Modeling Steel Moment Resisting Frames with OpenSees

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Agenda

✧ Nonlinear Modeling of Steel MRFs
  ✧ Steel Components for Nonlinear Modeling
✧ Distributed and Concentrated Plasticity
  ✧ Nonlinear Force-Based Elements
  ✧ Zero Length Elements (Concentrated Plasticity)
✧ Background on Available Steel Materials in OpenSees
✧ Examples and Applications
✧ Summary Remarks
Steel Components for Nonlinear Modeling in MRFs

(Images courtesy of Prof. M. Engelhardt)
Steel Components for Nonlinear Modeling in MRFs

Image courtesy of Prof. M. Engelhardt
Steel Components for Nonlinear Modeling in MRFs
-Beam Plastic Hinging

Local buckling of Beams with RBS

Lateral torsional buckling of Beams with RBS

(Images courtesy of Prof. M. Engelhardt)
Steel Components for Nonlinear Modeling in MRFs
-Panel Zone Shear Yielding

(Image courtesy of Prof. M. Engelhardt)
Steel Components for Nonlinear Modeling in MRFs
-Column Plastic Hinging

(Image from Suzuki and Lignos 2014)
Simulation Approach

(a) Plastic hinge
(b) Nonlinear spring hinge
(c) Finite length hinge zone
(d) Fiber section
(e) Finite element

Concentrated plasticity
Distributed plasticity

Image Source: NIST GSR 10-917-5
Concentrated Plasticity Models

**Advantages**
- Fairly simple
- Effective for interface effects
- Computationally efficient

**Disadvantages**
- Require the moment – rotation relationship (as opposed to engineering stress-strain)
- They don’t capture P-M interaction (critical for columns)

*Image Source: NIST GSR 10-917-5*
Distributed Plasticity Models

**Advantages**
- Force- and displacement-based element permits spread of plasticity along the element
- P-M interaction can be captured

**Disadvantages**
- Localization
- Requires fiber section discretization (# fibers matters)
- Deteriorating phenomena (local buckling) difficult to capture with available engineering stress-strain models in OpenSees

*Image Source: NIST GSR 10-917-5*
例: 今天演示的内容

- 4-story building with perimeter steel special moment frames (SMFs)
- Design location Bulk Center Los Angeles, CA
- Design provisions: ASCE 7-10, AISC 2010
- Fully-Restrained Beam-to-Column connections with Reduced Beam Sections (RBS) – See AISC-358-10 or FEMA-350
- First mode period: 1.51sec

(Source: Elkady and Lignos 2014)
Modeling with Distributed Plasticity

Perimeter

Leaning Column

Node i

Node j

Force- or Displacement-Based Element

Integration point

Fiber element

Engineering stress-strain domain

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Steel Material Models Available in OpenSees

Steel01-Simple Bilinear

Steel02-Giuffre Menegotto-Pinto Model with Isotropic Strain Hardening
Steel Material Models Available in OpenSees
Utilization of Steel01 for Modeling of Steel Components

<table>
<thead>
<tr>
<th>uniaxialMaterial Steel01 $matTag SFy $E0 $b $&lt;sa1 sa2 sa3 sa4&gt;</th>
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<tbody>
<tr>
<td><strong>$matTag</strong></td>
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<tr>
<td><strong>$Fy</strong></td>
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<td><strong>$E0</strong></td>
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<td><strong>$a3</strong></td>
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<tr>
<td><strong>$a4</strong></td>
</tr>
</tbody>
</table>

![Stress-strain curve for Steel01 material model](image)

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Steel Material Models Available in OpenSees
Utilization of Steel02 for Modeling of Steel Components

Example – Utilization of Steel02 Material Model

From calibration
Number of Fibers for Cross Section Discretization

Follow the recommendations by Kostic & Filippou (2012)

Fig. 1. Discretization of wide-flange cross section with midpoint integration rule (MP): (a) 12MP scheme; (b) 24MP scheme; (c) 40MP scheme, and (d) 108MP scheme

