HybridFEM: A PROGRAM FOR DYNAMIC TIME HISTORY ANALYSIS OF 2D INELASTIC FRAMED STRUCTURES AND REAL-TIME HYBRID SIMULATION

HybridFEM Version 4.2.4 User’s Manual

by

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DISCLAIMER

The program HybridFEM has been thoroughly tested and used. However, the user of the program understands that no warranty is implied by the development team on the accuracy of the program. The user is responsible to understand the assumptions and theoretical background of the program.
SOFTWARE UPDATES AND DOCUMENTATION

Professor James M. Ricles was responsible for the conception of HybridFEM. The program was developed for research purposes and is in constant evolution. For updates on software and documentation, please contact:

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1. INTRODUCTION

The program HybridFEM-2D runs:

(a) Under MATLAB to produce the time-history response of non-linear two-dimensional framed structures to ground accelerations.

(b) Under MATLAB/Simulink and compatible with Target PC for real-time hybrid simulation of non-linear two-dimensional framed structures.
2. MODELLING OPTIONS

The program has a wide variety of modelling options available to represent the structure. The current version of the program requires the user to work in the metric system with KN, m., and sec.

2.1 GLOBAL COORDINATE SYSTEM
X (horizontal axis) – Y (vertical axis with +Y being upward) – Z (satisfies the right-hand rule)

2.2 MASS
The mass of the structure is modelled by following the consistent mass method. The total mass matrix is formed by assembling the consistent mass matrices of the elements. Using Element Type 4, the user can specify concentrated lumped masses which are appropriately added to the total consistent mass matrix.

2.3 RESTRAINTS
The boundary conditions are specified.

2.4 CONSTRAINTS
The equal dof constraint is specified.

2.5 DAMPING
The damping exhibited by the structure is modelled by the commonly assumed Rayleigh damping. There is the option to specify multiplicative factors that define the contribution of each element to the formation of the assembled total structure Rayleigh damping matrix.

2.6 MATERIALS
TYPE 1: Elastic material
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3. INTEGRATION OF THE EQUATIONS OF MOTION

The unconditionally stable explicit CR algorithm is used to integrate the coupled 2\textsuperscript{nd} order differential equations of motion of the structure [1]. Alternatively, a user can choose Rosenbrock-W algorithm for the numerical integration [2].
4. INPUT FILE FOR HybridFEM-2D

In the following user guide, each line of input data is indicated by a box containing the data items. Below each box there is a table describing the data items. This table specifies whether the data item is an integer “I” or a floating “F” number. If a default integer or floating number value should be assigned to a data item, this will be specified in that table. Additional notes are provided for further explanation. The data items of each line should be separated by blank spaces. The format of the data items is free, e.g., a floating number may or may not have a decimal point and may or may not take a scientific form.

The input file for the structure is described by the following sequence of input lines. No blank lines are permitted. The program provides comment lines for free alphanumeric input (the rule for separation by blank spaces does not apply for these lines).

1. Comment line

| Any alphanumeric characters |

2. Comment line

| Any alphanumeric characters |

3. Comment line

| Any alphanumeric characters |
4. Structure data block line

<table>
<thead>
<tr>
<th>NN</th>
<th>NE</th>
<th>NM</th>
<th>NSEC</th>
<th>NDIM</th>
<th>NEN</th>
<th>NDN</th>
<th>ND</th>
<th>NSL</th>
<th>NGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN : Number of nodes</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE : Number of elements</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NM : Number of materials</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSEC : Number of sections</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDIM : 2 (default)</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEN : 2 (default)</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDN : 3 (default)</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND : Number of restrained dofs</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSL : Number of constrained (slaved) dofs</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGN : Number of dofs with gravity load</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Comment line

Any alphanumeric characters

6. Comment line

Any alphanumeric characters
7. Nodal data block line

**NN lines**

<table>
<thead>
<tr>
<th>NODE</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
</table>

- **NODE**: Node ID number
- **X**: Nodal coordinate X
- **Y**: Nodal coordinate Y
- **Z**: Nodal coordinate Z

**Notes**

1: The node ID number can be any integer number. There are no restrictions on the nodes numbering.

2: The free dynamic dofs of the structure are numbered sequentially, i.e., 1, 2, 3, ......, NN*3 – ND – NSL.

8. Comment line

**Any alphanumeric characters**

9. Comment line

**Any alphanumeric characters**
10. Boundary data block

ND lines

<table>
<thead>
<tr>
<th>NODE</th>
<th>UX</th>
<th>UY</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1: For each node, the user must specify the ID number of the three (UX, UY and THETA) associated dofs. (1 = fixed, 0 = free). Nodes not assigned boundary conditions are assumed to have all of their degrees of freedom free.

11. Comment line

Any alphanumeric characters

12. Comment line

Any alphanumeric characters
13. Equal DOF Constraint data block

**NSL lines**

<table>
<thead>
<tr>
<th>MNODE</th>
<th>SNODE</th>
<th>UX</th>
<th>UY</th>
<th>THETA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNODE : Master Node ID number</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNODE : Slave Node ID number</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UX : X direction dof</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UY : Y direction dof</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THETA : Rotational dof</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1: In order to constrain dofs, specify the master and slave node ID numbers and specify the dof to be constrained. (1 = constrained, 0 = free)

14. Comment line

Any alphanumeric characters

15. Comment line

Any alphanumeric characters
16. Material data block

**NM lines**

<table>
<thead>
<tr>
<th>MATID</th>
<th>MATTYPE</th>
<th>{Material properties}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1: The MAT ID number can be any integer number.

16.1: Material TYPE 1: Elastic material

\[ E \ (\text{data1}) \ : \ \text{Initial stiffness / Youngs modulus} \]

![Diagram of elastic behaviour](image)

**Fig. 1. Elastic behaviour**
16.2: Material TYPE 2: Bilinear elasto-plastic material

E \text{(data1)} : Initial modulus / stiffness
\sigma_Y \text{(data2)} : Yield stress / strength
\alpha \text{(data3)} : Post-yielding stiffness

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{Bilinear elasto-plastic behaviour}
\end{figure}

16.3: Material TYPE 3: Hysteretic material

pinchx \text{(data1)} : Pinching factor for deformation
pinchy \text{(data2)} : Pinching factor for force
damage1\text{(data3)} : Damage due to ductility
damage2\text{(data4)} : Damage due to energy
\beta \text{(data5)} : power used to determine the degraded unloading stiffness based on ductility
s1p \text{(data6)} : Force at first point of the envelope in the positive direction
e1p \text{(data7)} : Deformation at first point of the envelope in the positive direction
s2p \text{(data8)} : Force at second point of the envelope in the positive direction
e2p \text{(data9)} : Deformation at second point of the envelope in the positive direction
s3p \text{(data10)} : Force at third point of the envelope in the positive direction
e3p \text{(data11)} : Deformation at third point of the envelope in the positive direction
s1n \text{(data12)} : Force at first point of the envelope in the negative direction
**Notes**

1. This material model is equivalent to the OpenSEES Hysteretic material and the detail information can be found in Mazzoni et al [4]

2. Ductility, $\mu$, is calculated during analysis ($\mu \geq 1$)

![Hysteretic material envelope curve](image)

**Fig. 3. Hysteretic material envelope curve**

16.4: Material TYPE 4: Bouc-Wen material

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>Viscous damping coefficient</td>
<td>F</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Elastic stiffness</td>
<td>F</td>
</tr>
<tr>
<td>$K_2$</td>
<td>Stiffness</td>
<td>F</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Factor for elastic stiffness in non-hysteretic component ($0 &lt; \alpha &lt; 1$)</td>
<td>F</td>
</tr>
</tbody>
</table>
uy (data5) : Yield displacement

a (data6) : Power factor for nonlinear viscous damping (=1, linear viscous damping) in non-hysteretic component

Beta (data7) : Parameter that controls shape of hysteresis loop in a hysteretic component

Gamma (data8) : Parameter that controls shape of hysteresis loop in a hysteretic component

N (data9) : Parameter that controls smoothness of transition from linear to nonlinear range for a hysteretic component. As n increases the transition becomes sharper

