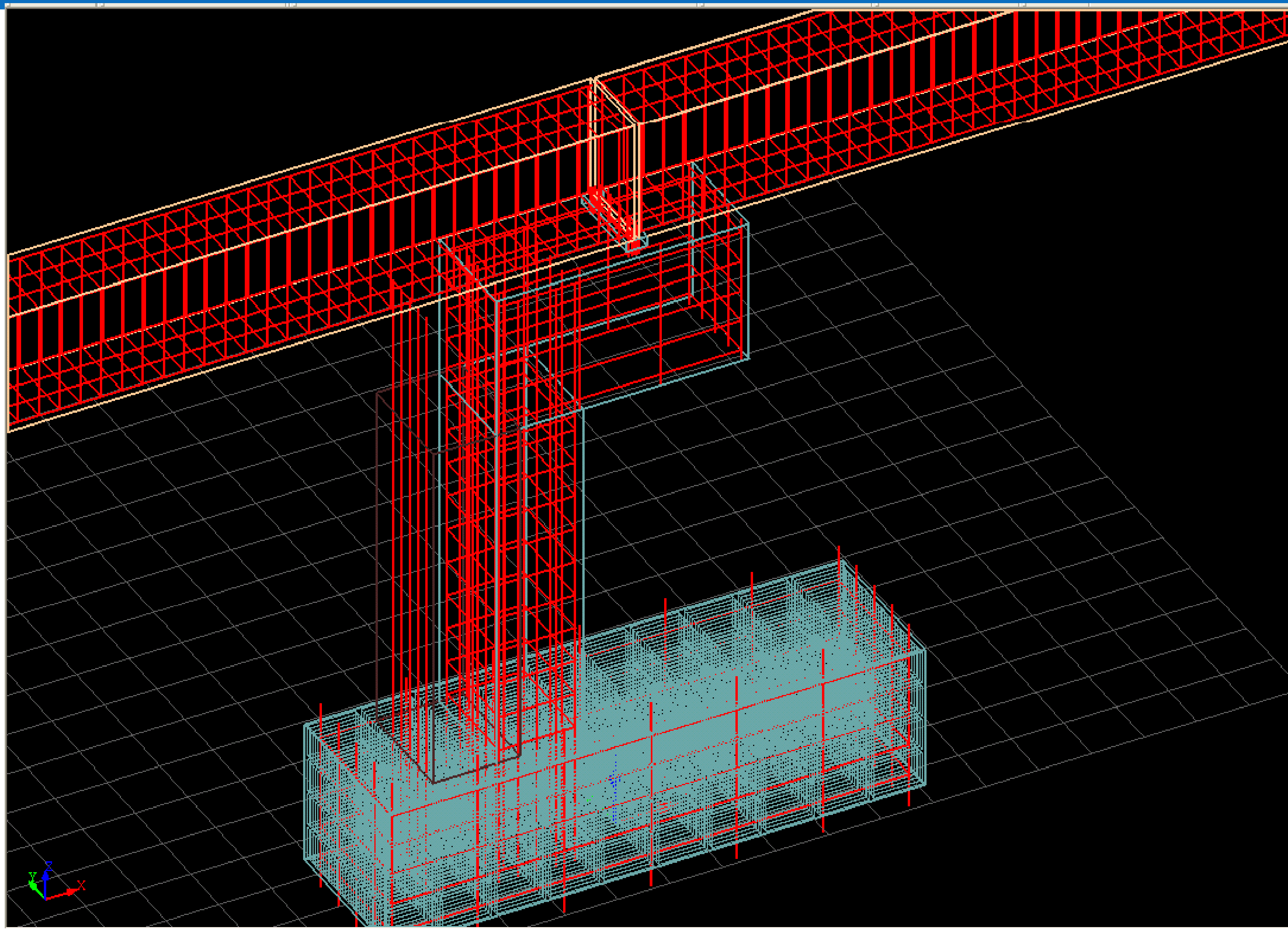
Solid Elements

In Simplified FEM link elements should be **located and defined** in the beginning.

In AEM, link between a column and a footing is **automatically** defined at Springs

Modeling Advantages of AEM compared to FEM

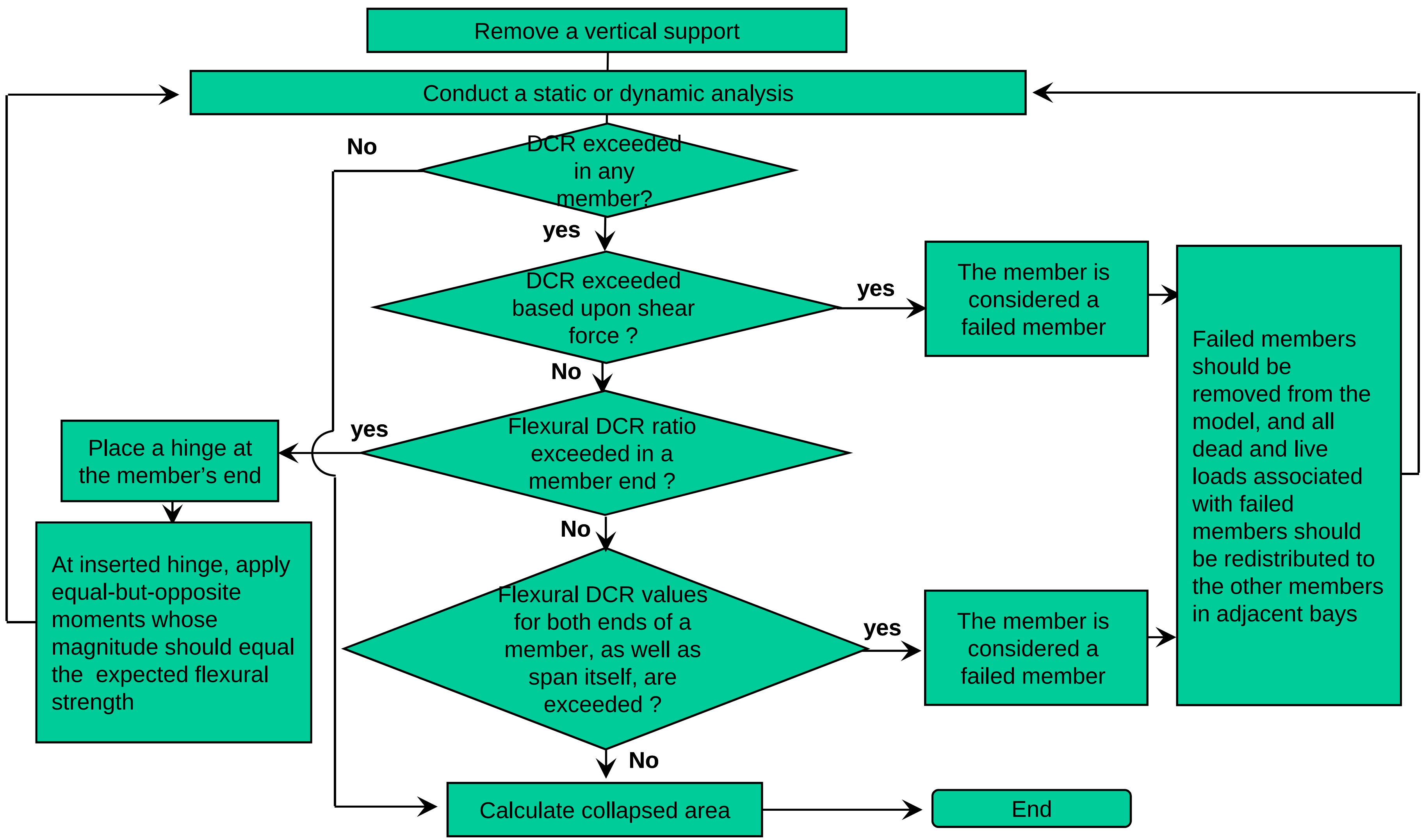
Easy Modeling of Reinforcement Details



Analysis Advantages of AEM compared to FEM

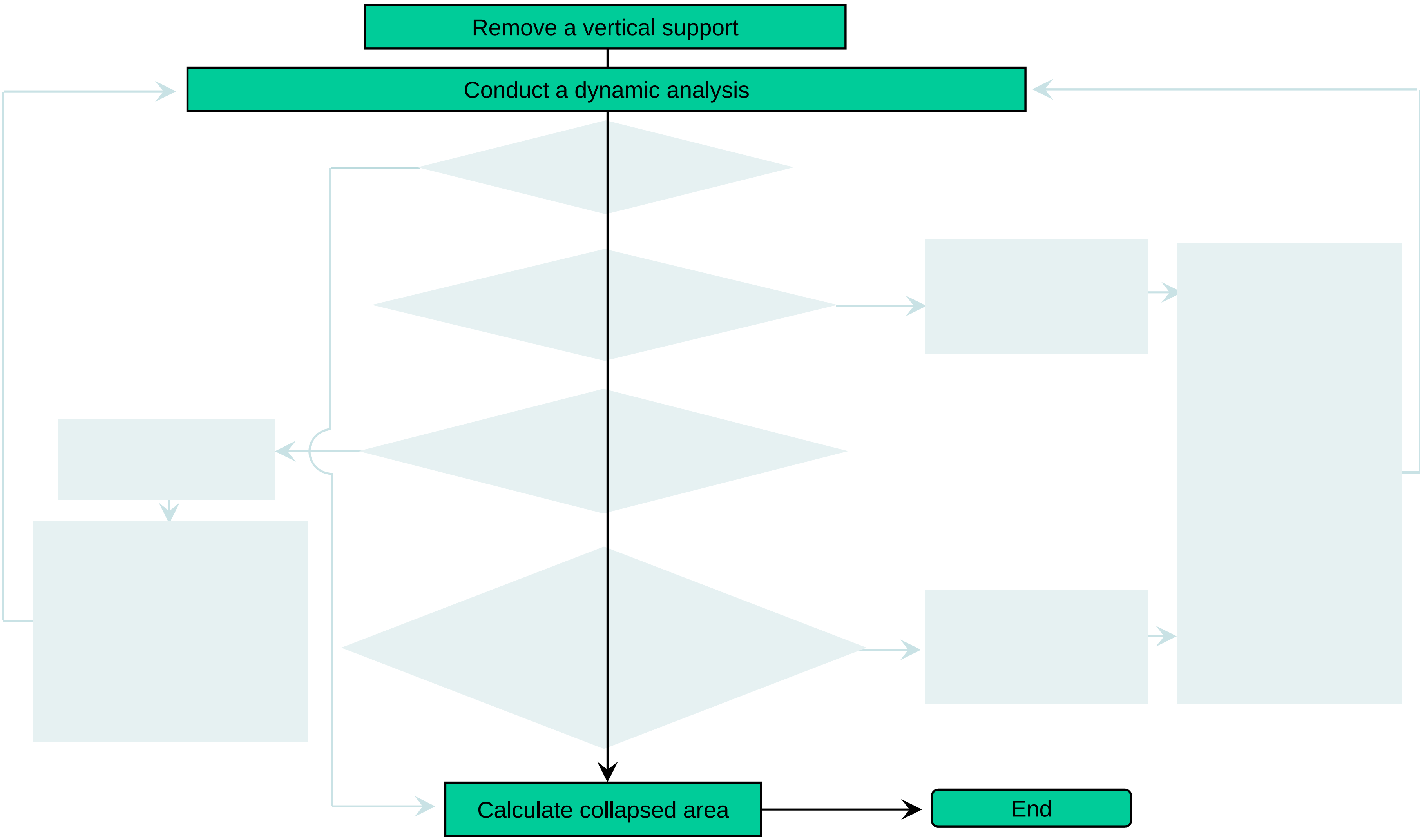
Analysis Advantages of AEM compared to FEM

Analysis Iterations using Simplified FEM



Analysis Advantages of AEM compared to FEM

No Need for Analysis Iterations using AEM



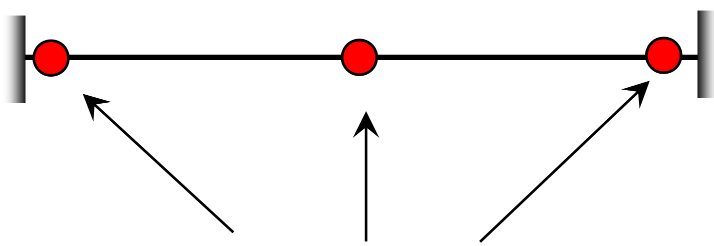
Analysis Advantages of AEM compared to FEM

Manual Formation of Plastic Hinges using Simplified FEM

1-In commercial FEM, usually explicit plastic hinges, in predefined locations, should be defined by the user in order to perform the nonlinear analysis.

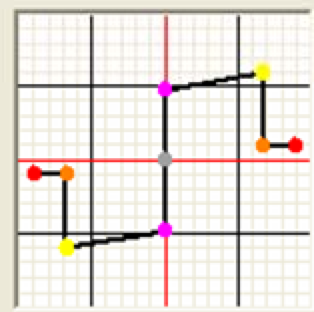
2-Both Moment-curvature and Moment-rotation relations in such a case should be estimated by the user before analysis

3-The user should be a qualified engineer



Predefined Plastic Hinges

Point	Moment/SF	Curvature/SF
E-	-0.2	-8
D-	-0.2	-6
C-	-1.25	-6
B-	-1	0
A	0	0
B	1.	0.
C	1.25	6.
D	0.2	6.
E	0.2	8.



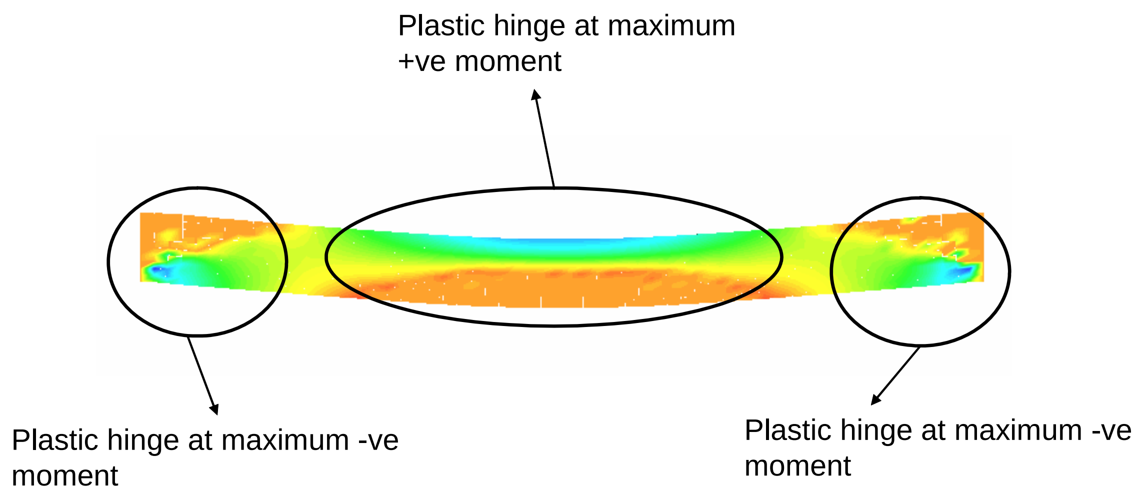
☑ Symmetric

Moment-Curvature

Analysis Advantages of AEM compared to FEM

Automatic Formation of Plastic Hinges

1- The Nonlinear analysis is automatically considered in ELS. Location, number and all properties of plastic hinges in ELS are automatically determined by the ELS.

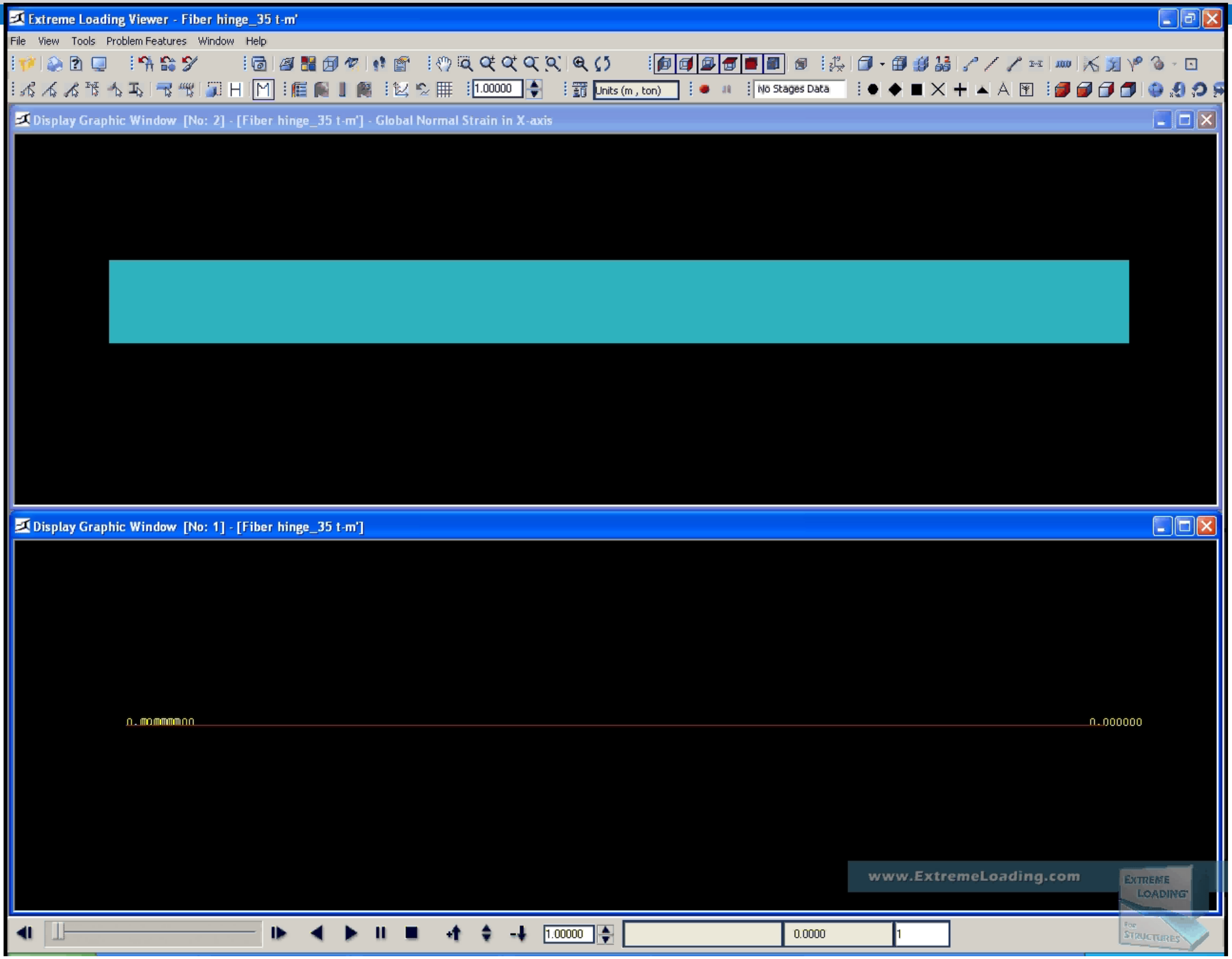


2- In FEM commercial software, fiber plastic hinges are used to overcome the disadvantage in (predefined moment-curvature), However definition of the Fiber hinge properties is difficult and needs large time to represent concrete and steel cells.