W-Shapes: 12 MP gives remarkable accuracy in terms of local response estimates
Biaxial bending and failures associated with weak axis bending: (40MP) 2x8 fibers (Flange) 1x8 fibers (Web)
Steel2.tcl – FiberSteelWsection2d

```tcl
proc FiberSteelWSection2d {sectTag sectType matTag nFlange nWeb args} {
    global WSection
    global in
    set Orient "XX"
    if {{[lsearch $args "YY"] != -1} {
        set Orient "YY"
    }
    set found 0
    foreach {section prop} [array get WSection $sectType] {
        set propList [split $prop]
        set d [expr [lindex $propList 1]*$in]
        set bf [expr [lindex $propList 2]*$in]
        set tw [expr [lindex $propList 3]*$in]
        set tf [expr [lindex $propList 4]*$in]
        Wsection $sectTag $matTag $d $bf $tf $tw $nFlange 1 1 $nWeb $Orient
        set found 1
    }
    if {$found == 0} {
        puts "FiberSteelWSection2d sectType: $sectType not found for sectTag: $sectTag"
    }
}
```
Nonlinear Beam-Column Elements in OpenSees

- Use of forceBeamColumn element

(Neuenhofer and Filippou 1997) → good discussion why you may want to consider using force based elements over displacement-based ones.

- Only one element is adequate
- 5 integration points along the member length are sufficient most of the times for modeling of steel MRFs

Recommendations by Kostic & Filippou (2012)
Steel2.tcl – Procedure: ForceBeamWSection2d

```tcl
proc ForceBeamWSection2d {eleTag :Node jNode sectType matTag transfTag args} {
    global FiberSteelWSection2d
    global ElasticSteelWSection2d

    set Orient "XX"
    if {![lsearch $args "YY"] != -1} {
        set Orient "YY"
    }

    set nFlange 10
    if {![lsearch $args "-nFlange"] != -1} {
        set loc [lsearch $args "-nFlange"]
        set nFlange [lindex $args [expr $loc+1]]
    }

    set nWeb 5
    if {![lsearch $args "-nWeb"] != -1} {
        set loc [lsearch $args "-nWeb"]
        set nWeb [lindex $args [expr $loc+1]]
    }

    set nip 4
    if {![lsearch $args "-nip"] != -1} {
        set loc [lsearch $args "-nip"]
        set nip [lindex $args [expr $loc+1]]
    }

    if {![lsearch $args "-release1"] != -1} {
        set hingeEnd1 node $eleTag$hingeEnd1 [nodeCoord $jNode 1] [nodeCoord $jNode 2]
equaADDF $jNode $eleTag$hingeEnd1 1 2
        set $jNode $eleTag$hingeEnd1
    }

    if {![lsearch $args "-release2"] != -1} {
        set hingeEnd2 node $eleTag$hingeEnd2 [nodeCoord $jNode 1] [nodeCoord $jNode 2]
equaADDF $jNode $eleTag$hingeEnd2 1 2
        set $jNode $eleTag$hingeEnd2
    }

    if {![lsearch $args "-elasticSection"] != -1} {
        set loc [lsearch $args "-elasticSection"]
        set $E [lindex $args [expr $loc+1]]
        ElasticSteelWSection2d $eleTag sectType SE $Orient
    } else {
        FiberSteelWSection2d $eleTag sectType $sectType $matTag $nFlange $nWeb $Orient
    }

    element forceBeamColumn $eleTag $jNode $jNode $nip $eleTag $transfTag
}
```

→Uses forceBeamColumn element
model Basic – ndm 2 – ndf 3
source Steel2d.tcl

# set some lists containing floor and column line locations and nodal masses
set floorLocs {0. 204. 384. 564.}; # floor locations in inches
set colLocs {0. 360. 720. 1080. 1440. 1800.}; # column line locations in inches
set massesX {0. 0.419 0.419 0.430}; # mass at nodes on each floor in x dirn
set massesY {0. 0.105 0.105 0.096}; # mass at nodes on each floor in y dirn

# add nodes at each floor at each column line location & fix nodes if at floor 1
foreach floor {1 2 3 4 5} floorLoc $floorLocs massX $massesX massY $massesY {
    foreach colLine {1 2 3 4} colLoc $colLocs {
        node $colLine$floor $colLoc $floorLoc -mass $massX $massY 0.
        if {$floor == 1} {fix $colLine$floor 1 1 1}
    }
}

# uniaxialMaterial Steel02 $tag $Fy $E $b $R0 $cr1 $cr2 $a1 $a2 $a3 $a4
uniaxialMaterial Steel02 1 55.0 29000. 0.02 19.0 0.925 0.15 0.12 0.90 0.18 0.90; # material to be used for steel elements

# set some list for col and beam sizes
set colSizes {W24x103 W24x103 W24x103 W24x64}; # col sizes stories 1, 2, 3 and 4
set beamSizes {W21x73 W21x73 W21x57 W21x57}; # beams sizes floor 1, 2, 3 and 4

