Refined Inelastic Truss Bar Element (Type 01) with Isotropic Hardening for Drain-2DX-Element Description and User Guide

Larry A. Fahnestock
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REFINED INELASTIC TRUSS BAR ELEMENT (TYPE 01) WITH ISOTROPIC HARDENING FOR DRAIN-2DX – ELEMENT DESCRIPTION AND USER GUIDE

by

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Abstract

The inelastic truss bar element (ITBE) in DRAIN-2DX [Prakash et al. 1993] includes kinematic hardening but not isotropic hardening. Due to the need to use DRAIN-2DX to model buckling-restrained braces (BRBs), which exhibit the characteristics of both kinematic and isotropic hardening, the ITBE in DRAIN-2DX was modified to include isotropic hardening. The isotropic hardening model is controlled by the maximum deformation and/or the cumulative plastic deformation of the ITBE. This report describes the modifications that were made to the ITBE in DRAIN-2DX and demonstrates how the modified ITBE can be used to model BRBs. A description of the updated element, the element user guide for DRAIN-2DX, and a sample DRAIN-2DX input file are included in two appendices.
Table of Contents

Acknowledgements ............................................................................................................................................... ii

Abstract ........................................................................................................................................................... iii

Table of Contents ........................................................................................................................................ iv

1. Introduction ................................................................................................................................................. 1

2. Model Description ...................................................................................................................................... 2

3. Buckling-Restrained Brace Application ................................................................................................. 6

4. Summary and Conclusions ....................................................................................................................... 9

References ..................................................................................................................................................... 10

Tables .......................................................................................................................................................... 11

Figures .......................................................................................................................................................... 12

Appendix A: Refined Inelastic Truss Bar Element (Type 01) with Isotropic Hardening for DRAIN-2DX – Element Description and User Guide .................................................................................... 17

E01.1 PURPOSE, FEATURES AND LIMITATIONS ...................................................................................... 17

  E01.1.1 PURPOSE ...................................................................................................................................... 17

  E01.1.2 ELEMENT MODEL ....................................................................................................................... 17

  E01.1.3 VISCIOUS DAMPING ................................................................................................................... 18

  E01.1.4 OVERSHOOT TOLERANCE ........................................................................................................ 18

  E01.1.5 ELEMENT LOADS .......................................................................................................................... 18

E01.2 INPUT DATA FOR *ELEMENTGROUP .......................................................................................... 19

  E01.2.1 Control Information .................................................................................................................... 19

  E01.2.2 Property Types ............................................................................................................................ 19

  E01.2.3 Element Generation Commands ............................................................................................... 20

E01.3 INPUT DATA FOR *ELEMENTLOAD ........................................................................................... 21

  E01.3.1 Load Sets ................................................................................................................................... 21

  E01.3.2 Loaded Elements and Load Set Scale Factors .......................................................................... 21

E01.4 INTERPRETATION OF RESULTS ................................................................................................. 22

  E01.4.1 Sign Conventions ......................................................................................................................... 22

  E01.4.2 Event codes .................................................................................................................................. 22

  E01.4.3 Envelope Output (.OUT and .E** files) .................................................................................... 22

  E01.4.4 Time History Printout (.OUT file) ............................................................................................... 22

  E01.4.4 Time History Post-processing (.RXX file) .................................................................................. 22

Appendix B: DRAIN-2DX Input File Example ............................................................................................ 26
1. Introduction

In the last 30 years, a significant amount of research effort has gone into developing a new type of structural member, called the buckling-restrained brace (BRB). Information related to the history and development of the BRB concept and its application in the United States can be found in Clark et al. [2001]. The unique feature of BRBs is that, unlike conventional steel braces, they do not buckle in compression. Rather, they yield in compression as well as in tension. Figure 1 schematically illustrates the basic components of a typical BRB. A steel core plate is restrained from global buckling by a confining element, such as a concrete-filled steel tube (Figure 1a). The steel core plate is debonded from the concrete so that the entire axial load imposed on the member is carried by the core. The core is tapered in the middle to create a region of contained yielding (Figure 1b).

Component tests on BRBs have demonstrated their excellent ductility and energy dissipation capacities through stable and predictable hysteretic behavior. Figure 2 illustrates the response from a typical cyclic test of a BRB [Merritt et al. 2003]. As shown in this figure, BRBs exhibit both kinematic and isotropic hardening. Kinematic hardening is the positive post-yield stiffness, and isotropic hardening is the expansion of the hysteresis loops. In order to accurately model BRBs, both of these hardening components should be included in the analytical model. Since BRBs are primarily axial load members, the inelastic truss bar element (ITBE) in DRAIN-2DX [Prakash et al. 1993] is an appropriate choice of element for modeling BRBs. However, the current ITBE includes kinematic hardening but not isotropic hardening. As a result, the ITBE in DRAIN-2DX was modified to include isotropic hardening.