Notes

1. The restoring force, Q, is modeled by non-hysteretic component and hysteretic component in parallel as shown in Figure 4. Its mathematical is written as

\[ Q(x, \dot{x}, t) = g(x, \dot{x}) + h(x) \]

where: non-hysteretic component g is written as

\[ g(x, \dot{x}) = c \cdot |\dot{x}|^\alpha \cdot \left( \frac{\dot{x}}{|\dot{x}|} \right) + \alpha \cdot k \cdot x \]

C is damping coefficient, Hysteretic component is

\[ h(x) = (1 - \alpha) \cdot k \cdot x \cdot z(t) \]

The state variable z is described as

\[ \dot{z}(t) = \frac{1}{u_y} \left[ A_0 \cdot \dot{x} - \nu \cdot |\dot{x}| \cdot |z|^\eta \cdot \text{sign}(z) + \beta \cdot \dot{x} \cdot |z|^\eta \right] \]

A_0 is set to be one in the element, \nu and \eta are set to 1 for non-degradation in the element, K is the initial stiffness of the element (=K1 + K2)

2. The detail information can be found in Wen [5]
16.5: Material TYPE 5: Trilinear material

- $V_y$ (data1): Yield shear strength
- $V_u$ (data2): Ultimate strength
- $D_y$ (data3): Yield displacement
- $D_u$ (data4): Ultimate displacement

Fig. 4. Schematic view of Bouc-Wen material model

Fig. 5. Trilinear material envelope curve
16.6: Material TYPE 6: Stiffness degrading material

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ip}$ (data1)</td>
<td>Initial stiffness in positive direction</td>
</tr>
<tr>
<td>$F_{yp}$ (data2)</td>
<td>Positive yield strength</td>
</tr>
<tr>
<td>$F_{up}$ (data3)</td>
<td>Positive ultimate strength</td>
</tr>
<tr>
<td>$U_{up}$ (data4)</td>
<td>Displacement corresponding to $F_{up}$</td>
</tr>
<tr>
<td>$F_{rp}$ (data5)</td>
<td>Positive residual strength</td>
</tr>
<tr>
<td>$U_{rp}$ (data6)</td>
<td>Displacement corresponding to $F_{rp}$</td>
</tr>
<tr>
<td>$K_{in}$ (data7)</td>
<td>Initial stiffness in negative direction</td>
</tr>
<tr>
<td>$F_{yn}$ (data8)</td>
<td>Negative yield strength</td>
</tr>
<tr>
<td>$F_{un}$ (data9)</td>
<td>Negative ultimate strength</td>
</tr>
<tr>
<td>$U_{un}$ (data10)</td>
<td>Displacement corresponding to $F_{un}$</td>
</tr>
<tr>
<td>$F_{rn}$ (data11)</td>
<td>Negative residual strength</td>
</tr>
<tr>
<td>$U_{rn}$ (data12)</td>
<td>Displacement corresponding to $F_{rn}$</td>
</tr>
</tbody>
</table>

Notes

1. The detail information on the hysteresis rule can be found in Wu [6]

![Stiffness degrading material envelope curve, Material Type 6](image)

Fig. 6. Stiffness degrading material envelope curve, Material Type 6
17. **Comment line**

| Any alphanumeric characters |

18. **Comment line**

| Any alphanumeric characters |
## 19. Section data block

**NSEC lines**

<table>
<thead>
<tr>
<th>SECID</th>
<th>SECTYPE</th>
<th>{Section properties}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECID</td>
<td>SECTYPE</td>
<td>I</td>
</tr>
<tr>
<td>SECTYPE</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>{...}</td>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1. The SECID and SECTYPE number can be any integer number. There are no restrictions on section numbering.
19.1: Section TYPE 1: Wide flange section

d (data1) : Section depth \( F \)

B (data2) : Section width \( F \)

tf (data3) : Flange thickness \( F \)

tw (data4) : Web thickness \( F \)

NFF (data5) : Number of fibers along flange thickness \( F \)

NFW (data6) : Number of fibers along web depth \( F \)

MATID (data7) : Material ID assigned to the section

19.2: Section TYPE 2: Rectangular RC section

H (data1) : Section height \( F \)

B (data2) : Section width \( F \)

CoverY (data3) : Cover thickness in y-direction \( F \)

CoverZ (data4) : Cover thickness in z-direction \( F \)

nfCoreY (data5) : Number of fibers in y direction in the core \( I \)

nfCoreZ (data6) : Number of fibers in y direction in the core \( I \)

nfCoverY (data7) : Number of fibers in y direction in the cover \( I \)

nfCoverZ (data7) : Number of fibers in Z direction in the cover \( I \)
nLayers (data8) : Number of layers in y direction \( I \)

As (data 9) : RS bars Section area at the top layer \( F \)

Nrs (data10) : Number of RS bars at the top layer \( I \)

As (data9+ nLayers) : RS bars Section area at the last layer \( F \)

Nrs (data10+nLayers) : Number of RS bars at the last layer \( I \)

matID1 (data11+nLayers) : Concrete material tag in the core (Confined concrete) \( I \)

matID2 (data12+nLayers) : Concrete material tag in the cover (Unconfined concrete) \( I \)

matID3 (data13+nLayers) : Reinforced steel bar material tag \( I \)
Figure 6. Fiber rectangular reinforced concrete section

e.g., nfCoreY = 16, nfCoreZ = 4, nfCoverY = 16, nfCoverZ = 1, nLayers = 2, Nrs = 2

20. Comment line

Any alphanumeric characters

21. Comment line

Any alphanumeric characters
22. Element data block

NE lines

<table>
<thead>
<tr>
<th>ELID</th>
<th>ELTYPE</th>
<th>NODEI</th>
<th>NODEJ</th>
<th>DAMPK</th>
<th>DAMPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>:</td>
<td>:</td>
<td>:</td>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>Element ID number</td>
<td>Element Type</td>
<td>ID number of NODE I</td>
<td>ID number of NODE J</td>
<td>Stiffness proportional damping</td>
<td>Mass proportional damping</td>
</tr>
<tr>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Notes

1. The element ID and TYPE numbers are any integer number. There are no restrictions on element numbering.

2. The number of data items \{data1, data2, ..., dataN\} depends on the element type and are given below:

22.1: Element TYPE 1: Elastic beam-column element

<table>
<thead>
<tr>
<th>MAT</th>
<th>A</th>
<th>I</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>(data1)</td>
<td>(data2)</td>
<td>(data3)</td>
<td>(data4)</td>
</tr>
<tr>
<td>Material ID number</td>
<td>Cross section (axial) area</td>
<td>Moment of inertia</td>
<td>Element gravity load per unit length</td>
</tr>
<tr>
<td>I</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Notes

1. The element gravity load per unit length is converted by the program to element mass per unit length according to: \(\text{Mass} = \text{Load} / g\), where \(g\) is the gravity of acceleration. The program assumes that \(g=9.81 \text{ m/sec}^2\).
2. The damping matrix of each element is calculated as 
\[ [C] = \text{DampK} \times A_0 \times [K] + \text{DampM} \times A_1 \times [M], \]
where \([K]\) is the stiffness matrix, \([M]\) is the mass matrix, and \(A_0\) and \(A_1\) are the Rayleigh proportional damping factors.

### 22.2: Element TYPE 2: Elastic spring element

<table>
<thead>
<tr>
<th>(K) (data1)</th>
<th>Stiffness of the spring</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{\text{exp}}) (data2)</td>
<td>Damping constant of experimental element</td>
<td>F</td>
</tr>
</tbody>
</table>

### Notes

1. This element connects nodes which can have the same coordinates (zero length element) or different coordinates.

2. The element is assumed to provide stiffness only for the horizontal global UX dof of the nodes.

3. \(C_{\text{exp}}\) is a damping constant which is appropriately added to the total damping matrix of the structure. However, the damping matrix that includes the effect of \(C_{\text{exp}}\) is used only for the calculation of the integration parameters of the CR algorithm and for extrapolation or the experimental substructure restoring force at the last substep of the “ramping” of the actuator command displacements during a hybrid test. The effect of \(C_{\text{exp}}\) is not considered in the damping matrix used during the solution of the equations of motion.

4. This element has the ability to represent a physical experimental element in the laboratory. In that case, the stiffness of the element contributes to the initial structure stiffness matrix, however, during the real-time hybrid simulation, the resisting force of the elements comes from the load cells attached to the physical experimental element.
22.3: Element TYPE 3: Plastic hinge inelastic beam-column element (parallel component theory)

**MATID (data1)** : Material ID number I
**A (data2)** : Cross section (axial) area F
**I (data3)** : Moment of inertia F
**Load (data4)** : Element gravity load per unit length F
**Hard (data5)** : Hardening F
**A_v (data6)** : Shear area F
**v (data7)** : Poisson’s ratio F
**M_p (data8)** : Plastic moment F
**N_p (data9)** : Plastic axial force F

**Notes**

1. The element has the same capabilities as the DRAIN-2DX plastic hinge beam column-element (parallel component theory).
2. The element requires a P-M interaction surface to account for inelastic response to account for axial force effect (see Figure 8)
3. Detail information on this element can be found in Prakash et al. [3]

Fig. 7. Schematic view of element Type 3
Fig. 8. P-M interaction surface defined in element Type 3

22.4: Element TYPE 4: Dummy column element

| W (data1) | Weight of the element for P-Δ effect | F |
| Mi (data2) | Mass on the node i | F |
| Mj (data3) | Mass on the node j | F |
| MDOF (data4) | Mass DOF | I |

Notes

1, The element can be used to model a lean-on column for P-D effect

2, To exclude P-Δ effect, set W = 0

3, Mi and Mj are the lumped mass assigned to nodes i and j.

4, DOF option in global coordinate for the assigned mass (MDOF=1 for X-direction, =2 for Y-direction, =3 for Rotational direction). Current version allows mass in only X-direction
22.5: Element TYPE 5: Rotational spring element with stiffness and strength deterioration capabilities

Ke (data1) : Initial stiffness F
As (data2) : Strain hardening ratio F
AsNeg (data3) : Strain hardening ratio in the negative direction F
My_pos (data4) : Positive yield moment F
My_neg (data5) : Negative yield moment F
LamdaS (data6) : Basic strength deterioration parameter F
LamdaK (data7) : Unloading stiffness deterioration parameter F
LamdaA (data8) : Accelerated reloading stiffness deterioration parameter F
LamdaD (data9) : Post-capping strength deterioration parameter F
Cs (data10) : Exponent for basic strength deterioration F
Ck (data11) : Exponent for unloading stiffness deterioration F
Ca (data12) : Exponent for accelerated reloading stiffness deterioration F
Cd (data13) : Exponent for post-capping strength deterioration F
Thetap_pos (data14) : Plastic rotation capacity for positive loading F
Thetap_neg (data15) : Plastic rotation capacity for negative loading F
Thetapc_pos (data16) : Post-capping rotation capacity for positive loading F
Thetapc_neg (data17) : Post-capping rotation capacity for negative loading F
K (data18) : Residual strength ratio F
KNeg (data19) : Residual strength ratio for negative loading F
Thetau_pos (data20) : Ultimate rotation capacity for positive loading F
Thetau_neg (data21) : Ultimate rotation capacity for negative loading F
DPlus (data22) : Composite action factor for positive loading F
DNeg (data23) : Composite action factor for negative loading F

Notes

1. The element is a rotational zero length element to simulate strength and stiffness deterioration at the plastic hinge region at the beam end during cyclic rotational response
2. The element parameter can be determined from regression analysis of experimental data and detail information on the hysteresis rule and regression parameters, $\theta_p$, $\theta_{pc}$, $\Lambda$ in for wide flange beam section, are shown below

For Non Reduced beam section,

$$\theta_p = 0.087 \left( \frac{h}{t_w} \right)^{-0.365} \left( \frac{b_f}{2t_f} \right)^{-0.14} \left( \frac{L}{d} \right)^{-0.14} \left( \frac{d}{c_{unit} \cdot 21^*} \right)^{-0.721} \left( \frac{c_{unit}^2 \cdot F_y}{50} \right)^{-0.23}$$

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

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

For Reduced beam section,

$$\theta_p = 0.19 \left( \frac{h}{t_w} \right)^{-0.314} \left( \frac{b_f}{2t_f} \right)^{-0.10} \left( \frac{L_b}{r_y} \right)^{-0.119} \left( \frac{L}{d} \right)^{0.113} \left( \frac{d}{c_{unit} \cdot 21^*} \right)^{-0.76} \left( \frac{c_{unit}^2 \cdot F_y}{50} \right)^{-0.07}$$

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

$$\Lambda = 500 \left( \frac{h}{t_w} \right)^{-1.138} \left( \frac{b_f}{2t_f} \right)^{-0.632} \left( \frac{L_b}{r_y} \right)^{-0.205} \left( \frac{c_{unit}^2 \cdot F_y}{50} \right)^{-0.391}$$

Where, $h/t_w$ is the fillet to fillet web depth over web thickness ratio; $L_b/r_y$ is the ratio between beam unbraced length $L_b$ over radius of gyration about the weak axis of the cross section; $b_f/2t_f$ is the flange width to thickness; $L/d$ is the shear span to depth ratio of the beam; $F_y$ is the yield strength of the flange of the beam in ksi; $c_{unit}^1$ and $c_{unit}^2$ are coefficients for units conversion. They both are 1.0 if inches and ksi are used, and they are 0.0254 and 0.145, respectively if $d$ is in meters and $F_y$ is in MPa; and $\Lambda$ is a cumulative plastic rotation parameter.
3. The element deterioration parameters, $\Lambda_S$, $\Lambda_K$, $\Lambda_A$, and $\Lambda_D$, are equal to the value of $\Lambda$ obtained from the regression equation above. The plastic rotation capacity parameters $\theta_p$ and $\theta_{pc}$ in both positive and negative directions are set equal in the current version of the element. According to Lignos and Krawinkler [7], the value of the post-yielding stiffness ratios, $A_S$ and $A_{SNeg}$, are determined to have the ratio of capping moment to effective yield moment equal to 1.1. The value of the residual strength ratios, $K$ and $KNeg$, is recommended as 0.4. The value of $\theta_{pu}$ in both negative and positive directions is recommended as 0.04 rad. The values of $C_S$, $C_k$, $C_a$ and $C_d$, are 1.0 by default. The values of $D_{Plus}$, $D_{Neg}$ are 1.0 by default.

4. More detail information on this element can be found in Lignos and Krawinkler [7].

Fig. 9. Schematic view of element Type 5
Fig. 10. Element Type 5 rotational behaviour (a) Envelop curve and (b) cyclic behaviour

22.6: Element TYPE 6: Displacement Based Fiber Beam-Column Element

SECID (data1) : Section ID number 
NIP (data2) : Number of integration points along the length of element 
Load (data3) : Element gravity load per unit length 

Notes
1. Integration scheme in the element is based on Gauss-Lobatto quadrature rule and two integration points at the element ends are included as shown in Figure 9

22.7: Element TYPE 7: Force Based Fiber Beam-Column Element

SECID (data1) : Section ID number 
NIP (data2) : Number of integration points along the length of element 
Load (data3) : Element gravity load per unit length 
ITER (data4) : Maximum number of iteration
**Notes**

1. Integration scheme in the element is based on Gauss-Lobatto quadrature rule

2. Maximum iteration and tolerance need to be specified to enable the iterative form of the flexibility formulation and the theoretical development for this element can be found in Spacone, et al. [8]

![Fig. 11. Schematic view of beam-column element Type 6 and Type 7 [4]](image)

**22.8: Element TYPE 8: Zerolength Element**

**DOF (data1)** : Direction of element in global coordinate  
**MATID (data2)** : Material ID number
Fig. 12. Schematic view of element Type 8

22.9: Element TYPE 9: 2D Planar Panel Zone Element

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODEI</td>
<td>Node i</td>
<td>I</td>
</tr>
<tr>
<td>NODEJ</td>
<td>Node j</td>
<td>I</td>
</tr>
<tr>
<td>NODEK</td>
<td>Node k</td>
<td>I</td>
</tr>
<tr>
<td>NODEL</td>
<td>Node l</td>
<td>I</td>
</tr>
<tr>
<td>DAMPK</td>
<td>Stiffness proportional damping</td>
<td>F</td>
</tr>
<tr>
<td>DAMPM</td>
<td>Mass proportional damping</td>
<td>F</td>
</tr>
<tr>
<td>MATID (data1)</td>
<td>Material ID number</td>
<td>I</td>
</tr>
<tr>
<td>ICOL (data2)</td>
<td>Column section moment of inertia</td>
<td>F</td>
</tr>
<tr>
<td>ACOL (data3)</td>
<td>Column section area</td>
<td>F</td>
</tr>
<tr>
<td>BCOL (data4)</td>
<td>Column flange width</td>
<td>F</td>
</tr>
<tr>
<td>tw (data5)</td>
<td>Column web thickness</td>
<td>F</td>
</tr>
<tr>
<td>tf (data6)</td>
<td>Column flange thickness</td>
<td>F</td>
</tr>
<tr>
<td>td (data7)</td>
<td>Double plate thickness</td>
<td>F</td>
</tr>
<tr>
<td>tcnt (data8)</td>
<td>Continuity plate thickness</td>
<td>F</td>
</tr>
<tr>
<td>SHMATID (data9)</td>
<td>Shear material ID number</td>
<td>I</td>
</tr>
<tr>
<td>Mass (data10)</td>
<td>Small mass assigned to the element</td>
<td>F</td>
</tr>
</tbody>
</table>

Notes

1. The element requires four node and the nodes are defined in counter-clockwise rotation.
2. Shear material in the panel zone element is defined with Trilinear material type (material type = 5).

3. The detail information on this element can be found in Seo, et al [9]

Fig. 13. (a) Schematic view of element Type 9 and (b) Deformation modes considered in the element

23. Comment line

Any alphanumeric characters

24. Comment line

Any alphanumeric characters
25. Gravity Analysis data block

<table>
<thead>
<tr>
<th>NODE</th>
<th>DOF</th>
<th>GRAVITYLOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODE</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>DOF</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>GRAVITYLOAD</td>
<td></td>
<td>F</td>
</tr>
</tbody>
</table>

**Notes**

1. Gravity analysis data block is optional. Gravity analysis is performed followed by dynamic transient analysis, when nonzero value is assigned to NGN in the Structure data block.

2. DOF in global coordinate (DOF=1 for X-direction, =2 for Y-direction, =3 for Rotational direction)

26. Comment line

Any alphanumeric characters

27. Comment line

Any alphanumeric characters
28. Analysis data block

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>KSI</th>
<th>SF</th>
<th>DT</th>
<th>INT</th>
</tr>
</thead>
</table>

- **T1**: First period of vibration
- **T2**: Second period of vibration
- **KSI**: Modal damping ratio
- **SF**: Scale factor of accelerogram
- **DT**: Time step of accelerogram
- **INT**: The number of steps interpolated within DT for analysis

29. Comment line

Any alphanumeric characters

30. Comment line

Any alphanumeric characters
31. Numerical Integration Option block

<table>
<thead>
<tr>
<th>TYPE</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Integration algorithm</strong> : I</td>
</tr>
<tr>
<td></td>
<td><strong>Integration parameters</strong> : F</td>
</tr>
</tbody>
</table>

30.1: TYPE 1: C-R algorithm

| Lambda | 1 by default, Integration parameters for CR algorithm : F |

Notes

1. The C-R algorithm is an unconditional explicit numerical integration algorithm and detail information can be found in Chen and Ricles [1]

30.2: TYPE 2: Rosenbrock-W algorithm

| Gamma  | 0.5 by default, Integration parameters for Rosenbrock-W algorithm : F |

Notes

1. The algorithm is an unconditional explicit numerical integration algorithm and detail information can be found in Lamarche, et al. [2]
5. Verification examples

5.1: Verification example 1: Elastic two-story frame

1. DATA

1.1 Units
kN-m-s.

1.2 Elements used
Type1 – Linear Beam Column Element
Type2 – Experimental Element
Type4 – Dummy Column Element

1.3 Geometry of structure – Node numbering – Element numbering
1.4 Restrained DOF
19 20 21 22 23: Ux=0 Uy=0 THETAz=0
3 6 12 15: THETAz=0

1.5 Constrained DOF
1 2 4 5 7 8 9: Ux
10 11 13 14 16 17 18: Ux
3 4: Uy
6 7: Uy
12 13: Uy
15 16: Uy
3 6: Ux
12 15: Ux

1.6 Element Section/Properties
All columns: W14x120
Beams 1st floor: W24x55
Beams 2nd floor: W18x40
Braces 1st floor: A=5.881e-3 I=0.0
Braces 2nd floor: A=3.0e-3 I=0.0
Dampers 1st floor: Stiffness=8461
Dampers 2nd floor: Stiffness=5615

1.7 P-Δ and concentrated masses – Two-storey lean on column
Lean-on column section: A=0.0976 I=7.125e-4
Pinned at the base
1st Floor Load: 6618.44
2nd Floor Load: 4633.03
Stiffness matrix (conventional + geometric): 
\[
\begin{bmatrix}
7009 & -4630.2 \\
-4630.2 & 1982.34
\end{bmatrix}
\]
Mass matrix: 
\[
\begin{bmatrix}
805 & 0 \\
0 & 578
\end{bmatrix}
\]
1.8 Time-history data
See input file below and directory for damping, dt, acceleration record, etc.

1.9 Linear Elastic Material Properties
E=200000000.0

1.10 HybridFem InputFile
Input file below is written for HybridFEM v 4.1
UNITS: KN-m-sec  HybridFEM V4.1 Input

--- END OF CONFIGURATION -------------------

ELEMENT LIBRARY AND ELEMENT DATA

type1: elastic beam column element
type2: experimental link element with initial stiffness
type3: hinge (concentrated plasticity) beam column element (drain2dx type 2)
type4: 2 story gravity column

--- END OF HYBRID TESTING DATA BLOCK ---
2. RESULTS

2.1 Modal analysis

SAP2000: \( T_1=1.18 \quad T_2=0.38 \)

HybridFem: \( T_1=1.18 \quad T_2=0.38 \)

2.2 Time-history analysis

![Graph of 1st floor displacement](image1)

![Graph of 2nd floor displacement](image2)
5.2: Verification example 2: Inelastic response of two-storey frame

1. DATA

1.1 Units
kN-m-s.

1.2 Elements Used
Type3 – Nonlinear Beam Column Element
Type4 – Dummy Element (not available after Version 4.2.3)

1.3 Geometry of Structure

1.4 Element Section/Properties
All columns: W14x120
Beams 1<sup>st</sup> floor: W24x55
Beams 2<sup>nd</sup> floor: W24x55

1.5 Concentrated Masses
Mass matrix: \[
\begin{bmatrix}
612.5 & 0 \\
0 & 612.5 \\
\end{bmatrix}
\]
1.6 Time-history Data
See input file for damping, dt, acceleration record, etc.

1.7 Nonlinear Material Properties
E=200000000.0   fy=345000

1.9 Input Files
Input files of HybridFEM v 4.1 and DRAIN-2DX are given in the next pages
HybridFEM input file (version 4.1)

UNIT: KN-m-sec

STRUCTURE DATA BLOCK
NN NE NM NDM NEN NDN ND NSLAVED
6 7 1 2 3 6 2

NODAL COORDINATE DATA BLOCK
NODE X Y UX UV THETA
1 0 6 1 2 3
2 6 6 1 4 5
3 0 3 6 7 8
4 6 3 6 9 10
5 0 0 200 200 200
6 6 0 200 200 200

MATERIAL DATA BLOCK
MATERIAL E
1 200000000.0

ELEMENT TYPE AND CONNECTIVITY DATA BLOCK
ELEM TYPE NODE1 NODE2 data5 data6 data7 data8 data9 data10 data11 data12 data13 data14 data15
1 3 1 2 1 0.0105 5.619e-4 0.8085 0.03 6.007e-3 0.03 757.62 3622.5 1 1
2 3 3 4 1 0.0105 5.619e-4 0.8085 0.03 6.007e-3 0.03 757.62 3622.5 1 1
3 3 3 1 1 0.0228 5.744e-4 1.7556 0.03 5.512e-3 0.03 1198.53 7866 1 1
4 3 4 2 1 0.0228 5.744e-4 1.7556 0.03 5.512e-3 0.03 1198.53 7866 1 1
5 3 5 3 1 0.0228 5.744e-4 1.7556 0.03 5.512e-3 0.03 1198.53 7866 1 1
6 3 6 4 1 0.0228 5.744e-4 1.7556 0.03 5.512e-3 0.03 1198.53 7866 1 1
7 4 2 0 0 0 612.64 612.64 1 1

HYBRID TESTING DATA BLOCK
T1 T2 KSI SF DT
1.4 0.41 0.03 10.01

---END OF CONFIGURATION---------

ELEMENT LIBRARY AND ELEMENT DATA
type1: elastic beam column element
type2: experimental link element with initial stiffness
type3: hinge (concentrated plasticity) beam column element (drain2Dx type 2)
type4: 2 story gravity column
!This is the DRAIN.INP input file for structure:frame
!erase permanent files
*STARTXX
!name of structure,execute,show progress,consider p-delta effects,perform energy calculations
frame         0 1 1 1                                                 frame
!NODE COORDINATES
*NODECOORDS
C        1         0         0
C        2         6         0
C        3         0         3
C        4         6         3
C        5         0         6
C        6         6         6
!RERAINTS
!Fixed at the ground level
*RESTRAINTS
S 111         1
S 111         2
!CONSTRAINTS
!All floors assumed to be diaphragms
*SLAVING
S 100         3         4         4
S 100         5         6         6
!NODAL MASSES: computed from a)structure selfweight(autocalculated in program)  
                                  b)uniform load on beams
*MASSES
S 110   0.26844         1                                            1       0.2
S 110   0.26844         2                                            1       0.2
S 110   306.595         3                                            1       0.2
S 110   306.595         4                                            1       0.2
S 110   306.326         5                                            1       0.2
S 110   306.326         6                                            1       0.2
*ELEMENTGROUP
02    1    1          0.003                                        COLUMNS
2    0    2
1    2e+008      0.03    0.0228 0.0005744    4    4    2  0.005512  0.30.0001
2    2e+008      0.03    0.0228 0.0005744    4    4    2  0.005512  0.30.0001
1    2   1198.53   1198.53      7866      7866  1.0 0.15  1.0 0.15
2    2   1198.53   1198.53      7866      7866  1.0 0.15  1.0 0.15
1    1         3              1         1    1
2    2         4              1         1    1
3    3         5              2         2    2
4    4         6              2         2    2
*ELEMENTGROUP
02    1    1          0.003                                         BEAMS
2    0    2
1    2e+008      0.03    0.0105 0.0005619    4    4    2  0.006007  0.30.0001
2    2e+008      0.03    0.0105 0.0005619    4    4    2  0.006007  0.30.0001
1    2   757.62    757.62    3622.5    3622.5  1.0 0.15  1.0 0.15
2    2   757.62    757.62    3622.5    3622.5  1.0 0.15  1.0 0.15
1    3         4              1         1    1
2    5         6              2         2    2
*GENDISP
1    1         -1
3    1         1
*GENDISP
3    1         -1
5    1         1
*GENDISP
1    1         0
3    1         1
*GENDISP
3    1         0
5    1         1
*RESULTS
NSD    001
DRAIN-2DX input file - Continued

```
*ELEMLOAD
  kata       katakoryfa
  G 1 2
  1 0  1  0.0  0.0  0.0  0.0  0.0  0.0
  2 0  1  0.0  0.0  0.0  0.0  0.0  0.0
  1  1  1
  2  1  1
  3  2  1
  4  2  1

  G 2 2
  1 0  1  0.0  0.0  0.0  0.0  0.0  0.0
  2 0  1  0.0  0.0  0.0  0.0  0.0  0.0
  1  1  1
  2  2  1

*ACCNREC
  elce       elce             (F15.7)   elce
  5479  1  0  2                          0.01  0.01

*PARAMETERS
  OD       0         0    0         0    0      0.01    0         0    0     54.79
  DC  1           -100

*GRAV
  KATAKORYFA FORTIA
  E  kata

*ACCN
  54.79 5480  1  0.01  3  3
  Time history for: elce

1 elce

*STOP
```
2. RESULTS

2.1 Modal Analysis

HybridFEM: \( T_1 = 1.4 \quad T_2 = 0.4 \)

DRAIN: \( T_1 = 1.4 \quad T_2 = 0.4 \)

2.2 Time-history Analysis

![Graph showing 2nd floor displacement over time for DRAIN-2DX and HybridFEM]
5.3: Verification example 3: Simulating stiffness and strength deterioration in the cyclic response of steel components using element type 5

1. Input Parameters for Element Type 5

\[
\begin{align*}
p_{Ke} &= 2790995; \\
p_{As} &= 0.023; \\
p_{AsNeg} &= 0.023; \\
p_{My\_pos} &= 15300; \\
p_{My\_neg} &= -15200; \\
p_{LamdaS} &= 1.10; \\
p_{LamdaK} &= 1.00; \\
p_{LamdaA} &= 1.00; \\
p_{LamdaD} &= 1.00; \\
p_{Cs} &= 1.0; \\
p_{Ck} &= 1.0; \\
p_{Ca} &= 1.0; \\
p_{Cd} &= 1.0; \\
p_{Thetap\_pos} &= 0.022; \\
p_{Thetap\_neg} &= 0.022; \\
p_{Thetapc\_pos} &= 0.22; \\
p_{Thetapc\_neg} &= 0.22; \\
p_{\theta} &= 0.40; \\
p_{\thetaNeg} &= 0.40; \\
p_{\Theta\_pos} &= 0.40; \\
p_{\Theta\_neg} &= 0.40; \\
D_{Plus} &= 1.0; \\
D_{Neg} &= 1.0;
\end{align*}
\]

2. Experimental Results

Refer to Lignos and Krawinkler [7]
3. Results
5.4: Verification example 2: Two-storey frame with P-Δ effect

1. DATA

1.1 Units
kN-m-s.

1.2 Elements Used
Type1 – Elastic Beam-Column Element
Type4 – Dummy Column Element

1.3 Geometry of Structure

![Diagram of two-storey frame]

1.4 Element Section/Properties
All columns: W14x120
Beams 1st floor: W24x55
Beams 2nd floor: W24x55
Lean-on column section: A=0.0976  I=7.125e-4
1.5 Concentrated Masses

Mass matrix: \[
\begin{bmatrix}
612.5 & 0 \\
0 & 612.5
\end{bmatrix}
\]

1.6 Seismic Weight
Weight at 2\textsuperscript{nd} story on lean on column : 6010
Weight at 1\textsuperscript{st} story on lean on column : 6010

1.7 Time-history Data
See input file for damping, dt, acceleration record, e.t.c

1.8 Linear Elastic Material Properties
E=200000000.0

1.9 Directory
HybridFEM input script and input motion directory:
…\HybridFEMv423\Systems\Element1Example\...

1.10 Input Files
Input files of HybridFEM v 4.2.3 and OpenSEES are given in the next pages
HybridFEM input file (version 4.2.3)

<table>
<thead>
<tr>
<th>UNITS: KN-m-sec</th>
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</thead>
<tbody>
<tr>
<td>STRUCTURE DATA BLOCK</td>
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<tr>
<td>NN   NE   NM   NSEC   N DIM   NEN   NDN   ND   NSLAVED   NGN</td>
</tr>
<tr>
<td>9     10    1     0      2       2      3     6     2       0</td>
</tr>
<tr>
<td>NODE COORDINATE DATA BLOCK</td>
</tr>
<tr>
<td>NODE  X  Y  Z</td>
</tr>
<tr>
<td>1     0     6     0</td>
</tr>
<tr>
<td>2     6     6     0</td>
</tr>
<tr>
<td>3     0     3     0</td>
</tr>
<tr>
<td>4     6     3     0</td>
</tr>
<tr>
<td>5     0     0     0</td>
</tr>
<tr>
<td>6     6     0     0</td>
</tr>
<tr>
<td>7     7     0     0</td>
</tr>
<tr>
<td>8     7     3     0</td>
</tr>
<tr>
<td>9     7     6     0</td>
</tr>
<tr>
<td>BOUNDARY CONDITION</td>
</tr>
<tr>
<td>NODE  X  Y  Z</td>
</tr>
<tr>
<td>5 1 1 0</td>
</tr>
<tr>
<td>6 1 1 0</td>
</tr>
<tr>
<td>7 1 1 0</td>
</tr>
<tr>
<td>CONSTRAINT</td>
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<tr>
<td>M  S  dof</td>
</tr>
<tr>
<td>4 8 1 0</td>
</tr>
<tr>
<td>2 9 1 0</td>
</tr>
<tr>
<td>MATERIAL DATA BLOCK</td>
</tr>
<tr>
<td>ID  TYPE  E</td>
</tr>
<tr>
<td>1   1   200000000.0</td>
</tr>
<tr>
<td>ELEMENT TYPE AND CONNECTIVITY DATA BLOCK</td>
</tr>
<tr>
<td>ELEM  TYPE  NODE1  NODE2  DampK  DampM  [Element Properties] 3</td>
</tr>
<tr>
<td>1    1    1    3     1 1 .022774148  .000574399  0.1</td>
</tr>
<tr>
<td>2    1    3    5     1 1 .022774148  .000574399  0.1</td>
</tr>
<tr>
<td>3    1    2    4     1 1 .022774148  .000574399  0.1</td>
</tr>
<tr>
<td>4    1    4    6     1 1 .022774148  .000574399  0.1</td>
</tr>
<tr>
<td>5    1    1    2     1 1 .010451592  .000561912  0.1</td>
</tr>
<tr>
<td>6    1    3    4     1 1 .010451592  .000561912  0.1</td>
</tr>
<tr>
<td>7    1    7    8     1 1 0.0976  7.125e-4  0.1</td>
</tr>
<tr>
<td>8    1    8    9     1 1 0.0976  7.125e-4  0.1</td>
</tr>
<tr>
<td>9    4    7    8     1 1 12820.0  0.0  612.64  1</td>
</tr>
<tr>
<td>10   4    8    9     1 1 16010.0  0.0  612.64  1</td>
</tr>
<tr>
<td>HYBRID TESTING DATA BLOCK</td>
</tr>
<tr>
<td>T1  T2  KSI  SF  DT  Interpolations</td>
</tr>
<tr>
<td>1.4  0.41  0.00  1  0.001  5</td>
</tr>
<tr>
<td>INTEGRATOR TYPE  [Parameters]</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>---END OF CONFIGURATION---------</td>
</tr>
</tbody>
</table>

ELEMENT LIBRARY AND ELEMENT DATA
- type1: elastic beam column element
- type2: experimental link element with initial stiffness
- type3: hinge (concentrated plasticity) beam column element (drain2dx type 2)
- type4: 2 story gravity column
- type5: SNAP (Stanford U) bilinear zero-length element with stiffness and strength deterioration capabilities

INTEGRATOR LIBRARY
- type1: CR Method
- type2: Rosenbrock-W Method
# To check element 4 in HybridFEM

```plaintext
model BasicBuilder -ndm 2 -ndf 3
```

# Define Basic Materials

```plaintext
set E        200000000.0
set Fy       345000.
set b        0.01
```

# Define Nodes and Boundary condition

```plaintext
node 1 0 6
node 2 6 6
node 3 0 3
node 4 6 3
node 5 0 0
node 6 6 0
node 7 7 0
node 8 7 3
node 9 7 6
set M [expr 612.64];
set smallM [expr 0.001]
mass 8 $M $smallM $smallM
mass 9 $M $smallM $smallM
fix 5 1 1 0
fix 6 1 1 0
fix 7 1 1 0
equalDOF 4 8 1
equalDOF 2 9 1
```

# Define Elements, gravity load and record

```plaintext
set PTrans 10
geomTransf PDelta $PTrans
set LTrans 11
geomTransf Linear $LTrans

element elasticBeamColumn 1 1 3 0.022774148 200000000. 0.000574399 $LTrans
element elasticBeamColumn 2 3 5 0.022774148 200000000. 0.000574399 $LTrans
element elasticBeamColumn 3 2 4 0.022774148 200000000. 0.000574399 $LTrans
element elasticBeamColumn 4 4 6 0.022774148 200000000. 0.000574399 $LTrans
element elasticBeamColumn 5 1 2 0.010451592 200000000. 0.000561912 $LTrans
element elasticBeamColumn 6 3 4 0.010451592 200000000. 0.000561912 $LTrans
element elasticBeamColumn 7 7 8 0.0976 200000000. 7.125e-4 $PTrans
element elasticBeamColumn 8 8 9 0.0976 200000000. 7.125e-4 $PTrans

pattern Plain 1 Linear {
    load 8 0 -6010 0
    load 9 0 -6010 0
}
recorder Node -file Displ.out -time -node 8 9 -dof 1 disp;
```

# Static Analysis

```plaintext
system UmfPack
constraints Transformation
test EnergyIncr 1e-10 60 1
numberer Plain
algorithm Linear
integrator LoadControl 1
analysis Static
analyze 1
loadConst -time 0.0
```
set outgm "NR0CPC196.OPS"
set dt 0.01
set duration 20.0
set Nsteps [expr int($duration/$dt)];
set Gaccel "Series -dt $dt -filePath $outgm -factor 1.0";

pattern UniformExcitation 2 1 -accel $Gaccel

test EnergyIncr 1.0e-5 10 0
constraints Transformation
numberer Plain
algorithm Newton
integrator Newmark 0.5 0.25
analysis Transient
analyze $Nsteps $dt
wipe
2. RESULTS

2nd story floor displacement comparison

![Graph showing 2nd story floor displacement comparison between Hybrid FEM and OpenSEES models.]

1st story floor displacement comparison

![Graph showing 1st story floor displacement comparison between Hybrid FEM and OpenSEES models.]

5.5: Verification example 2: Two-storey frame using displacement based beam column elements

1. DATA

1.1 Units
kN-m-s.

1.2 Elements Used
Type1 – Elastic Beam-Column Element
Type4 – Dummy Column Element
Type6 – Displacement Beam-Colum Element

1.3 Geometry of Structure

1.4 Element Section/Properties
All columns: W14x120
Beams 1st floor: W24x55
Beams 2nd floor: W24x55
Lean-on column section: A=0.0976  I=7.125e-4
1.5 Concentrated Masses

Mass matrix:

\[
\begin{bmatrix}
612.5 & 0 \\
0 & 612.5
\end{bmatrix}
\]

1.6 Seismic Weight

Weight at 2\textsuperscript{nd} story on lean on column : 6010
Weight at 1\textsuperscript{st} story on lean on column : 6010

1.7 Time-history Data

See input file for damping, dt, acceleration record, e.t.c

1.8 Nonlinear Material Properties

E=200000000.0   fy=345000

1.9 Directory

HybridFEM input script and input motion directory:

…\HybridFEMv423\Systems\Element6Example\...

1.10 Input Files

Input files of HybridFEM v 4.2.3 and OpenSEES are given in the next pages
UNITS: KN-m-sec

STRUCTURE DATA BLOCK

<table>
<thead>
<tr>
<th>NN</th>
<th>NE</th>
<th>NM</th>
<th>NSEC</th>
<th>NDim</th>
<th>NEN</th>
<th>NDN</th>
<th>ND</th>
<th>NSLAVED</th>
<th>NGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

NODAL COORDINATE DATA BLOCK

<table>
<thead>
<tr>
<th>NODE</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

BOUNDARY CONDITION

<table>
<thead>
<tr>
<th>NODE</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

CONSTRANT

<table>
<thead>
<tr>
<th>M</th>
<th>S</th>
<th>dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

MATERIAL DATA BLOCK

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>E</th>
<th>sigmaY</th>
<th>E2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>200000000.0</td>
<td>345000.0</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>200000000.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Section Data Block

SectionID SectionType Section data MaterialID {W14x120: h  bf tf tw}

<table>
<thead>
<tr>
<th>SectionID</th>
<th>SectionType</th>
<th>Section data</th>
<th>MaterialID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1</td>
<td>0.367792</td>
<td>0.372618</td>
<td>0.023876</td>
</tr>
<tr>
<td>2 1</td>
<td>0.598678</td>
<td>0.177927</td>
<td>0.012827</td>
</tr>
</tbody>
</table>

ELEMENT TYPE AND CONNECTIVITY DATA BLOCK

<table>
<thead>
<tr>
<th>ELEM</th>
<th>TYPE</th>
<th>NODE1</th>
<th>NODE2</th>
<th>DampK</th>
<th>DampM</th>
<th>{Element Properties}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2 0.0976 7.125e-4 0.1</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2 0.0976 7.125e-4 0.1</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1 0.0976 7.125e-4 0.1</td>
</tr>
</tbody>
</table>

GRAVITY LOADING BLOCK

<table>
<thead>
<tr>
<th>NODE</th>
<th>DOFNUM</th>
<th>LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2</td>
<td>-6010</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>-6010</td>
</tr>
</tbody>
</table>

HYBRID TESTING DATA BLOCK

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>KSI</th>
<th>SF</th>
<th>DT</th>
<th>Interpolations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.41</td>
<td>0.00</td>
<td>3</td>
<td>0.001</td>
<td>5</td>
</tr>
</tbody>
</table>

INTEGRATOR

<table>
<thead>
<tr>
<th>TYPE</th>
<th>{Parameters}</th>
<th>1</th>
<th>1.0</th>
</tr>
</thead>
</table>

----------END OF CONFIGURATION----------

ELEMENT LIBRARY AND ELEMENT DATA

| type1: elastic beam column element |
| type2: experimental link element with initial stiffness |
| type3: hinge (concentrated plasticity) beam column element (drain2dx type 2) |
| type4: 2 story gravity column |
| type5: SNAP (Stanford U) bilinear zero-length element with stiffness and strength deterioration capabilities |

INTEGRATOR LIBRARY

| type1: CR Method |
| type2: Rosenbrock-W Method |
OpenSEES input file

# To check element 4 in HybridFEM

```plaintext
model BasicBuilder -ndm 2 -ndf 3
source WFsection.tcl
logFile test.txt

######################################
# Define Basic Materials
######################################
set E 200000000.0
set Fy 345000.
set b 0.01

################################################
# Define Nodes and Boundary condition
################################################
node 1 0 6
node 2 6 6
node 3 0 3
node 4 6 3
node 5 0 0
node 6 6 0
node 7 7 0
node 8 7 3
node 9 7 6

set M [expr 612.64];
set smallM [expr 0.001]
mass 8 @M $smallM $smallM
mass 9 @M $smallM $smallM

fix 5 1 1 0
fix 6 1 1 0
fix 7 1 1 0
equalDOF 4 8 1
equalDOF 2 9 1

################################################
# Define Elements
################################################
# Beam integration points
set nI5 5

# Define parameters
set ABm 0.010451592
set IBm 0.000561912
set ICl 0.000574399
set ACl 0.022774148
set dCl 0.367792
set twCl 0.014986
set bfCl 0.372618
set tfCl 0.023876
set dBm 0.598678
set twBm 0.010033
set bfBm 0.177927
set tfBm 0.012827
set tdp 0.0;  # double plate thickness
set tcnt 0;   # continuity plate thickness

# Define sections for beams
uniaxialMaterial Steel01 1000 $Fy $E $b
WFsection 1001 1000 $dBm $twBm $bfBm $tfBm 10 3

# Columns section and materials
WFsection 2001 1000 $dCl $twCl $bfCl $tfCl 10 3
```

59
# Define Elements and gravity load

set PTrans 10
geomTransf PDelta $PTrans
set LTrans 11
geomTransf Linear $LTrans

element dispBeamColumn 1 1 3 $nI5 2001 $LTrans -mass [expr 0.0001/9.81]
element dispBeamColumn 2 3 5 $nI5 2001 $LTrans -mass [expr 0.0001/9.81]
element dispBeamColumn 3 2 4 $nI5 2001 $LTrans -mass [expr 0.0001/9.81]
element dispBeamColumn 4 4 6 $nI5 2001 $LTrans -mass [expr 0.0001/9.81]
element dispBeamColumn 5 1 2 $nI5 1001 $LTrans -mass [expr 0.0001/9.81]
element dispBeamColumn 6 3 4 $nI5 1001 $LTrans -mass [expr 0.0001/9.81]
element elasticBeamColumn 7 7 8 0.0976 200000000. 7.125e-4 $PTrans

pattern Plain 1 Linear {
  load 8 0 -6010 0
  load 9 0 -6010 0
}

# recorder and analysis

recorder Node -file Displ.out -time -node 8 9 -dof 1 disp;

system UmfPack
constraints Transformation
test EnergyIncr le-10 60 1
numberer Plain
algorithm Linear
integrator LoadControl 1
analyze Static
loadConst -time 0.0

set outgm "NR0CPC196.OPS"
set dt 0.01
set duration 20.0
set Nsteps [expr int($duration/$dt)];
set Gaccel "Series -dt $dt -filePath $outgm -factor 3.0";

pattern UniformExcitation 2 1 -accel $Gaccel

test EnergyIncr 1.0e-5 10 0
constraints Transformation
numberer Plain
algorithm Newton
integrator Newmark 0.5 0.25
analyze Transient
analyze $Nsteps $dt
wipe
2. RESULTS

2nd story floor displacement comparison

1st story floor displacement comparison
5.6: Verification example 2: Inelastic one-story frame using panel zone elements

1. DATA

1.1 Units
kN-m-s.

1.2 Elements Used
Type1 – Elastic Beam-Column Element
Type4 – Dummy Column Element
Type6 – Displacement Beam-Column Element
Type9 – Panel Zone Element

1.3 Geometry of Structure

1.4 Element Section/Properties
All columns: W14x120 (Linear elements)
Beams 1st floor: W24x55 (Nonlinear element)
Lean-on column section: A=0.0976   I=7.125e-4

1.5 Concentrated Masses
Mass: 612.64 on the lean-on column node
1.6 Seismic Weight
Seismic weight at 1st story on lean on column: 6010

1.7 Time-history Data
See input file for damping, dt, acceleration record, etc.

1.8 Nonlinear Material Properties
E=200000000.0   fy=345000

1.9 Directory
HybridFEM input script and input motion directory:
…\HybridFEMv423\Systems\Element9Example\...

1.10 Input Files
Input files of HybridFEM v 4.2.3 and OpenSEES are given in the next pages
UNITS: KN-m-sec
STRUCTURE DATA BLOCK
NN NE NM NSEC NDDM NEN NDN NSLAVED NGN
12 7 3 2 2 2 3 6 1 1
NODAL COORDINATE DATA BLOCK
NODE X Y Z UX UY THETA
1 0. 0. 0. NODAL COORDINATE DATA BLOCK
2 -0.183896 3. 0. 0.183896 3. 0. NODAL COORDINATE DATA BLOCK
3 0. 2.700661 0. NODAL COORDINATE DATA BLOCK
4 0.183896 3. 0. NODAL COORDINATE DATA BLOCK
5 0. 3.299339 0. 6 0. 0. NODAL COORDINATE DATA BLOCK
7 5.816104 3. 0. NODAL COORDINATE DATA BLOCK
8 6. 2.700661 0. 0.183896 3. 0. NODAL COORDINATE DATA BLOCK
9 6. 3.299339 0. NODAL COORDINATE DATA BLOCK
10 6. 3.299339 0. NODAL COORDINATE DATA BLOCK
11 7. 3. 0. NODAL COORDINATE DATA BLOCK
12 7. 0. 0. 0. NODAL COORDINATE DATA BLOCK
BOUNDARY CONDITION
NODE X Y Z
1 1 1 0
6 1 1 0
12 1 1 0
CONSTRAN INT
M S dof
11 9 1 0 0
MATERIAL DATA BLOCK
ID Type E sigmaY E2
1 2 200000000.0 345000. 0.01
2 5 1097.9 1341.719 0.00155 0.006201
3 1 200000000.0
Section Data Block
SectionID SectionType Section data MaterialID {W14x120: h bf tf tw}
1 1 0.367792 0.372618 0.023876 0.014986 3 10 1
2 1 0.598678 0.177927 0.012827 0.010033 3 10 1
ELEM TYPE AND CONNECTIVITY DATA BLOCK
ELEM TYPE NODE1 NODE2 DampK DampM {secID nIP DistLoad}
1 6 1 3 1 1 5 0.1
2 6 6 8 1 1 2 5 0.1
3 6 4 7 1 1 5 0.1
4 9 2 3 4 5 1 3 0.000574399 0.022774148 0.372618 0.014986 0.023876 0. 0. 2 0.1
5 9 7 8 9 10 1 3 0.000574399 0.022774148 0.372618 0.014986 0.023876 0. 0. 2 0.1
6 1 12 11 1 3 0.0976 0.0007125 0.1
7 4 12 11 1 3 0.0976 0.0007125 0.1
GRAVITY LOADING BLOCK
DOFNUM LOAD
11 2 -6010
HYBRID TESTING DATA BLOCK
T1 T2 SI SF DT
0.127443 10.0 0.0 3.0 0.001 2
INTEGRATOR
TYPE {Parameters}
1 1
OpenSEES input file

```plaintext
model BasicBuilder -ndm 2 -ndf 3
source WFsection.tcl
logFile test.txt

#########################################################################
# Define Basic Materials                                                #
#########################################################################
# Steel Material                                                       #
set E     200000000.0
set G     [expr $E/(2*(1+0.3))];
set Fy    345000.
set b     0.01

#########################################################################
# Define Nodes and Boundary Conditions                                 #
#########################################################################
node 1 0. 0.
node 2 -0.183896 3.
node 3 0. 2.700661
node 4 0.183896 3.
node 5 0. 3.299339
node 6 6. 0.
node 7 5.816104 3.
node 8 6. 2.700661
node 9 6.183896 3.
node 10 6. 3.299339
node 11 7. 3.
node 12 7. 0.
mass 11 612.64 0.0 0.0;
fix 1 1 1 0
fix 6 1 1 0
fix 12 1 1 0
equalDOF 9 11 1

#########################################################################
# Define Elements                                                       #
#########################################################################
# Beam integration points                                              #
set nI5 5
# Define parameters                                                     #
set ABm   0.010451592
set IBm   0.000561912
set ICl   0.000574399
set ACl   0.022774148
set dBm   0.367792
set twCl  0.014986
set bfCl  0.372618
set tfCl  0.023876
set dBm   0.598678
set twCl  0.010033
set bfCl  0.177927
set tfCl  0.012827
set tdp   0.0;     # double plate thickness
set tcnt  0;       # continuity plate thickness
# Define sections for beams                                            #
uniaxialMaterial Steel01 1000 $Fy $E $b
WFsection 1001 1000 $dBm $twBm $bfBm $tfBm 10 3
# Columns section and materials                                       #
WFsection 2001 1000 $dCl $twCl $bfCl $tfCl 10 3
# define material for panel zone element                              #
set d1    $dCl
set d2    [expr $dBm + 2.0*$tcnt]
```

# Axial stiffness
set SecA1 [expr $E*$SecA1/$d1];
set SecA2 [expr $ACl + ($d1 - 2.*$tfCl)*$tdp];
set K1 [expr $E*$SecA1/$d1];

# Bending stiffness
set I11 [expr $d2*$d2*$d2*$twCl/12.];
set I12 [expr 2.*$tcnt*$tcnt*$tcnt*($bfCl-$twCl)/12.];
set I13 [expr 2.*($bfCl-$twCl)*$tcnt*($d2-$tcnt)/4];
set I14 [expr $d2*$d2*$d2*$tdp/12.];
set K4 [expr $E*($I11+$I12+$I13+$I14)/$d1];
set I21 [expr ($d1-2.*$tfCl)*($d1-2.*$tfCl)*($d1-2.*$tfCl)*$tdp/12.];
set K5 [expr $E*($I21+$ICl)/$d2];

# Asym Bending stiffness
set K6 [expr 3.*$E*($I11+$I12+$I13+$I14)/$d1];
set K7 [expr 3.*$E*($I21+$ICl)/$d2];

# Asym Shear Stiffness
set K8 [expr 6.*$E*$G*$SecA1*$d1/(3.*$E*$d2*$d2 +2.*$G*$d1*$d1)];
set K9 [expr 6.*$E*$G*$SecA2*$d2/(3.*$E*$d1*$d1 +2.*$G*$d2*$d2)];

# Shear stiffness for Panel Zone element
set Vy [expr $Fy*$dCl*($twCl + $tdp)/1.732];
set Vupar1 [expr $Fy*$dCl*$twCl/1.732];
set Vupar2 [expr 1.0 + 3.45*$bfCl*$tfCl*$tfCl/($dBm*$dCl*$twCl)];
set Vupar3 [expr $Fy*($dCl-$tfCl)*$tdp/1.732];
set Vu [expr $Vupar1*$Vupar2+ $Vupar3];

# shear strain gamma
set gammay [expr $Fy/($G*1.732)];
set gammau [expr 4.*$gammay];

# deformation due to distortion
set Dy [expr $gammay *$dBm];
set Du [expr $gammau *$dBm];

# equivalent spring stiffness
set Kinit [expr $Vy/$Dy];
set Ky [expr ($Vu-$Vy)/($Du-$Dy)];
set Ku [expr 0.*$Kinit];

# decompose spring stiffness
set KEppPZ [expr $Kinit-$Ky];
set FySt01 [expr $Ky*$Du];
set aSt01 [expr $Ku/$Ky];

uniaxialMaterial Elastic 1001 [expr $K1*100]
uniaxialMaterial Elastic 1002 [expr $K2*100]
uniaxialMaterial Elastic 1004 [expr $K4*3]
uniaxialMaterial Elastic 1005 [expr $K5*3]
uniaxialMaterial Elastic 1006 [expr $K6*100]
uniaxialMaterial Elastic 1007 [expr $K7*100]
uniaxialMaterial Elastic 1008 [expr $K8*100]
uniaxialMaterial Elastic 1009 [expr $K9*100]

# inelastic material for shear mode deformation
uniaxialMaterial ElasticPP 1101 $KEppPZ $Dy
uniaxialMaterial Steel01 1102 $FySt01 $Sky $aSt01
uniaxialMaterial Parallel 1103 1101 1102

# Define elements
set PTrans 11
geomTransf PDelta $PTrans
element dispBeamColumn 1 1 3 $nI5 2001 $Trans -mass [expr 0.01/9.81]
element dispBeamColumn 2 6 8 $nI5 2001 $Trans -mass [expr 0.01/9.81]
element dispBeamColumn 3 4 7 $nI5 1001 $Trans -mass [expr 0.01/9.81]
element LehighJoint 4 2 3 4 5 1001 1002 1003 1004 1005 1006 1007 1008 1009
element LehighJoint 5 7 8 9 10 1001 1002 1003 1004 1005 1006 1007 1008 1009
element elasticBeamColumn 6 12 11 0.0976 200000000. 7.125e-4 $PTrans

OpenSEES input file- continued
OpenSEES input file- continued

```
# gravity load

pattern Plain 1 Linear {
  load 11 0 -6010 0
}

# recorder

recorder Node -file Displ.out -time -node 11 -dof 1 disp;

# Analysis

system UmfPack
constraints Transformation
test EnergyIncr 1e-10 60 1
numberer Plain
algorithm Linear

integrator LoadControl 1
analysis Static
analyze 1
loadConst -time 0.0

# Display Frames

set lambda [eigen 1];
set lambda1 [lindex $lambda 0];
set omega1 [expr pow($lambda1,0.5)];
set T1 [expr 2.*3.1415/$omega1];
puts "$T1 

set outgm "NR0CPC196.OPS"
set dt 0.01
set timeIncr [expr $dt/10];
set endTime 20.0
set Nsteps [expr int($endTime/$timeIncr )];
set Gaccel "Series -dt $dt -filePath $outgm -factor 3.0";

pattern UniformExcitation 2 1 -accel $Gaccel

set currentTime 0.0;
set calDt $timeIncr;
source SolutionAlgorithm.tcl;
```
2. RESULTS

Floor displacement comparison

![Graph showing floor displacement comparison between Hybrid FEM and OpenSEES.]
6. REAL-TIME SIMULATION

The HybridFEM program has the capabilities of running models in real-time using SIMULINK, Real Time Workshop and xPC. In the example systems, the file, “RealtimeSetup.m” contains the code to set up the system and the file, “RealtimeModel.mdl” contains the SIMULINK blocks that run the integration algorithm and compute the restoring forces. For new configuration, the user must run “ModelGenerator.m” in order to create a new SIMULINK model. The model is multi-tasking meaning that the integration time step is a multiple of the fundamental sample rate. This allows for actuator ramping at the fundamental sample rate while the complex integration algorithm performs its calculations over the full time step.

In the above system, the light blue block, “Integrator” represents the Integration algorithm. It generates the displacement command and accepts the total restoring force as input. It connects to the “Generate Element Restoring Forces” block which performs the per element restoring force calculations. The “Rate Transition” blocks are necessary to bridge the multi-tasking architecture since the “Integrator” block runs at the fundamental sample rate and the “Generate Element Restoring Forces” block runs at the integration time step.
To interface with this model, the user can connect to either the “Target Displacement” or “Ramped Displacement” output from the “Integrator” block. The “Target Displacement” output is the displacement command generated at every integration time step and the “Ramped Displacement” is the same single run through a linear interpolator at the fundamental sampling rate.
7. REFERENCES