# add columns at each column line between floors
geomTransf PDelta 1
foreach colLine {1 2 3 4} {
    foreach floor1 {1 2 3} floor2 {2 3 4 5} {
        set theSection [lindex $colSizes [expr $floor1 -1]]; # obtain section size for column
        ForceBeamWSection2d $colLine$floor1$colLine$floor2 $colLine$floor1 $colLine$floor2 $theSection 1 1 –nip 5
    }
}

# add beams between column lines at each floor
geomTransf Linear 2
foreach colLine1 {1 2 3} colLine2 {2 3 4} {
    foreach floor {2 3 4 5} {
        set theSection [lindex $beamSizes [expr $floor -2]]; # obtain section size for floor
        ForceBeamWSection2d $colLine1$floor$colLine2$floor $colLine1$floor $colLine2$floor $theSection 1 2
    }
}
Panel Zone Modeling

![Diagram of Panel Zone Modeling]

- **Perimeter SMF**
- **Leaning Column**
- **W21x73**
- **W21x57**
- **W24x103**
- **W24x62**
- **H = 16.60m**
- **3 bays @ 6.10m**
- **Rigid links**

**How to obtain the input parameters?**

- See Gupta and Krawinkler (1999)

**Diagram Details:**
- **Nonlinear force-beam column elements**
- **Elastic beam column elements**
- **d_b**
- **d_c**

**Graph:**
- **V** vs. **γ**
- **V_p**
- **V_y**
- **K_p**
- **αK_c**
- **γ_y**
- **γ_p**

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Procedure for Modeling Panel Zones
-Available from OpenSees Examples Posted by Dr. L. Eads

```matlab
proc elemPanelZone2D {eleID nodEr E A_PZ I_PZ transfTag} { 
    # define all nodes
    set node_x01 $nodesR; # top left of joint
    set node_x02 [expr $node_x01 + 1]; # top left of joint
    set node_x03 [expr $node_x01 + 2]; # top right of joint
    set node_x04 [expr $node_x01 + 3]; # top right of joint
    set node_x05 [expr $node_x01 + 4]; # middle right of joint (vertical middle, horizontal right)
    set node_x06 [expr $node_x01 + 5]; # btm right of joint
    set node_x07 [expr $node_x01 + 6]; # btm right of joint
    set node_x08 [expr $node_x01 + 7]; # btm left of joint
    set node_x09 [expr $node_x01 + 8]; # btm left of joint
    set node_x10 [expr $node_x01 + 9]; # middle left of joint (vertical middle, horizontal left)
    set node_x6 [expr ($node_x01-1)/10 + 6]; # btm center of joint
    set node_x7 [expr ($node_x01-1)/10 + 7]; # top center of joint

    # create element IDs as a function of first input eleID (8 per panel zone)
    set x1 $eleID; # left element on top of panel zone
    set x2 [expr $x1 + 1]; # right element on top of panel zone
    set x3 [expr $x1 + 2]; # top element on right side of panel zone
    set x4 [expr $x1 + 3]; # btm element on right side of panel zone
    set x5 [expr $x1 + 4]; # right element on btm of panel zone
    set x6 [expr $x1 + 5]; # left element on btm of panel zone
    set x7 [expr $x1 + 6]; # btm element on left side of panel zone
    set x8 [expr $x1 + 7]; # top element on left side of panel zone

    # create panel zone elements
    #
    element elasticBeamColumn $x1 $node_x02 $node_x7 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x2 $node_x07 $node_x6 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x3 $node_x05 $node_x04 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x4 $node_x06 $node_x05 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x5 $node_x07 $node_x07 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x6 $node_x08 $node_x6 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x7 $node_x09 $node_x10 $A_PZ E $I_PZ $transfTag;
    element elasticBeamColumn $x8 $node_x10 $node_x01 $A_PZ E $I_PZ $transfTag;
}
```
4-Story SMF – Distributed Plasticity Approach
Basic Results – Nonlinear Static Procedure
First Mode Lateral Load Pattern

Does not capture strength
deterioration of steel components
4-Story SMF – Distributed Plasticity Approach
Basic Results – Nonlinear Response History Analysis

Canoga Park Record
Northridge 1994 Earthquake

Unscaled (SF=1.0)

Does not include the effect of cyclic deterioration on flexural strength and stiffness of steel components
4-Story SMF – Concentrated Plasticity Approach

Zero Length element (rotational springs)
With idealized moment – rotation relationship

