OpenSees Command Language Manual --- Response Sensitivity Analysis based on the Direct Differentiation Method (DDM)

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OpenSees Command Language Manual: DDM-Based Response Sensitivity Analysis

Introduction

This manual is intended to outline the basic commands currently available within the OpenSees interpreter for performing DDM-based response sensitivity analysis. This interpreter is an extension of the Tcl/Tk language for use with OpenSees. The existing Tcl commands for Finite Element response-only computation are described in the OpenSees user's guide available online at http://opensees.berkeley.edu and, thus, are not repeated in this document. The notation used herein is the same as that used in the Tcl commands manual for response-only computation. Only new Tcl commands for DDM-based response sensitivity computation are presented and explained in detail.

This manual is subdivided as follows:

Reference:
Gu Q. (2008). "Finite element response sensitivity and reliability analysis of Soil-Foundation-Structure-Interaction (SFSI) systems." *Ph.D. dissertation*. University of California at San Diego, La Jolla, CA (USA).

CHAPTER 1

DDM-Based Response Sensitivity Computation Tcl Commands

General commands

reliability Command

This command creates the reliability domain in which the sensitivity, reliability and optimization components are kept. This reliability domain is parallel to the finite element (FE) domain in OpenSees. Currently, the commands for stand-alone sensitivity analysis (e.g., sensitivityIntegrator, sensitivityAlgorithm) are set in the reliability domain only and, thus, the ‘reliability’ command must be used before any stand-alone sensitivity analysis.

reliability

parameter Command

In DDM-based FE response sensitivity analysis, the sensitivity parameters can be material, geometry or discrete loading parameters. Each parameter should be defined as:

parameter $tag <specific object arguments>

$tag integer tag identifying the parameter.

Each parameter must be unique in the FE domain, and all parameter tags must be numbered sequentially starting from 1.

<specific object arguments> depend on the object in the FE model encapsulating the desired parameters. For example, to identify the elastic modulus, E, of the material 1 at section 3 of element 4, the <specific object arguments> string becomes:

parameter 1 element 4 section 3 material 1 E

To identify the elastic modulus, E, of elastic section 3 of element 4 (for elastic section, no specific material need to be defined), the <specific object arguments> string becomes:

parameter 1 element 4 section 3 E

To parameterize E for element 4 with material 1 (no section need to be defined), the <specific object arguments> string simplifies as:

parameter 1 element 4 material 1 E

Notice that the format of the <specific object arguments> is different for each considered element/section/material. The user is referred to the corresponding section of this manual for the specific set of parameters and the relative <specific object arguments> format.

addToParameter Command

In case that more objects (e.g., element, section) are mapped to an existing parameter, the following command can be used to relate these additional objects to the specific parameter:

addToParameter $tag <specific object arguments>

$tag integer tag identifying an existing parameter.

<specific object arguments> is the same as defined in the 'parameter' command.

updateParameter Command

Once the parameters in FE model are defined, their value can be updated:

updateParameter $tag $newValue

$tag	integer tag identifying an existing parameter that is to be updated
$newValue	the updated value to which the parameter needs to be set

Reference:

Scott M.H., Haukaas T. (2008). "Software framework for parameter updating and finite element response sensitivity analysis." *Journal of Computing in Civil Engineering*, 22(5):281-291.

sensitivityIntegrator Command

For static analysis, the only option currently available is:

sensitivityIntegrator -static

which must be defined before the ‘analysis’ command.

For the dynamic case, currently only the Newmark algorithm is available. Two command need to be used together:

integrator NewmarkWithSensitivity $gamma $beta

$gamma	Newmark parameter gamma
$beta	Newmark parameter beta

sensitivityIntegrator -definedAbove

Currently, ‘-definedAbove’ is the only option available in OpenSees. This means that the same integration scheme (i.e., ‘NewmarkWithSensitivity’) is used to perform both response and response sensitivity analysis.

References:

Haukaas T., Der Kiureghian A. (2004). “Finite element reliability and sensitivity methods for performance-based earthquake engineering.” *Report No. 2003/14*, Pacific Earthquake Engineering Research Center, April 2004.

Haukaas T., Der Kiureghian A. (2005). “Parameter sensitivity and importance measures in nonlinear finite element reliability analysis.” *Journal of Engineering Mechanics* (ASCE), 131(10):1013-1026.

sensitivityAlgorithm Command

The most general command is:

sensitivityAlgorithm -computeAtEachStep

which computes the response sensitivity at each time/load step, after the response has converged.

In those cases in which the sensitivity computation does not need to be performed at each step (e.g., for linear elastic systems subjected to static pushover analysis), the sensitivity computation may be performed only at the time/load steps required by user:

sensitivityAlgorithm -computeByCommand

However, before using the '-computeByCommand' option, it is the user's responsibility to make sure that the response sensitivities computation is not needed at each time/load step. For example, in case of incremental nonlinear FE analysis or dynamic analysis, using the '-computeByCommand' option will produce wrong sensitivity results.

recorder Command

To record the nodal response and response sensitivity, the most commonly used format is:

```
recorder Node -file  disp29.out  -time -node  29 -dof 1 <–precision 16 > disp

recorder Node -file ddm29G1.out  -time -node 29  -dof 1 "sensitivity 1"

recorder Node -file ddm29G1.out  -time -node 29  -dof 1 "velSensitivity 1"

recorder Node -file ddm29G1.out  -time -node 29  -dof 1 "accSensitivity 1"
```

The above ‘recorder’ commands (extended for recording response sensitivities) save into files (with the file name defined after the command ‘-file’) the responses and response sensitivities of the node 29 along the first degree of freedom (dof) direction. Response quantities can be ‘disp’ (displacements), ‘vel’ (velocities) and ‘acc’ (accelerations). Response sensitivities are denoted by a string in double quotes and containing the response quantity identifier (i.e., “sensitivity” for displacements, “velSensitivity” for velocities and “accSensitivity” for accelerations) and the sensitivity parameter specified by the parameter tag (in this example the tag is 1).

The command ‘-precision’ is optional, and allows users to change the number of digits used to record into file the response and/or response sensitivities. This command is particularly useful when the finite difference method is used to verify/validate DDM-based FE response sensitivities, since high accuracy in the results may be needed.

The user may also get responses and response sensitivities directly using the following Tcl commands:

```
nodeDisp  29 1

nodeVel 29 1

nodeAccel 29 1

sensNodeDisp 29 1 2

sensNodeVel 29 1 2

sensNodeAccel 29 1 2
```

These commands return the responses of the node 29 along the first dof, and their response sensitivities with respect to the parameter with tag 2

uniaxialMaterial commands

Several uniaxial materials are available for DDM-based FE response sensitivity computation.

SteelMP Command

This command is used to construct a uniaxial Menegotto-Pinto steel material object.

Reference:
Barbato M., Conte J.P. (2006). “Finite element structural response sensitivity and reliability analyses using smooth versus non-smooth material constitutive models.” *International Journal of Reliability and Safety*, 1(1-2):3-39.

uniaxialMaterial SteelMP $matTag $sigmaY $E $b

$matTag	unique material object integer tag
$sigmaY	yield stress or force
$E	initial tangent stiffness
$b	strain-hardening ratio (ratio between post-yield tangent and initial elastic tangent)

For this material class, the sensitivity parameters can be: **sigmaY, E, b**

SmootPSConcrete Command

This command is used to construct a uniaxial smoothed Popovics-Saenz concrete material object.

Reference:
Zona A., Barbato M., Conte J.P. (2005). “Finite element response sensitivity analysis of steel-concrete composite beams with deformable shear connection.” *Journal of Engineering Mechanics* (ASCE), 131(11):1126–1139.

uniaxialMaterial SmoothPSConcrete $matTag $fc $fu $Ec $epso $epsu $eta

$matTag	unique material object integer tag
$fc	concrete compressive strength (positive for compression)
$fu	concrete crushing strength (positive for compression)
$Ec	initial tangent stiffness
$epsco	concrete strain at maximum strength (positive for compression)
$epscu	concrete strain at crushing strength (positive for compression)
$eta	smoothing parameter (default value = 0.2).

For this material class, the sensitivity parameters can be: **fc, fu, Ec, epsco, epscu, eta**

UniaxialJ2Plasticity Command

This command is used to construct a uniaxial J_2 Plasticity material object with isotropic and kinematic hardening.

Reference:
Conte J.P., Vijalapura P., Meghella M. (2003). "Consistent finite element response sensitivities analysis." *Journal of Engineering Mechanics* (ASCE), 129(12):1380-1393.

uniaxialMaterial UniaxialJ2Plasticity $matTag $E $sigmaY $Hkin $Hiso

$ matTag	unique material object integer tag
$E	initial tangent stiffness
$sigmaY	yield stress (or force)
$Hkin	kinematic hardening Modulus
$Hiso	isotropic hardening Modulus

For this material class, the sensitivity parameters can be: **E, sigmaY, Hkin, Hiso**

Hardening Command

This command is used to construct a uniaxial material object with combined linear kinematic and isotropic hardening.

uniaxialMaterial Hardening $matTag $E $sigmaY $Hiso $Hkin

$matTag	unique material object integer tag
$E	initial tangent stiffness
$sigmaY	yield stress (or force)
$Hiso	isotropic hardening modulus
$Hkin	kinematic hardening modulus

For this material class, the sensitivity parameters can be: **E, sigmaY, Hkin, Hiso**

Concrete01 Command -- Zero Tensile Strength

This command is used to construct a uniaxial Kent-Scott-Park concrete material object with degraded linear unloading/reloading stiffness according to the work of Karsan-Jirsa and no tensile strength (refer to http://peer.berkeley.edu).

uniaxialMaterial Concrete01 $matTag $fc $epsco $fcu $epscu

$matTag	unique material object integer tag
$fc	concrete compressive strength (with positive value)
$epsco	concrete strain at maximum strength (with positive value)
$fcu	concrete crushing strength (with positive value)
$epscu	concrete strain at crushing strength (with positive value)

For this material class, the sensitivity parameters can be: **fc, epsco, fcu, epscu**

Steel01 Command -- Zero Tensile Strength

This command is used to construct a uniaxial bilinear steel material object with kinematic hardening and optional isotropic hardening described by a non-linear evolution equation (refer to http://peer.berkeley.edu).

uniaxialMaterial Steel01 $matTag $sigmaY $E $b <$a1 $a2 $a3 $a4>

$matTag	unique material object integer tag
$E	initial tangent stiffness
$sigmaY	yield strength
$b	strain-hardening ratio (ratio between post-yield tangent and initial elastic tangent stiffness)
$a1 $a2 $a3 $a4	isotropic hardening parameters: (optional, default: no isotropic hardening)

For this material class, the sensitivity parameters can be: **E, sigmaY, b, a1, a2, a3, a4**

Elastic Command

This command is used to construct a linear elastic uniaxial material object (with optional material damping)

uniaxialMaterial Elastic $matTag $E <$eta>

$matTag	unique material object integer tag
$E	elastic stiffness
$eta	stiffness proportional damping coefficient (optional, default=0.0)

For this material class, the sensitivity parameters can be: **E, eta**

nDmaterial commands

Currently, only one multi-axial material model has been extended for DDM-based FE response sensitivity computation.

MultiYieldSurfaceClay Command

The ‘MultiYieldSurfaceClay’ is an elastic-plastic material in which plasticity exhibits only in the deviatoric stress-strain response. The volumetric stress-strain response is linear-elastic and is independent of the deviatoric response. This material is implemented to simulate monotonic or cyclic response of materials whose shear behavior is pressure independent. Such materials include, for example, organic soils or clay under fast (undrained) loading conditions.

This material is available for sensitivity computation in both 2-D and 3-D models. It is another version of PressureIndependMultiYield material. However there are three differences between this model and PressureIndependMultiYield:

1. This model uses the consistent tangent modulus instead of the continuum tangent modulus.
2. This model does not support the ‘updateMaterialStage’ command.
3. This model does not support further discretization of the strain increment in each iteration.

Reference:

Gu Q., Conte J.P., Elgamal A., Yang Z. (2009). “Finite element response sensitivity analysis of multi-yield-surface J_2 plasticity model by direct differentiation method.” *Computer Methods in Applied Mechanics and Engineering*, 198(30-32):2272-2285.

nDmaterial MultiYieldSurfaceClay $matTag $nd $rho $G $K $cohesion $peakShearStrain

$matTag	unique material object integer tag
$nd	number of dimensions, 2 for 2-D analysis (plane-strain), and 3 for 3-D analysis
$rho	saturated soil mass density
$G	reference low-strain shear modulus
$K	reference bulk modulus
$cohesion	peak shear (apparent cohesion at zero effective confinement)
$peakShearStrain	strain at peak shear, i.e., the octahedral shear strain at which the maximum shear strength is reached

For this material class, the sensitivity parameters can be: **G**, **K**, **cohesion**.

section commands

Currently, only two cross-section models and the section aggregator have been extended for DDM-based FE response sensitivity computation.

Fiber Command

Both 2-D and 3-D fiber sections are available for response sensitivity computation.

References:

http://opensees.berkeley.edu/OpenSees/manuals/usermanual/index.html

Spacone E., Filippou F.C., Taucer F.F. (1996). "Fibre beam-column element for nonlinear analysis of R/C frames. Part I: Formulation." *Earthquake Engineering and Structural Dynamics*, 25:711-725.

```
section Fiber $secTag {
  fiber <fiber arguments>
  patch <patch arguments>
  layer <layer arguments>
}
```

Elastic Command

Both 2-D and 3-D elastic sections are available for response sensitivity computation.

References:

http://opensees.berkeley.edu/OpenSees/manuals/usermanual/index.html

section Elastic $secTag $E $A $Iz <$Iy $G $J>

$secTag	unique section object integer tag
$E	Young's modulus
$A	cross section area
$Iz	second moment of area about the local z-axis
$Iy	second moment of area about the local y-axis (optional, used for 3-D analysis)
$G	shear modulus (optional, used for 3-D analysis)
$J	torsional moment of inertia of section (optional, used for 3-D analysis)

For 2-D elastic sections, the sensitivity parameters can be: **E, A, I.**

For 3-D elastic sections, the sensitivity parameters can be: **E, A, Iz, Iy, G, J.**

Aggregator Command

This command is used to construct a SectionAggregator object which groups previously-defined UniaxialMaterial objects into a single section force-deformation model.