This report describes the modifications that were made to the ITBE in DRAIN-2DX to incorporate isotropic hardening behavior. The isotropic hardening model and its implementation
in DRAIN-2DX are described in Section 2. Section 3 illustrates the how the modified ITBE can be used to model BRBs. A summary and conclusions are presented in Section 4. Appendix A contains the updated element description and user guide for DRAIN-2DX and Appendix B contains a sample DRAIN-2DX input file.

2. Model Description

As mentioned above, the base element that was modified in the present study was the inelastic truss bar element (ITBE), element type 01, in DRAIN-2DX. The ITBE models hysteretic behavior in two ways: (1) yielding in tension and compression, or (2) yielding in tension and elastic buckling in compression. However, realistic post-buckling hysteretic behavior is not included in the ITBE model. Of interest in the present study is the case of yielding in tension and compression. The ITBE allows for different tension and compression yield strengths to be specified. The post-yielding stiffness is the same for tension and compression.

The ITBE model is composed of two components, an elastic component with stiffness designated by $k_e$, and an elastic-plastic component with elastic stiffness designated by $k_{e-p}$ (Figure 3). These two components combine to create a bilinear force-deformation relationship. While the ITBE model accounts for post-yield force increase with increasing deformation (kinematic hardening), it does not account for the additional increase in yield strength (isotropic hardening) that can occur in steel members subjected to cyclic loading. To incorporate isotropic hardening into the ITBE model, the compression and tension yield strengths need to be updated based on the cyclic loading history of the ITBE.

The isotropic hardening rule adopted for the present study allows for the ITBE yield strengths to be controlled by two deformation parameters: (1) maximum deformation and (2)
cumulative plastic deformation. The hardening rule uses exponential functions that lead to decaying hardening rates as the controlling deformation parameters increase. The form of the hardening rule is based on analytical work by Ricles and Popov [1987] to model isotropic hardening of shear links in steel eccentrically braced frames (EBFs). The EBF isotropic hardening rule used cumulative plastic deformation as the single controlling deformation parameter. The use of two parameters in the ITBE isotropic hardening rule allows for the parameters to be used individually, or in combination. Since the ITBE model allows different yield strengths in tension and compression, compression and tension hardening parameters are also specified separately. Figure 4 illustrates the overall behavior of the isotropic hardening rule.

The hardening rule is used to update the yield force when the ITBE begins to unload elastically, after yielding in a given direction. This means that the tension (positive) yield force is updated when the ITBE is in compression and its incremental deformation changes from negative to positive (see point 2 on Figure 4). As a result, the expression for isotropic hardening of the positive yield force is controlled by the cumulative plastic deformation and/or the maximum negative deformation. The expression defining the new positive (tension) yield force due to isotropic hardening, \( P_{yp,IH} \), is:

\[
P_{yp,IH} = P_{yp,max} - (P_{yp,max} - P_{yp,o}) \left[ \gamma_p \exp \left( - \beta_p \frac{\Delta_{max,n}}{\Delta_{yn}} \right) + (1 - \gamma_p) \exp \left( - \alpha_p \frac{\sum \Delta_{plastic}}{\Delta_{yn}} \right) \right]
\]  

where:

\( P_{yp,max} \) = the maximum positive yield force for the fully saturated isotropic hardening condition,

\( P_{yp,o} \) = the initial positive yield force before isotropic hardening,

\( \alpha_p \) = parameter that controls the positive yield force hardening rate due to cumulative plastic deformation,
β_p = parameter that controls the positive yield force hardening rate due to maximum deformation,

γ_p = weighting parameter for positive yield force hardening,

Δ_y_n = negative yield deformation,

Δ_{max,n} = maximum negative deformation,

ΣΔ_{plastic} = cumulative plastic deformation.

