



Outline

Nonlinear Simulation of Super Tall Buildings and Large Span Bridges Based on OpenSees

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Outline

- Introduction
- nDMaterial Concrete and Multi-layer Shell Element
- Modeling Technology and Pre-/Post- Process
- 64-bit Version and Selection of Analysis Domain
- Examples

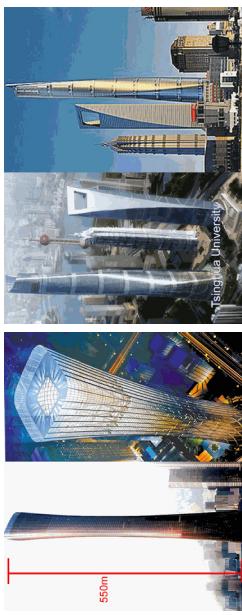
Introduction

- Initiative:
- Simulation of Super-Tall Buildings and Large Span Bridges with OpenSees
 - From National Nature Science Foundation of China (NSFC)
- Challenge:
- Element Model for Shear Walls/Core Tubes
 - Large Scale Computing
 - Modeling Complicated Structures

- Introduction
- nDMaterial Concrete and Multi-layer Shell Element
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- Examples

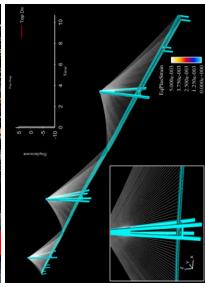
Introduction

Introduction



Fiber beam + Multi-layer shell
+ Elemental deactivation

Collapse simulation of reinforced concrete
high-rise building induced by extreme
earthquakes. *Earthquake Engineering &
Structural Dynamics*. 2013; 42(5): 705-723.



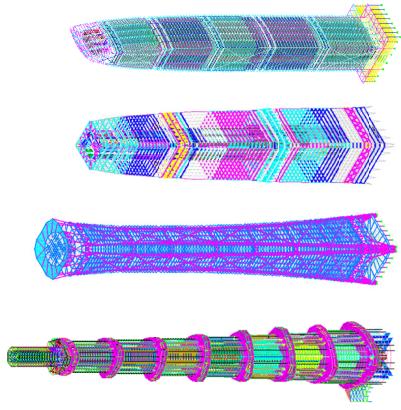
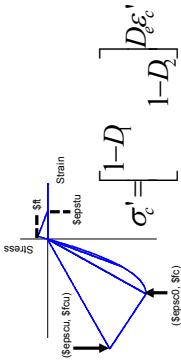
Outline

- Introduction
- **nDMaterial Concrete and Multi-layer Shell Element**
- Modeling Technology and Pre-/Post- Process
- Selection of Analysis Domain and 64-bit Version
- Examples

nDMaterial Concrete



- 2D plane stress constitutive model
- A very simple concrete model
 - Damage mechanism and smeared crack
 - Compression: Løland model
 - Tension: Mazars model



DOF > 300,000; Num. Elements > 100,000; Num. Section > 100;

nDMaterial Concrete

■ Material Definition Interface

```
extern "C"
{
    void ESMAT(int *instatev, int *props, double *props,
               double *stress, double *strain, double *strainl,
               double *statev, double *tangents);
}

//null constructor
PlaneStressConcreteMaterial::PlaneStressConcreteMaterial()
: nDMaterial(0, ND_TAGS_PlaneStressConcreteMaterial),
  strain0(3), strain(3), stress0(3), stress(3),
  tangent(3), ETangent(3), PProps(0),
  mstarev(0), mProps(0)
{ }

subroutine psumat(instatev,props,props,
& stress, strain0,strain1,dstrain,
& statev, tangents)
use Concrete
integer instatev, props
real*8 stress(3), strain0(3), strain(3), dstrain(3), tangent(3,3)
statev(instatev), pProps(props)
real*8*8
```