References:

http://opensees.berkeley.edu/OpenSees/manuals/usermanual/index.html

section Aggregator $secTag $matTag1 $string1 $matTag2 $string2 …… <-section $sectionTag>

$secTag	unique section object integer tag
$matTag1, $matTag2 …	previously-defined UniaxialMaterial Objects
$string1, $string2 …	force-deformation relations corresponding to each section object. One of the following strings can be used:

P	axial force-deformation
Mz	moment-curvature about section local z axis
Vy	shear force-deformation along section local y-axis
My	moment-curvature about section local y axis
Vz	shear force-deformation along section local z-axis
T	torsion force-deformation

<-section $sectionTag>	specifies a previously defined Section object (identified by the argument $sectionTag) to which these UniaxialMaterial objects are added to define a new Section object

The 'section Aggregator' command does not introduce additional sensitivity parameters. However, sensitivity parameters can be defined for each force-deformation relation used in the section aggragator.

element commands

Currently, several element types have been extended for DDM-based FE response sensitivity computation.

dispBeamColumnWithSensitivity

This command is used to construct a 2-D or 3-D distributed-plasticity displacement-based beam-column (frame) element.

element dispBeamColumnWithSensitivity $eleTag $iNode $jNode $numIntgrPts $secTag $transfTag <integration method>

$eleTag	unique element object tag
$iNode $jNode	end nodes
$numIntgrPts	number of integration points along the element
$secTag	identifier for previously-defined section object
$transfTag	identifier for previously-defined coordinate-transformation (CrdTransf) object
integration method	optional (available options = ‘Lobatto’ or ‘Legendre’, default = ‘Legendre’)

Currently, there are no sensitivity parameters in the ‘dispBeamColumnWithSensitivity’ element command.

quadWithSensitivity

This command is used to construct a 2D four-node quadrilateral element object based on a bilinear isoparametric formulation.

element quadWithSensitivity $eleTag $iNode $jNode $kNode $lNode $thick $type $matTag <$pressure $rho $b1 $b2>

$eleTag	unique element object tag
$iNode $jnode $kNode $lNode	four nodes defining element boundaries (numbered following a counter-clockwise order around the element)
$thick	element thickness (constant)
$type	string representing material behavior. Valid options depend on the nDMaterial object and the corresponding available material formulations. The ‘type’ parameter can be either "PlaneStrain" or "PlaneStress".
$matTag	tag associated with previously-defined NDMaterial object
$pressure	surface pressure (set temporarily equal to zero for DDM-based sensitivity analysis)
$rho	element mass density (per unit volume) from which a lumped element mass matrix is computed (optional, default=0.0)
$b1 $b2	constant body forces defined in the isoparametric domain (optional, default=0.0)

All parameters are the same as those in the ‘quad’ element command. Currently there are no sensitivity parameters in the ‘quadWithSensitivity’ element command.

bbarBrickWithSensitivity

This command is used to construct an eight-node 3D brick element object based on a trilinear isoparametric formulation.

element bbarBrickWithSensitivity $eleTag $node1 $node2 $node3 $node4 $node5 $node6 $node7 $node8 $matTag

$eleTag	unique element object tag
$node1 - $node8	eight nodes defining element boundaries (numbered as shown in the figure below)
$matTag	tag associated with previously-defined nDMaterial object

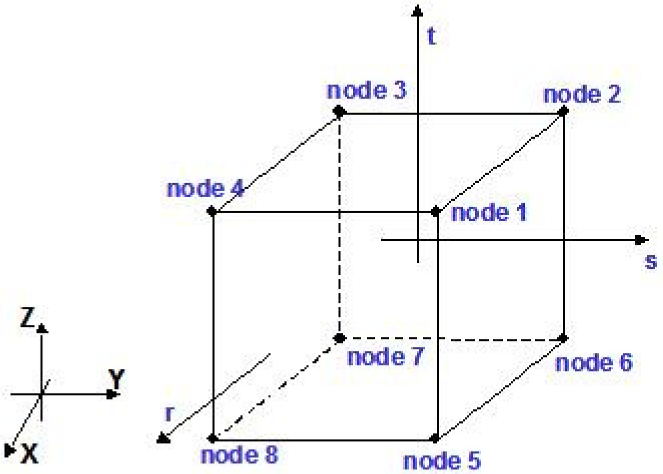

Figure 1.1 Numbering of nodes for the B-bar brick element

Currently, there are no sensitivity parameters in the ‘bbarBrickWithSensitivity’ element command.

constraints commands

Currently, only one constraint handler has been extended for DDM-based FE response sensitivity computation.

Transformation Command

This command is used to construct a multi-point constraint handler based on the transformation equation method.

constraints Transformation

Reference:

Gu Q., Barbato M., Conte J.P. (2009) "Handling of Constraints in Finite Element Response Sensitivity Analysis." *Journal of Engineering Mechanics* (ASCE), 135(12):1427-1438.

CHAPTER 2

Demonstration Examples

In this chapter, four demonstration examples are used to illustrate and validate the DDM-based response sensitivity analysis components implemented in OpenSees.

The results presented in this manual have been obtained by using the official executable version of OpenSees (version 2.2.0), available at http://OpenSees.berkeley.edu. The demonstration examples and the user's manual are available at http://www.cee.lsu.edu/people/mbarbato/Library/OpenSees.aspx.

Example 1: 2D soil column subjected to earthquake base excitation

This example consists of a multi-layered soil column finite element model, with each layer modeled by using the 'MultiYieldSurfaceClay' material with different properties, and subjected to earthquake base excitation. This soil column is representative of the local soil condition at the site of the Humboldt Bay Middle Channel Bridge near Eureka in northern California.

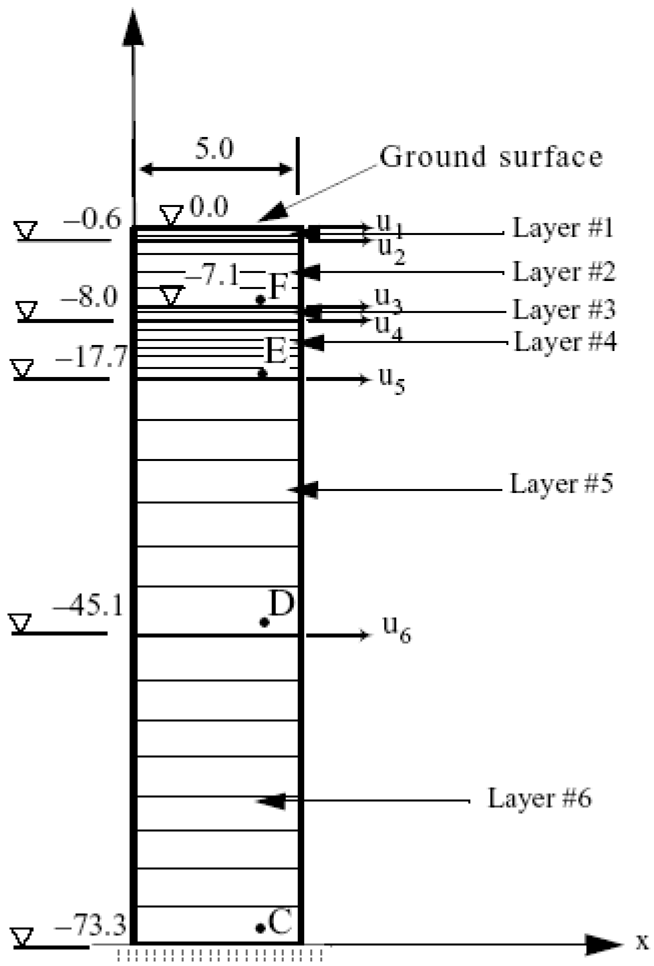

Figure 2.1 Layered soil column subjected to total base acceleration with finite element mesh in thin lines (unit: m)

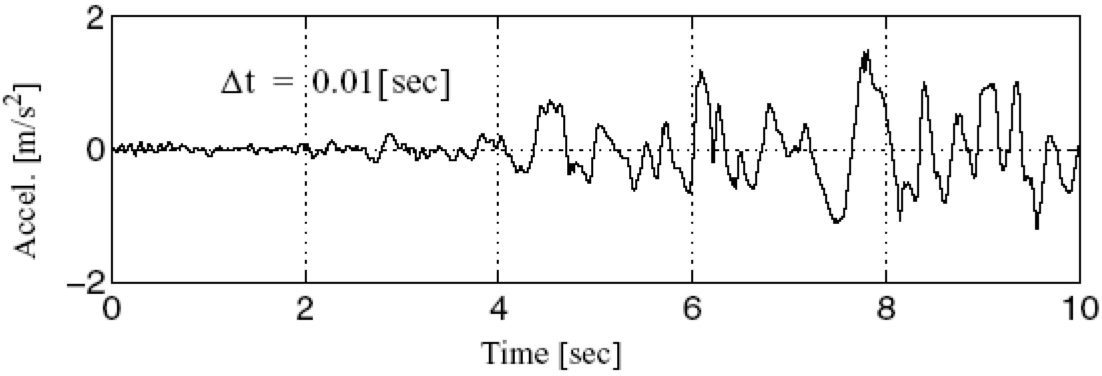

Figure 2.2 Total acceleration time history at the base of the soil column

Material #	G(KPa)	τ_{max}(KPa)
1	54450	33
2	33800	26
3	96800	44
4	61250	35
5	180000	60
6	369800	86

Figure 2.3 Material properties of various layers of soil column (from ground surface to base of soil column)

To run this example, the user needs to run Example1_soil2D.tcl in OpenSees to perform FE response and response sensitivity analysis. To verify the DDM results of the nodal horizontal displacement at node 29 (u_6 in Figure 2.1) with respect to parameter G_1 of the top soil layer (layer #1) using forward finite difference （FFD）analysis, the user needs to run Example1_soil2D_FFD.tcl. Finally, the user needs to run in Matlab Example1_cmp.m to visualize the results.

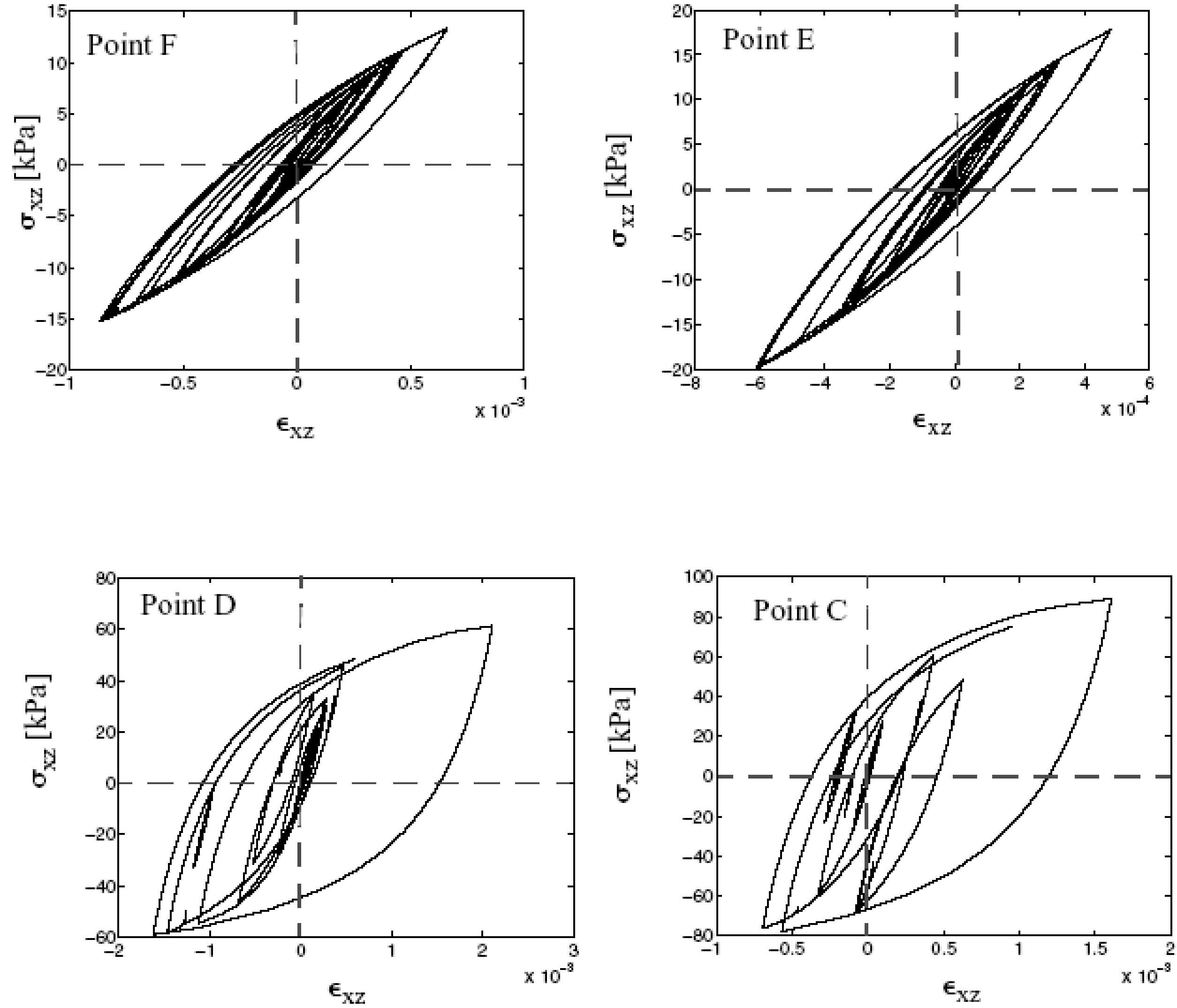

Figure 2.4 Shear stress–strain hysteric responses at Gauss points C, D, E, and F (see Figure 2.1)