Similarly, the expression defining the magnitude of the new negative (compression) yield force due to isotropic hardening, P_{yn,IH}, is:

\[
P_{yn,IH} = P_{yn,max} - (P_{yn,max} - P_{yn,o}) \left[ \gamma_n \exp\left(-\beta_n \frac{\Delta_{max,p}}{\Delta_{yp}} \right) + (1 - \gamma_n) \exp\left(-\alpha_n \frac{\Sigma\Delta_{plastic}}{\Delta_{yp}} \right) \right]
\]

(2)

where:

P_{yn,max} = the maximum negative yield force for the fully saturated isotropic hardening condition,

P_{yn,o} = the initial negative yield force before isotropic hardening,

α_n = parameter that controls the negative yield force hardening rate due to cumulative plastic deformation,

β_n = parameter that controls the negative yield force hardening rate due to maximum deformation,

γ_n = weighting parameter for negative yield force hardening,

Δ_{yp} = positive yield deformation,

Δ_{max,p} = maximum positive deformation.

ΣΔ_{plastic} = cumulative plastic deformation.

The finite element code for DRAIN-2DX was originally written in FORTRAN. Therefore, Digital Visual FORTRAN was used to modify and compile the new code. DRAIN-
2DX is a modular program, where each element is defined in terms of a particular set of subroutines. In the case of element 01, the following subroutines were modified: INEL01, which defines the input format and storage; FACT01, which carries out the event factor calculation for the element; and RESP01, which performs the response calculation and state determination of the element.

For each ITBE in DRAIN-2DX, eight input parameters are required to define the isotropic hardening behavior. The variables are defined as follows:

\( APP = \) first positive hardening parameter \((\alpha_p\) as defined above), parameter that controls the positive yield force hardening rate due to cumulative plastic deformation;

\( BPP = \) second positive hardening parameter \((\beta_p\) as defined above), parameter that controls the positive yield force hardening rate due to maximum deformation;

\( CPP = \) third positive hardening parameter \((\gamma_p\) as defined above), weighting parameter for positive yield force hardening;

\( APN = \) first negative hardening parameter \((\alpha_n\) as defined above), parameter that controls the negative yield force hardening rate due to cumulative plastic deformation;

\( BPN = \) second negative hardening parameter \((\beta_n\) as defined above), parameter that controls the negative yield force hardening rate due to maximum deformation;

\( CPN = \) third negative hardening parameter \((\gamma_n\) as defined above), weighting parameter for negative yield force hardening;

\( PYPOS\)M = ratio of saturated positive yield force to initial yield force (equal to \( P_{yp,\text{max}} / P_{yp,\text{o}}\));

\( PYNEG\)M = ratio of saturated negative yield force to initial yield force (equal to \( P_{yn,\text{max}} / P_{yn,\text{o}}\)).

The initial and maximum yield force values \((P_{yp,\text{o}}, P_{yp,\text{max}}, P_{yn,\text{o}}\) and \(P_{yn,\text{max}}\)\) and isotropic hardening parameters \((\alpha_p, \beta_p, \gamma_p, \alpha_n, \beta_n \) and \(\gamma_n\)) contained in Equations 1 and 2 should be
determined based on representative experimental data. To use the isotropic hardening option in DRAIN-2DX, isotropic hardening parameters must be specified for each element in an element group. The variable $HCODE$ has been added as a flag to control the isotropic hardening option. The modified ITBE input is structured so that the input for the unmodified ITBE will allow the modified ITBE to function properly. Appendix A contains the revised element description and user guide for the DRAIN-2DX ITBE.

3. Buckling-Restrained Brace Application

As discussed in the introduction, the motivation for modifying the ITBE in DRAIN-2DX was the need to model the behavior of buckling-restrained braces (BRBs) for use in nonlinear analysis of braced frames. To implement the isotropic hardening model described in the previous section, experimental data from isolated BRB tests are required to determine representative parameters. Through regression analysis of the BRB test data, appropriate isotropic hardening parameters can be determined. These parameters can then be used to model similar BRBs.

To extract the pertinent isotropic hardening data from experimental results, the hysteretic behavior should be simplified using a bilinear approximation. Figure 5 illustrates this approximation for typical BRB behavior. Once this simplification has been made, the required data points, as shown in Figure 4, can be extracted. Each new yield force level is associated with the maximum deformation and the cumulative plastic deformation at that point. As stated earlier, this process is conducted separately for positive and negative behavior. After hardening data have been extracted from a cyclic BRB test and increases in the positive and negative yield forces have been associated with the appropriate deformation levels, the required hardening
parameters can be determined through regression. Figure 6 shows the results of regression analysis for a BRB cyclic test.