3-Preprocessing time in SAP is longer than ELS. Post processing time is equal in SAP and ELS.

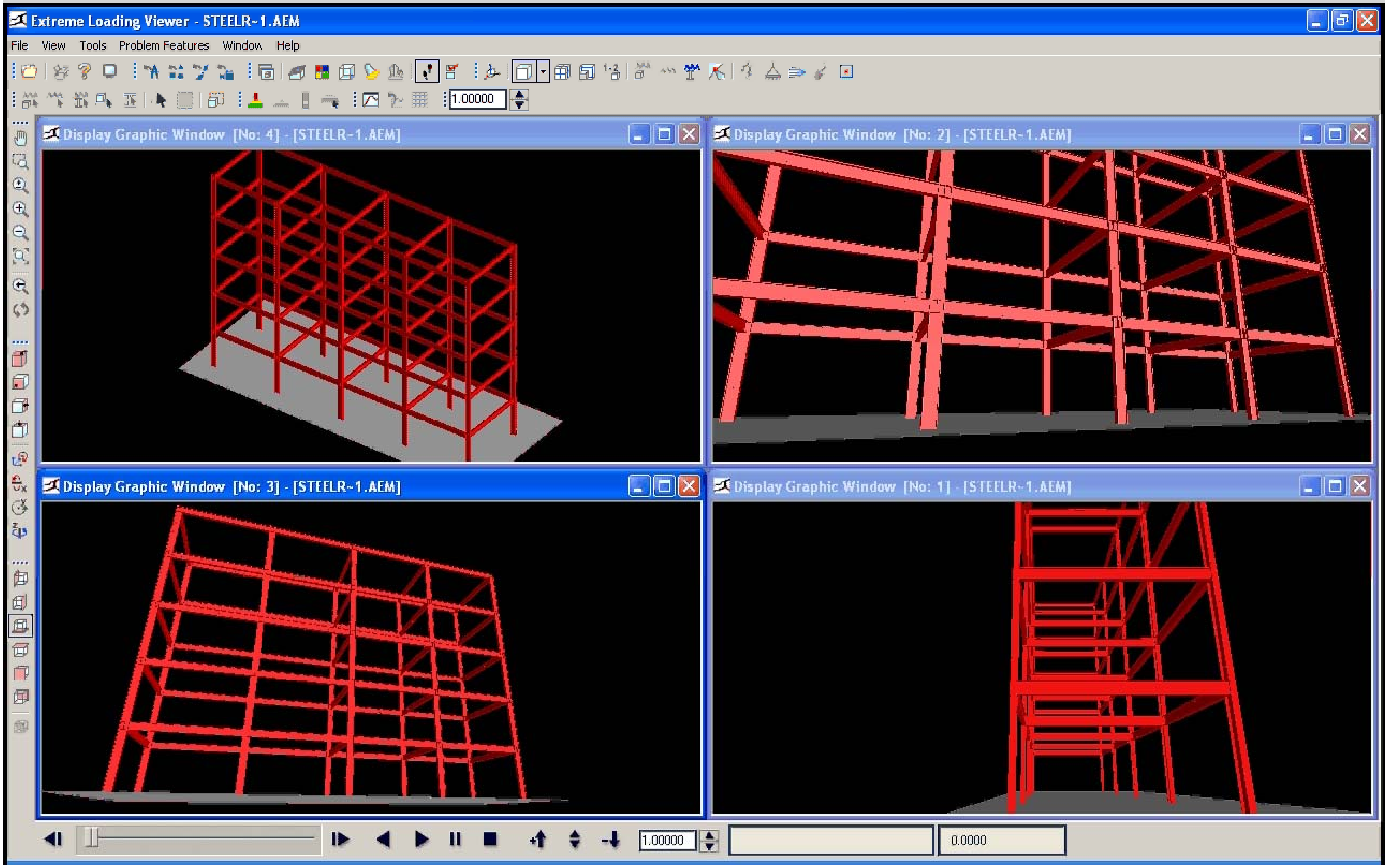
Analysis Advantages of AEM compared to FEM

Automatic Formation of Plastic Hinges



Analysis Advantages of AEM compared to FEM

Automatic Formation of Plastic Hinges



Analysis Advantages of AEM compared to FEM

Comparison between Progressive Collapse Analysis using AEM and FEM

(1) In FEM analysis, no bar rupture available➔ ***Not accurate***

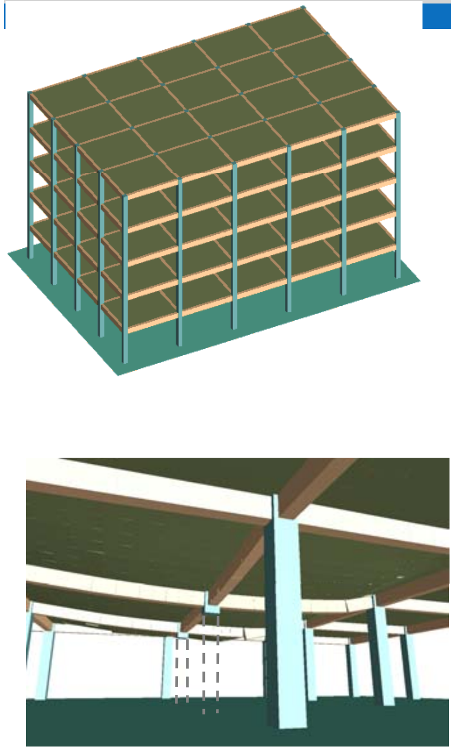
(2) In FEM analysis, no element separation and collision available ➔ ***Not accurate***

(3) Since no progressive collapse can be simulated with FEM, Iterative analysis is carried out in order to remove collapsed elements and to redistribute their loads to adjacent elements ➔ ***Time consuming and not accurate***

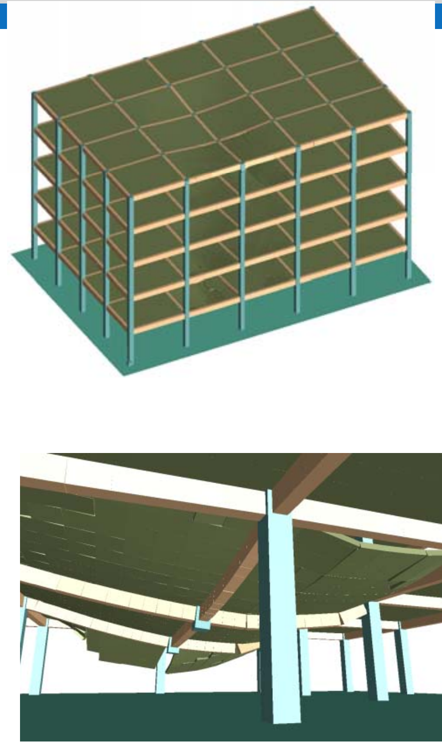
(4) In AEM, Plastic hinge formation, failure and collapse of members is automated ➔ ***Advantage of AEM***

Analysis Advantages of AEM compared to FEM

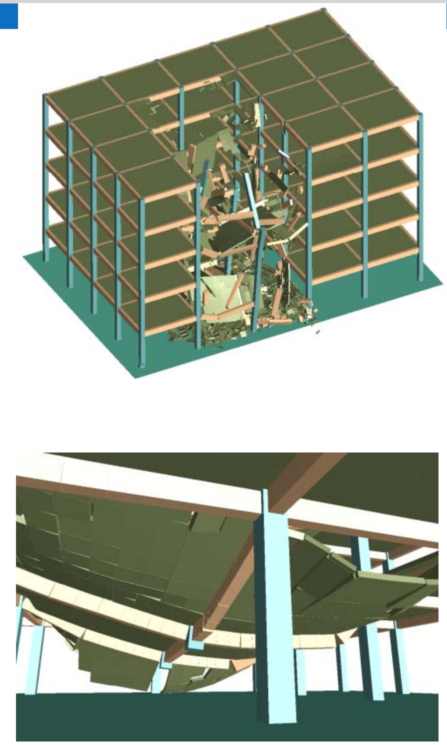
Localization of Failed Areas



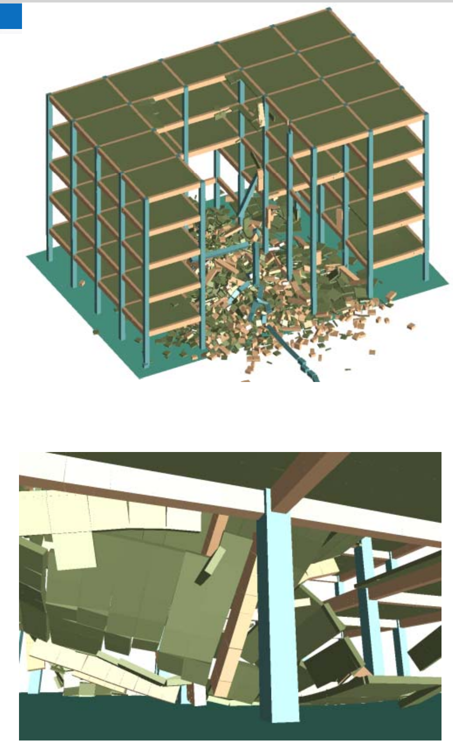
Cracking and Plastic Hinges Formation



Mechanisms Formation and Elements Failure



Progressive collapse of Elements

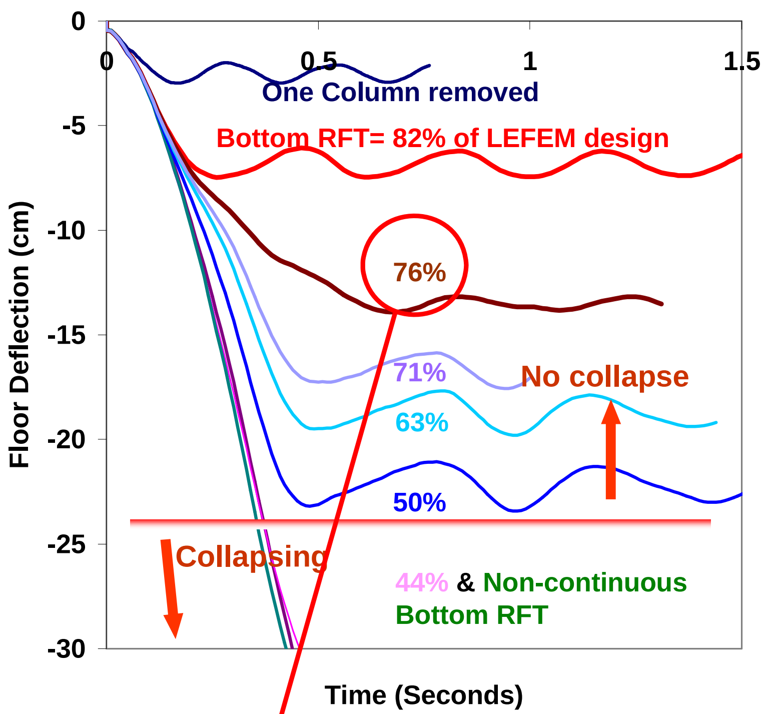


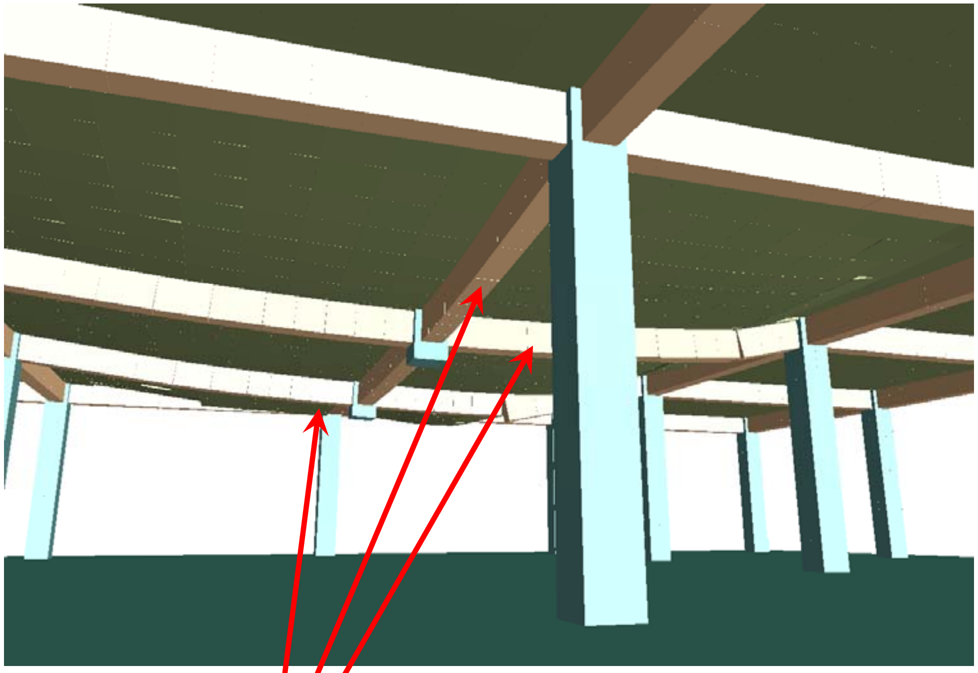
Collision and Progressive collapse of Parts of Structures

Automatic prediction in one analysis

Analysis Advantages of AEM compared to FEM

Effects of Reinforcement Bars



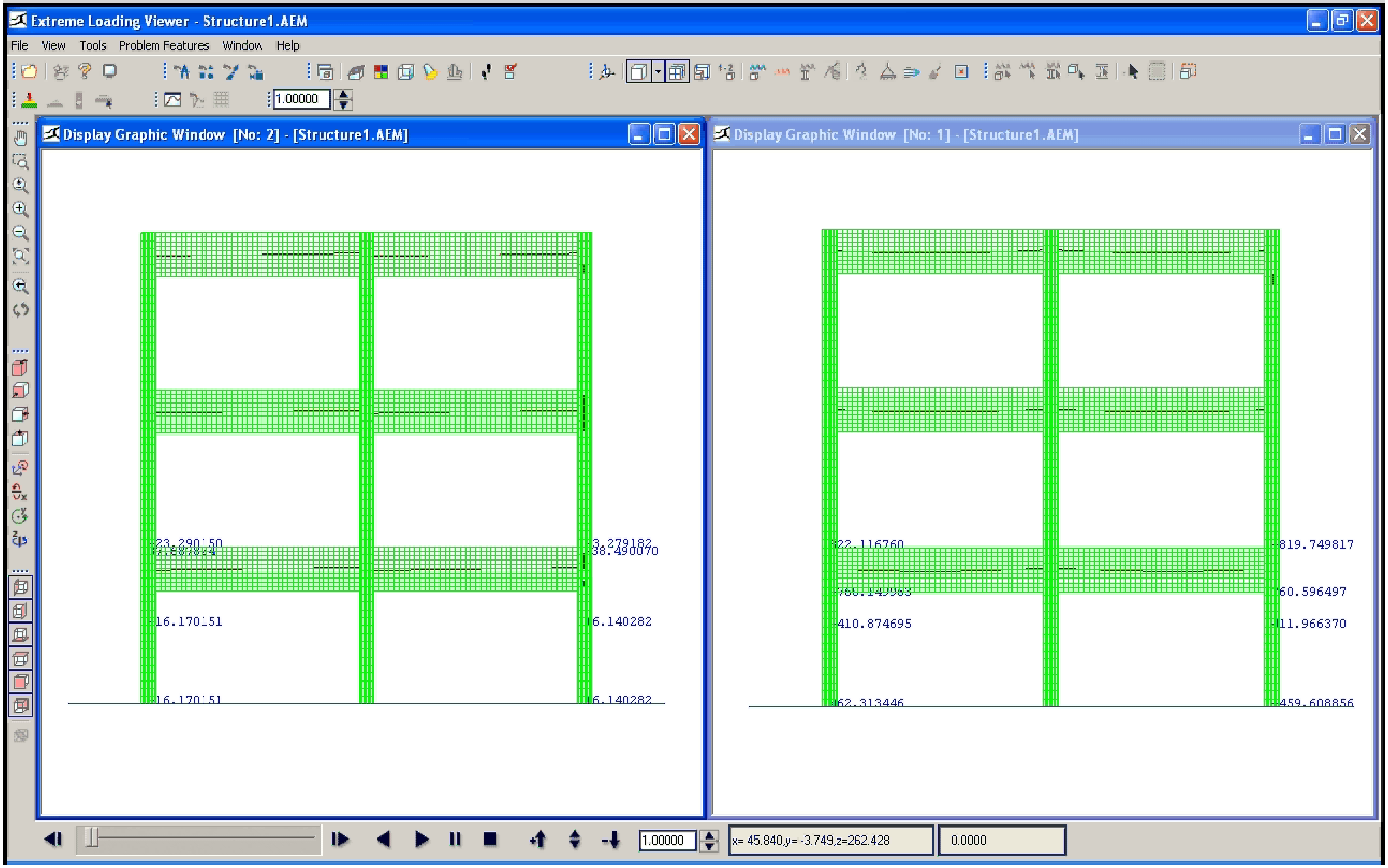


Amount of additional RFT (calculated as a percentage of RFT based upon elastic analysis after element removal)

Strengthened Girders (above collapsed columns)