nDMaterial Concrete

■ Material Definition Interface

```
#include "nDMaterial.h"
#include "nDMaterialConcrete.h"
#include "nDMaterialPlateRebar.h"
#include "nDMaterialPlatedFromPlaneStress.h"
#include "nDMaterialSection.h"
#include "nDMaterialMultiLayerShell.h"
#include "nDMaterialSectionCommand.h"

nDMaterialPlaneStress(nDMaterialConcrete, SPC)
nDMaterialConcrete(SPC)
nDMaterialPlateRebar(SPC)
nDMaterialPlatedFromPlaneStress(SPC)
nDMaterialSection(SPC)
nDMaterialMultiLayerShell(SPC)
nDMaterialSectionCommand(SPC)
```

```
SmatTag integer tag identifying material
Sfc concrete compressive strength at 28 days (positive)
Sfr concrete tensile strength (negative)
Sfu concrete crushing strength (negative)
Spcel concrete strain at maximum strength (negative)
Spcu concrete strain at crushing strength (negative)
Sptu ultimate tensile strain (positive)
Ssc shear transfer coefficient
```

```
#include "nDMaterialConcrete.h"
#include "nDMaterialPlateRebar.h"
#include "nDMaterialPlatedFromPlaneStress.h"
#include "nDMaterialSection.h"
#include "nDMaterialMultiLayerShell.h"
#include "nDMaterialSectionCommand.h"

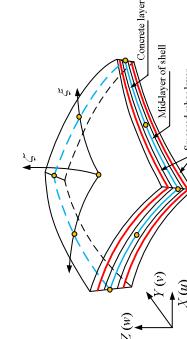
nDMaterialPlaneStress(nDMaterialConcrete, SPC)
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```

Multi-layer Shell Element

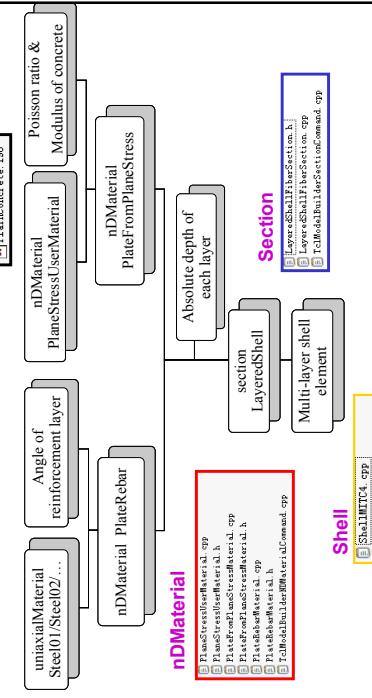
■ Features

- Composite Material Mechanics
- Coupled in-plane/out-of-plane Bending and in-plane Direct Shear
- Coupled Bending-shear



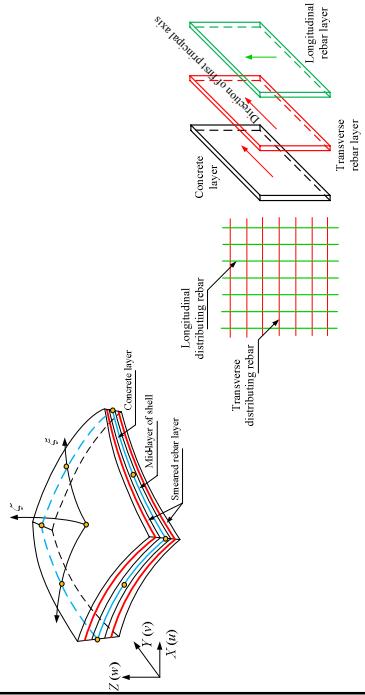
Multi-layer Shell Element

■ Framework of the element



Multi-layer Shell Element

■ Shell MITC4



Multi-layer Shell Element

nDmaterial PlateRebar \$SnowmatTag \$Sita

new integer tag identifying material deriving from
pre-defined uniaxial steel material
SmatTag integer tag identifying uniaxial steel material
Sita define the angle of steel layer, 90° (longitudinal
steel), 0° (transverse steel)

```
#$#=$0 钢力筋柱区钢筋
uniaxialMaterial $Steel102
#$#=$0 钢筋柱用钢筋
uniaxialMaterial $Steel102
#$#=$0 钢筋
nDmaterial
#$#=$6
#$#=$0 平筋
nDmaterial
#$#=$6
#$#=$0 箍筋
nDmaterial
#$#=$6
#$#=$0 钢筋
nDmaterial
```

Multi-layer Shell Element

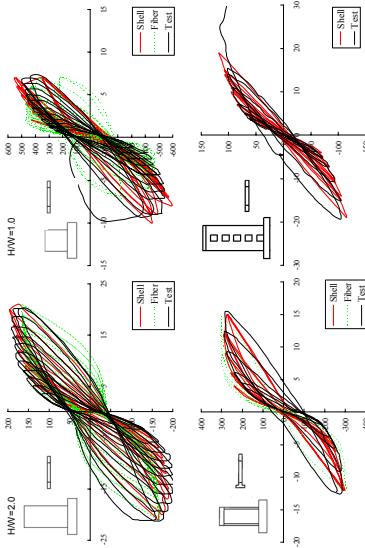
section LayeredShell \$SectionTag \$nLayers \$MatTag1 \$Thickness1...\$MatTagN \$ThicknessN

SectionTag unique tag among sections
nLayers total numbers of layers
\$MatTag1 material tag of first layer
Thickness1 thickness of first layer
...
\$MatTagn material tag of last layer
ThicknessN thickness of last layer

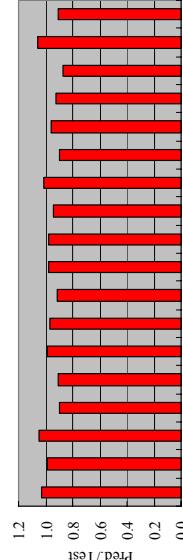
Element ShellMITC4 \$Layer \$Thickness1 \$ThicknessN \$Node1 \$Node2 \$Node3 \$Node4

\$Layer unique element tag
\$Node1 four nodes defining element boundaries, input in counter-clockwise order around the tag associated with previously-defined SectionForConcreteOrFiber object.
Currently must be either a PlateFiberSection, or ElasticMaterialAndPlateSection
\$Thickness1

Validation with Experiments



Validation with Experiments



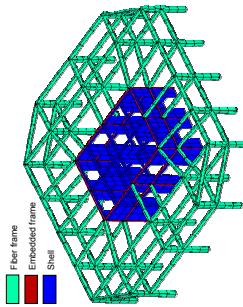
nMaterial Photostress (nMaterial Photostress)	
Sic	integer tag identifying material
Sfr	concrete compressive strength at 28 days (positive)
Sft	concrete tensile strength (positive)
Sfrn	concrete crushing strength (negative)
Sfrm	concrete strain at maximum strength (negative)
Sepcu	concrete strain at crushing strength (negative)
Sepsu	ultimate tensile strain (positive)
Sfrt	shear transfer coefficient

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Modeling technology

- Fiber beam elements for beams and columns
- Multi-layer shell elements for shear walls and coupling beams
- Embedded beam elements to connect fiber beam elements and multi-layer shear wall elements



Pre-/Post- Process

MSC Software®
“Simulating Reality, Delivering Certainty”



The models in MSC.Matca can be found in Collapse simulation of reinforced concrete high-rise building induced by extreme earthquakes. *Earthquake Engineering & Structural Dynamics*, 2013, 42(6), 705-723.

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- **64-bit Version and Selection of Analysis Domain**
- Examples

64-bit Version

- Model size:
 - Nodes > 53,000; Elements > 88,000
 - DOF > 300,000
- Recompile OpenSees.exe in 64-bit environment
- Maximum thread memory size > 28 GB

Selection of Analysis Domain

- Matrix solver
 - BandGeneral SOE: Failed
 - BandSPD SOE: Failed
 - ProfileSPD SOE: Failed
 - SuperLU SOE: Failed
 - Mumps: Failed
 - UmfPack SOE: Works but Slow
 - SparseSYM SOE: Feasible

Selection of Analysis Domain

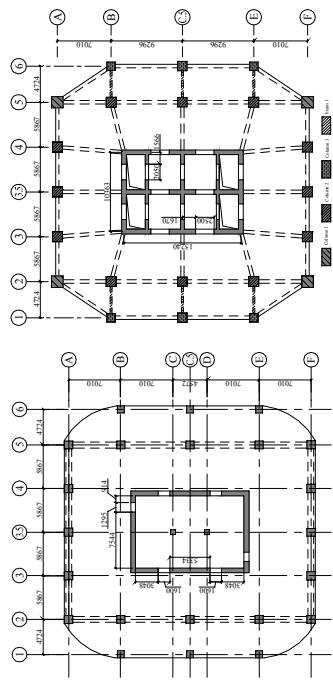
- Eigen solver
 - Symmetric Arpack: Failed
 - Band Arpack : Failed
 - Profile SPD: Feasible
- Constraints
 - Plain: Failed
 - Lagrange: Failed
 - Penalty: Failed
 - Transformation : Feasible



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TBI Building 2



US Design

Download URL: <http://www.luxinzheng.net/download/OpenSeesTHU.zip>

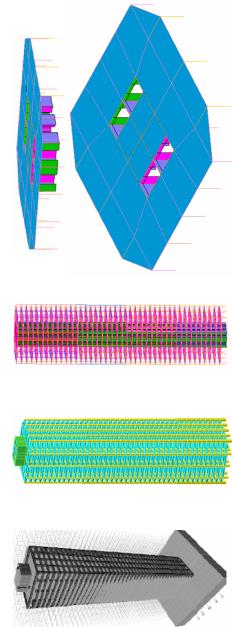
Chinese Design

TBI Building 2

- H=141.8m, 42 stories
- 8,469 nodes
- 9,744 fiber elements
- 4,707 shell elements



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TBI Building 2

- Gravity and vibration period



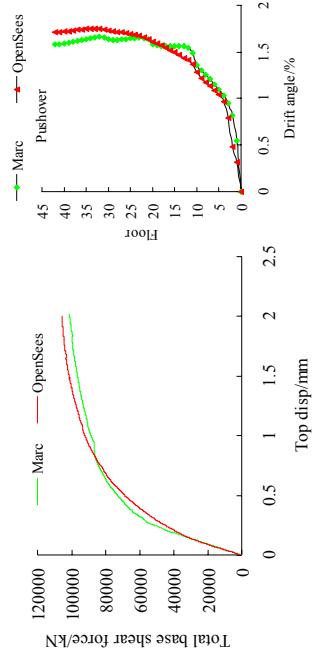
Tsinghua University
Tsinghua University

	Marc	OpenSees	Relative Error
T_1 (X translation)	1.791	1.815	1.3%
T_2 (Y translation)	1.580	1.579	0.06%
T_3 (Torsion)	0.900	0.890	1.1%
Gravity (ton)	5.4964×10^4	5.4964×10^4	0%

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TBI Building 2

■ Static Pushover



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TBI Building 2

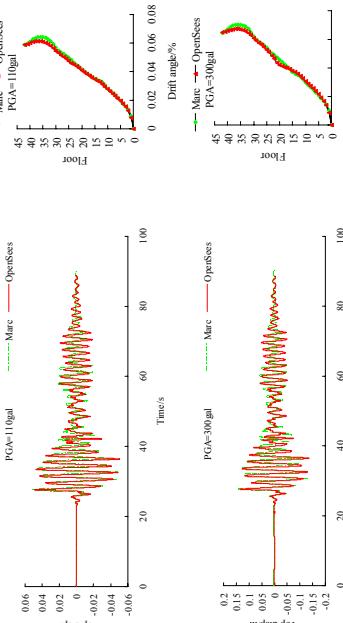
■ Nonlinear time history analysis

- Chi-Chi: 110gal、300gal、510gal & 1000gal
- El-Centro: 1000gal
- Northridge: 1000gal

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TBI Building 2

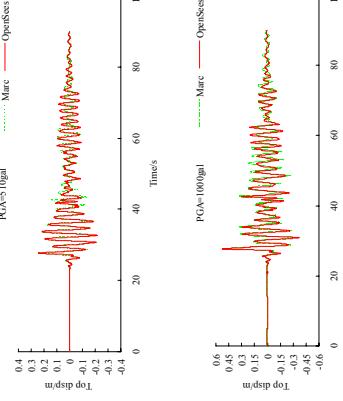
■ Chi-Chi



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TBI Building 2

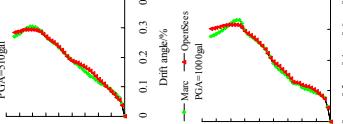
■ Chi-Chi



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Taiwan University

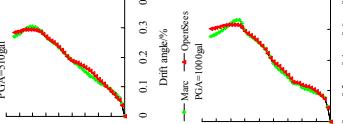
■ Chi-Chi



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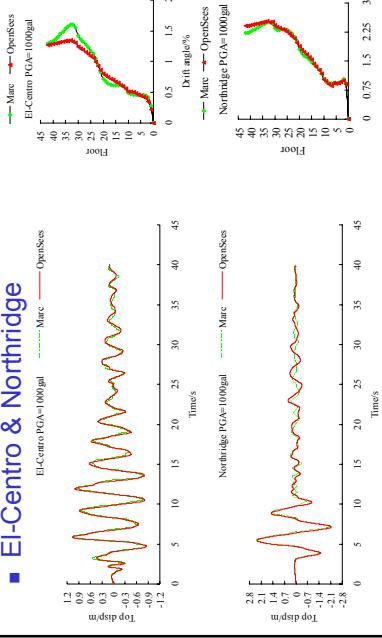
■ Chi-Chi



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F. Plaza

■ El-Centro & Northridge



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F. Plaza

■ H=315.47m, 62 stories

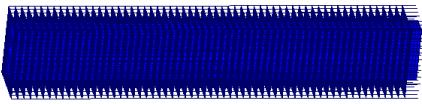
■ El-Centro PGA=1000gal

■ Northridge PGA=1000gal

■ 46,028 nodes

■ 31,556 fiber elements

■ 37,160 shell elements



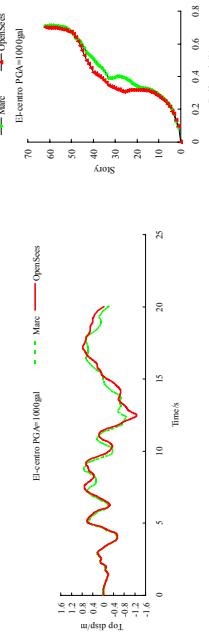
F. Plaza

■ Gravity and vibration period

	Marc	OpenSees	Relative Error
T_1 (X translation)	4.9925	4.9261	1.33%
T_2 (Y translation)	3.2940	3.3290	1.06%
T_3 (Torsion)	1.051	1.061	0.95%
Gravity (ton)	4.90894×10^5	4.90894×10^5	0%

F. Plaza

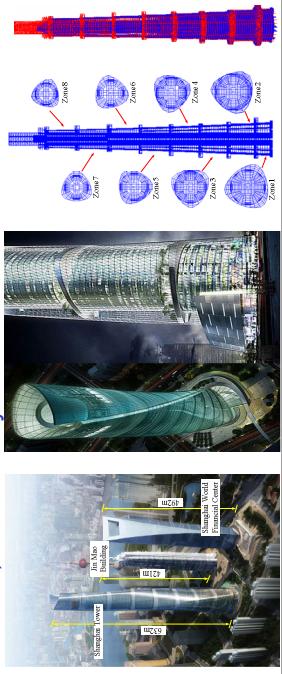
■ Nonlinear time history analysis



Shanghai Tower (上海中心)



- H=632m, 121 stories
- 53,006 Nodes
- 48,774 fiber beam elements
- 39,315 Multi-layer shell elements



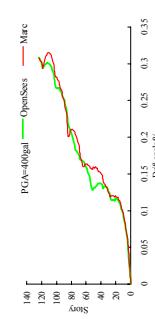
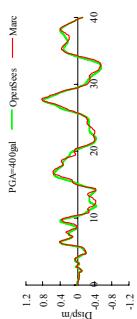
Shanghai Tower (上海中心)

- Gravity and vibration period

	Mac	OpenSees	Relative Error
T_1 (X)	9.6525	9.5238	1.33%
T_2 (Y)	9.5511	9.4518	1.04%
T_3 (Torsion)	4.7916	4.6847	2.23%
Gravity (ton)	5.10738×10^5	5.10738×10^5	0%

Shanghai Tower (上海中心)

- Time history analysis



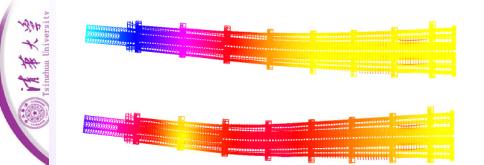
Qiongzhou Strait Bridge (琼州海峡大桥)

- Qiongzhou Strait Bridge (琼州海峡大桥)
 - Between Guangdong Province and Hainan Island.
 - Width=30km.
 - Average depth 44m. Maximum depth 144m.
- Qiongzhou Strait Bridge (琼州海峡大桥)
 - Total length=4304m.
 - Main span=1500m.
 - Height of main tower=460m.



Qiongzhou Strait Bridge (琼州海峡大桥)

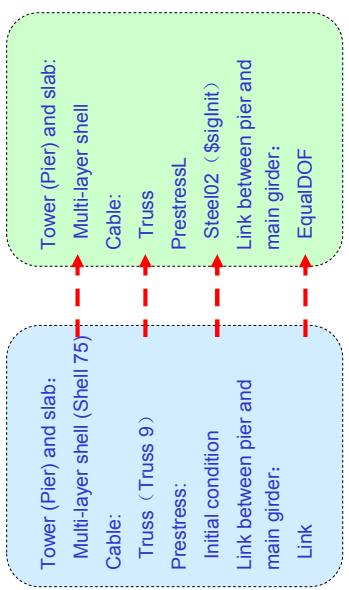
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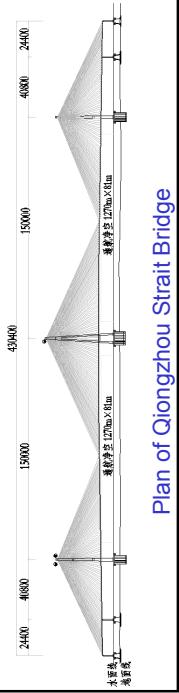
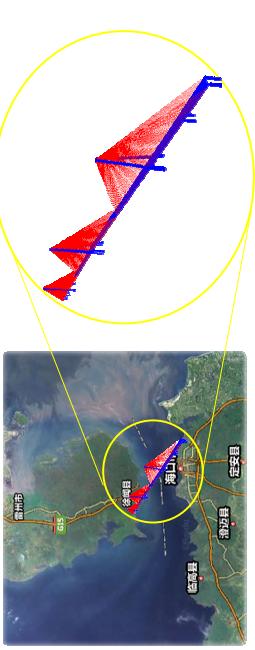
Modeling technology



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Qiongzhou Strait Bridge



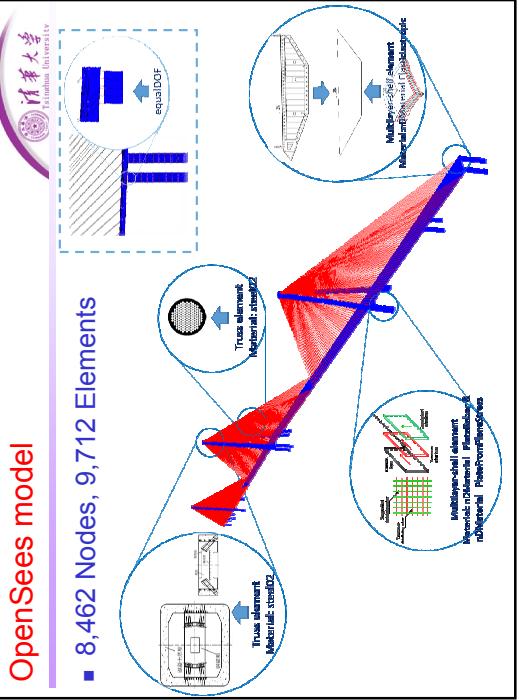
Results

- Gravity and free vibration modes

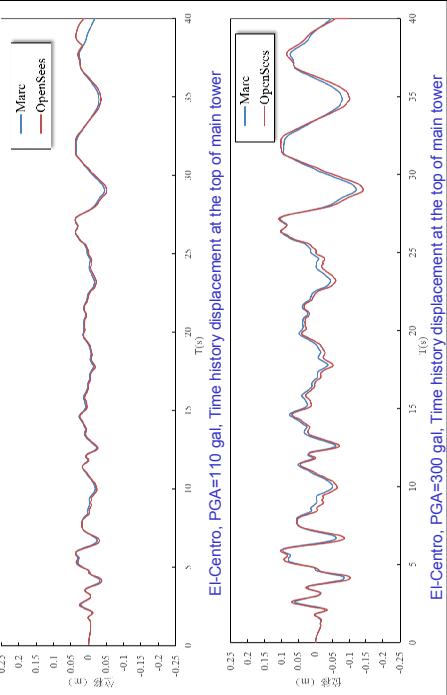
	Marc	OpenSees	Relative error
T_1	15.68	15.25	2.75%
T_2	8.54	8.17	4.25%
T_3	7.55	7.25	4.00%
T_4	6.07	5.86	0.55%
T_5	5.45	5.24	3.50%
Mass (ton)	9.34×10^5	8.95×10^5	4.11%

OpenSees model

- 8,462 Nodes, 9,712 Elements

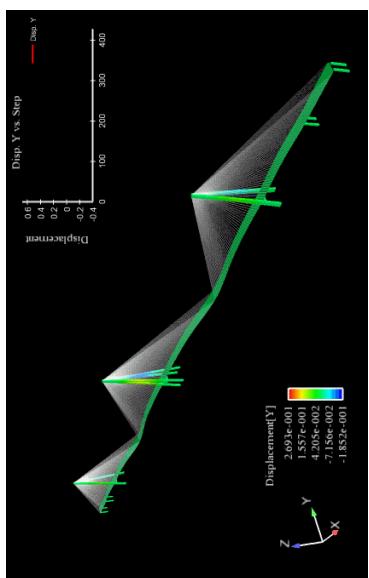


Results

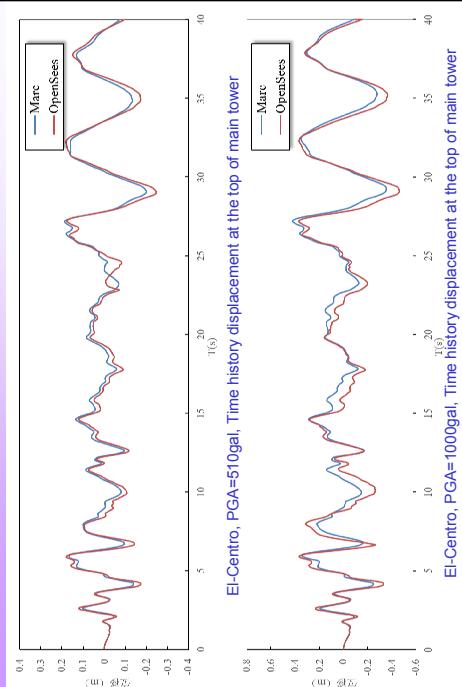


Results

■ Nonlinear time history analysis



Results



Thanks!

Any Questions?

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