In order to model BRBs for use in nonlinear time-history analysis of BRBFs [Fahnestock et al. 2003], experimental data from three BRB tests conducted by Merritt et al. [2003] were used to determine representative parameters for the BRB hardening model. The cyclic loading history for these tests is listed in Table 1. It should be noted that deformation levels beyond those listed in Table 1 were explored in the tests by Merritt et al. [2003]. However, these data were not used to calibrate the hardening model since strength increases due to factors other than material behavior were observed. The initial yield forces, $P_{yp,0}$ and $P_{yn,0}$, were based on the BRB test data. The initial positive and negative yield forces were very similar and were defined to be the same. The saturated yield forces, $P_{yp,max}$ and $P_{yn,max}$, and hardening parameters $\alpha$, $\beta$, and $\gamma$ (positive and negative) were determined through regression analysis of the BRB test data. Specifically, these parameters were obtained by minimizing the error between the BRB test data and the analytical expressions describing the isotropic hardening behavior. This procedure was performed numerically using the solver function in Microsoft Excel. Other computer programs, such as TableCurve 2D [Systat 2002], are also capable of performing this type of nonlinear regression analysis. The hardening parameters that were calculated for Specimens 1, 2 and 3 tested by Merritt et al. [2003] are listed in Table 2. As indicated in Table 2, the regression analysis of results for these specimens returned values of zero for both $\gamma_p$ and $\gamma_n$, indicating that the isotropic hardening behavior of these BRBs is best described by using cumulative plastic deformation as the controlling deformation parameter. However, other BRBs may be more accurately modeled by using a combination of both deformation parameters (maximum deformation and cumulative plastic deformation).
It is important to note that the cumulative plastic deformation and maximum deformation effects are not entirely uncoupled. As a result, other values may be calculated for the isotropic hardening parameters depending upon the cyclic loading history of the test that provides the data for the model calibration. The goal of the BRB hardening model calibration is not a precise replication of the hardening behavior for a specific cyclic test, but rather a good overall representation of the BRB strength increase that comes from isotropic hardening.

Figure 6 shows the increase in strength of Specimen 2 due to isotropic hardening. Experimental data are plotted along with the relationships obtained through regression analysis. The relationships defining positive and negative hardening, respectively, are presented below.

\[
\frac{P_{yp,IH}}{P_{yp,o}} = 1.3 - 0.3 \left[ \exp \left( -0.0064 \sum \frac{\Delta_{\text{plastic}}}{\Delta_{yn}} \right) \right]
\]  
\text{(3)}

\[
\frac{P_{yn,IH}}{P_{yn,o}} = 1.6 - 0.6 \left[ \exp \left( -0.013 \sum \frac{\Delta_{\text{plastic}}}{\Delta_{yp}} \right) \right]
\]  
\text{(4)}

In these equations, the yield forces due to isotropic hardening, \(P_{yp,IH}\) and \(P_{yn,IH}\), are normalized by the respective initial yield forces, \(P_{yp,o}\) and \(P_{yn,o}\). Similarly, cumulative plastic deformation is normalized by the negative yield deformation in Equation 3 and by the positive yield deformation in Equation 4. Thus, Figure 6 plots normalized axial force versus normalized cumulative plastic deformation.

As indicated by Equations 3 and 4, and shown in Figure 6, the negative yield force increases more rapidly than the positive yield force. This phenomenon is due to partial transverse confinement of the steel core when the BRB is in compression. The confinement of the core increases the effective material yield stress.
Figure 7 compares experimental data for Specimen 2 with a simulation of the test using the modified DRAIN-2DX ITBE. While the bilinear response of the ITBE cannot capture all aspects of BRB behavior, the strength increase due to isotropic hardening is modeled adequately. The BRB analytical model can be refined by using parallel ITBEs to create trilinear force-deformation behavior that more closely matches the cyclic response of BRBs. However, this refinement is not necessary to capture the strength increase due to isotropic hardening. Appendix B contains the DRAIN-2DX input file used for the analytical simulation of the Specimen 2 experiment.

4. Summary and Conclusions

The current inelastic truss bar element (ITBE) in DRAIN-2DX includes only kinematic hardening behavior. The modified ITBE presented in this report allows for isotropic hardening to be modeled as well. The isotropic hardening rule implemented in the modified ITBE is controlled by maximum total deformation, cumulative plastic deformation, or a combination of the two. Separate hardening parameters may be specified for the ITBE tension and compression forces. Application of the modified ITBE was illustrated through simulation of a cyclic test performed on a buckling-restrained brace (BRB). This simulation demonstrated the ability of the modified ITBE to accurately model the BRB strength increase due to kinematic and isotropic hardening.
References


**Tables**

Table 1 – Cyclic loading history of tests used for calibration [Merritt et al. 2003].