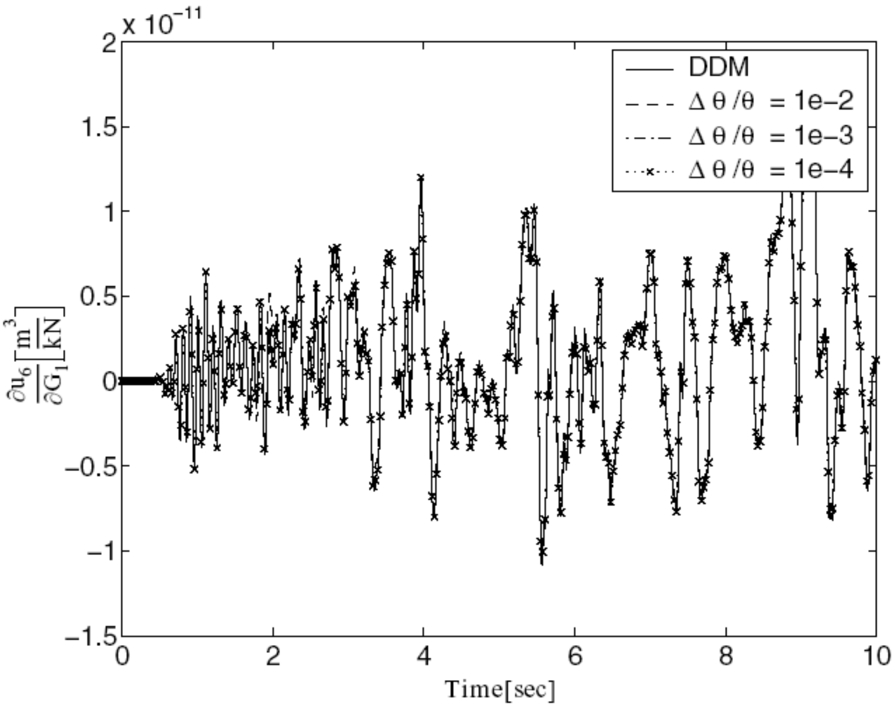

Figure 2.5 Sensitivity of displacement response u_6 (see Figure 2.1) to shear modulus G_1 obtained using DDM and forward finite difference with increasingly small perturbations of sensitivity parameter

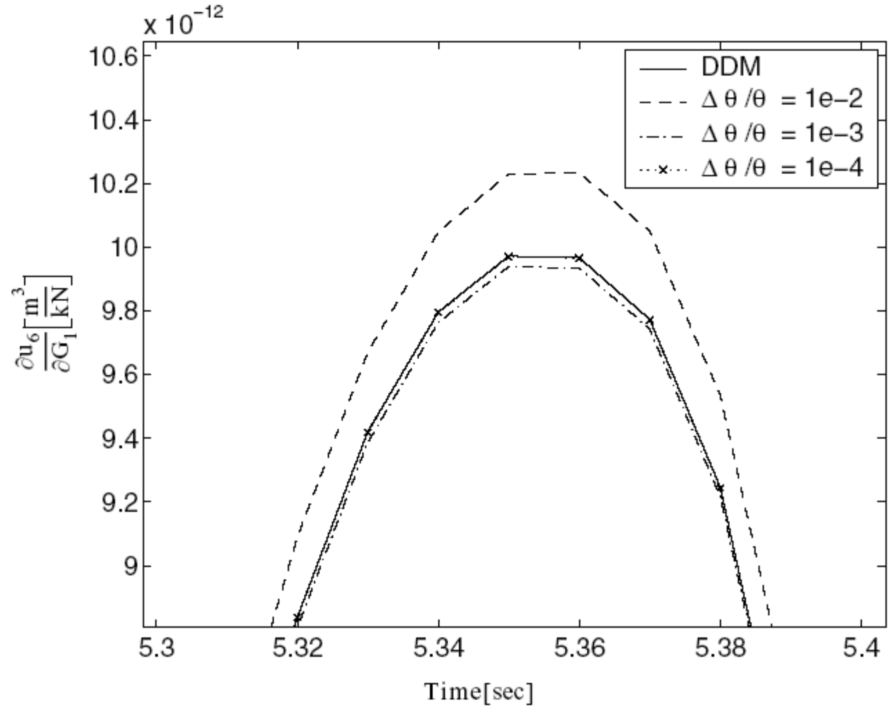

Figure 2.6 Sensitivity of displacement response u_6 to shear modulus G_1 obtained using DDM and forward finite difference with increasingly small perturbations of sensitivity parameter (zoom view)

Reference:

Gu Q., Conte J.P., Elgamal A., Yang Z. (2009) "Response sensitivity analysis of a multi-yield-surface J_2 plasticity model by direct differentiation method." *Computer Methods in Applied Mechanics and Engineering,* 198(30-32):2272-2285.

Example 2: 3D soil block subjected to static push over

In this example, a three-dimensional (3D) cubic block of soil with sides of length 1m is subjected to quasi-static cyclic loading in both horizontal directions simultaneously. The block is discretized into 8 brick elements defined as displacement-based eight-noded, trilinear isoparametric finite elements with eight integration points each. The soil material consists of a medium clay with the following material constitutive parameters: low-strain shear modulus G = $6.0X10^4$ kPa, elastic bulk modulus B = $2.4X10^5$ kPa (Poisson's ratio = 0.38), and maximum shear stress τ_{max} = 30 kPa. The bottom nodes of the finite element (FE) model are fixed and top nodes {A, B, C} and {A, D, E} are subjected to five cycles of harmonic, 90 degrees out-of-phase, concentrated horizontal forces $F_{x1}=2.0\sin(0.2\pi t)$ and $F_{x2}=2.0\sin(0.2\pi t+0.5\pi)$, respectively. The number of yield surfaces is set to 20. A time increment of Δt = 0.01 s is used to integrate the equations of quasi-static equilibrium (i.e., without inertia and damping effects).

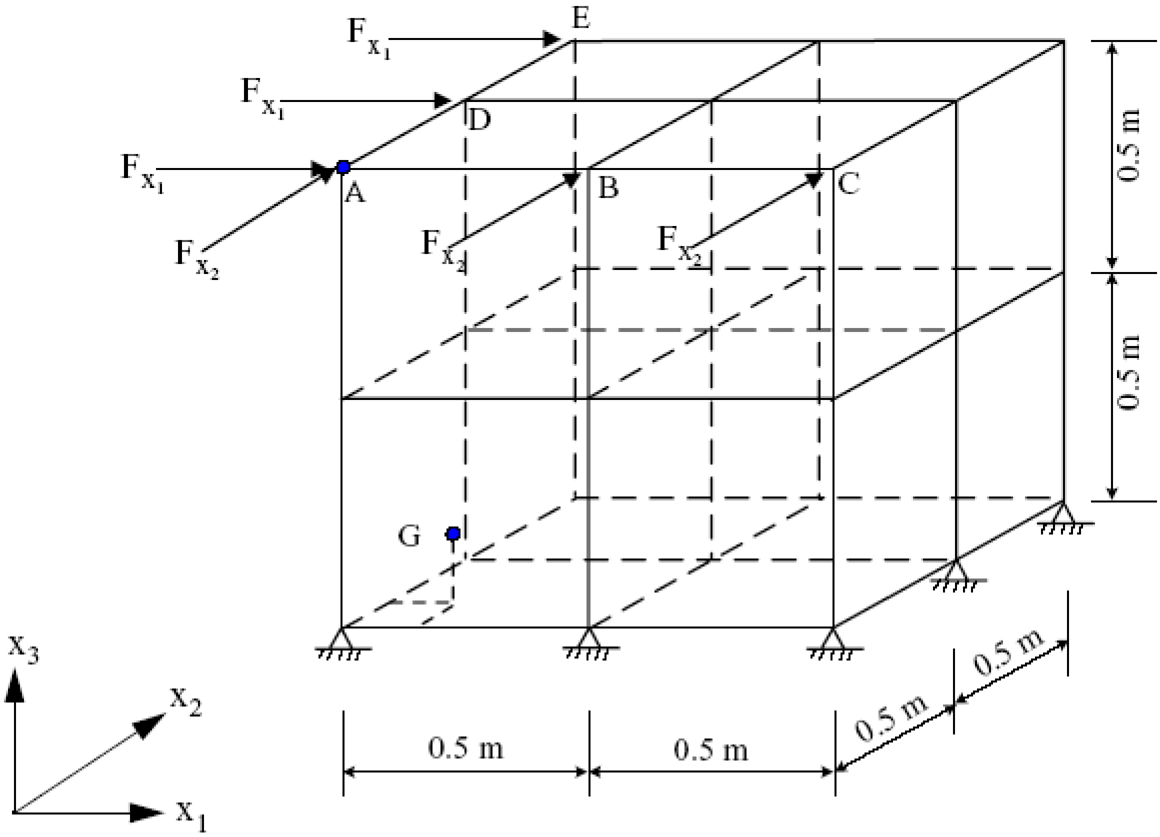

Figure 2.7 Cubic block of clay subjected to horizontal quasi-static cyclic loading under undrained condition

To run this example, the user needs to run Example2_Soil3D.tcl in OpenSees to perform FE response and response sensitivity analysis. To verify the DDM results of the nodal horizontal displacement at node A (see Figure 2.7) with respect to parameter G of the soil material using forward finite difference (FFD) analysis, the user needs to run Example2_Soil3D_FFD.tcl. Finally, the user needs to run in Matlab Example2_cmp.m to visualize the results.

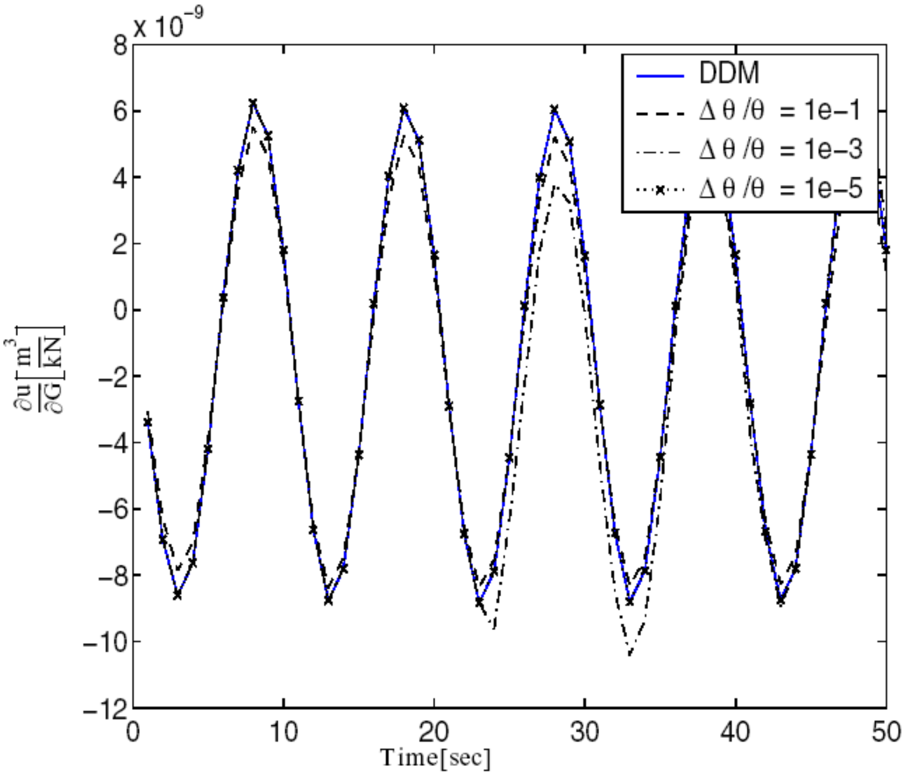

Figure 2.8 Sensitivity of displacement response u(t) of node A in the x_1-direction to the low-strain shear modulus G computed using DDM and forward finite difference

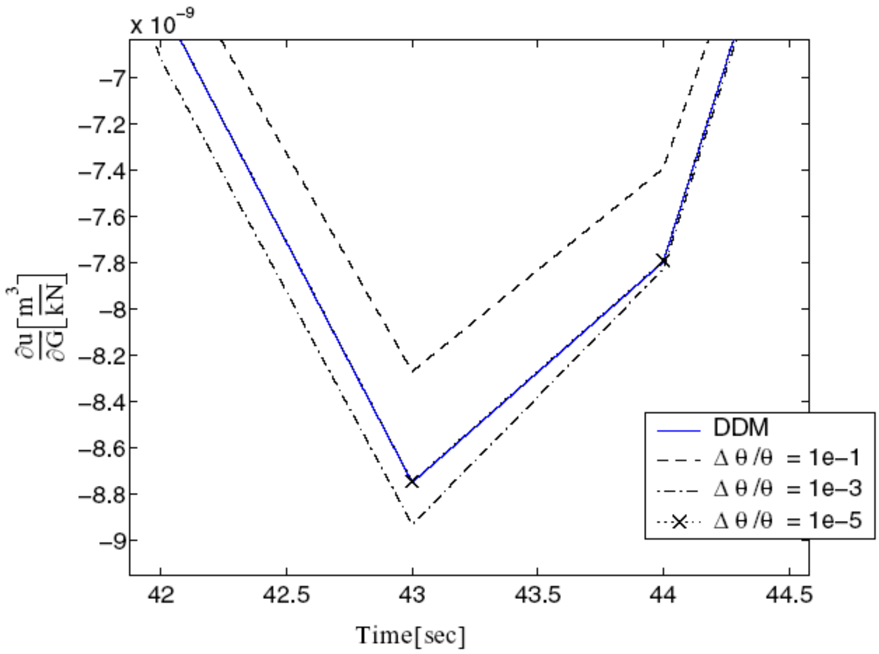

Figure 2.9 Sensitivity of displacement response u(t) of node A in the x_1-direction to the low-strain shear modulus G computed using DDM and forward finite difference (zoom view)

Reference:

Gu Q., Conte J.P., Elgamal A., Yang Z. (2009) "Response sensitivity analysis of a multi-yield-surface J_2 plasticity model by direct differentiation method." *Computer Methods in Applied Mechanics and Engineering,* 198(30-32):2272-2285.

Example 3: 2D RC frame subjected to earthquake base excitation

This application example consists of a two-dimensional two-story two-bay reinforced concrete frame subjected to earthquake base excitation. The frame structure is modeled by using displacement based Euler-Bernoulli frame elements with distributed plasticity, each with five Gauss-Legendre integration points. Section stress resultants at the integration points are computed by discretizing the frame sections by layers. The concrete is modeled by using a uniaxial smoothed Popovics-Saenz concrete material object. Different material parameters are used for confined (core) and unconfined (cover) concrete in the columns (refer to appendix for details on the material parameters). The constitutive behavior of the steel reinforcement is modeled by using a one-dimensional Menegotto-Pinto model. The total horizontal acceleration at the base of the frame is obtained through deconvolution of a ground surface free field motion, and scaled by 10 (PGA = 14.89 m/s^2).

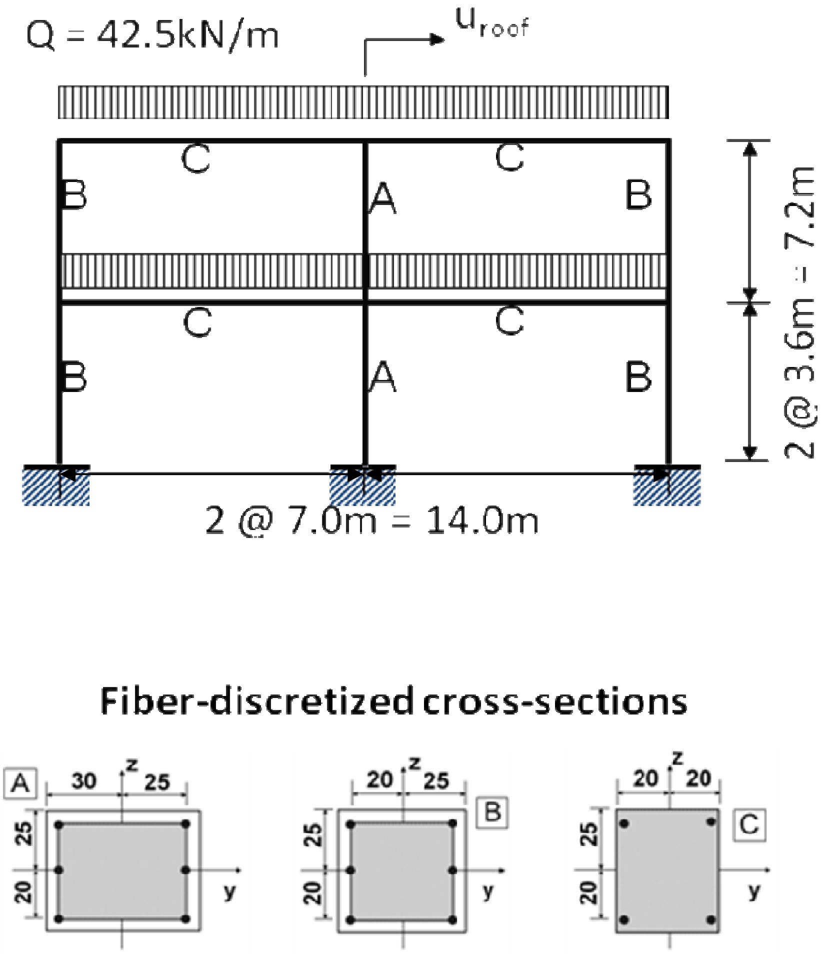

Figure 2.10 Geometry, loading due to gravity and cross-sectional properties for the 2-D two-story two-bay reinforced concrete frame

To run this example, the user needs to run Example3_Frame2D.tcl in OpenSees to perform FE response and response sensitivity analysis. To verify the DDM results using forward finite difference analysis, the user needs to run Example3_Frame2D_FFD.tcl. Finally, the user needs to run in Matlab Example3_cmp.m to visualize the results.

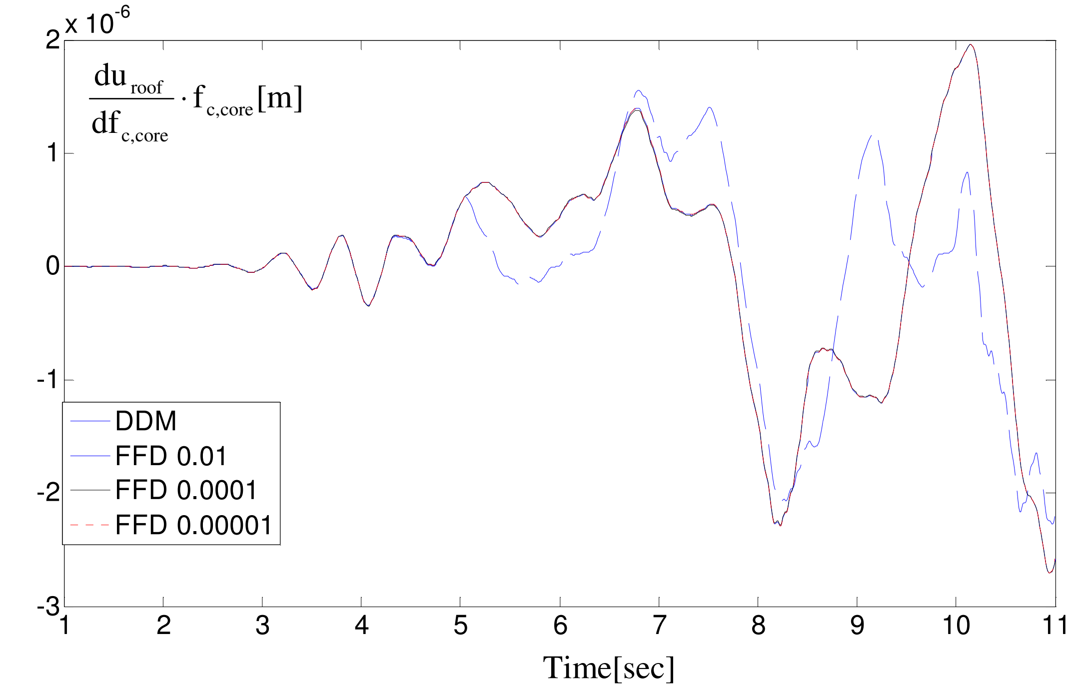

Figure 2.11 Sensitivity of roof horizontal displacement response u_{roof} to the core concrete strength parameter, f_c, computed using DDM and forward finite difference

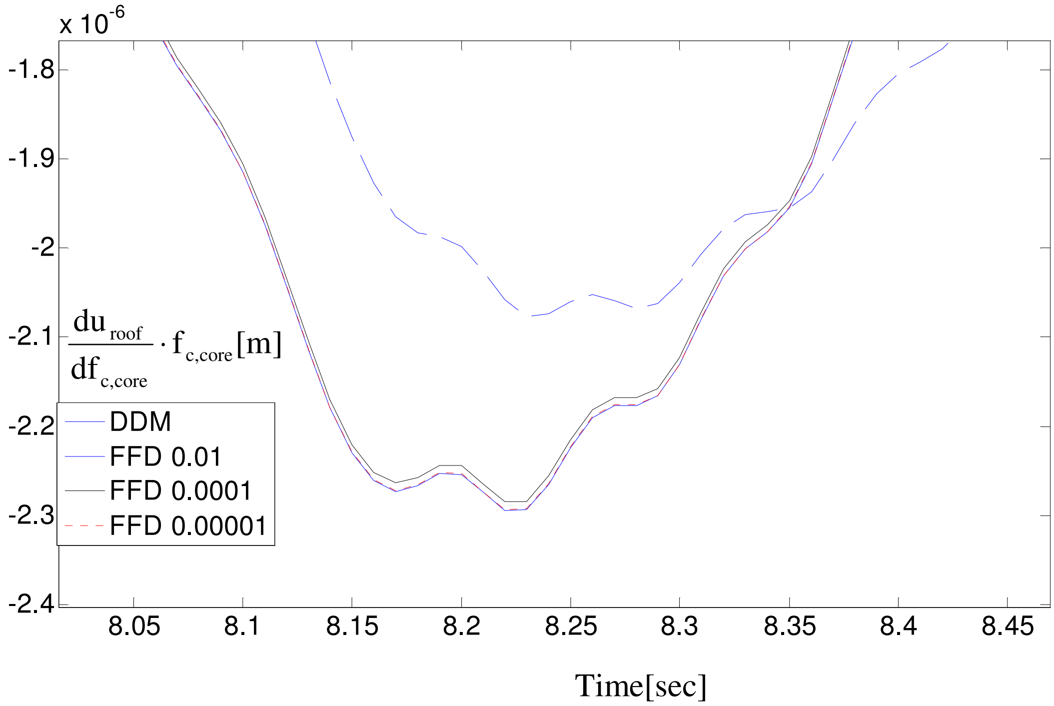

Figure 2.12 Sensitivity of roof horizontal displacement response u_{roof} to the core concrete strength parameter, f_c, computed using DDM and forward finite difference (zoom view)

Example 4: 3-D RC frame subjected to earthquake base excitation

This example is taken as a 3-D three-story reinforced concrete frame structure with rigid diaphragm behavior at each floor, subjected to bidirectional earthquake base excitation with ground acceleration time histories taken as the two horizontal components of the 1978 Tabas earthquake.

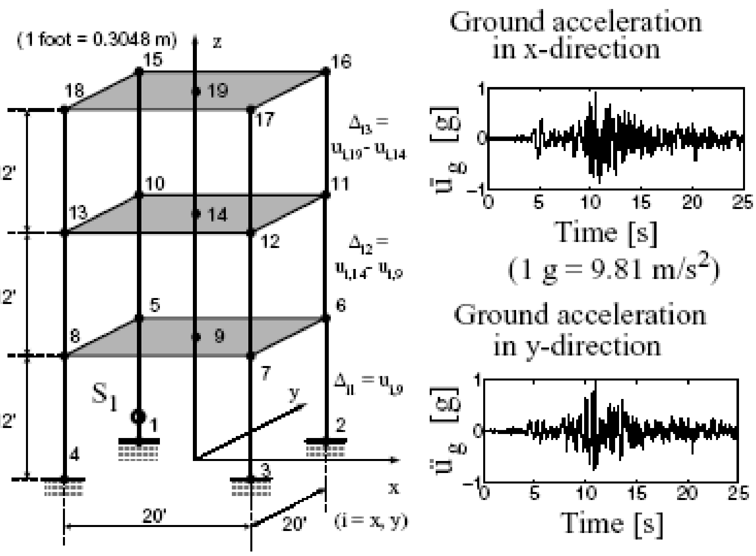

Figure 2.13 3-D one-bay three-story reinforced concrete building: structural model and input ground motion

To run this example, the user needs to run Example4_Frame3D.tcl in OpenSees to perform FE response and response sensitivity analysis. To verify the DDM results using forward finite difference analysis, the user needs to run Example4_Frame3D_FFD.tcl. Finally, the user needs to run in Matlab the file Example4_cmp.m to visualize the results.

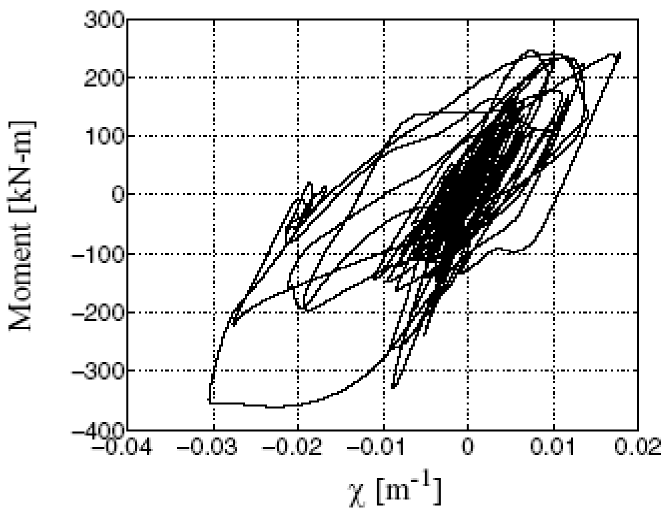

Figure 2.14 Response of 3-D building: moment-curvature hysteretic response about the x-axis at Section 1 (see Figure 2.13)

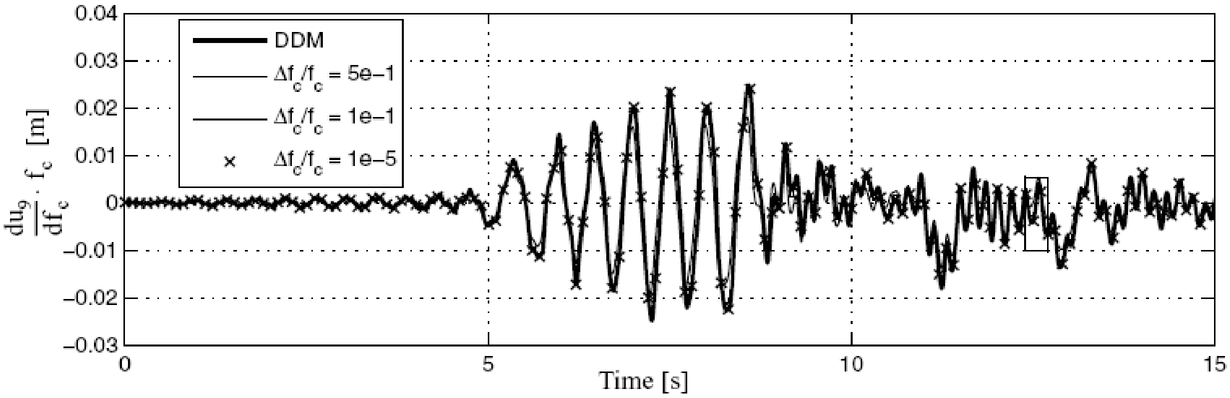

Figure 2.15 Validation of DDM results for 3-D building through forward finite difference analysis: normalized sensitivity of first interstory drift in the x-direction to core concrete strength f_c.

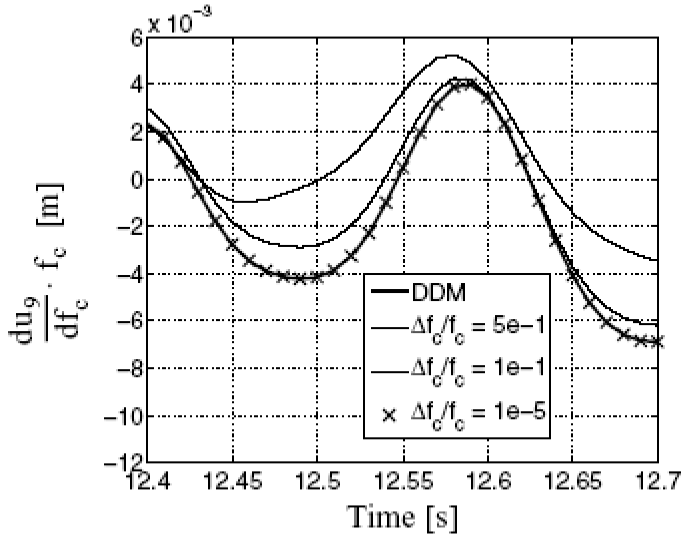

Figure 2.16 Validation of DDM results for 3-D building through forward finite difference analysis: normalized sensitivity of first interstory drift in the x-direction to core concrete strength f_c.(zoom view)

Reference:

Gu Q., Barbato M., Conte J.P. (2009) "Handling of Constraints in Finite Element Response Sensitivity Analysis." *Journal of Engineering Mechanics* (ASCE), 135(12):1427-1438.

CHAPTER 3

Extension of an existing material, cross section, and element for DDM based response sensitivity computation

In this chapter, the necessary functions needed for implementation of the DDM-based response sensitivity computation are listed and explained.

Sensitivity interface at Element Level

The following functions need to be implemented in each element for sensitivity computation:

```
int setParameter(const char **argv, int argc, Parameter &param);
int updateParameter (int parameterID, Information &info);
int activateParameter(int passedParameterID);

const Vector & getResistingForceSensitivity(int gradIndex);
int commitSensitivity(int gradIndex, int numGrads);

const Matrix & getInitialStiffSensitivity(int gradIndex);
const Matrix & getDampSensitivity(int gradIndex);
const Matrix & getMassSensitivity(int gradIndex);
```

Sensitivity interface at Section Level

The following functions need to be implemented in each section for sensitivity computation:

```
int setParameter(const char **argv, int argc, Parameter &param);
int updateParameter (int parameterID, Information &info);
int activateParameter(int passedParameterID);

const Vector& getStressResultantSensitivity(int gradIndex, bool conditional);
const Vector& getSectionDeformationSensitivity(int gradIndex);
const Matrix& getInitialTangentSensitivity(int gradIndex);
int commitSensitivity(const Vector& sectionDeformationGradient,int gradIndex, int numGrads);
```

Sensitivity interface at Material Level

The following functions need to be implemented in each material for sensitivity computation:

```
int setParameter (const char **argv, int argc, Parameter &param);
int updateParameter (int parameterID, Information &info);
int activateParameter (int parameterID);

double getStressSensitivity (int gradIndex, bool conditional);
double getInitialTangentSensitivity (int gradIndex);
int commitSensitivity (double strainGradient, int gradIndex, int numGrads);
double getStrainSensitivity(int gradIndex);
```

Acknowledgement

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Appendix: TCL input files

Example 1:

```
#   unit. meter, K-N, K-Pa,K-Kg

set h G
set g  -9.8
model basic -ndm 2 -ndf 2


#----------------------------------------------------
# Nodes Definition
#----------------------------------------------------

node   1     272.9    -43.426  -mass     0     0
node   2     272.9    -38.728  -mass     0     0
node   3     272.9    -34.031  -mass     0     0
node   4     272.9    -29.334  -mass     0     0
node   5     272.9    -24.636  -mass     0     0
node   6     272.9    -19.939  -mass     0     0
node   7     272.9    -15.242  -mass     0     0
node   8     272.9    -11.813  -mass     0     0
node   9     272.9    -8.3835  -mass     0     0
node   10    272.9    -4.9543  -mass     0     0
node   11    272.9    -1.5252  -mass     0     0
node   12    272.9     1.904  -mass     0     0
node   13    272.9    5.3331  -mass     0     0
node   14    272.9    8.7623  -mass     0     0
node   15    272.9    12.191  -mass     0     0
node   16    272.9    14.096  -mass     0     0
node   17    272.9    16.001  -mass     0     0
node   18    272.9    17.905  -mass     0     0
node   19    272.9     19.81  -mass     0     0
node   20    272.9    20.877  -mass     0     0
node   21    272.9    21.945  -mass     0     0
node   22    272.9    22.402  -mass     0     0
node   23    272.9    22.859  -mass     0     0
node   24    272.9    24.459  -mass     0     0
node   25    272.9    26.059  -mass     0     0
node   26    272.9    27.659  -mass     0     0
node   27    272.9    29.259  -mass     0     0
node   28    272.9    29.602  -mass     0     0
node   29    272.9    29.945  -mass     0     0
node   30    267.27   -43.426  -mass     0     0
node   31    267.27   -38.728  -mass     0     0
node   32    267.27   -34.031  -mass     0     0
node   33    267.27   -29.334  -mass     0     0
node   34    267.27   -24.636  -mass     0     0
node   35    267.27   -19.939  -mass     0     0
node   36    267.27   -15.242  -mass     0     0
node   37    267.27   -11.813  -mass     0     0
node   38    267.27   -8.3835  -mass     0     0
node   39    267.27   -4.9543  -mass     0     0
node   40    267.27   -1.5252  -mass     0     0
node   41    267.27     1.904  -mass     0     0
node   42    267.27    5.3331  -mass     0     0
node   43    267.27    8.7623  -mass     0     0
node   44    267.27    12.191  -mass     0     0
node   45    267.27    14.096  -mass     0     0
node   46    267.27    16.001  -mass     0     0
node   47    267.27    17.905  -mass     0     0
```

```
node    48       267.27       19.81  -mass           0           0
node    49       267.27      20.877  -mass           0           0
node    50       267.27      21.945  -mass           0           0
node    51       267.27      22.402  -mass           0           0
node    52       267.27      22.859  -mass           0           0
node    53       267.27      24.432  -mass           0           0
node    54       267.27      26.012  -mass           0           0
node    55       267.27      27.593  -mass           0           0
node    56       267.27      29.166  -mass           0           0
node    57       267.27      29.497  -mass           0           0
node    58       267.27      29.828  -mass           0           0

#                              massDen    G      B       cohension  PeakShearStrain
nDMaterial MultiYieldSurfaceClay      1 2  0.0      54450        1.6e5     33.         .1
nDMaterial MultiYieldSurfaceClay      2 2  0.0      33800        1.0e5     26.         .1
nDMaterial MultiYieldSurfaceClay      3 2  0.0      96800        2.9e5     44.         .1
nDMaterial MultiYieldSurfaceClay      4 2  0.0      61250        1.8e5     35.         .1
nDMaterial MultiYieldSurfaceClay      5 2  0.0      180000       5.4e5     60.         .1
nDMaterial MultiYieldSurfaceClay      6 2  0.0      369800       1.1e6     86.         .1

#-----------------------------------------------------
# Soil Elememets Definition
#-----------------------------------------------------
#                                       thick    material   Mat  Press  mDensity   gravity

element quadWithSensitivity   1    57  28  29  58 6.0957 "PlaneStrain" 1    0      2.0      0 $g
element quadWithSensitivity   2    56  27  28  57 6.0957 "PlaneStrain" 1    0      2.0      0 $g
element quadWithSensitivity   3    55  26  27  56 6.0957 "PlaneStrain" 2    0      2.0      0 $g
element quadWithSensitivity   4    54  25  26  55 6.0957 "PlaneStrain" 2    0      2.0      0 $g
element quadWithSensitivity   5    53  24  25  54 6.0957 "PlaneStrain" 2    0      2.0      0 $g
element quadWithSensitivity   6    52  23  24  53 6.0957 "PlaneStrain" 2    0      2.0      0 $g
element quadWithSensitivity   7    51  22  23  52 6.0957 "PlaneStrain" 3    0      2.0      0 $g
element quadWithSensitivity   8    50  21  22  51 6.0957 "PlaneStrain" 3    0      2.0      0 $g
element quadWithSensitivity   14   15  16  45  44 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   13   16  17  46  45 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   12   17  18  47  46 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   11   18  19  48  47 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   10   19  20  49  48 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   9    20  21  50  49 6.0957 "PlaneStrain" 4    0      2.0      0 $g
element quadWithSensitivity   15   44  43  14  15 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   16   43  42  13  14 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   17   42  41  12  13 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   18   41  40  11  12 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   19   40  39  10  11 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   20   39  38   9  10 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   21   38  37   8   9 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   22   37  36   7   8 6.0957 "PlaneStrain" 5    0      2.0      0 $g
element quadWithSensitivity   23   36  35   6   7 6.0957 "PlaneStrain" 6    0      2.0      0 $g
element quadWithSensitivity   24   35  34   5   6 6.0957 "PlaneStrain" 6    0      2.0      0 $g
element quadWithSensitivity   25   34  33   4   5 6.0957 "PlaneStrain" 6    0      2.0      0 $g
element quadWithSensitivity   26   33  32   3   4 6.0957 "PlaneStrain" 6    0      2.0      0 $g
element quadWithSensitivity   27   32  31   2   3 6.0957 "PlaneStrain" 6    0      2.0      0 $g
element quadWithSensitivity   28   31  30   1   2 6.0957 "PlaneStrain" 6    0      2.0      0 $g

fix    1   1    1
fix   30   1    1

equalDOF 29 58 1 2
equalDOF 28 57 1 2
equalDOF 27 56 1 2
equalDOF 26 55 1 2
equalDOF 25 54 1 2
equalDOF 24 53 1 2
equalDOF 23 52 1 2
equalDOF 22 51 1 2
equalDOF 21 50 1 2
equalDOF 20 49 1 2
```

```
equalDOF 19 48 1 2
equalDOF 18 47 1 2
equalDOF 17 46 1 2
equalDOF 16 45 1 2
equalDOF 15 44 1 2
equalDOF 14 43 1 2
equalDOF 13 42 1 2
equalDOF 12 41 1 2
equalDOF 11 40 1 2
equalDOF 10 39 1 2
equalDOF  9 38 1 2
equalDOF  8 37 1 2
equalDOF  7 36 1 2
equalDOF  6 35 1 2
equalDOF  5 34 1 2
equalDOF  4 33 1 2
equalDOF  3 32 1 2
equalDOF  2 31 1 2

# ------------------------- add sensitivity ------------------------
reliability

set h G

# --- G1 ---
parameter         1 -element 1 -material $h
addToParameter    1 -element 2 -material $h

# --- G2 ---
parameter      2 -element 3 -material $h
addToParameter 2 -element 4 -material $h
addToParameter 2 -element 5 -material $h
addToParameter 2 -element 6 -material $h

# --- G3 ---
parameter      3 -element 7 -material $h
addToParameter 3 -element 8 -material $h

# --- G4 ---

parameter      4 -element  9 -material $h
addToParameter 4 -element 10 -material $h
addToParameter 4 -element 11 -material $h
addToParameter 4 -element 12 -material $h
addToParameter 4 -element 13 -material $h
addToParameter 4 -element 14 -material $h

# --- G5 -----
parameter      5 -element 15 -material $h
addToParameter 5 -element 16 -material $h
addToParameter 5 -element 17 -material $h
addToParameter 5 -element 18 -material $h
addToParameter 5 -element 19 -material $h
addToParameter 5 -element 20 -material $h
addToParameter 5 -element 21 -material $h
addToParameter 5 -element 22 -material $h

# ---- G6 -----
parameter      6 -element 23 -material $h
addToParameter 6 -element 24 -material $h
addToParameter 6 -element 25 -material $h
addToParameter 6 -element 26 -material $h
addToParameter 6 -element 27 -material $h
addToParameter 6 -element 28 -material $h

# -----
set h cohesion
```

```
# ---- h7 --------
parameter      7 -element 1 -material $h
addToParameter 7 -element 2 -material $h

# ---- h8 --------
parameter      8 -element 3 -material $h
addToParameter 8 -element 4 -material $h
addToParameter 8 -element 5 -material $h
addToParameter 8 -element 6 -material $h

# ---- h9 --------
parameter      9 -element 7 -material $h
addToParameter 9 -element 8 -material $h

# ---- h10 --------
parameter      10 -element  9 -material $h
addToParameter 10 -element 10 -material $h
addToParameter 10 -element 11 -material $h
addToParameter 10 -element 12 -material $h
addToParameter 10 -element 13 -material $h
addToParameter 10 -element 14 -material $h

# ---- h11 --------
parameter      11 -element 15 -material $h
addToParameter 11 -element 16 -material $h
addToParameter 11 -element 17 -material $h
addToParameter 11 -element 18 -material $h
addToParameter 11 -element 19 -material $h
addToParameter 11 -element 20 -material $h
addToParameter 11 -element 21 -material $h
addToParameter 11 -element 22 -material $h

# ---- h12 --------
parameter      12 -element 23 -material $h
addToParameter 12 -element 24 -material $h
addToParameter 12 -element 25 -material $h
addToParameter 12 -element 26 -material $h
addToParameter 12 -element 27 -material $h
addToParameter 12 -element 28 -material $h



# -----
set h K

# ------ k13 --------
parameter      13 -element 1 -material $h
addToParameter 13 -element 2 -material $h

# ------ k14 --------
parameter      14 -element 3 -material $h
addToParameter 14 -element 4 -material $h
addToParameter 14 -element 5 -material $h
addToParameter 14 -element 6 -material $h

# ------ k15 --------
parameter      15 -element 7 -material $h
addToParameter 15 -element 8 -material $h

# ------ k16 --------
parameter      16 -element  9 -material $h
addToParameter 16 -element 10 -material $h
addToParameter 16 -element 11 -material $h
addToParameter 16 -element 12 -material $h
addToParameter 16 -element 13 -material $h
addToParameter 16 -element 14 -material $h
```

```
# ------ k17 --------
parameter      17 -element 15 -material $h
addToParameter 17 -element 16 -material $h
addToParameter 17 -element 17 -material $h
addToParameter 17 -element 18 -material $h
addToParameter 17 -element 19 -material $h
addToParameter 17 -element 20 -material $h
addToParameter 17 -element 21 -material $h
addToParameter 17 -element 22 -material $h

# ------ k18 --------
parameter      18 -element 23 -material $h
addToParameter 18 -element 24 -material $h
addToParameter 18 -element 25 -material $h
addToParameter 18 -element 26 -material $h
addToParameter 18 -element 27 -material $h
addToParameter 18 -element 28 -material $h



# ------------------------ recorder ----------------------------------
recorder Node -file disp29.out  -time -node 29  -precision 16  -dof 1 disp
recorder Node -file disp27.out  -time -node 27  -dof 1 disp
recorder Node -file disp23.out  -time -node 23  -dof 1 disp
recorder Node -file disp21.out  -time -node 21  -dof 1 disp
recorder Node -file disp15.out  -time -node 15  -dof 1 disp
recorder Node -file  disp7.out  -time -node  7  -dof 1 disp

recorder Node -file ddm29G1.out  -time -node 29  -dof 1 -precision 16 "sensitivity 1"
recorder Node -file ddm27G1.out  -time -node 27  -dof 1 "sensitivity 1"
recorder Node -file ddm23G1.out  -time -node 23  -dof 1 "sensitivity 1"
recorder Node -file ddm21G1.out  -time -node 21  -dof 1 "sensitivity 1"
recorder Node -file ddm15G1.out  -time -node 15  -dof 1 "sensitivity 1"
recorder Node -file ddm7G1.out   -time -node  7  -dof 1 "sensitivity 1"

recorder Node -file ddm29G2.out  -time -node 29  -dof 1 "sensitivity 2"
recorder Node -file ddm27G2.out  -time -node 27  -dof 1 "sensitivity 2"
recorder Node -file ddm23G2.out  -time -node 23  -dof 1 "sensitivity 2"
recorder Node -file ddm21G2.out  -time -node 21  -dof 1 "sensitivity 2"
recorder Node -file ddm15G2.out  -time -node 15  -dof 1 "sensitivity 2"
recorder Node -file  ddm7G2.out  -time -node  7  -dof 1 "sensitivity 2"

recorder Node -file ddm29G3.out  -time -node 29  -dof 1 "sensitivity 3"
recorder Node -file ddm27G3.out  -time -node 27  -dof 1 "sensitivity 3"
recorder Node -file ddm23G3.out  -time -node 23  -dof 1 "sensitivity 3"
recorder Node -file ddm21G3.out  -time -node 21  -dof 1 "sensitivity 3"
recorder Node -file ddm15G3.out  -time -node 15  -dof 1 "sensitivity 3"
recorder Node -file  ddm7G3.out  -time -node  7  -dof 1 "sensitivity 3"

recorder Node -file ddm29G4.out  -time -node 29  -dof 1 "sensitivity 4"
recorder Node -file ddm27G4.out  -time -node 27  -dof 1 "sensitivity 4"
recorder Node -file ddm23G4.out  -time -node 23  -dof 1 "sensitivity 4"
recorder Node -file ddm21G4.out  -time -node 21  -dof 1 "sensitivity 4"
recorder Node -file ddm15G4.out  -time -node 15  -dof 1 "sensitivity 4"
recorder Node -file  ddm7G4.out  -time -node  7  -dof 1 "sensitivity 4"

recorder Node -file ddm29G5.out  -time -node 29  -dof 1 "sensitivity 5"
recorder Node -file ddm27G5.out  -time -node 27  -dof 1 "sensitivity 5"
recorder Node -file ddm23G5.out  -time -node 23  -dof 1 "sensitivity 5"
recorder Node -file ddm21G5.out  -time -node 21  -dof 1 "sensitivity 5"
recorder Node -file ddm15G5.out  -time -node 15  -dof 1 "sensitivity 5"
recorder Node -file  ddm7G5.out  -time -node  7  -dof 1 "sensitivity 5"

recorder Node -file ddm29G6.out  -time -node 29  -dof 1 "sensitivity 6"
recorder Node -file ddm27G6.out  -time -node 27  -dof 1 "sensitivity 6"
recorder Node -file ddm23G6.out  -time -node 23  -dof 1 "sensitivity 6"
```

```
recorder Node -file ddm21G6.out  -time -node 21  -dof 1 "sensitivity 6"
recorder Node -file ddm15G6.out  -time -node 15  -dof 1 "sensitivity 6"
recorder Node -file  ddm7G6.out  -time -node  7  -dof 1 "sensitivity 6"

##
recorder Node -file ddm29t1.out  -time -node 29  -dof 1 "sensitivity 7"
recorder Node -file ddm27t1.out  -time -node 27  -dof 1 "sensitivity 7"
recorder Node -file ddm23t1.out  -time -node 23  -dof 1 "sensitivity 7"
recorder Node -file ddm21t1.out  -time -node 21  -dof 1 "sensitivity 7"
recorder Node -file ddm15t1.out  -time -node 15  -dof 1 "sensitivity 7"
recorder Node -file  ddm7t1.out  -time -node  7  -dof 1 "sensitivity 7"

recorder Node -file ddm29t2.out  -time -node 29  -dof 1 "sensitivity 8"
recorder Node -file ddm27t2.out  -time -node 27  -dof 1 "sensitivity 8"
recorder Node -file ddm23t2.out  -time -node 23  -dof 1 "sensitivity 8"
recorder Node -file ddm21t2.out  -time -node 21  -dof 1 "sensitivity 8"
recorder Node -file ddm15t2.out  -time -node 15  -dof 1 "sensitivity 8"
recorder Node -file  ddm7t2.out  -time -node  7  -dof 1 "sensitivity 8"

recorder Node -file ddm29t3.out  -time -node 29  -dof 1 "sensitivity 9"
recorder Node -file ddm27t3.out  -time -node 27  -dof 1 "sensitivity 9"
recorder Node -file ddm23t3.out  -time -node 23  -dof 1 "sensitivity 9"
recorder Node -file ddm21t3.out  -time -node 21  -dof 1 "sensitivity 9"
recorder Node -file ddm15t3.out  -time -node 15  -dof 1 "sensitivity 9"
recorder Node -file  ddm7t3.out  -time -node  7  -dof 1 "sensitivity 9"

recorder Node -file ddm29t4.out  -time -node 29  -dof 1 "sensitivity 10"
recorder Node -file ddm27t4.out  -time -node 27  -dof 1 "sensitivity 10"
recorder Node -file ddm23t4.out  -time -node 23  -dof 1 "sensitivity 10"
recorder Node -file ddm21t4.out  -time -node 21  -dof 1 "sensitivity 10"
recorder Node -file ddm15t4.out  -time -node 15  -dof 1 "sensitivity 10"
recorder Node -file  ddm7t4.out  -time -node  7  -dof 1 "sensitivity 10"

recorder Node -file ddm29t5.out  -time -node 29  -dof 1 "sensitivity 11"
recorder Node -file ddm27t5.out  -time -node 27  -dof 1 "sensitivity 11"
recorder Node -file ddm23t5.out  -time -node 23  -dof 1 "sensitivity 11"
recorder Node -file ddm21t5.out  -time -node 21  -dof 1 "sensitivity 11"
recorder Node -file ddm15t5.out  -time -node 15  -dof 1 "sensitivity 11"
recorder Node -file  ddm7t5.out  -time -node  7  -dof 1 "sensitivity 11"

recorder Node -file ddm29t6.out  -time -node 29  -dof 1 "sensitivity 12"
recorder Node -file ddm27t6.out  -time -node 27  -dof 1 "sensitivity 12"
recorder Node -file ddm23t6.out  -time -node 23  -dof 1 "sensitivity 12"
recorder Node -file ddm21t6.out  -time -node 21  -dof 1 "sensitivity 12"
recorder Node -file ddm15t6.out  -time -node 15  -dof 1 "sensitivity 12"
recorder Node -file  ddm7t6.out  -time -node  7  -dof 1 "sensitivity 12"

# ----
recorder Node -file  ddm29k1.out  -time -node  29  -dof 1 "sensitivity 13"
recorder Node -file  ddm29k2.out  -time -node  29  -dof 1 "sensitivity 14"
recorder Node -file  ddm29k3.out  -time -node  29  -dof 1 "sensitivity 15"
recorder Node -file  ddm29k4.out  -time -node  29  -dof 1 "sensitivity 16"
recorder Node -file  ddm29k5.out  -time -node  29  -dof 1 "sensitivity 17"
recorder Node -file  ddm29k6.out  -time -node  29  -dof 1 "sensitivity 18"

#-----
recorder Element -element 1 -time -file stress1.out material 1 stress -dT 0.01
recorder Element -element 1 -time -file strain1.out material 1 strain -dT 0.01
recorder Element -element 15 -time -file stress15.out material 1 stress -dT 0.01
recorder Element -element 15 -time -file strain15.out material 1 strain -dT 0.01
recorder Element -element 22 -time -file stress22.out material 1 stress -dT 0.01
recorder Element -element 22 -time -file strain22.out material 1 strain -dT 0.01
recorder Element -element 28 -time -file stress28.out material 1 stress -dT 0.01
recorder Element -element 28 -time -file strain28.out material 1 strain -dT 0.01


#-------------------------------------------------------
```

```
# Soil Gravity Analysis Model Definition
#-------------------------------------------------------
system BandGeneral
test NormDispIncr 1.E-12 50 2
constraints Transformation
integrator LoadControl 1 1 1 1
algorithm Newton
numberer RCM

# ---------------- add sensitivity ---------------------
sensitivityIntegrator -static
sensitivityAlgorithm -computeAtEachStep

analysis Static
analyze 1

puts "soil gravity nonlinear analysis completed ..."

wipeAnalysis

constraints Transformation
test NormDispIncr 1.E-12 50  2
algorithm Newton
numberer RCM
system BandGeneral

integrator NewmarkWithSensitivity  0.55 0.2756
sensitivityIntegrator -definedAbove
sensitivityAlgorithm -computeAtEachStep
analysis Transient

pattern UniformExcitation    1     1    -accel "Series -factor 1 -filePath acce.txt -dt 0.01"

set startT [clock seconds]
analyze 1000 0.01
set endT [clock seconds]
puts "Execution time: [expr $endT-$startT] seconds."
```