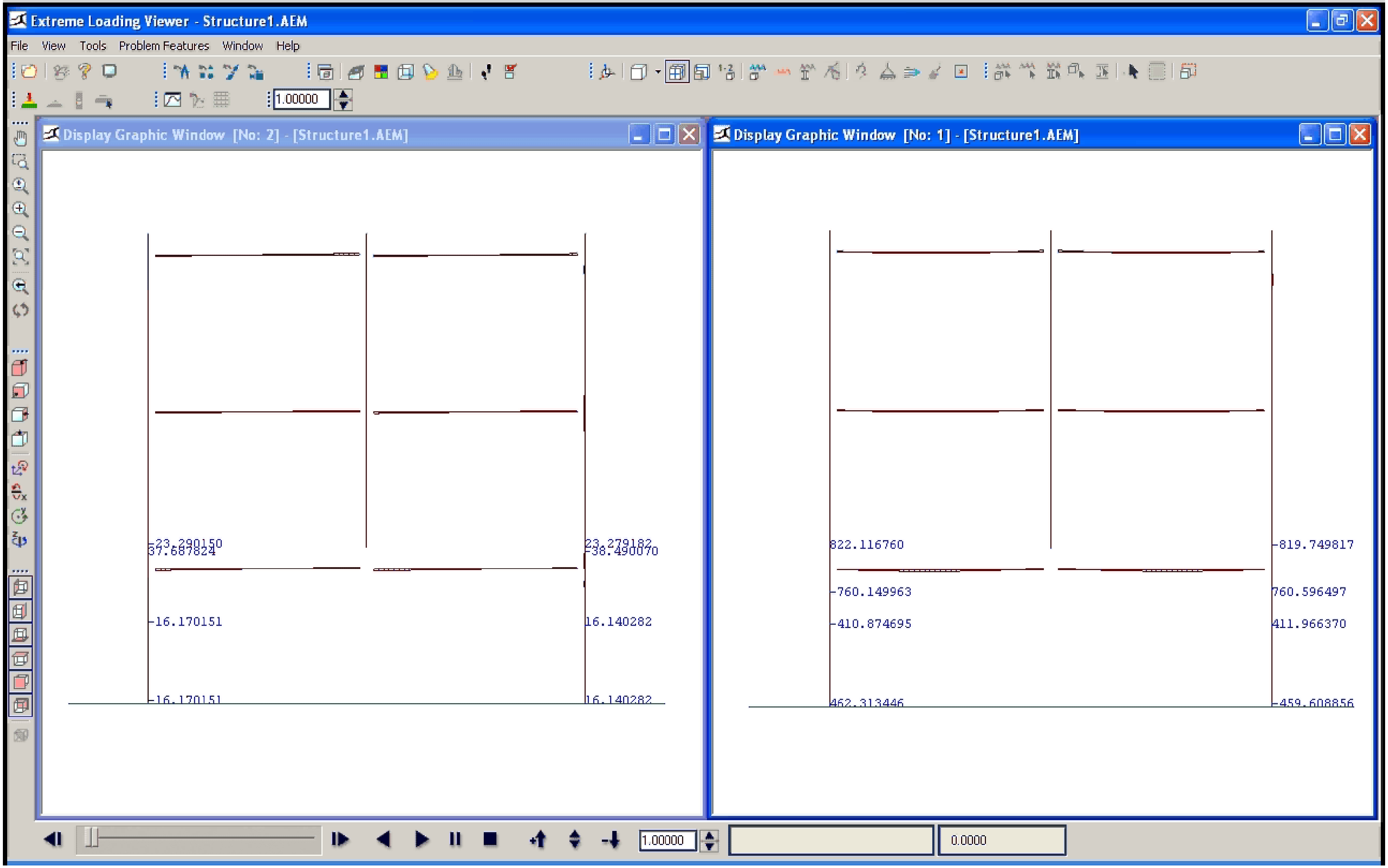
Analysis Advantages of AEM compared to FEM

Internal Force Diagrams Through Integration of Stresses



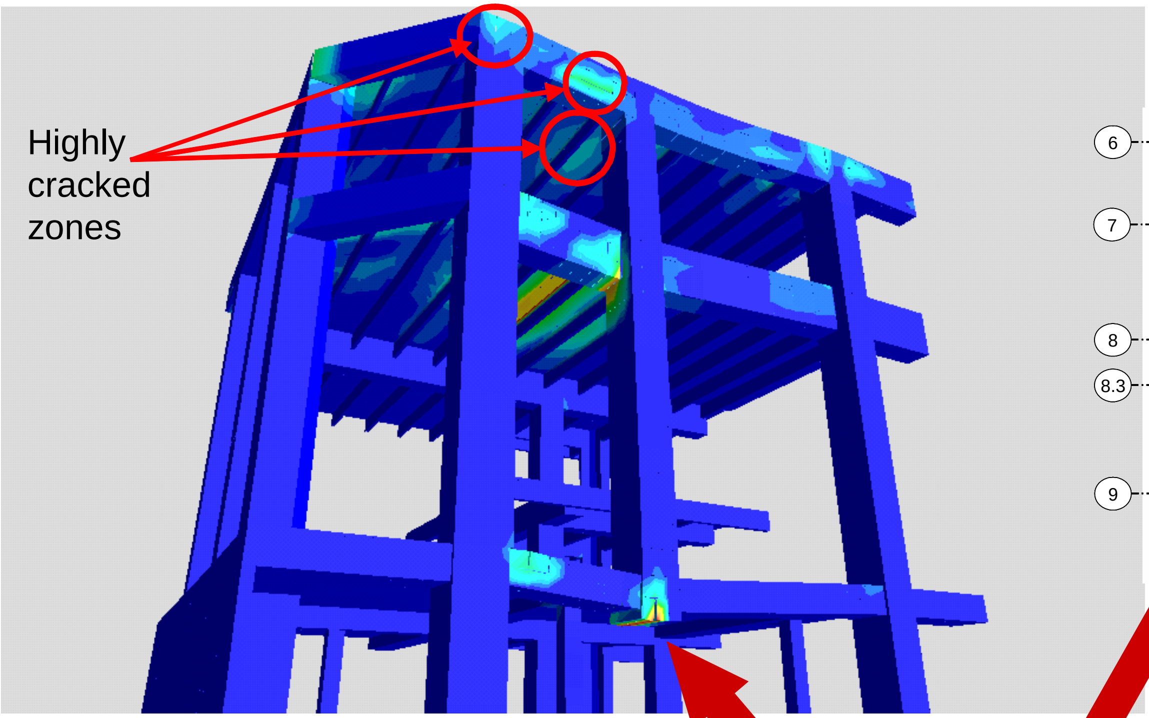
Analysis Advantages of AEM compared to FEM

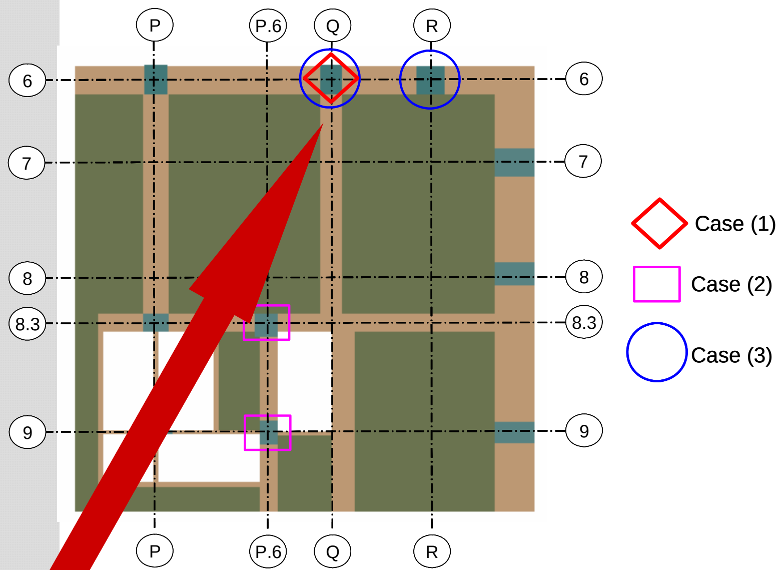
Internal Force Diagrams Through Integration of Stresses



Analysis Advantages of AEM compared to FEM

Damage assessments due to column removal

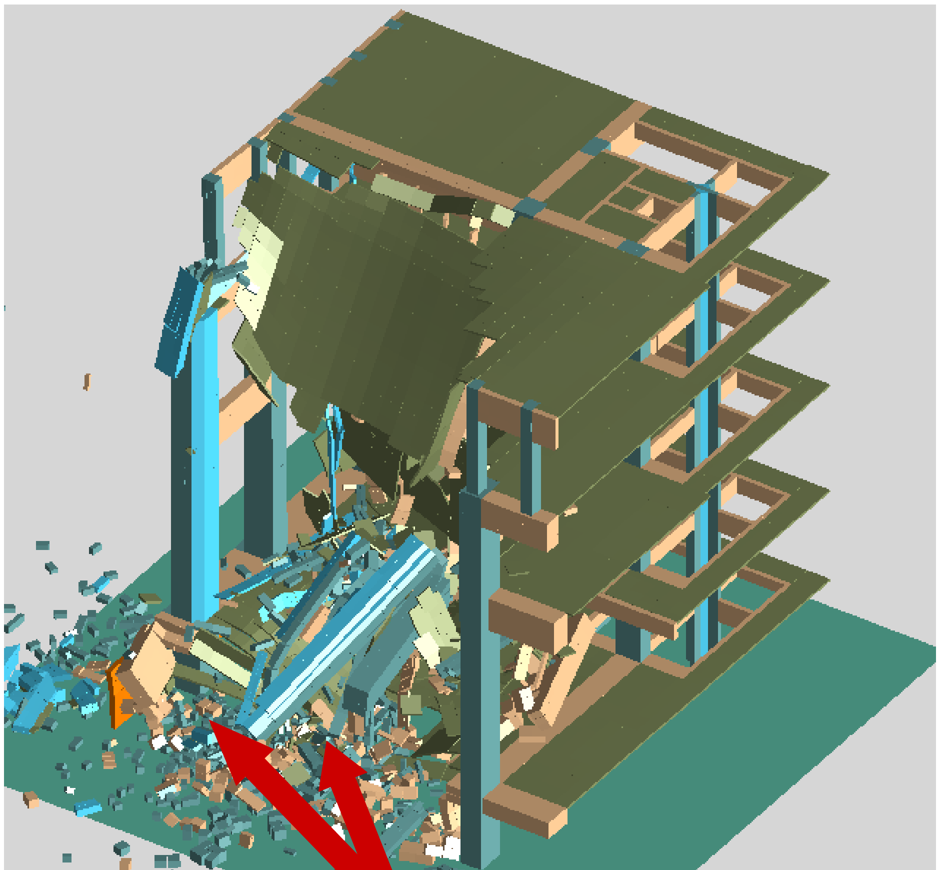


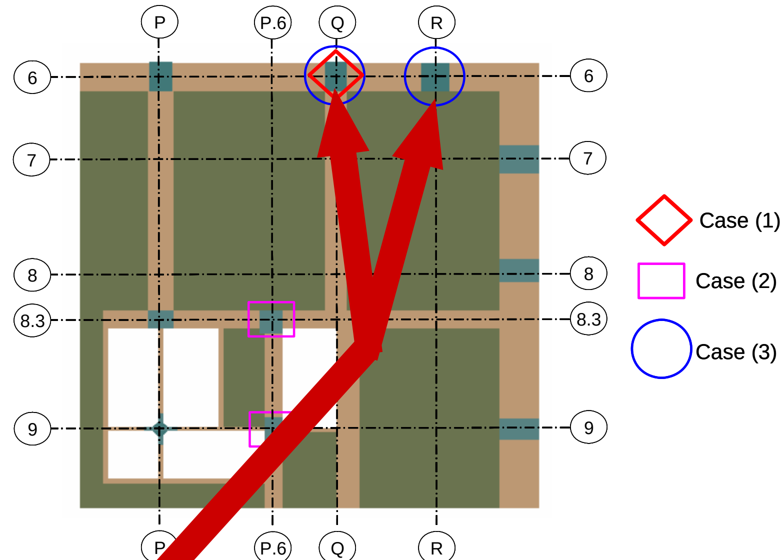


Collapse of Column Q-6

Analysis Advantages of AEM compared to FEM

Damage assessments due to two column removal

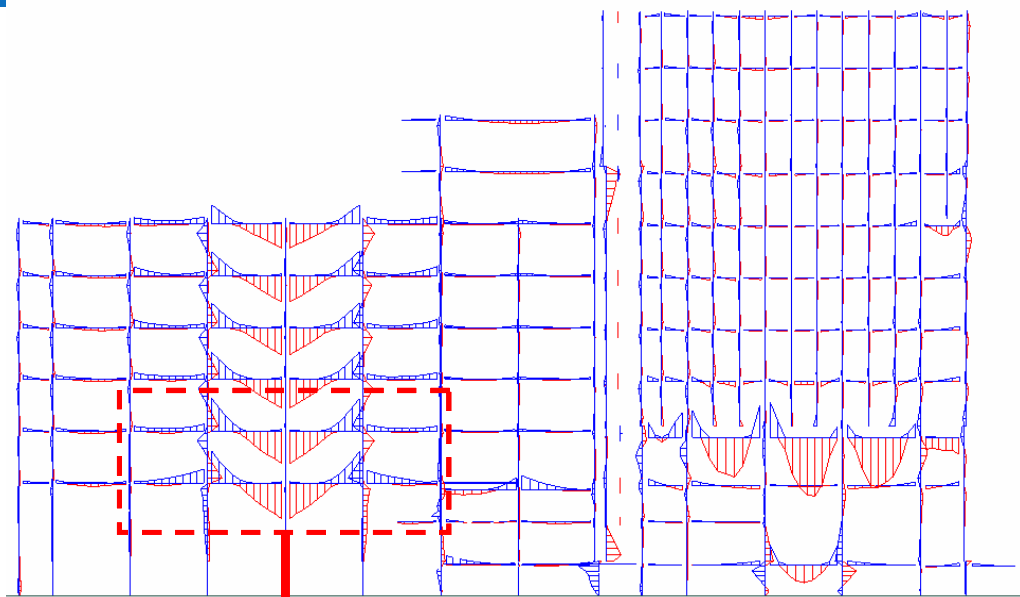


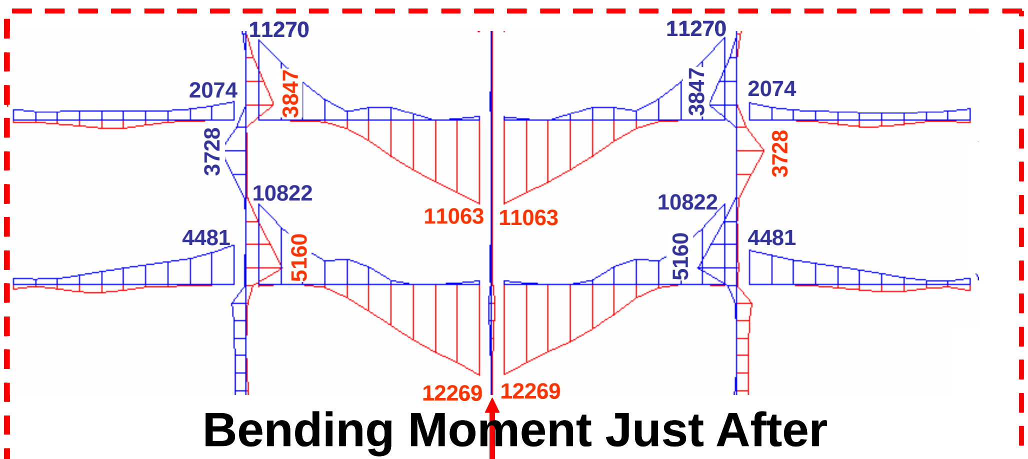


Collapse of Columns Q-6 and R-6

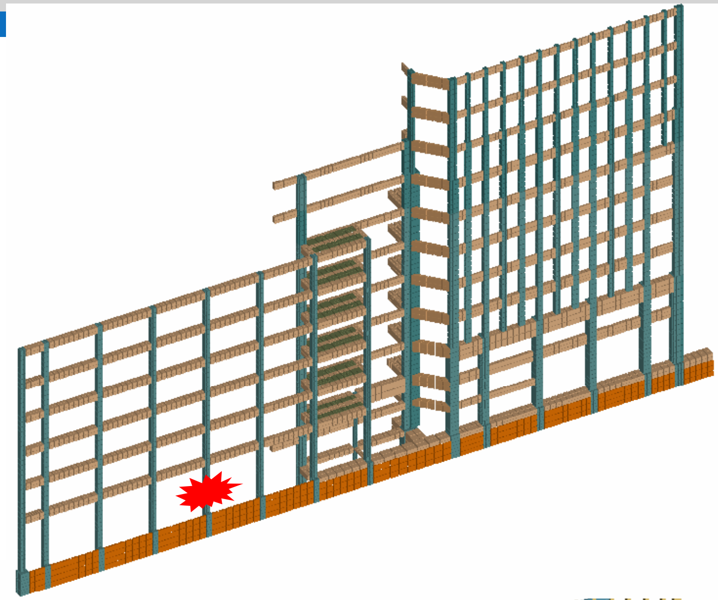
Analysis Advantages of AEM compared to FEM

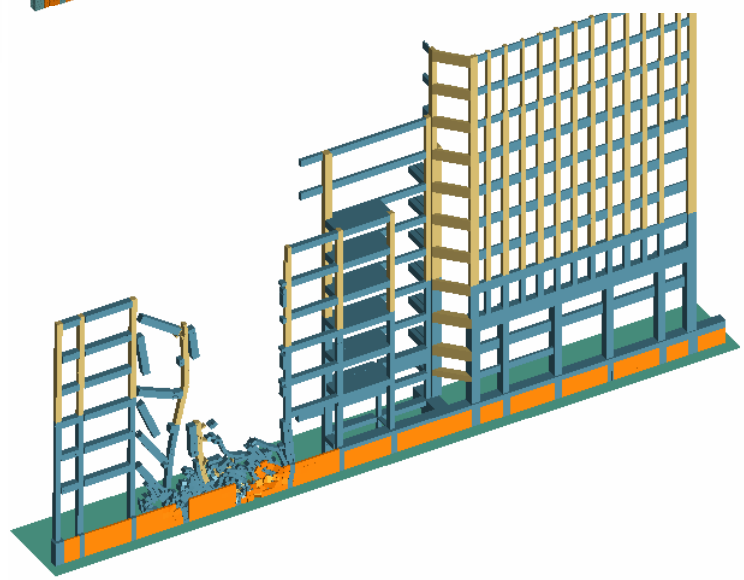
Damage assessments due to column removal