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>Multiple of yield displacement</th>
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<tbody>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
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Table 2 – Isotropic hardening control parameters.

<table>
<thead>
<tr>
<th>Specimen Number*</th>
<th>$P_{y,max}/P_y$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
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<tr>
<td>1</td>
<td>positive</td>
<td>1.4</td>
<td>0.0058</td>
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</tr>
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</tr>
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<td>1.3</td>
<td>0.0070</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>negative</td>
<td>1.6</td>
<td>0.0086</td>
<td>0</td>
</tr>
</tbody>
</table>

*Merritt et al. [2003]*

Figures

Figure 1 – Schematic of a BRB: (a) complete brace; (b) steel core detail.

Figure 2 – Typical BRB cyclic behavior [Merritt et al. 2003].
Figure 3 – DRAIN-2DX ITBE model: (a) parallel components; (b) combined behavior.
Figure 4 – Isotropic hardening behavior implemented in DRAIN-2DX ITBE.
Figure 5 – BRB isotropic hardening: (a) typical behavior; (b) bilinear approximation.

Figure 6 – Isotropic hardening effect for Specimen 2 [Merritt et al. 2003].
Figure 7 – BRB cyclic behavior: (a) experimental data (adapted from Merritt et al. 2003); (b) modified DRAIN-2DX ITBE.
Appendix A: Refined Inelastic Truss Bar Element (Type 01) with Isotropic Hardening for DRAIN-2DX – Element Description and User Guide

E01.1 PURPOSE, FEATURES AND LIMITATIONS

E01.1.1 PURPOSE

This is a simple inelastic bar element. It can be used for truss bars, simple columns, buckling-restrained braces, and nonlinear support springs.

E01.1.2 ELEMENT MODEL

Elements may be oriented arbitrarily in the XY plane, but can transmit axial load only. Two alternative modes of inelastic behavior may be specified, namely (1) yielding in both tension and compression, as shown in Figure E01.2(a), and (2) yielding in tension with elastic buckling in compression as shown in Figure E01.2(b). Kinematic hardening effects are included by dividing each element into two parallel components, one elastic and one elastic-perfectly plastic, as shown in Figure E01.3. Note that only kinematic hardening is illustrated in Figure E01.2. Isotropic hardening is included by modifying the yield forces (tension and compression) based on the total accumulated plastic deformation and/or the maximum deformation. Figure E01.3 schematically illustrates the element behavior when isotropic hardening is included. The expressions that control isotropic hardening are composed of exponential functions, as shown in Equations E01.1.2-1 and E01.1.2-2. In these expressions, PYPOSIH and PYNEGIH are ratios of current yield forces (due to isotropic hardening) to initial yield forces.

\[
PYPOSIH = PYPOSM - (PYPOSM - 1) \left[ (CPP) \exp \left( -BPP \frac{\Delta_{\text{max},n}}{\Delta_{\text{yn}}} \right) + (1 - CPP) \exp \left( -APP \frac{\sum \Delta_{\text{plastic}}}{\Delta_{\text{yn}}} \right) \right]
\]

EQUATION E01.1.2-1

\[
PYNEGIH = PYNEGEM - (PYNEGEM - 1) \left[ (CPN) \exp \left( -BPN \frac{\Delta_{\text{max},p}}{\Delta_{\text{yp}}} \right) + (1 - CPN) \exp \left( -APN \frac{\sum \Delta_{\text{plastic}}}{\Delta_{\text{yp}}} \right) \right]
\]

EQUATION E01.1.2-2

PYPOSM and PYNEGEM are ratios of the maximum yield forces at the fully saturated conditions to the initial yield forces. APP, BPP, CPP, APN, BPN, and BPN are parameters obtained through regression analysis of representative test data. \(\Delta_{\text{max},p}, \Delta_{\text{yp}}, \Delta_{\text{max},n},\) and \(\Delta_{\text{yn}}\) are the maximum and yield deformations for positive and negative behavior, respectively. \(\Sigma\Delta_{\text{plastic}}\) is the total accumulated plastic deformation for the element, equal to the sum of accumulated positive and negative plastic deformations as defined in Figure E01.6.

P-\(\Delta\) effects can be considered.

Static loads applied along the element length, or initial forces due to other causes, can be taken into account by specifying fixed end forces.
**E01.1.3 VISCOUS DAMPING**

If \( \beta K \) damping is specified, a linear viscous damping element is added in parallel with the basic element. The viscous element stiffness is \( \beta \) multiplied by the initial (elastic) stiffness of the element.

The stiffness of the viscous element remains constant for any dynamic analysis, even if the basic element yields. However, the amount of viscous damping can be changed if the structure is in a static state, using the “VS” and/or “VE” options in the *PARAMETERS* input section. These allow the \( \beta \) values to be changed for subsequent dynamic analysis.

If mode shapes and frequencies are calculated (*MODE* analysis), the proportions of critical damping implied by the current \( \beta \) values are shown for each mode in the .OUT file. These proportions should be checked, to make sure that they are reasonable.

The amounts of energy absorbed by the viscous damping elements in each element group are shown in the .SLO (solution log) file. These values should be checked to make sure that they are reasonable. The .SLO file should also be checked to make sure that there is an energy balance. If there is a large difference between the external and the internal energies, the analysis results may be inaccurate.

**E01.1.4 OVERSHOOT TOLERANCE**

If event-to-event analysis is to be used, an overshoot tolerance must be specified. This is a tolerance on the element yield force.

An “event” corresponds to a change in stiffness of an element, due to yield, inelastic unloading, etc. If event-to-event analysis is used, the structure stiffness is reformed at each event. It is usually wise to use even-to-event analysis.

Consider the case where the event is element yield. If a zero value is input for the overshoot tolerance, the event factor is calculated so that the most critical element just yields. If a nonzero value is input, the event factor is chosen so that the force in the element is its yield value plus the tolerance. That is, the element is allowed to “overshoot” beyond its nominal yield value. As a result, there will be an equilibrium unbalance at the event, and the analysis will be less accurate. However, the number of events (stiffness reformulations) may be reduced, because a number of elements may yield in a single analysis substep. In general, a small overshoot tolerance will give a more accurate analysis, but will require more execution time.

The amount of overshoot can be controlled in two ways, first by specifying an overshoot tolerance as part of the element properties, and second by specifying “event overshoot scale factors” with the “F” option in the *PARAMETERS* input section. If no overshoot scale factors are input, these factors default to 1.0, and the overshoot tolerances are scaled by these factors. Separate overshoot scale factors can be input for static and dynamic analyses, and for each element group. The overshoot tolerances can thus be changed at any time, by changing the overshoot scale factors. One way to define overshoot tolerances is to specify a unit value with the element properties, and then control the actual value with overshoot scale factors.

**E01.1.5 ELEMENT LOADS**

Static loads applied along the lengths of an element, or element initial forces, can be taken into account by specifying fixed end forces as shown in Figure E01.5. These are the forces that must act on the element ends to prevent end displacements.

---

\(^\dagger\) Reproduced from Prakash et al. [1993]
### E01.2 INPUT DATA FOR *ELEMENTGROUP

See Figures E01.1, E01.2 and E01.3 for element geometry, properties and behavior.

#### E01.2.1 Control Information

One line.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable (Type)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5(I)</td>
<td></td>
<td>NPROP</td>
<td>No. of property types (min. 1, max. 40). See Section E01.2.2</td>
</tr>
<tr>
<td>6-10(I)</td>
<td></td>
<td>HCODE</td>
<td>Isotropic hardening code, as follows. 0 = isotropic hardening is not considered. 1 = isotropic hardening is considered.</td>
</tr>
</tbody>
</table>

#### E01.2.2 Property Types

NPROP lines, one line per property type.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable</th>
<th>Data</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>Property type number, in sequence beginning with 1.</td>
</tr>
<tr>
<td>6-15(R)</td>
<td></td>
<td>E</td>
<td>Young’s modulus, E.</td>
</tr>
<tr>
<td>16-25(R)</td>
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<td>H</td>
<td>Strain hardening ratio, Eh/E. Must be &gt; 0 and &lt; 1.</td>
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<tr>
<td>26-35(R)</td>
<td></td>
<td>A</td>
<td>Cross section area, A.</td>
</tr>
<tr>
<td>36-45(R)</td>
<td></td>
<td>Syc</td>
<td>Initial yield stress in compression, or buckling stress in compression, Syc.</td>
</tr>
<tr>
<td>46-55(R)</td>
<td></td>
<td></td>
<td>Buckling code, as follows. 0 = yields in compression without buckling. 1 = buckles elastically in compression.</td>
</tr>
<tr>
<td>61-70(R)</td>
<td></td>
<td></td>
<td>Force overshoot tolerance.</td>
</tr>
</tbody>
</table>

NPROP lines, one line per property type.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5(I)</td>
<td></td>
<td>APP</td>
<td>Property type number, in sequence beginning with 1.</td>
</tr>
<tr>
<td>6-15(R)</td>
<td></td>
<td>BPP</td>
<td>First positive hardening parameter.</td>
</tr>
<tr>
<td>16-25(R)</td>
<td></td>
<td>CPP</td>
<td>Second positive hardening parameter.</td>
</tr>
<tr>
<td>26-35(R)</td>
<td></td>
<td>APN</td>
<td>Third positive hardening parameter.</td>
</tr>
<tr>
<td>36-45(R)</td>
<td></td>
<td>BPN</td>
<td>First negative hardening parameter.</td>
</tr>
<tr>
<td>46-55(R)</td>
<td></td>
<td>CPN</td>
<td>Second negative hardening parameter.</td>
</tr>
<tr>
<td>56-65(R)</td>
<td></td>
<td>PYPOSM</td>
<td>Third negative hardening parameter.</td>
</tr>
<tr>
<td>66-70(R)</td>
<td></td>
<td>PYNEGM</td>
<td>Ratio of saturated positive yield force to initial positive yield force.</td>
</tr>
<tr>
<td>71-75(R)</td>
<td></td>
<td></td>
<td>Ratio of saturated negative yield force to initial negative yield force.</td>
</tr>
</tbody>
</table>
E01.2.3 Element Generation Commands

One line for each command.

Elements must be numbered in sequence beginning with 1.
Lines for the first and last elements must be provided. Intermediate elements may be generated.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable (Type)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5(I)</td>
<td></td>
<td></td>
<td>Element number or number of first element in a sequentially numbered series of elements to be generated by this command.</td>
</tr>
<tr>
<td>6-15(I)</td>
<td></td>
<td></td>
<td>Node number at end I.</td>
</tr>
<tr>
<td>16-25(I)</td>
<td></td>
<td></td>
<td>Node number at end J.</td>
</tr>
<tr>
<td>36-40(I)</td>
<td></td>
<td></td>
<td>Property type.</td>
</tr>
</tbody>
</table>
E01.3 INPUT DATA FOR *ELEMENTLOAD

E01.3.1 Load Sets

NLOD lines (see Element Group line of *ELEMENTLOAD section), one line per element load set.

See Figure E01.5 for sign convention.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5(I)</td>
<td></td>
<td></td>
<td>Load set number, in sequence beginning with 1.</td>
</tr>
<tr>
<td>6-10(R)</td>
<td></td>
<td></td>
<td>Coordinate code.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 = forces are in local (element) coordinates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = forces are in global (structural) coordinates</td>
</tr>
<tr>
<td>11-20(R)</td>
<td></td>
<td>Force Pi.</td>
<td></td>
</tr>
<tr>
<td>21-30(R)</td>
<td></td>
<td>Force Vi.</td>
<td></td>
</tr>
<tr>
<td>31-40(R)</td>
<td></td>
<td>Force Pj.</td>
<td></td>
</tr>
<tr>
<td>41-50(R)</td>
<td></td>
<td>Force Vj.</td>
<td></td>
</tr>
</tbody>
</table>

E01.3.2 Loaded Elements and Load Set Scale Factors

As many lines as needed. Terminate with a blank line.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Notes</th>
<th>Variable</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5(I)</td>
<td></td>
<td></td>
<td>Number of first element in series.</td>
</tr>
<tr>
<td>6-10(I)</td>
<td></td>
<td></td>
<td>Number of last element in series. Default = single element.</td>
</tr>
<tr>
<td>16-20(I)</td>
<td></td>
<td></td>
<td>Load set number.</td>
</tr>
<tr>
<td>21-30(R)</td>
<td></td>
<td></td>
<td>Load set scale factor.</td>
</tr>
<tr>
<td>31-45(LR)</td>
<td></td>
<td></td>
<td>Optional second load set number and scale factor.</td>
</tr>
<tr>
<td>46-60(LR)</td>
<td></td>
<td></td>
<td>Optional third load set number and scale factor.</td>
</tr>
<tr>
<td>61-75(LR)</td>
<td></td>
<td></td>
<td>Optional fourth load set number and scale factor.</td>
</tr>
</tbody>
</table>
E01.4 INTERPRETATION OF RESULTS

E01.4.1 Sign Conventions

Tension force and axial extension are positive.

Accumulated plastic deformations are calculated as shown in Figure E01.6

E01.4.2 Event codes

In an event-to-event analysis, the element that governs the event is identified in the .ECH file, with a code that shows the type of event. The event types are as follows.

<table>
<thead>
<tr>
<th>Code</th>
<th>Event type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tension yield.</td>
</tr>
<tr>
<td>2</td>
<td>Compression yield.</td>
</tr>
<tr>
<td>3</td>
<td>Buckling.</td>
</tr>
<tr>
<td>4</td>
<td>Unloading from tension yield.</td>
</tr>
<tr>
<td>5</td>
<td>Unloading from compression yield.</td>
</tr>
<tr>
<td>6</td>
<td>Unloading from buckling.</td>
</tr>
</tbody>
</table>

E01.4.3 Envelope Output (.OUT and .E** files)

E01.4.4 Time History Printout (.OUT file)

E01.4.4 Time History Post-processing (.RXX file)

The following items (8 4-byte words) are output for each element in the .RXX file. To change these output items, see subroutine SAVE01 in the ANAL01.FOR source code file.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Static force.</td>
</tr>
<tr>
<td>2</td>
<td>Viscous force.</td>
</tr>
<tr>
<td>3</td>
<td>Deformation.</td>
</tr>
<tr>
<td>4</td>
<td>Accumulated positive plastic deformation.</td>
</tr>
<tr>
<td>5</td>
<td>Accumulated negative plastic deformation.</td>
</tr>
<tr>
<td>6</td>
<td>Node number at end I.</td>
</tr>
<tr>
<td>7</td>
<td>Node number at end J.</td>
</tr>
<tr>
<td>8</td>
<td>Yield code (0 = not yielded, 1 = yielded or buckled).</td>
</tr>
</tbody>
</table>
FIGURE E01.1 – ELEMENT GEOMETRY

(a) Yield in tension and compression \hspace{1cm} (b) Yield in tension, buckling in compression

FIGURE E01.2 – ELEMENT BEHAVIOR

§ Reproduced from Prakash et al. [1993]
FIGURE E01.3 – ISOTROPIC HARDENING BEHAVIOR

FIGURE E01.4 – PARALLEL COMPONENTS

\[\text{Reproduced from Prakash et al. [1993]}\]
FIGURE E01.5 – FIXED END FORCES

(a) Code = 0 (local)  
(b) Code = 1 (global)

FIGURE E01.6 – ACCUMULATED PLASTIC DEFORMATIONS

Accumulated positive deformation = sum of positive yield excursions

Accumulated negative deformation = sum of negative yield excursions

§ Reproduced from Prakash et al. [1993]
Appendix B: DRAIN-2DX Input File Example

*STARTXX
S250T1  0  0  1  1  1            Star Seismic, Specimen 2, Test 1
!Isolated Brace Test
!Star Seismic, Specimen 2, Test 1
!Test performed at UCSD, November 19-25, 2002
*NODECOORDS
C        1         0         0
C        2       252         0
*RESTRAINTS
S 110         1         1         1
S 010         2         2         1
*ELEMENTGROUP
!Brace
!Element Group 1
  01    1    0         .00000          BRACE
  1
  1  21600  0.018  6.94  36.0  36.0  0  .0001
!Isotropic Hardening Parameters
  1  0.0064         0         0  0.013         0         0 1.32 1.56
!Element generation
  1         1         2              1
*RESULTS
NSD    001
E      001
*NODALOAD
AXIA                                   AXIAL LOAD
  S     1.00         0         0         2         2         1
*PARAMETERS
OS       0    0   -1    0    0
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        2         1    1        .1      0.42
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        1         2    1        .1      0.84
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        2         1    1        .1      1.33
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        1         2    1        .1      1.67
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        2         1    1        .1      1.67
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        1         2    1        .1      1.67
*STAT                                   BRACE AXIAL LOAD
N     AXIA       1.0
D        2         1    1        .1      1.67
*STAT
N  AXIA  1.0  
D  2  1  1  .1  1.67  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  1.67  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  2.43  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  3.22  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  4.07  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  4.88  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  4.88  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  4.88  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  4.06  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  3.25  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  4.61  
*STAT
N  AXIA  1.0  
D  1  2  1  .1  6.12  
*STAT
N  AXIA  1.0  
D  2  1  1  .1  6.12  

BRACE AXIAL LOAD
<table>
<thead>
<tr>
<th>N</th>
<th>AXIA</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>AXIA</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>N</td>
<td>AXIA</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>AXIA</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>N</td>
<td>AXIA</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>