Elastic beam-column element
4-Story SMF – Concentrated Plasticity Approach

From Steel2d.tcl: Procedure to Create Elastic Beam-Column Element

```tcl
proc ElasticBeamWSection2d {eleTag :eleTag :Node iNode sectType E transfTag args} {
    global WSection
    global in
    set found 0

    set Orient "XX"
    if {{[lsearch $args "args"] == -1} {
        set Orient "YY"
    }

    if {{[lsearch $args "--release1"] == -1} {
        set hingeEnd1 1
        node $eleTag$hingeEnd1 [nodeCoord $iNode 1] [nodeCoord $iNode 2]
        equalDOF $iNode $eleTag$hingeEnd1 1 2
        set iNode $eleTag$hingeEnd1
    }

    if {{[lsearch $args "--release2"] == -1} {
        set hingeEnd2 2
        node $eleTag$hingeEnd2 [nodeCoord $jNode 1] [nodeCoord $jNode 2]
        equalDOF $jNode $eleTag$hingeEnd2 1 2
        set jNode $eleTag$hingeEnd2
    }

    foreach {section prop} [array get WSection $sectType] {
        set propList [split $prop]

        set A [expr [lindex $propList 0]*$in*$in]
        set Ixx [expr [lindex $propList 5]*$in*$in*$in]
        set Iyy [expr [lindex $propList 6]*$in*$in*$in*$in]
        if {$Orient == "YY"} {
            element elasticBeamColumn $eleTag $iNode $jNode $A $E $Iyy $transfTag
        } else {
            element elasticBeamColumn $eleTag $iNode $jNode $A $E $Ixx $transfTag
        }
        set found 1
    }

    if {$found == 0} {
        puts "ElasticBeamWSection2d sectType: $sectType not found for ee: $eleTag"
    }
}
```
Available Steel Material Models for Modeling the Moment – Rotation Relationship of a Steel Component

✧ Steel01 (Basic Bilinear)

✧ Steel02 (Giuffre Menegotto-Pinto Model with Isotropic Strain Hardening)

✧ Modified Ibarra-Medina-Krawinkler (IMK) Deterioration Model with Bilinear Hysteretic Response (or Bilin in OpenSees) → Considers Strength and Stiffness Deterioration of Steel Components
The Modified IMK Deterioration Model
-Input Model Parameters

The deduced moment rotation relationship of the component under consideration is needed for input parameter identification

(Image Source: Lignos and Krawinkler 2012)
The Modified IMK Deterioration Model
-Considering Slab Effects (see Elkady and Lignos 2014)

The deduced moment rotation relationship of the component under consideration is needed for input parameter identification.
Utilizing the Modified IMK Model in OpenSees
Visit: dimitrios.lignos.research.mcgill.ca/databases/steel/

Contains data from more than 300 experiments from steel beams
Utilizing the Modified IMK Model in OpenSees
Sample Model Calibrations

(Sources: Lignos and Krawinkler 2011, 2013)
Utilizing the Modified IMK Model in OpenSees

Visit: dimitrios.lignos.research.mcgill.ca/databases/component/

Pre-capping plastic rotation, $\theta_{pc}$, for beams with non-RBS connections:

$$\theta_{pc} = 0.087 \cdot \left( \frac{h}{t_w} \right)^{-0.365} \cdot \left( \frac{b_f}{2 \cdot t_f} \right)^{-0.14} \cdot \left( \frac{L}{d} \right)^{0.34} \cdot \left( \frac{d}{c_{\text{unit}}^{1} \cdot 21''} \right)^{-0.721} \cdot \left( \frac{c_{\text{unit}}^{2} \cdot F_y}{50} \right)^{-0.23}$$

Pre-capping plastic rotation, $\theta_{pc}$, for beams with RBS connections:

$$\theta_{pc} = 0.19 \cdot \left( \frac{h}{t_w} \right)^{-0.314} \cdot \left( \frac{b_f}{2 \cdot t_f} \right)^{-0.10} \cdot \left( \frac{L}{d} \right)^{-0.1185} \cdot \left( \frac{L}{r_y} \right)^{0.113} \cdot \left( \frac{d}{c_{\text{unit}}^{1} \cdot 21''} \right)^{-0.76} \cdot \left( \frac{c_{\text{unit}}^{2} \cdot F_y}{50} \right)^{-0.07}$$