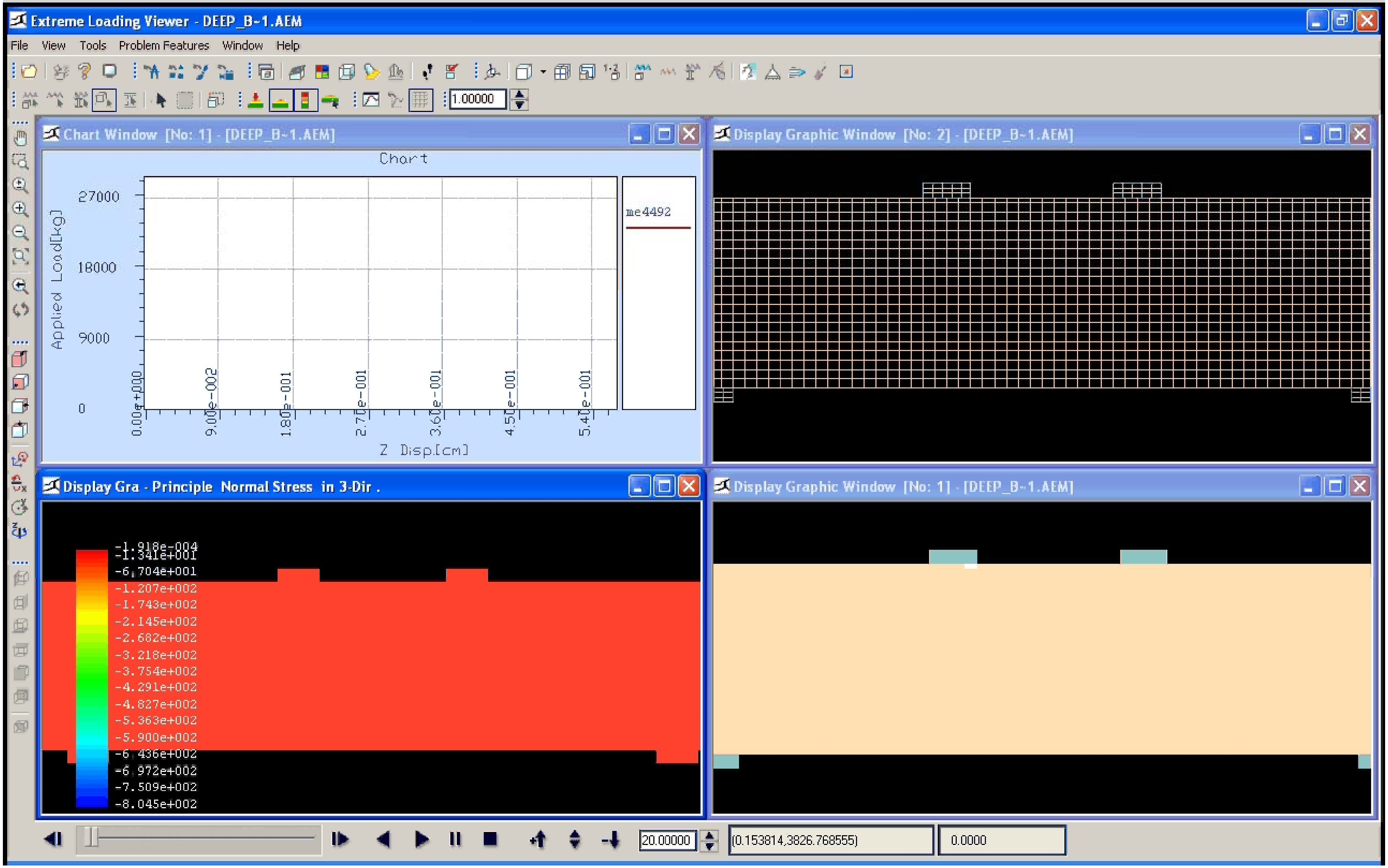
Bending Moment Just After Column Collapse





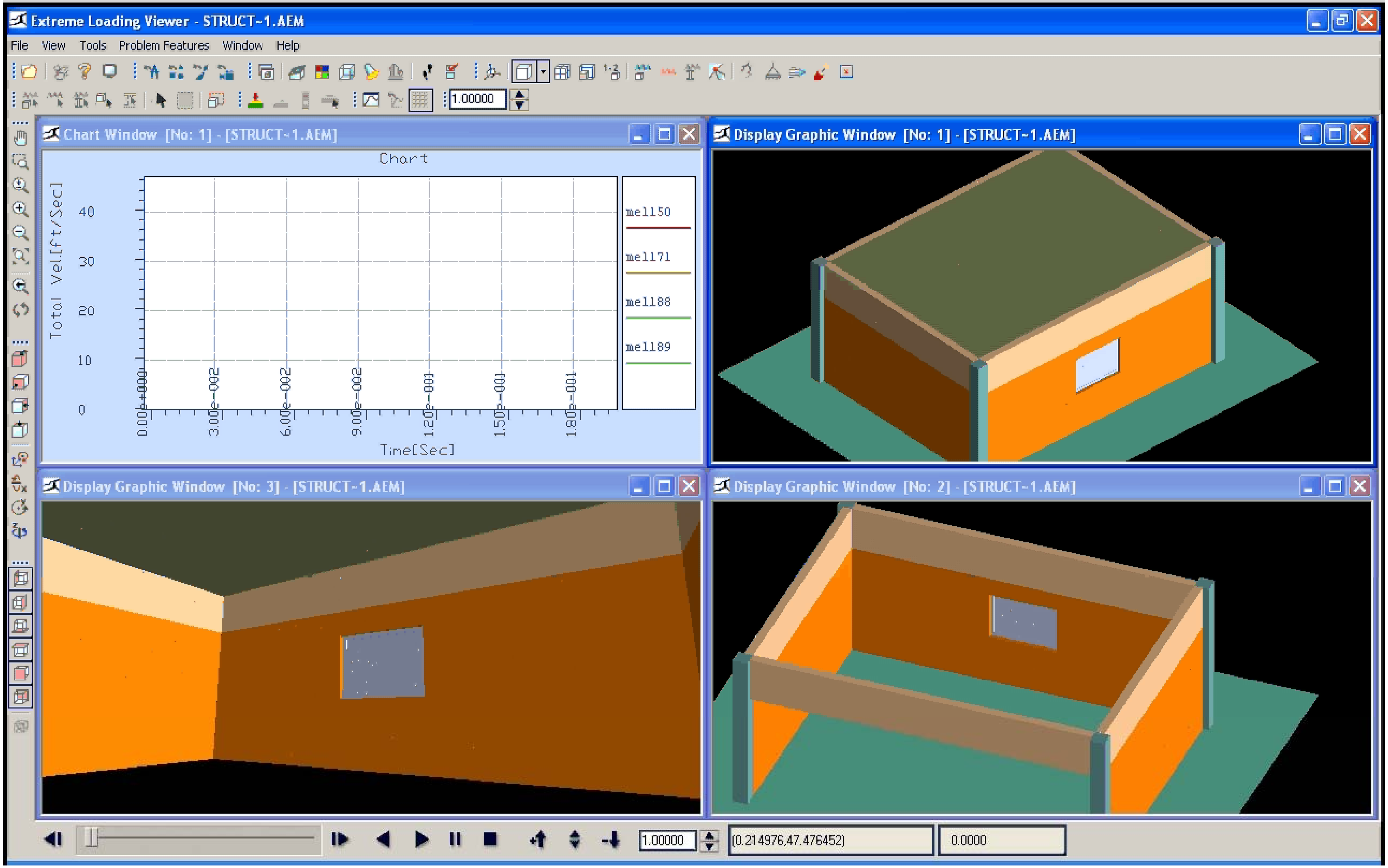
Analysis Advantages of AEM compared to FEM

Visual Damage Assessments



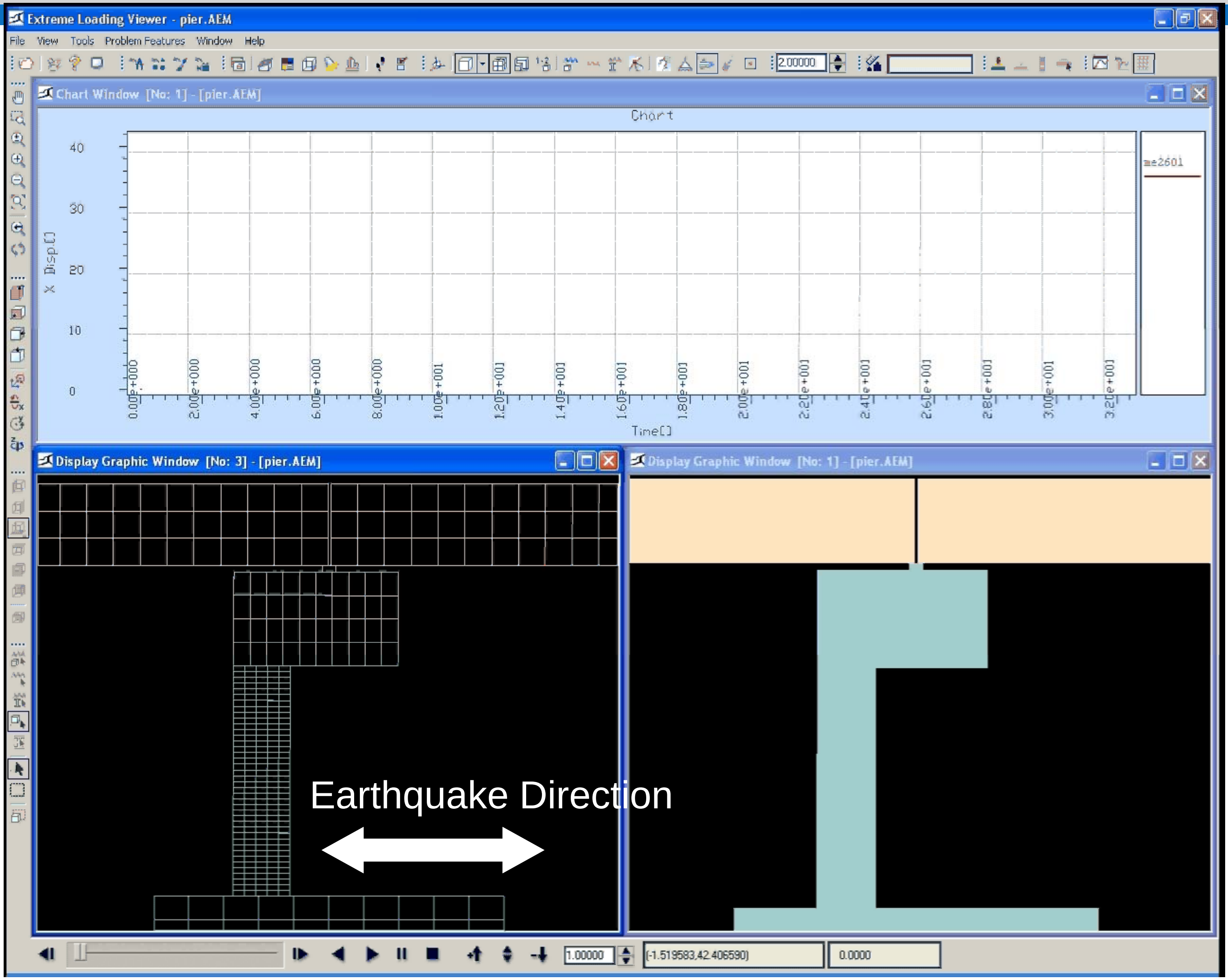
Analysis Advantages of AEM compared to FEM

Visual Damage/Non-Structural Components



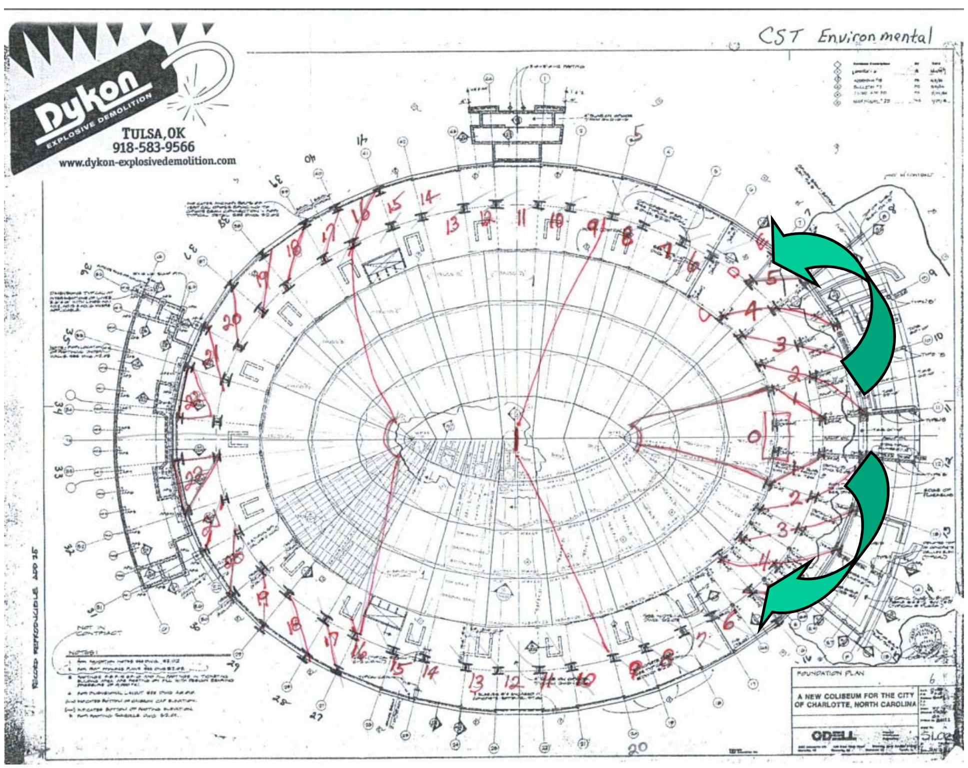
Analysis Advantages of AEM compared to FEM

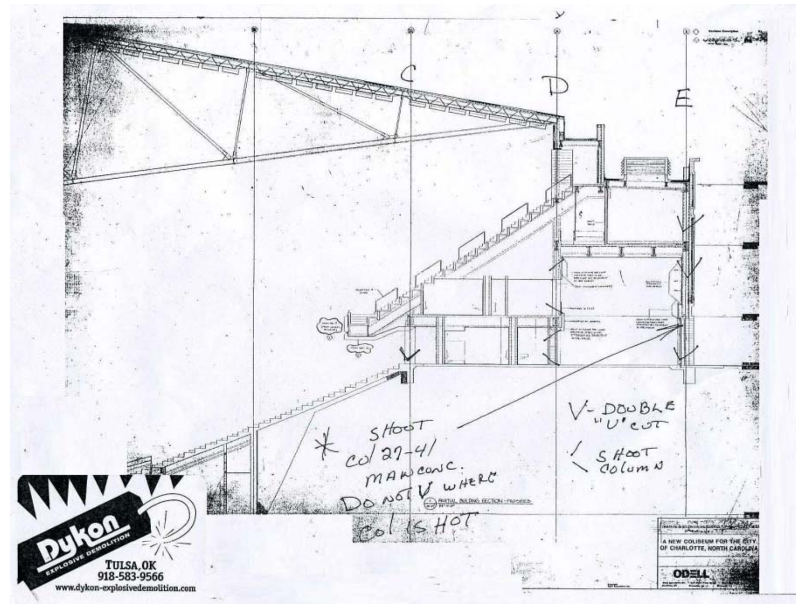
Visual Damage/Automatic Contact Detection

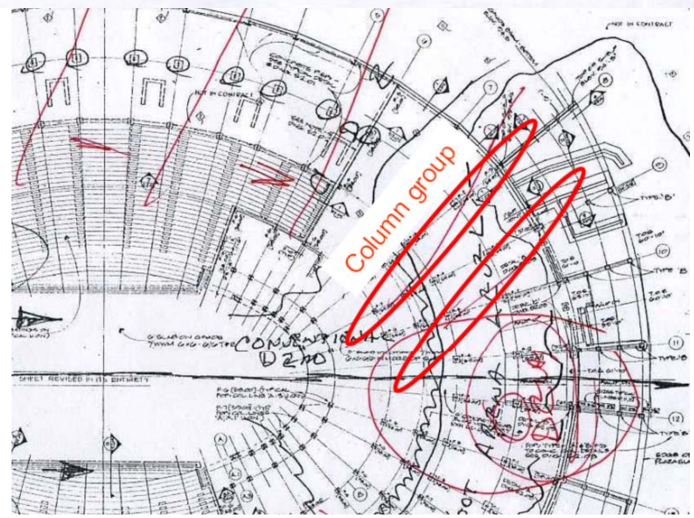


Verification Examples

Demolition Scenario



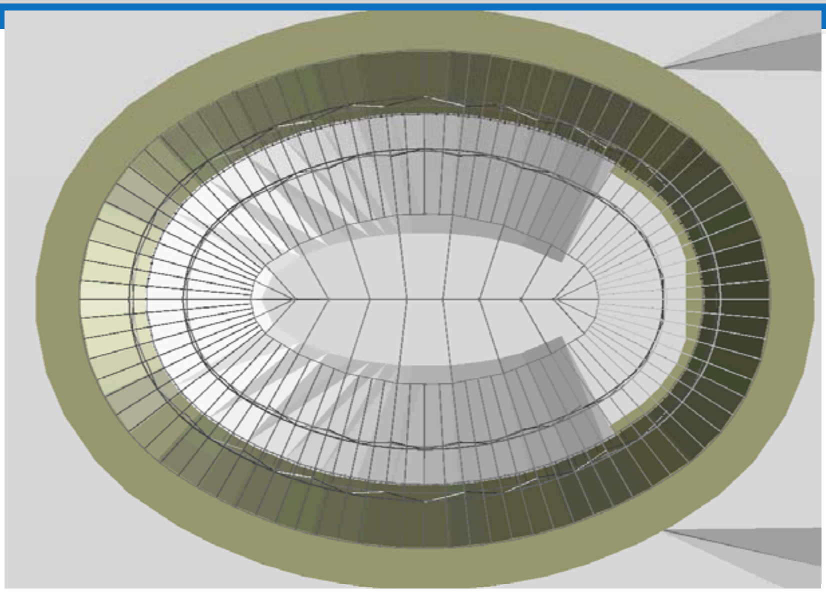


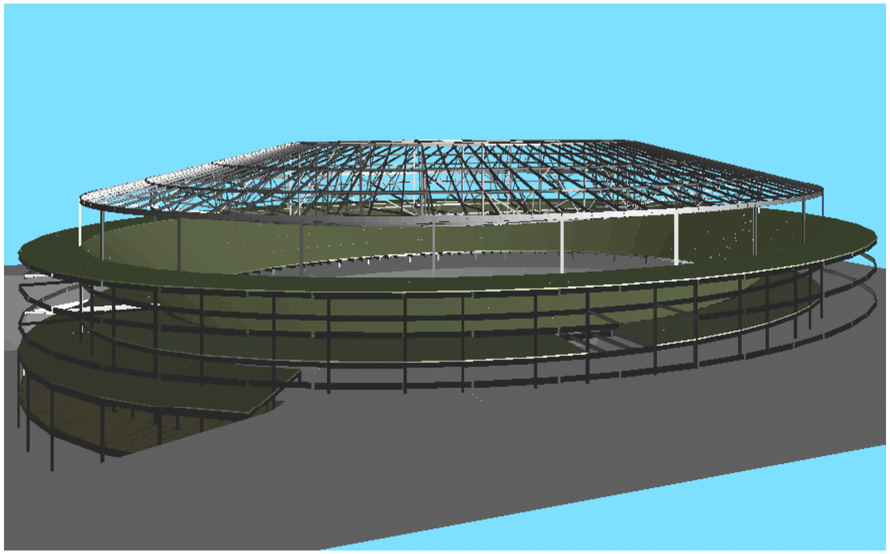


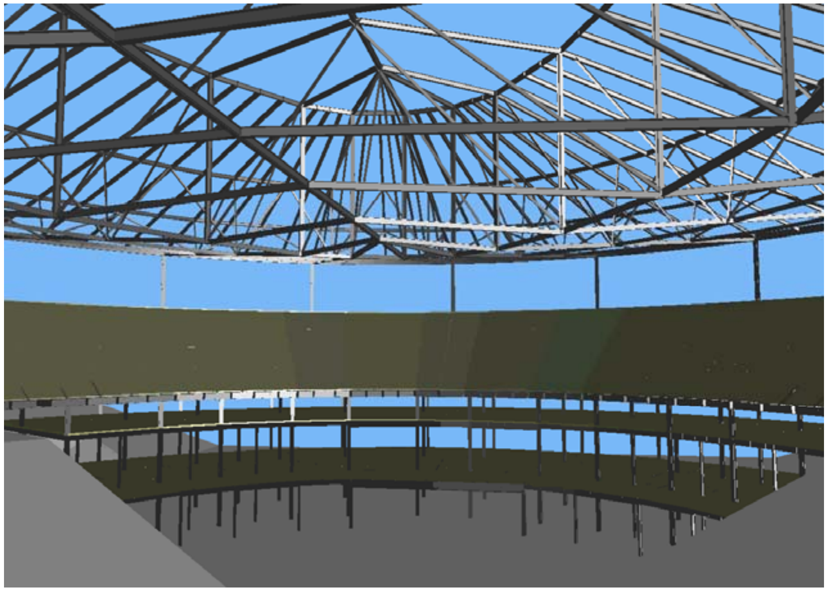
Verification Examples

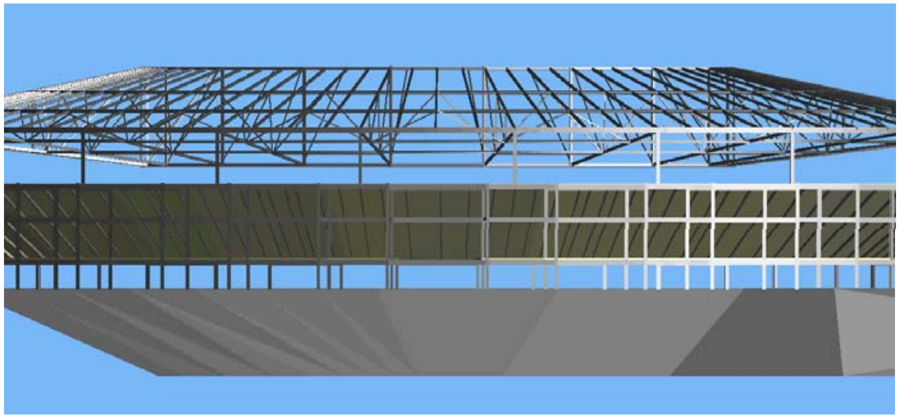
Charlotte Coliseum, North Carolina

AEM Model





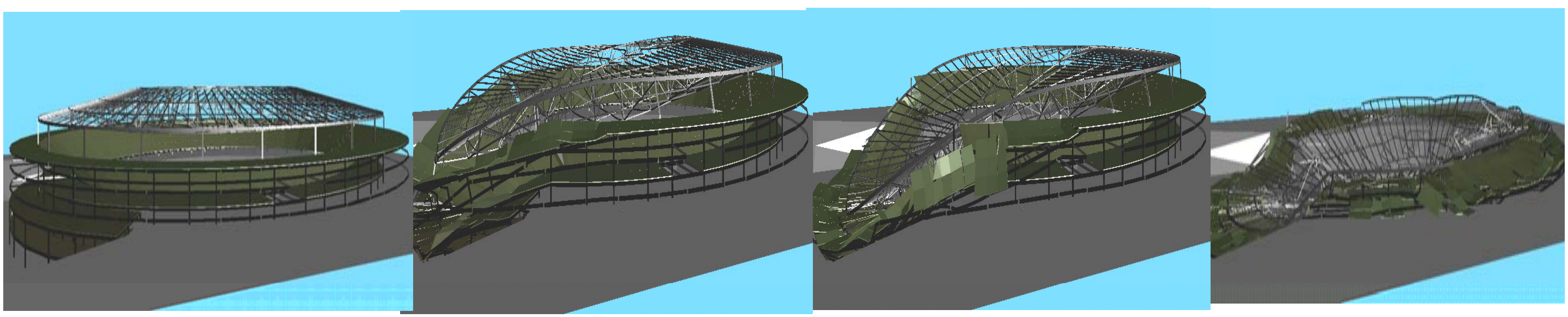




Verification Examples

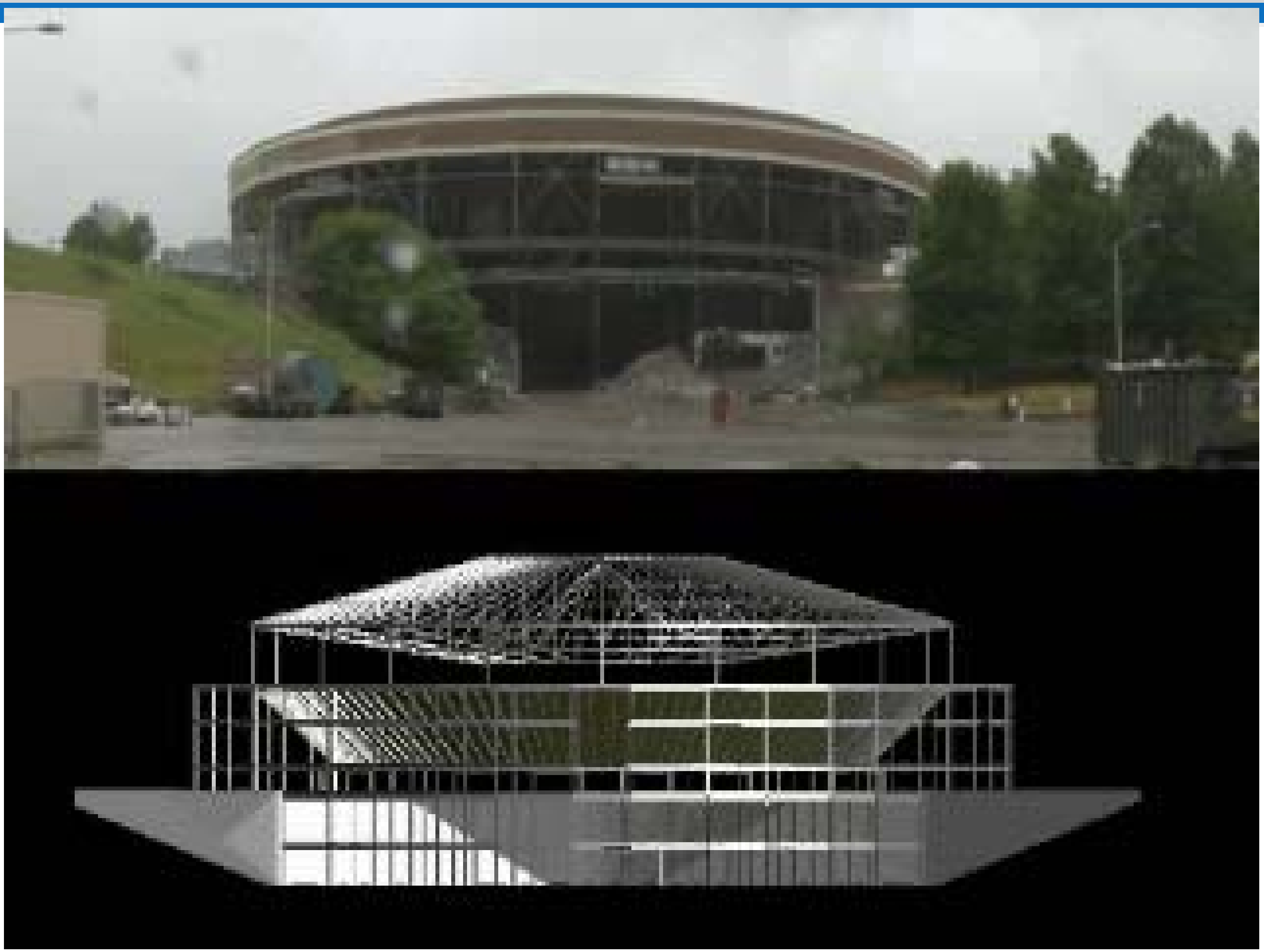
Charlotte Coliseum, North Carolina

1 2 3 4



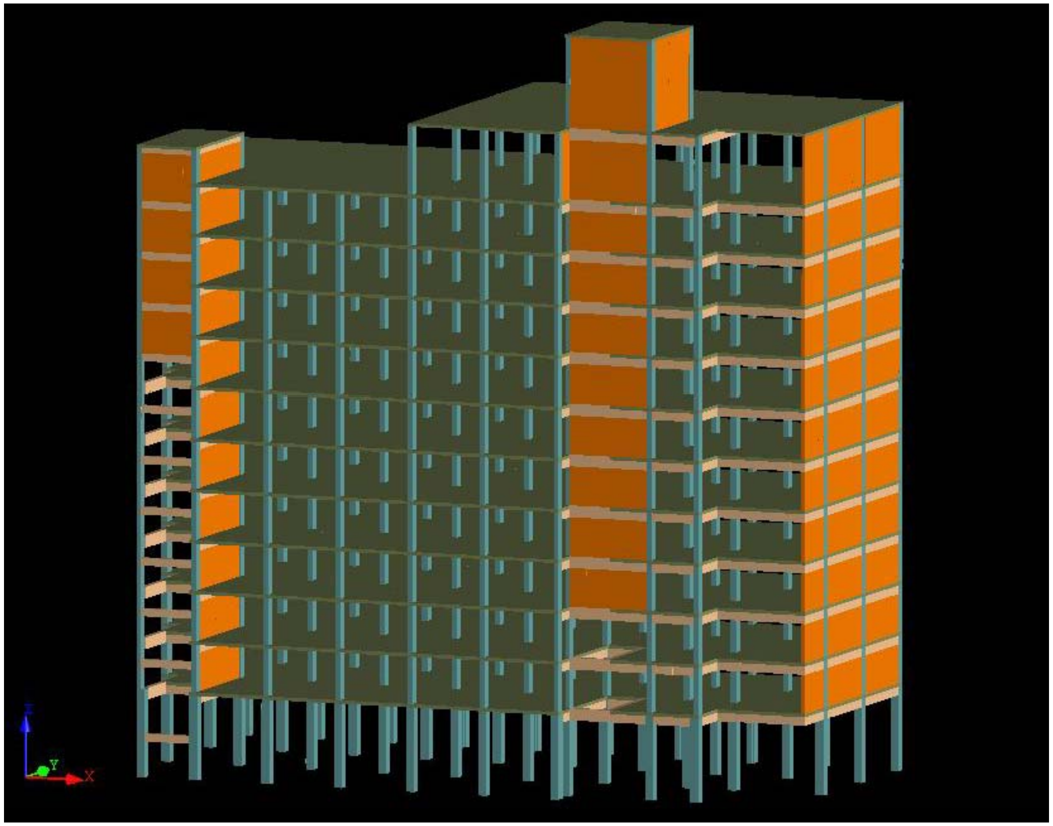
Verification Examples

Charlotte Coliseum, North Carolina



Layout

AEM Model



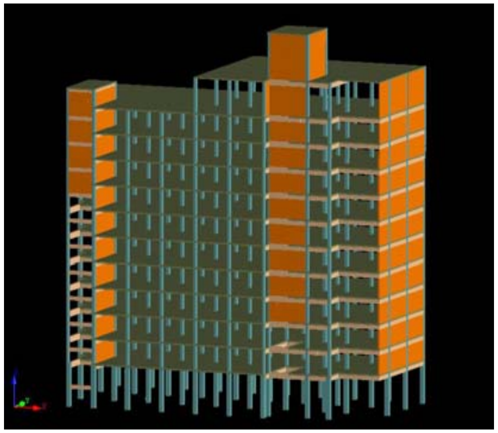
Verification Examples

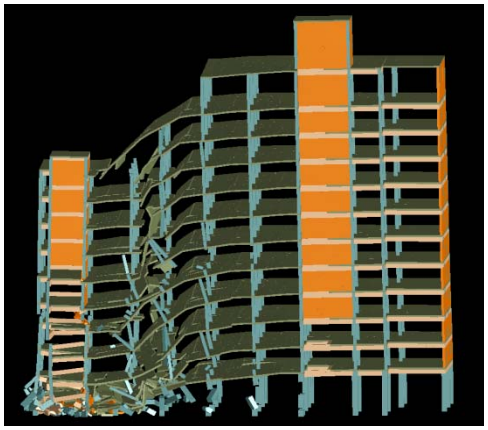
Sheraton Hotel, Raleigh North Carolina

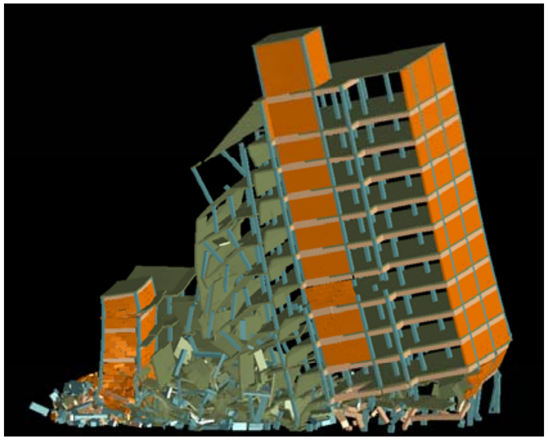
1

2

3

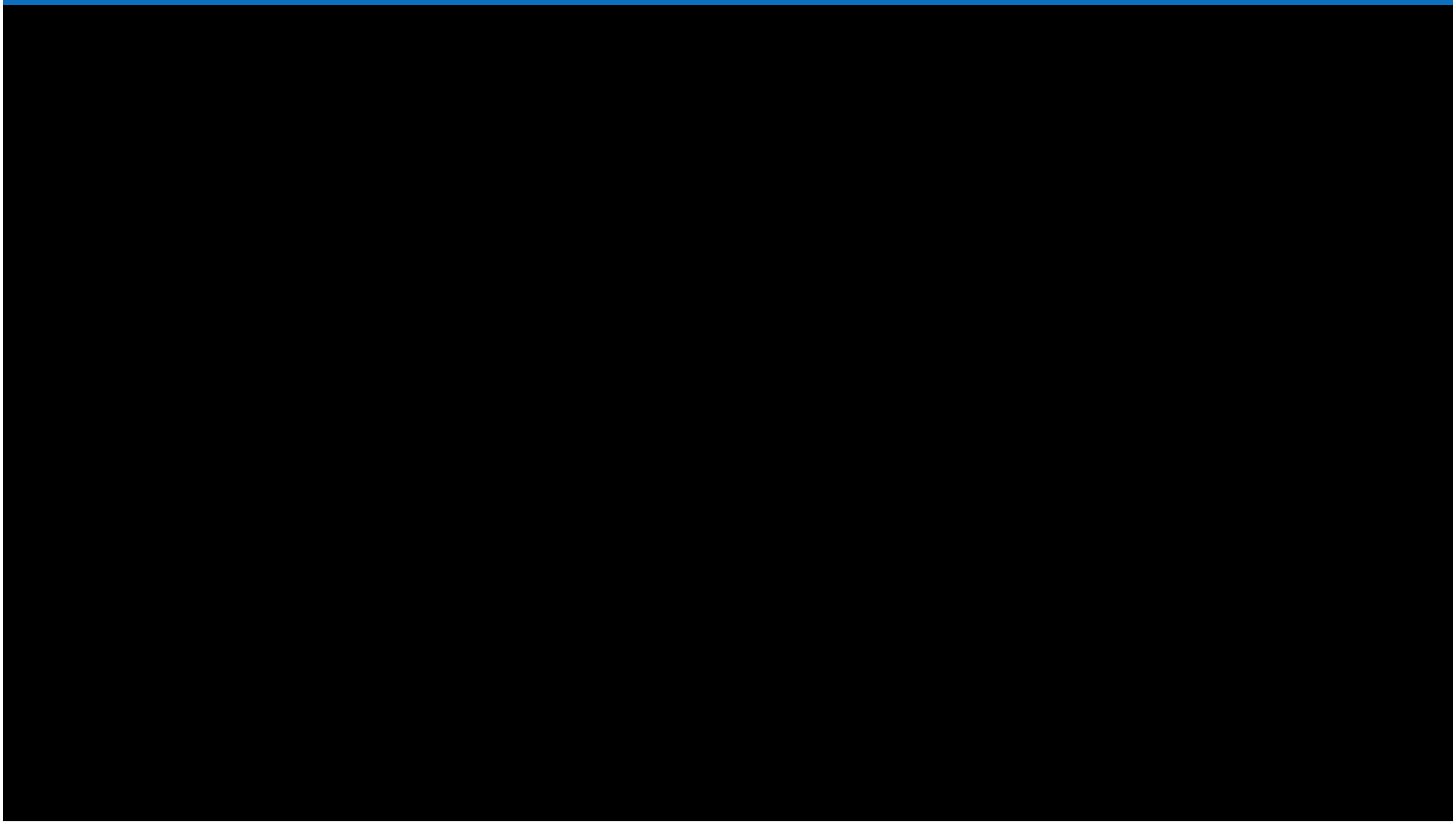




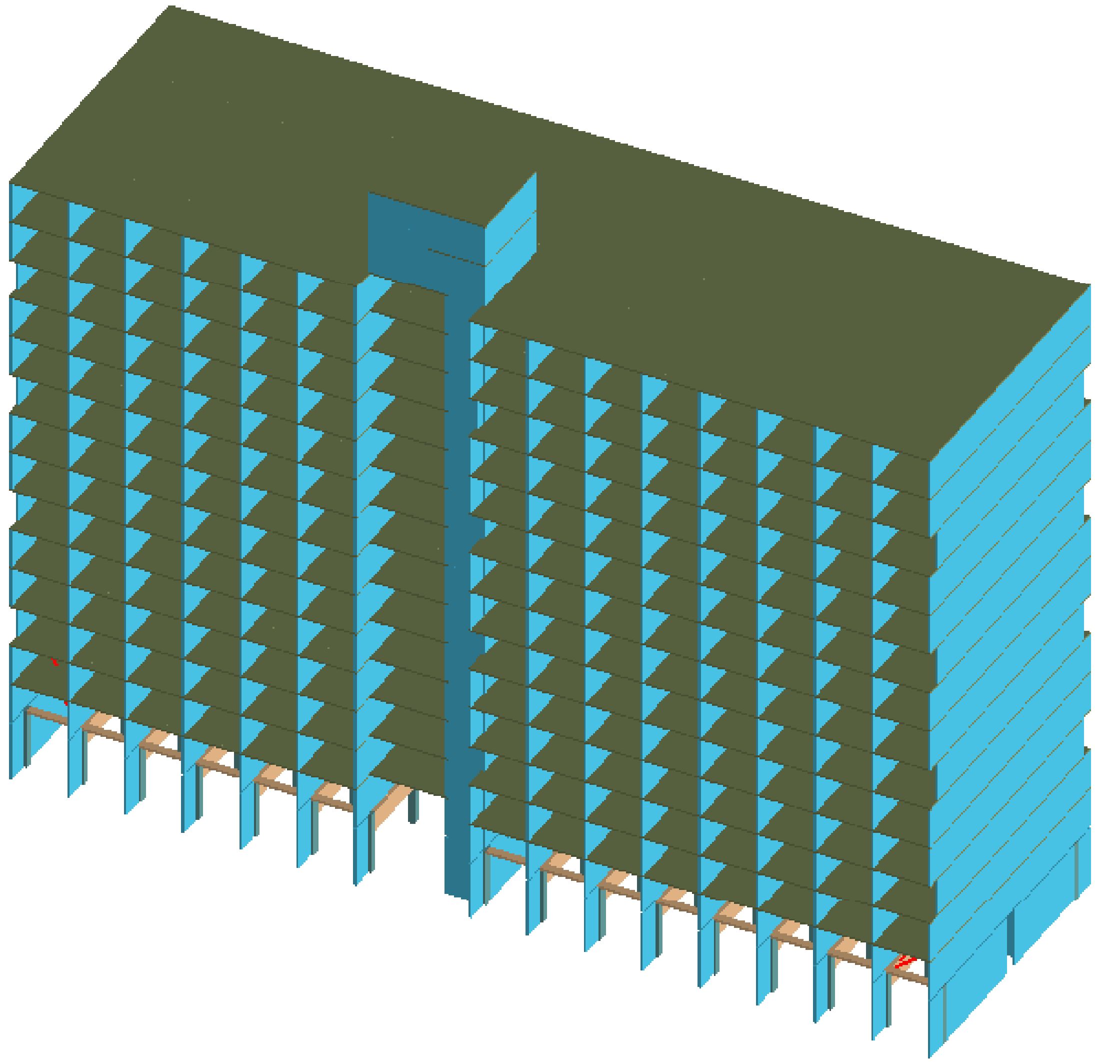


Verification Examples

Sheraton Hotel, Raleigh North Carolina



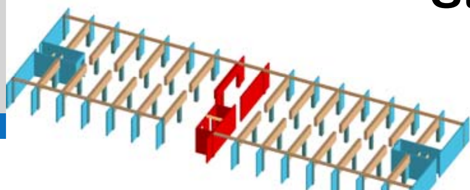
ELS Model



Verification Examples

Stubbs Tower, Savannah, Georgia

The removed components are shown in red



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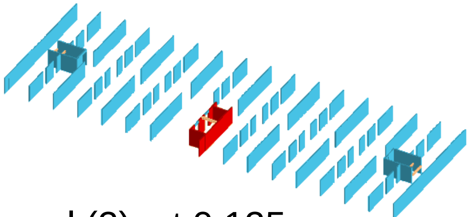
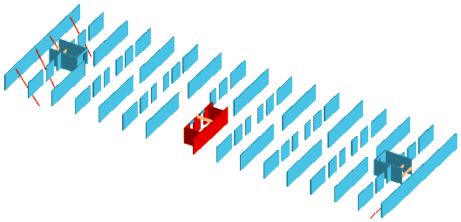


Level (2) at 0.125 sec



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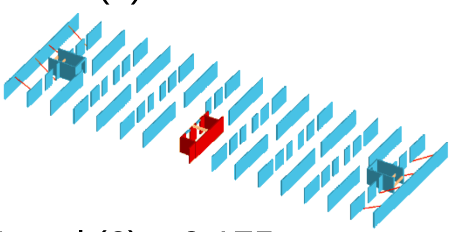

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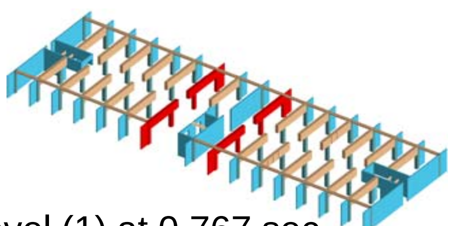
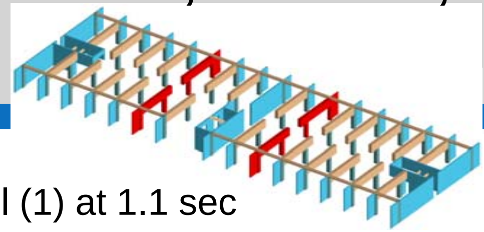


Level (1) at 0.767 sec



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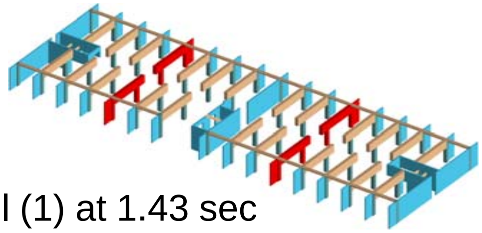

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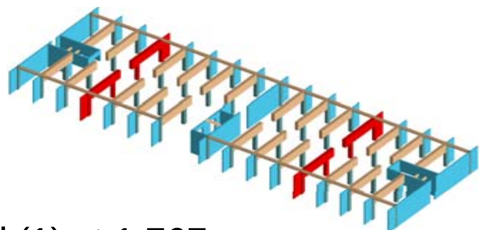

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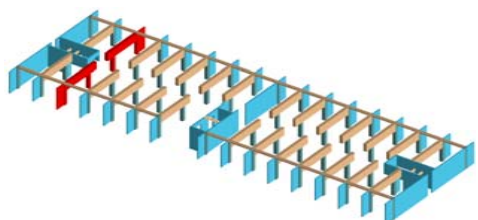

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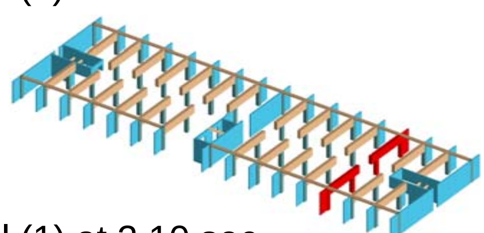

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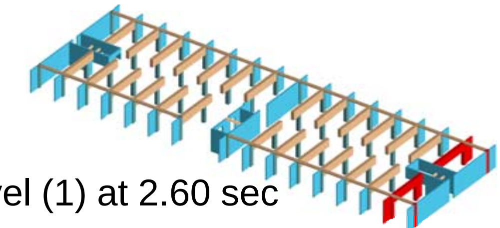
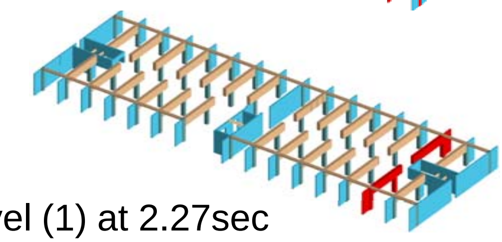
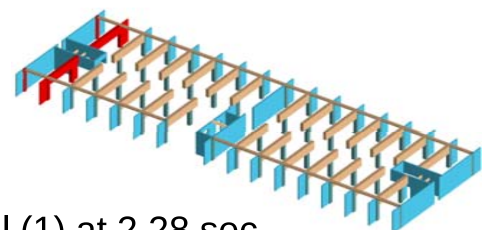


Level (1) at 2.60 sec



Level (1) at 2.27sec

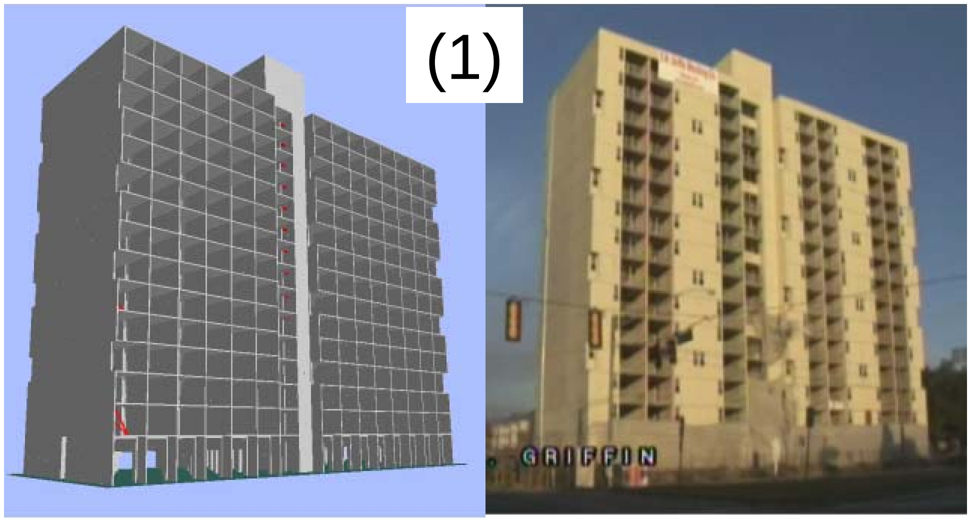


Level (1) at 2.28 sec

Verification Examples

Stubbs Tower, Savannah, Georgia

(1)



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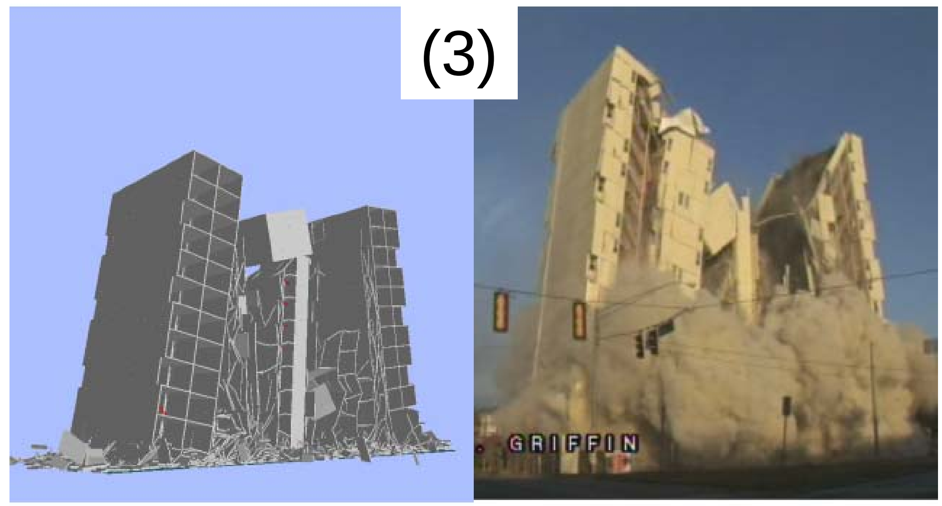

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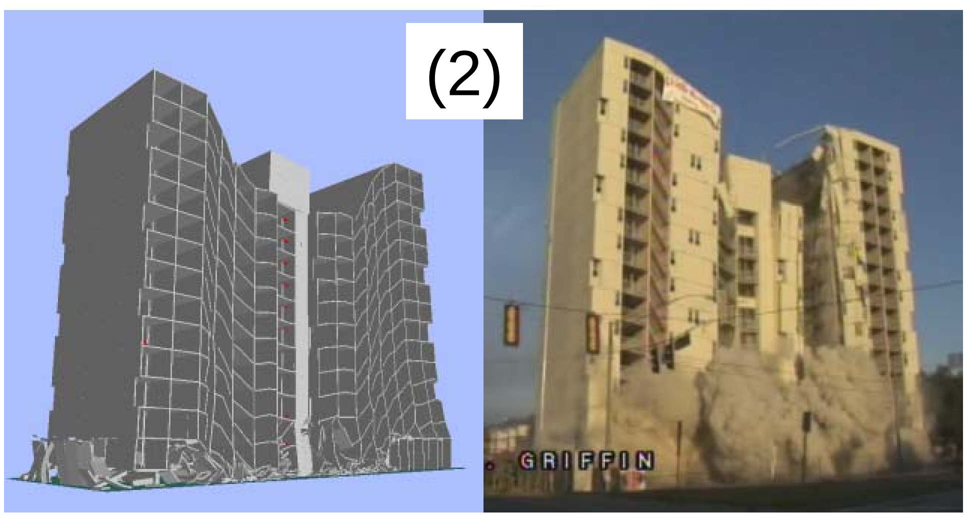

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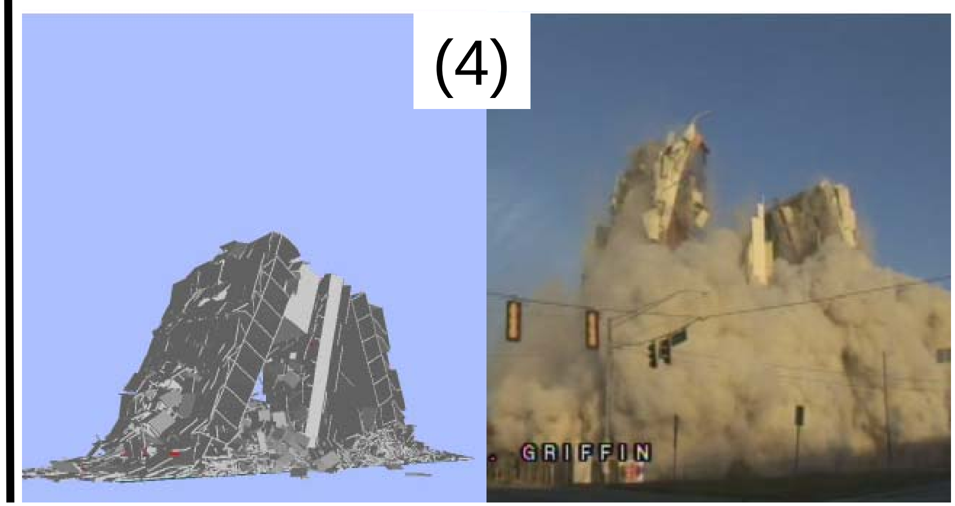

Verification Examples

Stubbs Tower, Savannah, Georgia

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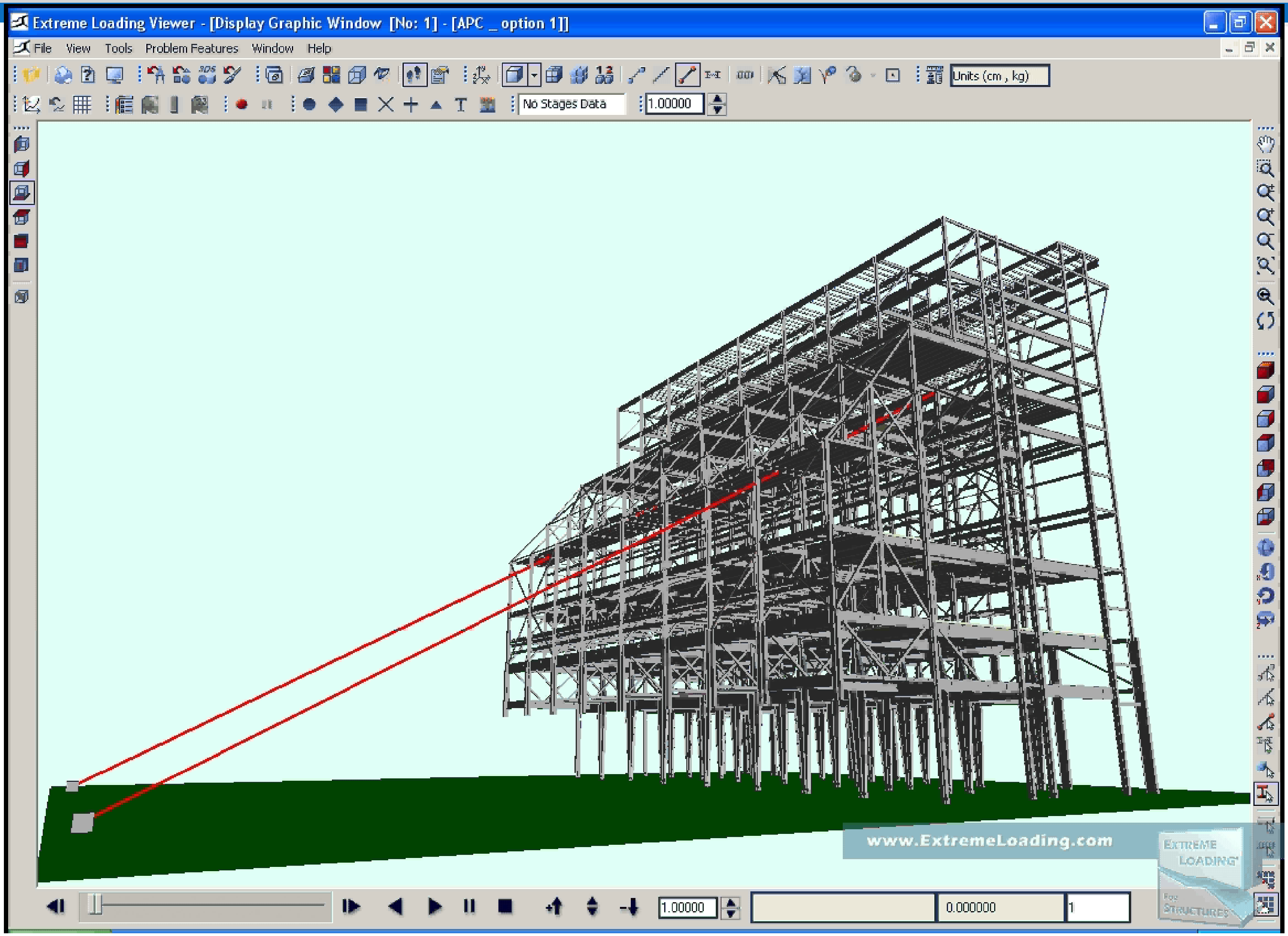
Verification Examples

Briquetting Structure, Australia

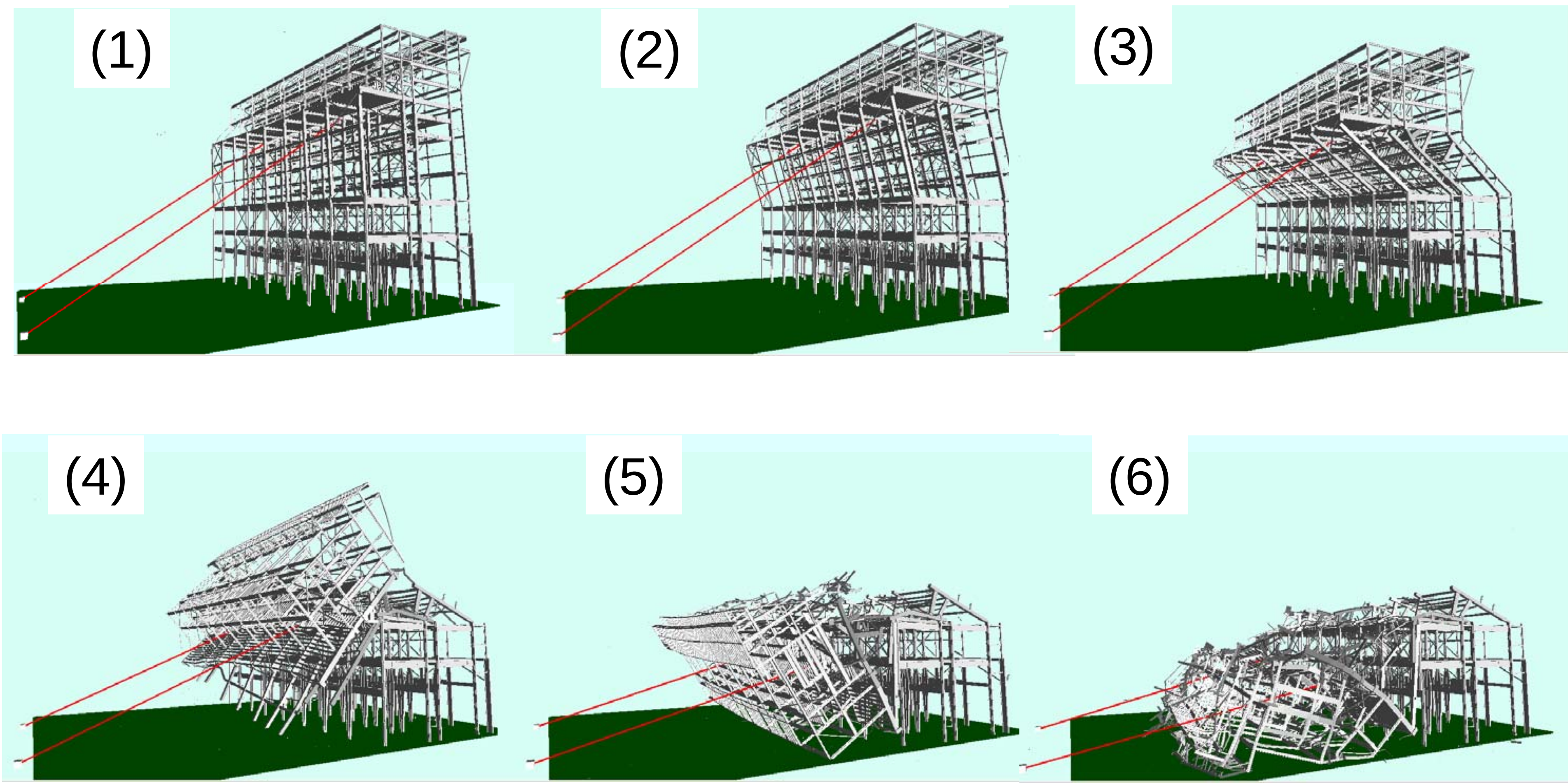
Verification Examples

Briquetting Structure, Australia



Verification Examples

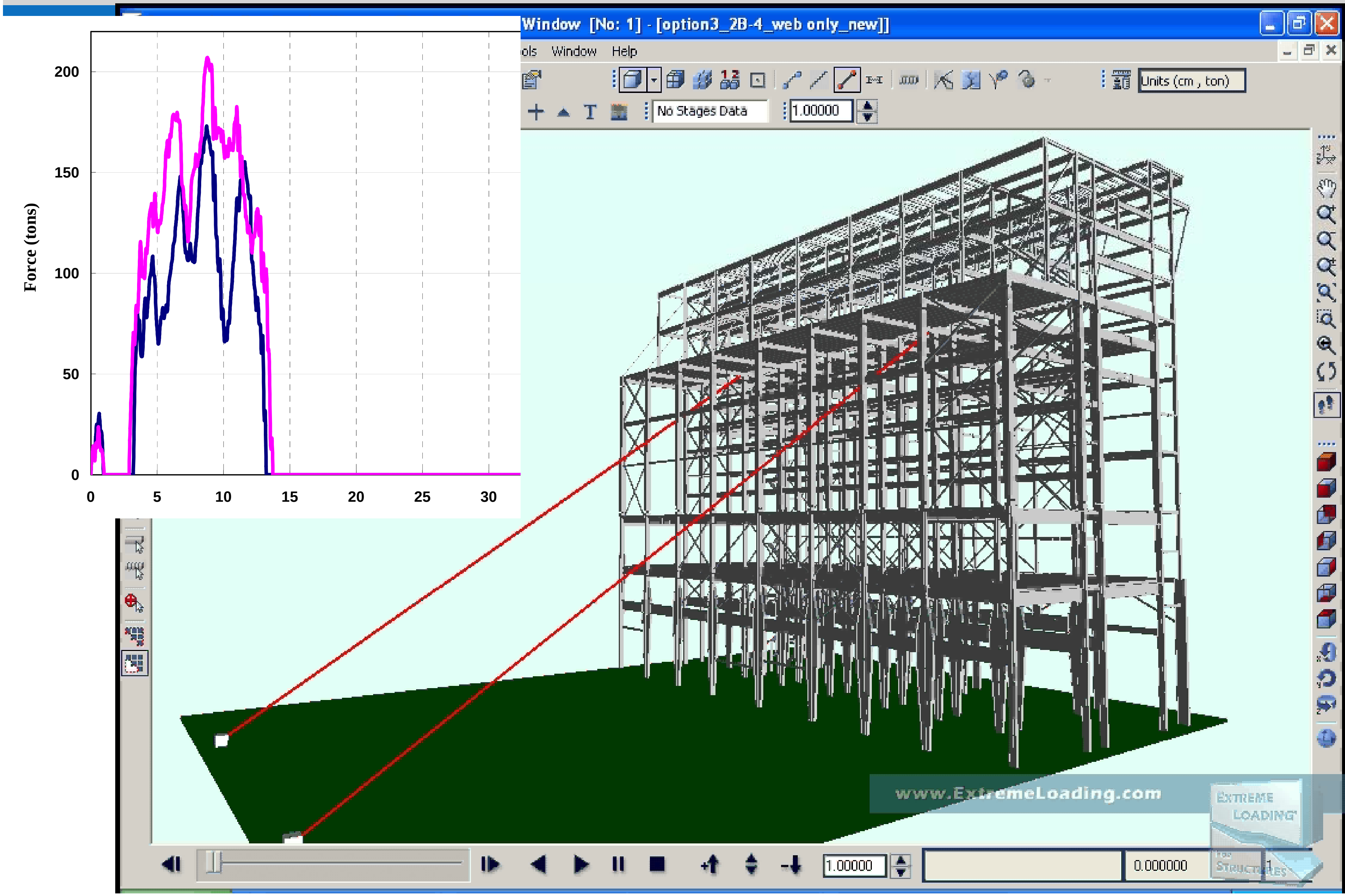
Briquetting Structure, Australia



NAFEMS

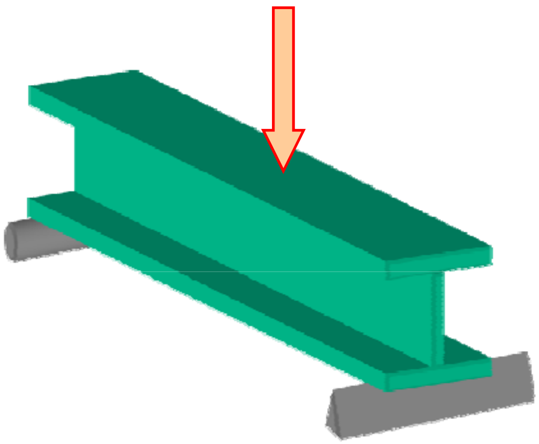
Verification Examples

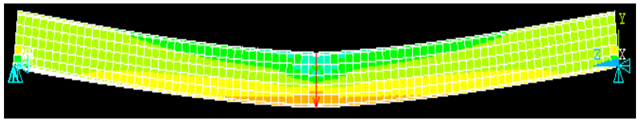
Briquetting Structure, Australia



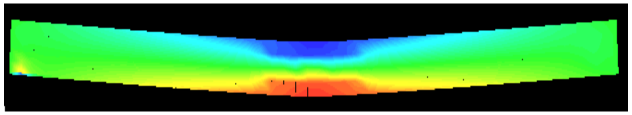
Verification Example of Steel Structures

Hot rolled steel beam under flexure

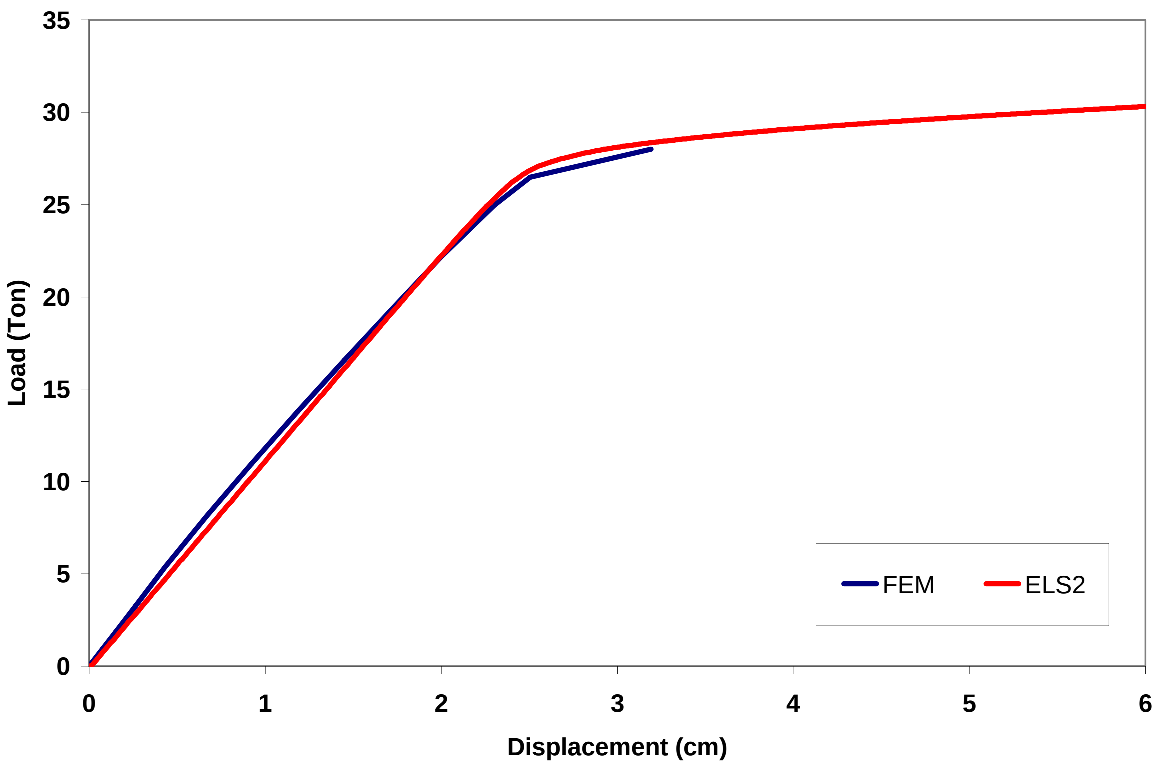




FEM

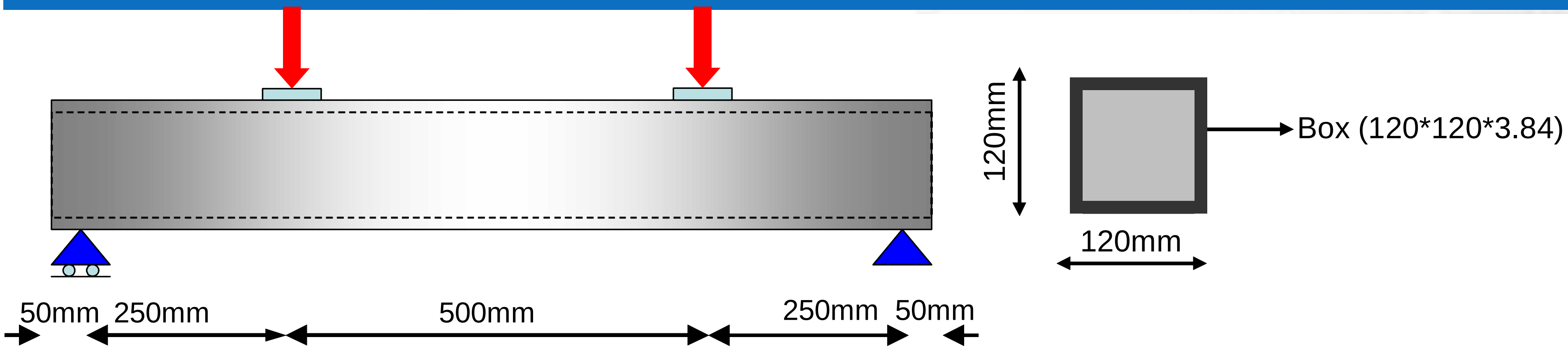


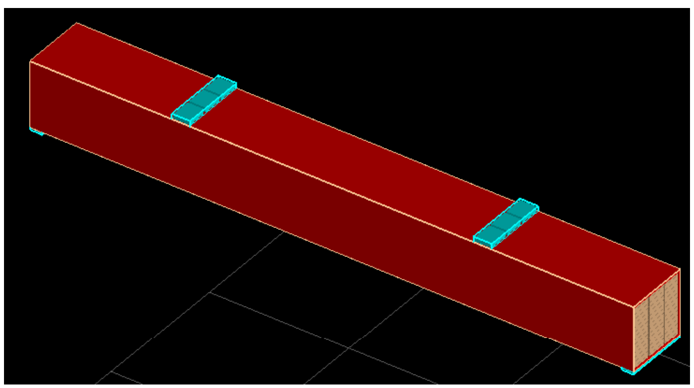
AEM
Stress contours

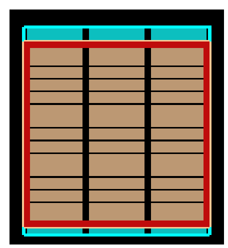


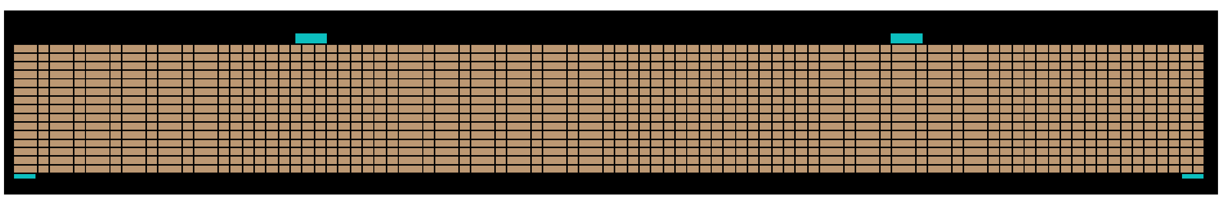
Verification Example of Steel Structures

Concrete-Filled Tube Girder under Four-Point Loading



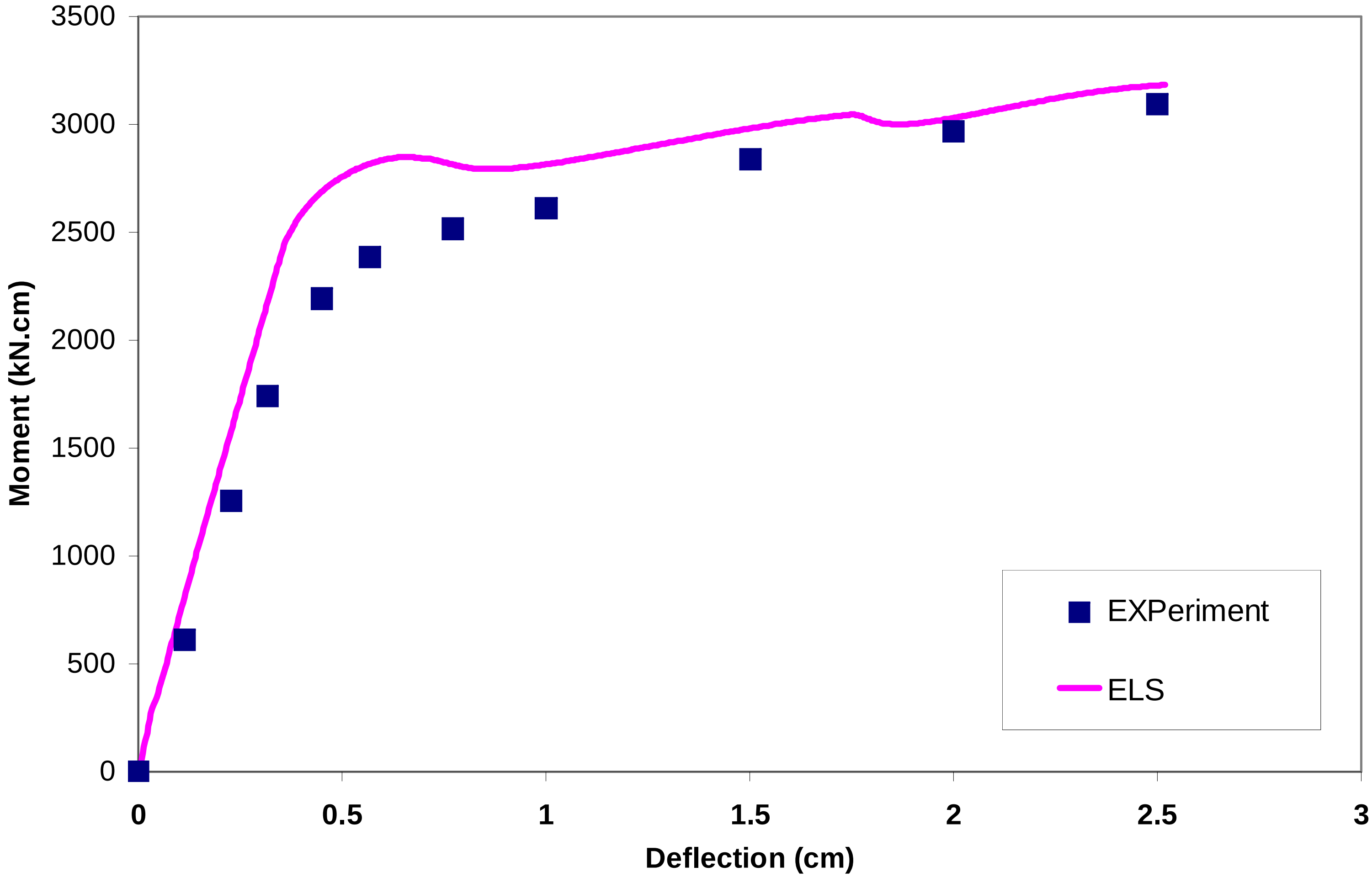






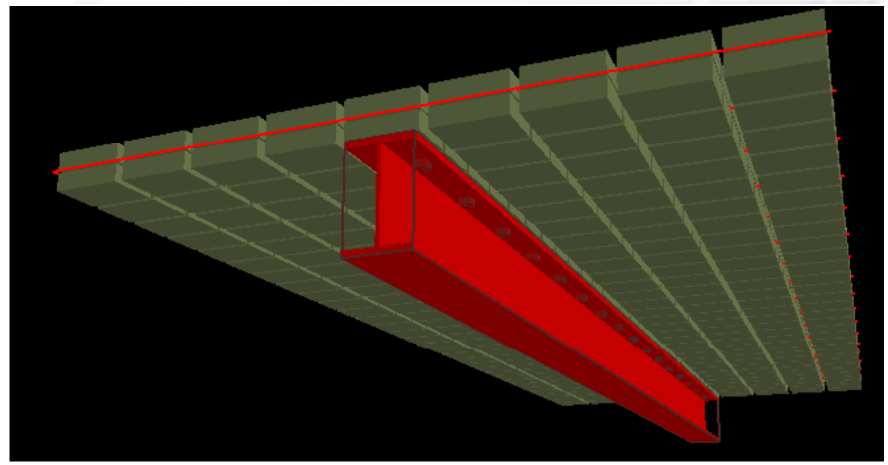
Verification Example of Steel Structures

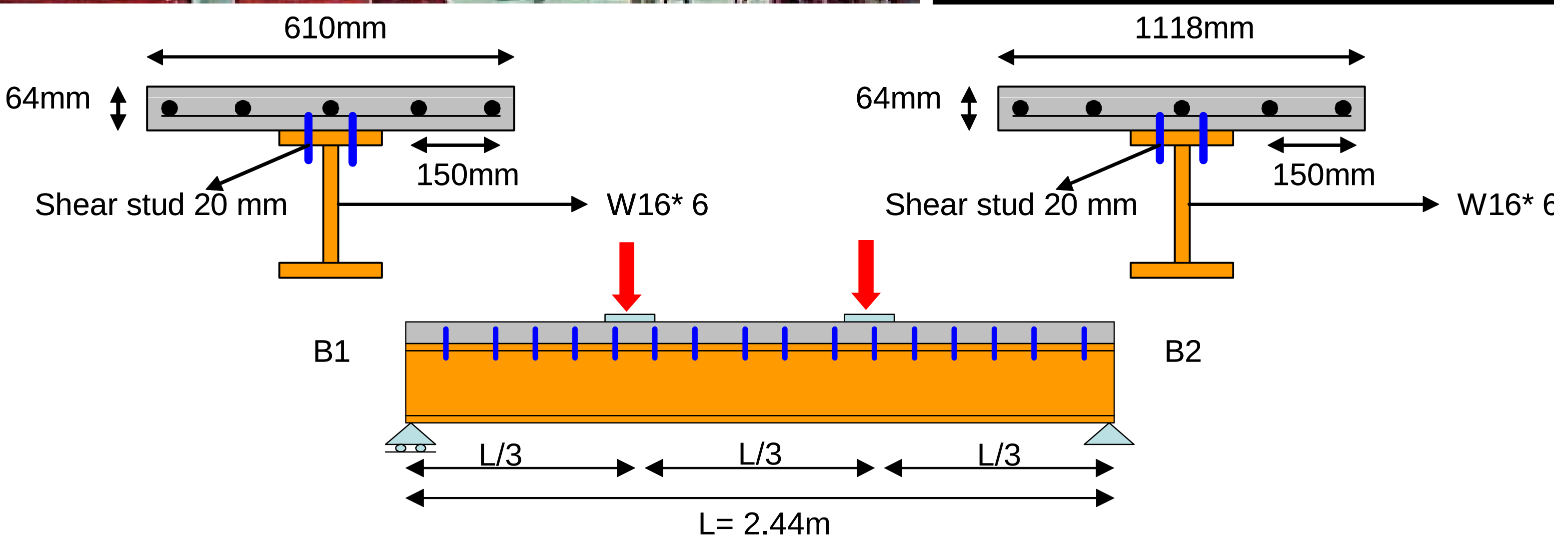
Concrete-Filled Tube Girder under Four-Point Loading



Verification Example of Steel Structures

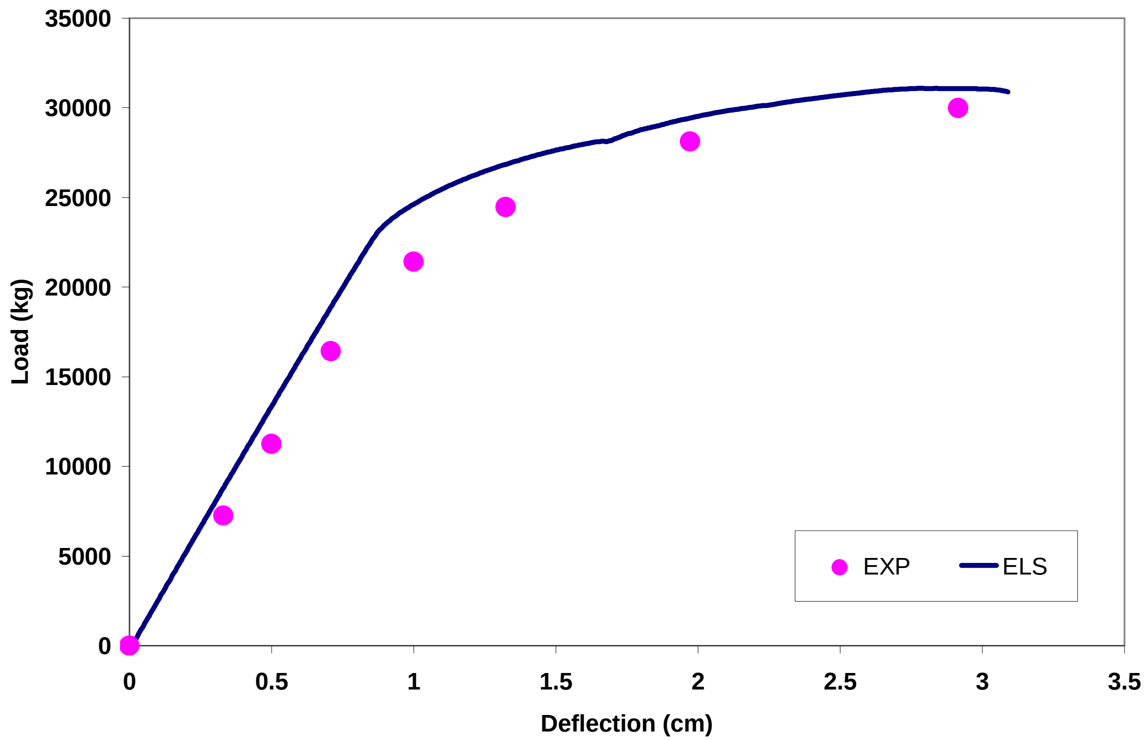
Steel Composite Beam under Four-Point Loading

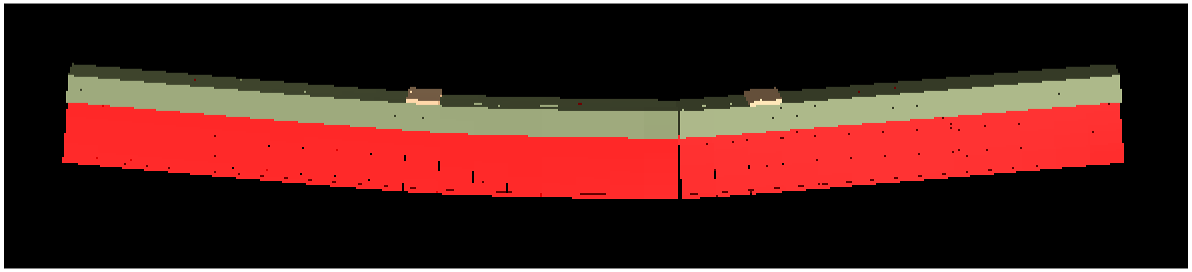




Verification Example of Steel Structures

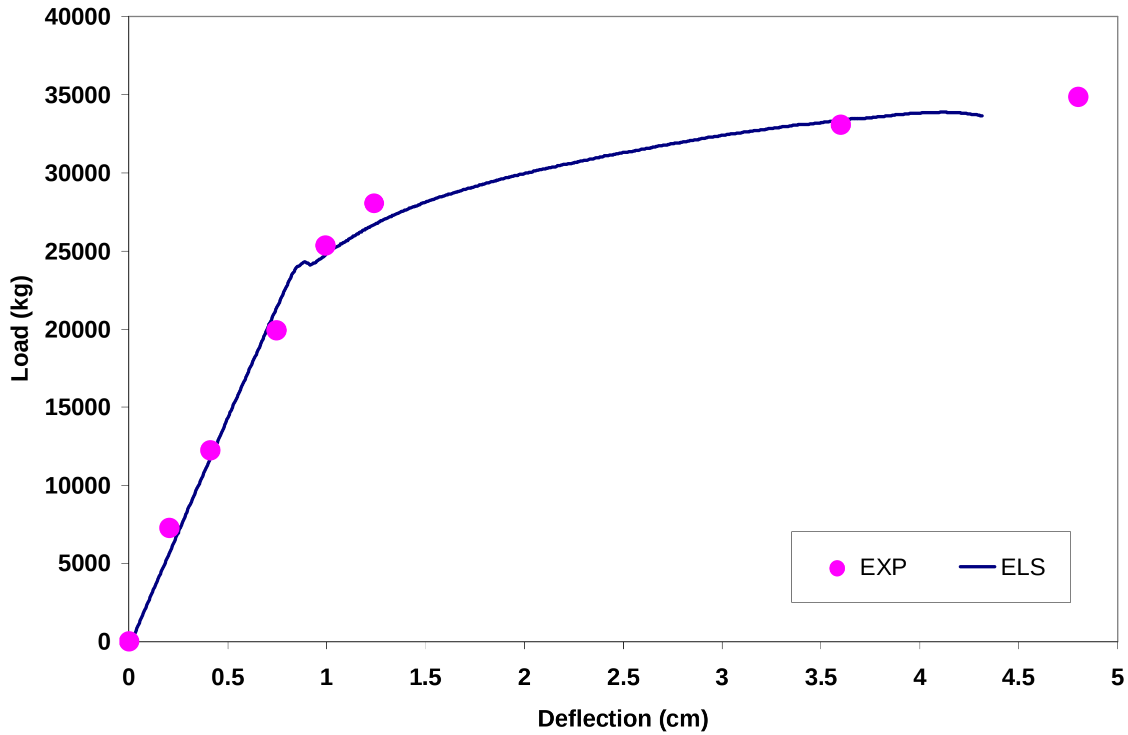
Steel Composite Beam under Four-Point Loading (B1)





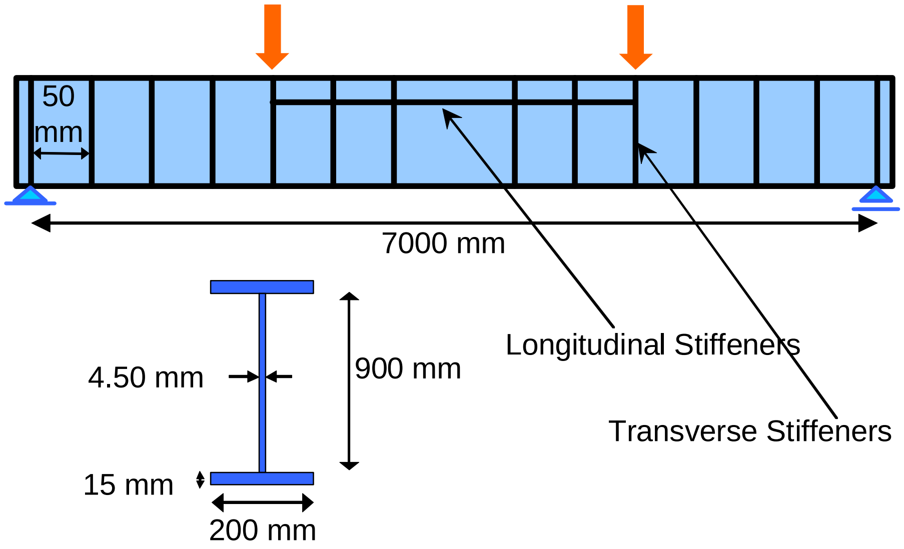
Verification Example of Steel Structures

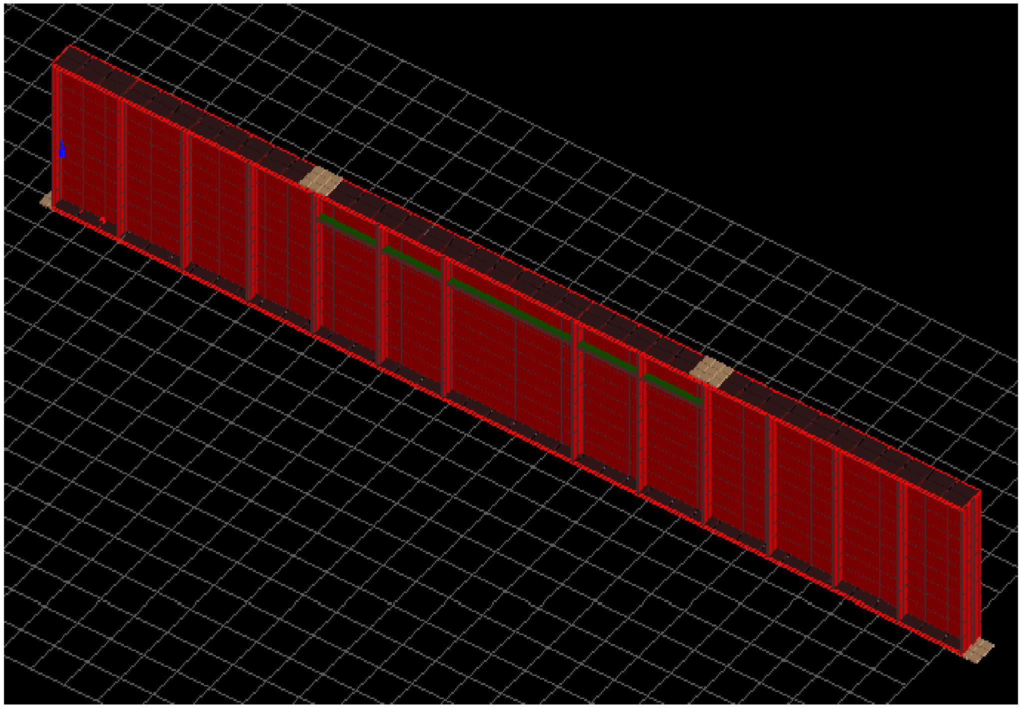
Steel Composite Beam under Four-Point Loading (B2)



Verification Example of Steel Structures

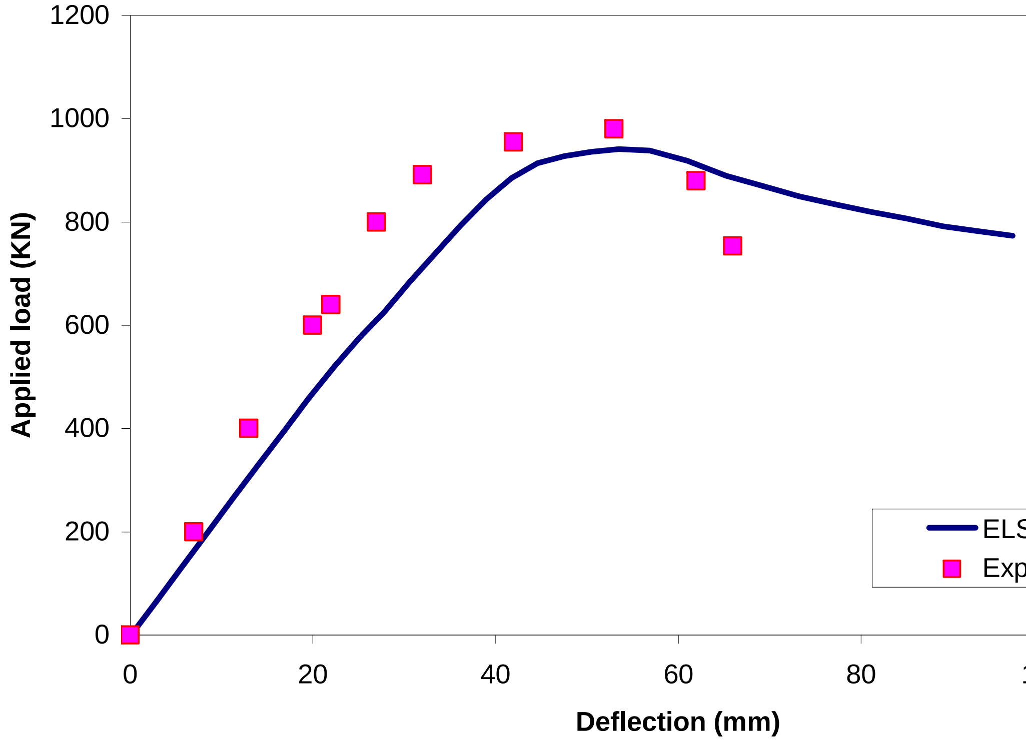
Hybrid Steel Girder with Longitudinal and Transverse Stiffeners

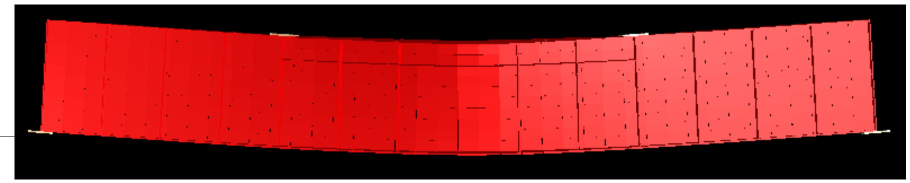




Verification Example of Steel Structures

Hybrid Steel Girder with Longitudinal and Transverse Stiffeners





Deflection Pattern obtained by ELS (elevation).

Deflection Pattern obtained by ELS (plan)

Lateral torsional buckling observed in the experiment

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Q&A Session

Using the Q&A tool, please submit any questions you may have for our panel.

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Thank you!

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