Example 2:

```
#   unit. meter, K-N, K-Pa,K-Kg
#create the ModelBuilder

model BasicBuilder -ndm 3 -ndf 3
reliability

#                              massDen     G         B              cohension  peakshear
nDMaterial MultiYieldSurfaceClay      2 3   1.5      60000.0    240000.            30.0      0.1

#        create meshes
node       1      0.00000     0.0000    0.00000
node       2      0.00000     0.0000    0.5000
node       3      0.00000     0.0000    1.000000
node       4      0.00000     0.5000    0.00000
node       5      0.00000     0.5000    0.5000
node       6      0.00000     0.5000    1.000000
node       7      0.00000     1.00000    0.00000
node       8      0.00000     1.00000    0.5000
node       9      0.00000     1.00000   1.000000
node       10     0.5000     0.0000    0.00000
node       11     0.5000     0.0000    0.5000
node       12     0.5000     0.0000    1.000000
node       13     0.5000     0.5000    0.00000
node       14     0.5000     0.5000    0.5000
node       15     0.5000     0.5000    1.000000
node       16     0.5000     1.00000    0.00000
node       17     0.5000     1.00000    0.5000
node       18     0.5000     1.00000   1.000000
node       19     1.000000    0.0000    0.00000
node       20     1.000000    0.0000    0.5000
node       21     1.000000    0.0000    1.000000
node       22     1.000000    0.5000    0.00000
node       23     1.000000    0.5000    0.5000
node       24     1.000000    0.5000    1.000000
node       25     1.000000    1.00000    0.00000
node       26     1.000000    1.00000    0.50000
node       27     1.000000    1.00000   1.000000

#                          ele    Node                        mat
element bbarBrickWithSensitivity    1     1    10   13   4    2   11    14   5   2
element bbarBrickWithSensitivity    2     2    11   14   5    3   12    15   6   2
element bbarBrickWithSensitivity    3    10    19   22  13   11   20    23  14   2
element bbarBrickWithSensitivity    4    11    20   23  14   12   21    24  15   2
element bbarBrickWithSensitivity    5     4    13   16   7    5   14    17   8   2
element bbarBrickWithSensitivity    6    13    22   25  16   14   23    26  17   2
element bbarBrickWithSensitivity    7    14    23   26  17   15   24    27  18   2
element bbarBrickWithSensitivity    8     5    14   17   8    6   15    18   9   2

fix     1     1     1     1   0   0   0
fix     4     1     1     1   0   0   0
fix     7     1     1     1   0   0   0
fix    10     1     1     1   0   0   0
fix    13     1     1     1   0   0   0
fix    16     1     1     1   0   0   0
fix    19     1     1     1   0   0   0
fix    22     1     1     1   0   0   0
fix    25     1     1     1   0   0   0

# -------- define random variable ---------------------------------

set h G
parameter         1 -element 1 -material $h
addToParameter    1 -element 2 -material $h
```

```
addToParameter    1 -element 3 -material $h
addToParameter    1 -element 4 -material $h
addToParameter    1 -element 5 -material $h
addToParameter    1 -element 6 -material $h
addToParameter    1 -element 7 -material $h
addToParameter    1 -element 8 -material $h

 set h cohesion
parameter         2 -element 1 -material $h
addToParameter    2 -element 2 -material $h
addToParameter    2 -element 3 -material $h
addToParameter    2 -element 4 -material $h
addToParameter    2 -element 5 -material $h
addToParameter    2 -element 6 -material $h
addToParameter    2 -element 7 -material $h
addToParameter    2 -element 8 -material $h

set h K
parameter         3 -element 1 -material $h
addToParameter    3 -element 2 -material $h
addToParameter    3 -element 3 -material $h
addToParameter    3 -element 4 -material $h
addToParameter    3 -element 5 -material $h
addToParameter    3 -element 6 -material $h
addToParameter    3 -element 7 -material $h
addToParameter    3 -element 8 -material $h

# -------------- recorder -----------------------------------------------
recorder Node -file ddm3G.out  -time -node 3 -dof 1 2 3 -precision 16 "sensitivity 1"
recorder Node -file ddm3cohesion.out  -time -node 3 -dof 1 2 3 "sensitivity 2"
recorder Node -file ddm3k.out  -time -node 3 -dof 1 2 3 "sensitivity 3"
recorder Node -file disp3.out  -time -node 3 -dof 1 2 3 -precision 16 disp
recorder Element -ele 1 -time -file stress.out material 2 stress
recorder Element -ele 1 -time -file strain.out material 2 strain

pattern Plain 1 "Sine 0.0 1000.0 10.0 -factor 0.8 " {
load  3    2.5    0.0   0
load  6    2.5    0.0   0
load  9    2.5    0.0   0
}

pattern Plain 2 "Sine 0.0 1000.0 10.0  -shift 1.5708 -factor 0.8" {
load  3     0.0    2.5   0
load  12    0.0    2.5   0
load  21    0.0    2.5   0
}

system BandGeneral
test NormDispIncr 1.E-12 50 2
constraints Transformation
integrator LoadControl 1 1 1 1
algorithm Newton
numberer RCM

sensitivityIntegrator -static
sensitivityAlgorithm -computeAtEachStep

analysis Static

set startT [clock seconds]
analyze 50
set endT [clock seconds]
puts "Execution time: [expr $endT-$startT] seconds."
```

Example 3:

```
#   unit. meter, K-N, K-Pa,K-Kg ver 2.0

model BasicBuilder -ndm 2 -ndf 3
reliability
# ------------------- DEFINE beam NODES  ---------------------------------

set framemass1 15.0
set framemass2 30.0
set framemass3  4.0

#    tag  X     Y
node  1   0     0    -mass $framemass1 $framemass1 0.0
node  2   0    3.6   -mass $framemass1 $framemass1 0.0
node  3   0    7.2   -mass $framemass1 $framemass1 0.0
node  4  7.0   0.0   -mass $framemass2 $framemass2 0.0
node  5  7.0   3.6   -mass $framemass2 $framemass2 0.0
node  6  7.0   7.2   -mass $framemass2 $framemass2 0.0
node  7 14.0   0.0   -mass $framemass1 $framemass1 0.0
node  8 14.0   3.6   -mass $framemass1 $framemass1 0.0
node  9 14.0   7.2   -mass $framemass1 $framemass1 0.0

fix 1 1 1 1
fix 4 1 1 1
fix 7 1 1 1

# ------------------- weight load -------------------------------
set framemass1 15.0
set framemass2 30.0

set upperload1 [expr -$framemass1*10.0]
set upperload2 [expr -$framemass2*10.0]

pattern Plain 1 "Constant"  {
load 1 0.0 $upperload1 0
load 2 0.0 $upperload1 0
load 3 0.0 $upperload1 0
load 4 0.0 $upperload2 0
load 5 0.0 $upperload2 0
load 6 0.0 $upperload2 0
load 7 0.0 $upperload1 0
load 8 0.0 $upperload1 0
load 9 0.0 $upperload1 0

}

# --------------------------- DEFINE MATERIALS ---------------------------
# --------------------------- UPPERGROUND FRAMES -------------------------

# Cover concrete            tag     -f'c      -epsco      -f'cu     -epscu
#uniaxialMaterial Concrete01  1     -27588.5   -0.002        0.0    -0.008
#                                    fc     fu         Ec          eps0     epsu     eta
uniaxialMaterial    SmoothPSConcrete     1   27579.04  1000.0   2.4910e7      0.002    0.012    0.2


# Core concrete             tag     -f'c      -epsco      -f'cu     -epscu
#uniaxialMaterial Concrete01  2     -34485.6    -0.004      -20691.4  -0.014
#                                     fc      fu        Ec          eps0     epsu     eta
uniaxialMaterial    SmoothPSConcrete     2    34473.8   25723.0   2.7851e7      0.005    0.02     0.2

#  b=Hkin/(E+Hkin)=0.008
# Steel model              tag      E        fy         Hiso      Hkin
#uniaxialMaterial Hardening   3     2.0e8   248200.      0.0      1.6129e6
```

```
uniaxialMaterial SteelMP  3  248200.  2.1e8    0.02

# -----------------------------------------------------------------------------


# --------------------------- DEFINE SECTIONS ----------------------------
# --------------------------- UPPERGROUND FRAMES -------------------------
# Interior column section

section fiberSec 1 {
  #         mat nfIJ nfJK   yI     zI      yJ      zJ      yK      zK       yL     zL
  patch quadr  2    1   12 -0.2500  0.2000 -0.2500 -0.2000  0.2500 -0.2000  0.2500  0.2000
  patch quadr  1    1   14 -0.3000 -0.2000 -0.3000 -0.2500  0.3000 -0.2500  0.3000 -0.2000
  patch quadr  1    1   14 -0.3000  0.2500 -0.3000  0.2000  0.3000  0.2000  0.3000  0.2500
  patch quadr  1    1    2 -0.3000  0.2000 -0.3000 -0.2000 -0.2500 -0.2000 -0.2500  0.2000
  patch quadr  1    1    2  0.2500  0.2000  0.2500 -0.2000  0.3000 -0.2000  0.3000  0.2000

  #            mat nBars   area     yI         zI        yF       zF
  layer straight  3    3   0.000645 -0.2000   0.2000    -0.2000   -0.2000
  layer straight  3    3   0.000645  0.2000   0.2000     0.2000   -0.2000
}
#   steel:  Ag/As = 6*0.000645/(0.6*0.5) =1.29%

# Exterior column section
section fiberSec 2 {
  #         mat nfIJ nfJK   yI       zI      yJ      zJ      yK      zK      yL     zL
  patch quadr 2   1   10    -0.2000  0.2000 -0.2000 -0.2000  0.2000 -0.2000  0.2000  0.2000
  patch quadr 1   1   12    -0.2500 -0.2000 -0.2500 -0.2500  0.2500 -0.2500  0.2500 -0.2000
  patch quadr 1   1   12    -0.2500  0.2500 -0.2500  0.2000  0.2500  0.2000  0.2500  0.2500
  patch quadr 1   1    2    -0.2500  0.2000 -0.2500 -0.2000 -0.2000 -0.2000 -0.2000  0.2000
  patch quadr 1   1    2     0.2000  0.2000  0.2000 -0.2000  0.2500 -0.2000  0.2500  0.2000

  #            mat nBars area       yI     zI      yF      zF
  layer straight 3    3   0.00051   -0.2000 0.2000 -0.2000 -0.2000
  layer straight 3    3   0.00051    0.2000 0.2000  0.2000 -0.2000
}
#   steel:  Ag/As = 6*0.000510/(0.5*0.5) =1.22%

# Girder section
section fiberSec 3 {
  #         mat nfIJ nfJK   yI         zI        yJ       zJ        yK        zK        yL        zL
  patch quadr 1  1     12   -0.2500     0.2000     -0.2500  -0.2000    0.2500   -0.2000    0.2500    0.2000

  #            mat nBars area       yI      zI         yF        zF
  layer straight 3    2    0.000645 -0.2000   0.2000    -0.2000   -0.2000
  layer straight 3    2    0.000645  0.2000   0.2000     0.2000   -0.2000
}
#   steel:  Ag/As = 4*0.000645/(0.4*0.4) =1.6%

# -----------------------------------------------------------------------------

# NUMBER OF INTEGRATION POINTS
set nP 5

# GEOMETRIC TRANSFORMATION
geomTransf Linear 1

# ----------------- DEFINE DISPLACEMENT BEAM-COLUMN ELEMENT ---------------------
# --------------------------- UPPERGROUND FRAMES -------------------------

# Columns                            tag ndI ndJ  nPts secID transf
element dispBeamColumnWithSensitivity  1   1   2    $nP   2      1
element dispBeamColumnWithSensitivity  2   2   3    $nP   2      1
element dispBeamColumnWithSensitivity  3   4   5    $nP   1      1
element dispBeamColumnWithSensitivity  4   5   6    $nP   1      1
element dispBeamColumnWithSensitivity  5   7   8    $nP   2      1
element dispBeamColumnWithSensitivity  6   8   9    $nP   2      1
```

```
# Beams
element dispBeamColumnWithSensitivity  7   2   5    $nP   3     1
element dispBeamColumnWithSensitivity  8   5   8    $nP   3     1
element dispBeamColumnWithSensitivity  9   3   6    $nP   3     1
element dispBeamColumnWithSensitivity 10   6   9    $nP   3     1

# ============= SENSITIVITY ANALYSIS MODEL =================

#-----------------------------------------------------------------
#                                                   |
#    Upper structural sensitivity                              |
#                                                   |
# -----------------1: Core  fc  ------------------------------

set h fc
set gradNumber 1

parameter      $gradNumber   -element 1    -section 2 -material 2 $h
addToParameter $gradNumber   -element 2    -section 2 -material 2 $h
addToParameter $gradNumber   -element 3    -section 1 -material 2 $h
addToParameter $gradNumber   -element 4    -section 1 -material 2 $h
addToParameter $gradNumber   -element 5    -section 2 -material 2 $h
addToParameter $gradNumber   -element 6    -section 2 -material 2 $h

## -----------------2: Core  fcu  ------------------------------

set h fcu
set gradNumber 2

parameter      $gradNumber   -element 1    -section 2 -material 2 $h
addToParameter $gradNumber   -element 2    -section 2 -material 2 $h
addToParameter $gradNumber   -element 3    -section 1 -material 2 $h
addToParameter $gradNumber   -element 4    -section 1 -material 2 $h
addToParameter $gradNumber   -element 5    -section 2 -material 2 $h
addToParameter $gradNumber   -element 6    -section 2 -material 2 $h

#-------------------- 3: Core epsco -----------------------

set h epsco
set gradNumber 3

parameter      $gradNumber   -element 1    -section 2 -material 2 $h
addToParameter $gradNumber   -element 2    -section 2 -material 2 $h
addToParameter $gradNumber   -element 3    -section 1 -material 2 $h
addToParameter $gradNumber   -element 4    -section 1 -material 2 $h
addToParameter $gradNumber   -element 5    -section 2 -material 2 $h
addToParameter $gradNumber   -element 6    -section 2 -material 2 $h

# -----------------4: Core epscu ---------------------

set h epscu
set gradNumber 4


parameter      $gradNumber   -element 1    -section 2 -material 2 $h
addToParameter $gradNumber   -element 2    -section 2 -material 2 $h
addToParameter $gradNumber   -element 3    -section 1 -material 2 $h
addToParameter $gradNumber   -element 4    -section 1 -material 2 $h
addToParameter $gradNumber   -element 5    -section 2 -material 2 $h
addToParameter $gradNumber   -element 6    -section 2 -material 2 $h


# -----------------5: Core  Ec  ------------------------------


set h Ec
```

```
set gradNumber 5


parameter      $gradNumber   -element 1    -section 2 -material 2 $h
addToParameter $gradNumber   -element 2    -section 2 -material 2 $h
addToParameter $gradNumber   -element 3    -section 1 -material 2 $h
addToParameter $gradNumber   -element 4    -section 1 -material 2 $h
addToParameter $gradNumber   -element 5    -section 2 -material 2 $h
addToParameter $gradNumber   -element 6    -section 2 -material 2 $h


# -----------------6: Steel E  ------------------------------

set h E
set gradNumber 6


parameter      $gradNumber   -element 1    -section 2 -material 3 $h
addToParameter $gradNumber   -element 2    -section 2 -material 3 $h
addToParameter $gradNumber   -element 3    -section 1 -material 3 $h
addToParameter $gradNumber   -element 4    -section 1 -material 3 $h
addToParameter $gradNumber   -element 5    -section 2 -material 3 $h
addToParameter $gradNumber   -element 6    -section 2 -material 3 $h
addToParameter $gradNumber   -element 7    -section 3 -material 3 $h
addToParameter $gradNumber   -element 8    -section 3 -material 3 $h
addToParameter $gradNumber   -element 9    -section 3 -material 3 $h
addToParameter $gradNumber   -element 10   -section 3 -material 3 $h

#-------------------- 7: Upper structural sigmaY ----------------------

set h sigmaY
set gradNumber 7

parameter      $gradNumber   -element 1    -section 2 -material 3 $h
addToParameter $gradNumber   -element 2    -section 2 -material 3 $h
addToParameter $gradNumber   -element 3    -section 1 -material 3 $h
addToParameter $gradNumber   -element 4    -section 1 -material 3 $h
addToParameter $gradNumber   -element 5    -section 2 -material 3 $h
addToParameter $gradNumber   -element 6    -section 2 -material 3 $h
addToParameter $gradNumber   -element 7    -section 3 -material 3 $h
addToParameter $gradNumber   -element 8    -section 3 -material 3 $h
addToParameter $gradNumber   -element 9    -section 3 -material 3 $h
addToParameter $gradNumber   -element 10   -section 3 -material 3 $h

#-------------------- 8: Upper structural b ----------------------

set h b
set gradNumber 8

parameter      $gradNumber   -element 1    -section 2 -material 3 $h
addToParameter $gradNumber   -element 2    -section 2 -material 3 $h
addToParameter $gradNumber   -element 3    -section 1 -material 3 $h
addToParameter $gradNumber   -element 4    -section 1 -material 3 $h
addToParameter $gradNumber   -element 5    -section 2 -material 3 $h
addToParameter $gradNumber   -element 6    -section 2 -material 3 $h
addToParameter $gradNumber   -element 7    -section 3 -material 3 $h
addToParameter $gradNumber   -element 8    -section 3 -material 3 $h
addToParameter $gradNumber   -element 9    -section 3 -material 3 $h
addToParameter $gradNumber   -element 10   -section 3 -material 3 $h


recorder Node -file node.out -time -node 6 -dof  1 2 -precision 16  disp
recorder Node -file node_sens1.out -time -node 6 -dof  1 "sensitivity 1"
recorder Node -file node_sens2.out -time -node 6 -dof  1 "sensitivity 2"
recorder Node -file node_sens3.out -time -node 6 -dof  1 "sensitivity 3"
recorder Node -file node_sens4.out -time -node 6 -dof  1 "sensitivity 4"
recorder Node -file node_sens5.out -time -node 6 -dof  1 "sensitivity 5"
```

```
recorder Node -file node_sens6.out -time -node 6 -dof  1 "sensitivity 6"
recorder Node -file node_sens7.out -time -node 6 -dof  1 "sensitivity 7"
recorder Node -file node_sens8.out -time -node 6 -dof  1 "sensitivity 8"

constraints Transformation
numberer RCM
#test NormUnbalance 1.0e-6 25 0
test NormDispIncr 1.0e-9  50
integrator LoadControl 1 1 1  1
algorithm Newton
system BandGeneral
sensitivityIntegrator -static
sensitivityAlgorithm -computeAtEachStep
analysis Static




analyze 1

puts "soil gravity nonlinear analysis completed ..."

wipeAnalysis

constraints Transformation
test NormDispIncr 1.E-12 50  2
algorithm Newton
numberer RCM
system BandGeneral

integrator NewmarkWithSensitivity  0.55 0.2756
sensitivityIntegrator -definedAbove
sensitivityAlgorithm -computeAtEachStep
analysis Transient

pattern UniformExcitation    2     1    -accel "Series -factor 1 -filePath acce.txt -factor 10 -dt 0.01"

set startT [clock seconds]
analyze 1000 0.01
set endT [clock seconds]
puts "Execution time: [expr $endT-$startT] seconds."
```

Example 4:

```
#  Unit: kN k-kg, kPa, m, sec.

model BasicBuilder -ndm 3 -ndf 6
reliability
set h 3.6576;       # Story height
set by 6.096;      # Bay width in Y-direction
set bx 6.096;      # Bay width in X-direction

#    tag           X           Y          Z
node  1  [expr -$bx/2] [expr  $by/2]         0
node  2  [expr  $bx/2] [expr  $by/2]         0
node  3  [expr  $bx/2] [expr -$by/2]         0
node  4  [expr -$bx/2] [expr -$by/2]         0
node  5  [expr -$bx/2] [expr  $by/2]        $h
node  6  [expr  $bx/2] [expr  $by/2]        $h
node  7  [expr  $bx/2] [expr -$by/2]        $h
node  8  [expr -$bx/2] [expr -$by/2]        $h
node 10  [expr -$bx/2] [expr  $by/2] [expr 2*$h]
node 11  [expr  $bx/2] [expr  $by/2] [expr 2*$h]
node 12  [expr  $bx/2] [expr -$by/2] [expr 2*$h]
node 13  [expr -$bx/2] [expr -$by/2] [expr 2*$h]
node 15  [expr -$bx/2] [expr  $by/2] [expr 3*$h]
node 16  [expr  $bx/2] [expr  $by/2] [expr 3*$h]
node 17  [expr  $bx/2] [expr -$by/2] [expr 3*$h]
node 18  [expr -$bx/2] [expr -$by/2] [expr 3*$h]

# ----------------- Master nodes for rigid diaphragm ---------
#    tag X Y          Z
node  9  0 0        $h
node 14  0 0 [expr 2*$h]
node 19  0 0 [expr 3*$h]

# ----------------- Set base constraints --------------------
#   tag DX DY DZ RX RY RZ
fix  1   1  1  1  1  1  1
fix  2   1  1  1  1  1  1
fix  3   1  1  1  1  1  1
fix  4   1  1  1  1  1  1

# --------------- Define rigid diaphragm multi-point constraints --

#              normalDir  master     slaves
rigidDiaphragm     3         9      5  6  7  8
rigidDiaphragm     3        14      10 11 12 13
rigidDiaphragm     3        19      15 16 17 18

# -------------- Constraints for rigid diaphragm master nodes ------
#   tag DX DY DZ RX RY RZ
fix  9   0  0  1  1  1  0
fix 14   0  0  1  1  1  0
fix 19   0  0  1  1  1  0

# ------------- Define materials for nonlinear columns ------------

#--- --------- Core concrete (confined) -------------------
#                         tag    f'c     epsc0   f'cu       epscu
uniaxialMaterial Concrete01  1  -34473.8  -0.005   -24131.66  -0.02

# ------------ Cover concrete (unconfined) ---------------
set fc 27579.04
uniaxialMaterial Concrete01  2   -$fc -0.002    0.0 -0.006

# ------------- Reinforcing steel ------------------------
```

```
#                      tag   fy      E        b
uniaxialMaterial Steel01  3  248200.  2.1e8    0.02


# Column width
set d 0.4572
source RCsection.tcl
#        id  h  b  coverThick    coreID  coverID steelID nBars  area       nfCoreY nfCoreZ nfCoverY nfCoverZ
RCsection  1 $d $d   0.04          1      2        3       3   0.00051       8       8       10       10

# Concrete elastic stiffness
# set E [expr 57000.0*sqrt($fc*1000)/1000]; American unit
set E 24855585.89304;

# ---Column torsional stiffness
 set GJ 68947600000000;
# ---Linear elastic torsion for the column
 uniaxialMaterial Elastic 10 $GJ
# ---Attach torsion to the RC column section
#               tag uniTag uniCode       secTag
section Aggregator 2    10      T    -section 1
set colSec 2

# -------------- Define column elements -----------------------

geomTransf Linear  1   1 0 0

# Number of column integration points (sections)
set np 4
# Create the nonlinear column elements
#                          tag ndI ndJ nPts   secID  transf
element dispBeamColumnWithSensitivity  1   1   5   $np  $colSec    1
element dispBeamColumnWithSensitivity  2   2   6   $np  $colSec    1
element dispBeamColumnWithSensitivity  3   3   7   $np  $colSec    1
element dispBeamColumnWithSensitivity  4   4   8   $np  $colSec    1
element dispBeamColumnWithSensitivity  5   5  10   $np  $colSec    1
element dispBeamColumnWithSensitivity  6   6  11   $np  $colSec    1
element dispBeamColumnWithSensitivity  7   7  12   $np  $colSec    1
element dispBeamColumnWithSensitivity  8   8  13   $np  $colSec    1
element dispBeamColumnWithSensitivity  9  10  15   $np  $colSec    1
element dispBeamColumnWithSensitivity  10 11  16   $np  $colSec    1
element dispBeamColumnWithSensitivity  11 12  17   $np  $colSec    1
element dispBeamColumnWithSensitivity  12 13  18   $np  $colSec    1

# ------------ Define beam elements ------------
# Define material properties for elastic beams
# Using beam depth of 24 and width of 18
# --------------------------------------------
set Abeam 0.278709

# "Cracked" second moments of area
set Ibeamzz 0.004315;
set Ibeamyy 0.002427;
# Define elastic section for beams
#              tag  E    A      Iz       Iy     G    J
section Elastic  3  $E $Abeam $Ibeamzz $Ibeamyy $GJ   1.0
set beamSec 3

# Geometric transformation for beams
#               tag  vecxz

geomTransf Linear 2   1 1 0

set np 3
# ---------- Create the beam elements----------------
#                      tag ndI ndJ nPts    secID   transf
element dispBeamColumnWithSensitivity  13  5   6   $np  $beamSec     2    Legendre
```

```
element dispBeamColumnWithSensitivity  14  6   7   $np  $beamSec    2   Legendre
element dispBeamColumnWithSensitivity  15  7   8   $np  $beamSec    2   Legendre
element dispBeamColumnWithSensitivity  16  8   5   $np  $beamSec    2   Legendre
element dispBeamColumnWithSensitivity  17 10  11   $np  $beamSec    2   Legendre
element dispBeamColumnWithSensitivity  18 11  12   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  19 12  13   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  20 13  10   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  21 15  16   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  22 16  17   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  23 17  18   $np  $beamSec    2          Legendre
element dispBeamColumnWithSensitivity  24 18  15   $np  $beamSec    2          Legendre

# --------------- Define gravity loads ----------------
# Gravity load applied at each corner node
# 10% of column capacity

set p  74.0

# --------------- Mass lumped at master nodes ---------
set g 9.8;           # Gravitational constant
set m 30.0;

# Rotary inertia of floor about master node
set i [expr $m*($bx*$bx+$by*$by)/12.0]
# Set mass at the master nodes
#    tag MX MY MZ RX RY RZ
mass  9  $m $m  0  0  0 $i
mass 14  $m $m  0  0  0 $i
mass 19  $m $m  0  0  0 $i
# Define gravity loads
#pattern Plain 1 Constant {
pattern Plain 1 {Series -time {0.0 2.0 100000.0} -values {0.0 1.0 1.0} } {
   foreach node {5 6 7 8  10 11 12 13  15 16 17 18} {
      load $node 0.0 0.0 -$p 0.0 0.0 0.0
   }
}

#------------------------------------------------------------------------------------
#                              CORE CONCRETE
#
# -------------------- R.V.#1 Core concrete epsco---------------------------------------
set h epsco
set gradNumber 1

parameter      $gradNumber   -element 1   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 1 $h


recorder Node -file ddmCore9epsco.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 1"
recorder Node -file ddmCore14epsco.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 1"
recorder Node -file ddmCore19epsco.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 1"

# ----------------------------- R.V.#2 Core concrete fc-----------------------------
set h fc
set gradNumber 2

parameter      $gradNumber   -element 1   -section 2 -section  -material 1 $h
```

```
addToParameter $gradNumber   -element 2   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 1 $h


recorder Node -file ddmCore9fc.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 2"
recorder Node -file ddmCore14fc.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 2"
recorder Node -file ddmCore19fc.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 2"

# ------------------------------ R.V.#3 Core concrete epscu------------------------
set h epscu
set gradNumber 3

parameter      $gradNumber   -element 1   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 1 $h

recorder Node -file ddmCore9epscu.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 3"
recorder Node -file ddmCore14epscu.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 3"
recorder Node -file ddmCore19epscu.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 3"


# ------------------------------ R.V.#4 Core concrete fcu----------------------------
set h fcu
set gradNumber 4

parameter      $gradNumber   -element 1   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 1 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 1 $h

recorder Node -file ddmCore9fcu.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 4"
recorder Node -file ddmCore14fcu.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 4"
recorder Node -file ddmCore19fcu.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 4"


#--------------------------------------------------------------------------------
#                              COVER CONCRETE
#
# ------------------------------ R.V.#5 Cover concrete epsco------------------------
set h epsco
set gradNumber 5
```

```
parameter      $gradNumber   -element 1   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 2 $h

recorder Node -file ddmCover9epsco.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 5"
recorder Node -file ddmCover14epsco.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 5"
recorder Node -file ddmCover19epsco.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 5"

# ------------------------------ R.V.#6 Cover concrete fc---------------------------
set h fc
set gradNumber 6

parameter      $gradNumber   -element 1   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 2 $h

recorder Node -file ddmCover9fc.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 6"
recorder Node -file ddmCover14fc.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 6"
recorder Node -file ddmCover19fc.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 6"

# ------------------------------ R.V.#7 Cover concrete epscu---------------------
set h epscu
set gradNumber 7


parameter      $gradNumber   -element 1   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 2 $h

recorder Node -file ddmCover9epscu.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 7"
recorder Node -file ddmCover14epscu.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 7"
recorder Node -file ddmCover19epscu.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 7"

# ------------------------------ R.V.#8 Cover concrete fcu--------------------------
set h fcu
set gradNumber 8

parameter      $gradNumber   -element 1   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 2 $h
```

```
addToParameter $gradNumber   -element 3   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 2 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 2 $h

recorder Node -file ddmCover9fcu.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 8"
recorder Node -file ddmCover14fcu.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 8"
recorder Node -file ddmCover19fcu.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 8"

#----------------------------------------------------------------------------------------------
#                              STEEL SENSITIVITY
#
# ------------------------------ R.V.#9 steel fy ---------------------------------------------
set h sigmaY
set gradNumber 9

parameter      $gradNumber   -element 1   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 3 $h

recorder Node -file ddmSteel9fy.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 9"
recorder Node -file ddmSteel14fy.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 9"
recorder Node -file ddmSteel19fy.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 9"

# ------------------------------ R.V.#10 steel E ---------------------------------------------
set h E
set gradNumber 10

parameter      $gradNumber   -element 1   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 4   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 3 $h

recorder Node -file ddmSteel9E.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 10"
recorder Node -file ddmSteel14E.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 10"
recorder Node -file ddmSteel19E.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 10"

# ------------------------------ R.V.#11 steel b ---------------------------------------------
set h b
set gradNumber 11

parameter      $gradNumber   -element 1   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 2   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 3   -section 2 -section  -material 3 $h
```

```
addToParameter $gradNumber   -element 4   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 5   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 6   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 7   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 8   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 9   -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 10  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 11  -section 2 -section  -material 3 $h
addToParameter $gradNumber   -element 12  -section 2 -section  -material 3 $h

recorder Node -file ddmSteel9b.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 11"
recorder Node -file ddmSteel14b.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 11"
recorder Node -file ddmSteel19b.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 11"

# ------------------------------ R.V.#12 column GJ ---------------------------------------------
set h E
set gradNumber 12

parameter      $gradNumber   -element 1   -section 2   $h
addToParameter $gradNumber   -element 2   -section 2   $h
addToParameter $gradNumber   -element 3   -section 2   $h
addToParameter $gradNumber   -element 4   -section 2   $h
addToParameter $gradNumber   -element 5   -section 2   $h
addToParameter $gradNumber   -element 6   -section 2   $h
addToParameter $gradNumber   -element 7   -section 2   $h
addToParameter $gradNumber   -element 8   -section 2   $h
addToParameter $gradNumber   -element 9   -section 2   $h
addToParameter $gradNumber   -element 10  -section 2   $h
addToParameter $gradNumber   -element 11  -section 2   $h
addToParameter $gradNumber   -element 12  -section 2   $h


recorder Node -file ddm9GJ.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 12"
recorder Node -file ddm14GJ.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 12"
recorder Node -file ddm19GJ.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 12"


#------------------------------------------------------------------------------------------
#
#                          ELASTIC BEAM
#
#------------------------------------------------------------------------------------------

# ------------------------------ R.V.#13 Beam E ---------------------------------------------
set h E
set gradNumber 13

parameter      $gradNumber  -element 13  -section 3  $h
addToParameter $gradNumber  -element 14  -section 3  $h
addToParameter $gradNumber  -element 15  -section 3  $h
addToParameter $gradNumber  -element 16  -section 3  $h
addToParameter $gradNumber  -element 17  -section 3  $h
addToParameter $gradNumber  -element 18  -section 3  $h
addToParameter $gradNumber  -element 19  -section 3  $h
addToParameter $gradNumber  -element 20  -section 3  $h
addToParameter $gradNumber  -element 21  -section 3  $h
addToParameter $gradNumber  -element 22  -section 3  $h
addToParameter $gradNumber  -element 23  -section 3  $h
addToParameter $gradNumber  -element 24  -section 3  $h


recorder Node -file ddm9BeamE.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 13"
recorder Node -file ddm14BeamE.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 13"
recorder Node -file ddm19BeamE.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 13"


# ------------------------------ R.V.#14 Beam G ---------------------------------------------
```

```
set h G
set gradNumber 14

parameter      $gradNumber  -element 13  -section 3  $h
addToParameter $gradNumber  -element 14  -section 3  $h
addToParameter $gradNumber  -element 15  -section 3  $h
addToParameter $gradNumber  -element 16  -section 3  $h
addToParameter $gradNumber  -element 17  -section 3  $h
addToParameter $gradNumber  -element 18  -section 3  $h
addToParameter $gradNumber  -element 19  -section 3  $h
addToParameter $gradNumber  -element 20  -section 3  $h
addToParameter $gradNumber  -element 21  -section 3  $h
addToParameter $gradNumber  -element 22  -section 3  $h
addToParameter $gradNumber  -element 23  -section 3  $h
addToParameter $gradNumber  -element 24  -section 3  $h

recorder Node -file ddm9BeamG.out  -time -node  9 -dof 1 2 3 4 5 6 "sensitivity 14"
recorder Node -file ddm14BeamG.out -time -node 14 -dof 1 2 3 4 5 6 "sensitivity 14"
recorder Node -file ddm19BeamG.out -time -node 19 -dof 1 2 3 4 5 6 "sensitivity 14"

# ---------------------- Define earthquake excitation ------------
# Set up the acceleration records for Tabas fault normal and fault parallel
set tabasFN "Path -filePath tabasFN.txt -dt 0.02 -factor $g"
set tabasFP "Path -filePath tabasFP.txt -dt 0.02 -factor $g"

#                         tag dir         accel series args
pattern UniformExcitation  2   1  -accel      $tabasFN
pattern UniformExcitation  3   2  -accel      $tabasFP

recorder Node -file node.out -time -node 9 14 19 -dof 1 2 3 4 5 6 -precision 16 disp

# ------------------------- add static analysis ------------------------
constraints Transformation
#                tol   maxIter  printFlag
test EnergyIncr 1.0e-16   20         2
integrator LoadControl 1 1 1 1
algorithm Newton
system BandGeneral
numberer RCM

sensitivityIntegrator -static
sensitivityAlgorithm -computeAtEachStep

analysis Static

set startT [clock seconds]
analyze 3
puts "soil gravity nonlinear analysis completed ..."

# ------------------------- add analysis ------------------------
wipeAnalysis

#                tol   maxIter  printFlag
test EnergyIncr 1.0e-16   20         2
algorithm Newton
system BandGeneral
constraints Transformation
#integrator Newmark   0.5  0.25
numberer RCM

integrator NewmarkWithSensitivity  0.55 0.275625
# (0.55+0.5)^2/4=0.275625
sensitivityIntegrator -definedAbove
sensitivityAlgorithm -computeAtEachStep

analysis Transient
analyze   2500   0.01
```

```
set endT [clock seconds]
puts "Execution time: [expr $endT-$startT] seconds."
```