Post-capping rotation, $\theta_{pc}$, for beams with non-RBS connections:

$$\theta_{pc} = 5.70 \cdot \left( \frac{h}{t_w} \right)^{-0.565} \cdot \left( \frac{b_f}{2 \cdot t_f} \right)^{-0.80} \cdot \left( \frac{L}{d} \right)^{-0.28} \cdot \left( \frac{d}{c_{\text{unit}}^{1} \cdot 21''} \right)^{-0.43} \cdot \left( \frac{c_{\text{unit}}^{2} \cdot F_y}{50} \right)^{-0.43}$$

Post-capping rotation, $\theta_{pc}$, for beams with RBS connections:

$$\theta_{pc} = 9.62 \cdot \left( \frac{h}{t_w} \right)^{-0.513} \cdot \left( \frac{b_f}{2 \cdot t_f} \right)^{-0.863} \cdot \left( \frac{L}{r_y} \right)^{-0.108} \cdot \left( \frac{c_{\text{unit}}^{2} \cdot F_y}{50} \right)^{-0.36}$$

Reference cumulative plastic rotation, $A$, for beams with non-RBS connections:

$$A = \frac{E_t}{M_y} = 500 \left( \frac{h}{t_w} \right)^{-1.34} \cdot \left( \frac{b_f}{2 \cdot t_f} \right)^{-0.595} \cdot \left( \frac{c_{\text{unit}}^{2} \cdot F_y}{50} \right)^{-0.36}$$

(Sources: Lignos and Krawinkler 2011, 2013)
Utilizing the Modified IMK Model in OpenSees
Visit: dimitrios.lignos.research.mcgill.ca/databases/component/
4-Story – Concentrated Plasticity Approach

Steel2d.tcl: Rotational Spring with SteelWsectionMR

```
proc SteelWSectionMR {matTag E Fy Ix Zx H L d tw bf tf Lb ry Com_Type Comp_Action args} {

# Procedure to Construct the Modified IMK Material with Moment-Rotation curve for steel
#
# The input parameters for bare steel components (beams, columns) are based on the following papers:
#
#    Collapse Prediction of Steel Moment Frames under Earthquake Loading”,
#
#    Component Databases for Performance-Based Earthquake Engineering”,
#
#
#
#
#

→Look for SteelWSectionMR

Uses the multivariate-regression equations and utilizes the modified IMK model in OpenSees
```
4-Story SMF – Concentrated Plasticity- Deterioration
Nonlinear Static Analysis – First Mode Lateral Load Pattern
Comparisons with Distributed Plasticity Model

Formation of a 3-story mechanism (Did not change in this case)

Due to strength deterioration

Base Shear/Seismic Weight, V/W

Roof Drift Ratio, Δ/H [rad]

Normalized Floor Displacement [rad]
4-Story SMF – Concentrated Plasticity- Deterioration
Nonlinear Response History Analysis with Canoga Park Record
Comparisons with Distributed Plasticity Model

The effect of cyclic deterioration on the structural response is minimal for SF = 1.0 (close to design level earthquake)

The effect of cyclic deterioration on the structural response is significant
4-Story SMF – Concentrated Plasticity- Deterioration
Nonlinear Response History Analysis with Canoga Park Record
Comparisons with Distributed Plasticity Model

Due to strength deterioration
Approaching dynamic collapse
Collapse Assessment of Steel SMFs
Using Concentrated Plasticity Approach

Case studies: Archetype office steel buildings with perimeter steel special moment frames designed in Urban California (ASCE 7-10, AISC-2010)

(Sources: Elkady and Lignos 2014)

Source: National Seismic Hazard Map (USGS 2008)
Example: Collapse Risk of 4-Story Steel SMF
Incremental Dynamic Analysis – Utilization of 44 Ground Motions

Source: Elkady and Lignos (2014)
Concluding Remarks

✧ **Modeling Steel Moment Resisting Frames in OpenSees**
  ➢ You can use a number of readily available tools (procedures in tcl, examples, web-based tools, etc)

✧ **Steel Components to Consider**
  ✓ Steel Beams, Columns and Panel Zones

✧ **Distributed Versus Concentrated Plasticity Approach**
  ✓ For low rise code-compliant steel buildings with perimeter MRFs the differences should not be large for “design level earthquakes” – Distributed plasticity models capture cyclic hardening, P-M interaction

✧ **If Performance Evaluation at Large Deformations is the Objective: Component Deterioration Must be Considered**
  ✓ Concentrated Plasticity with Degrading Phenomenological Models will do reasonably well for low- to mid-rise steel MRFs.
Thank you for your kind attention!

For more information visit: dimitrios-lignos.research.mcgill.ca

References:


