Monotonic and Cyclic Simulation of Screw-Fastened Connections for Cold-Formed Steel Framing

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ABSTRACT

This thesis introduces an approach for modeling the monotonic and cyclic response of cold-formed steel framing screw-fastened connections in commercial finite element programs. The model proposed and verified herein lays the groundwork for seismic modeling of cold-formed steel (CFS) framing including shear walls, gravity walls, floor and roof diaphragms, and eventually whole building seismic analysis considering individual fastener behavior and CFS structural components modeled with thin-shell elements. An ABAQUS user element (UEL) is written and verified for a nonlinear hysteretic model that can simulate pinching and strength and stiffness degradation consistent with CFS screw-fastened connections. The user element is verified at the connection level, including complex cyclic deformation paths, by comparing to OpenSees connection simulation results. The connection model is employed in ABAQUS shear wall simulations of recent monotonic and cyclic experiments where each screw-fastened connection is represented as a UEL. The experimental and simulation results are consistent for shear wall load-deformation response and cyclic strength and stiffness degradation, confirming the validity of the UEL element and demonstrating that light

steel framing performance can be directly studied with simulations as an alternative to experiments.

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Go Hokies!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Cold-Formed Steel Structures

Cold formed steel (CFS) is manufactured by rolling thin steel sheets into specific shapes. With the development of first design specification in 1946, cold-formed steel structure has been widely designed and constructed in the U.S. In recent decades, cold-formed steel has been proved to be an efficient and low-cost solution to low-rise and mid-rise buildings. In comparison to other types of structures, cold-formed steel structure normally has shorter construction period and lower cost because of standardized subsystem components. However, despite widespread usage, the behavior of cold-formed steel structure under seismic loads and subsystem interactions have not been fully understood, and performance-based seismic design methods have not been fully applied to cold-formed steel structure.

1.2 Cold-Formed Steel Framed Shear Walls

Cold-formed steel (CFS) framed shear wall is a subsystem of cold-formed steel structure, composed of cold-formed steel framing members and sheathing boards. The connections between framing members and sheathing boards are created by mechanical fasteners. These fastened connections ensure that framing members and sheathing boards can work together under loads. As the main lateral force resisting system, cold-formed steel framed shear walls are critical to structural seismic performance. But so far CFS framed shear wall failure mechanisms are still not very clear and high-fidelity computational modeling of CFS framed shear walls is needed for further research.

1.3 CFS-Sheathing Connections

The cold-formed steel (CFS) – sheathing connection is the key component in a CFS framed shear wall subsystem. Under cyclic loading, the sequential failures of CFS-sheathing connections control the overall shear wall behavior. Therefore, to perform high-fidelity computational modeling of a CFS framed shear wall, the CFS-sheathing connection behaviors need to be effectively simulated. However, the CFS-sheathing connection hysteretic behavior is complicated, involving pinching and degradation. This thesis develops a new element to provide an effective solution to simulate this behavior in commercial finite element software.

1.4 Research Objective

Sheathed shear walls are typically the main lateral force resisting system in cold-formed steel structures. Despite their importance in lateral resistance, high-fidelity computational modeling of CFS framed shear walls is a challenge. The key to achieving high-fidelity modeling is simulating CFS-sheathing connection behavior in a commercial finite element software. Thus, the research objective herein is to propose a CFS-sheathing connection model which fully simulates connection behavior and can be easily applied to CFS framed shear wall model in ABAQUS. A flowchart as shown in Fig. 1.1 describes this motivation. Hopefully, this CFS-sheathing connection model can be a stepping stone towards more in-depth research on CFS framed shear walls with simulation as an alternative to experiments.

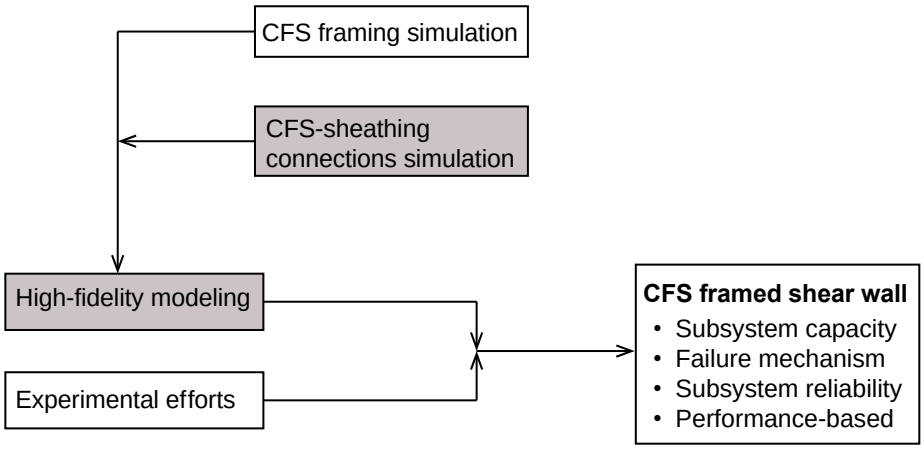


Fig. 1.1. Research objective flow chart

1.5 Thesis Organization

This thesis begins with Chapter 1, the Introduction, which introduces cold-formed steel framing and describes the research objective. Chapter 2, Literature Review, summarizes past experimental and numerical research on CFS framed shear walls, and concludes with a plan for taking converting a pinching material model in OpenSees to commercial FEA software. Chapter 3 introduces the Pinching4 material model. Chapter 4 then explains the approach used to move the OpenSees Pinching4 material into ABAQUS. Chapter 5 validates the Pinching4 material simulation results obtained from ABAQUS against OpenSees results. Chapter 6 demonstrates how UEL can be applied to shear wall modeling in ABAQUS. Finally, some conclusions and suggestions for future work can be found in Chapter 7.

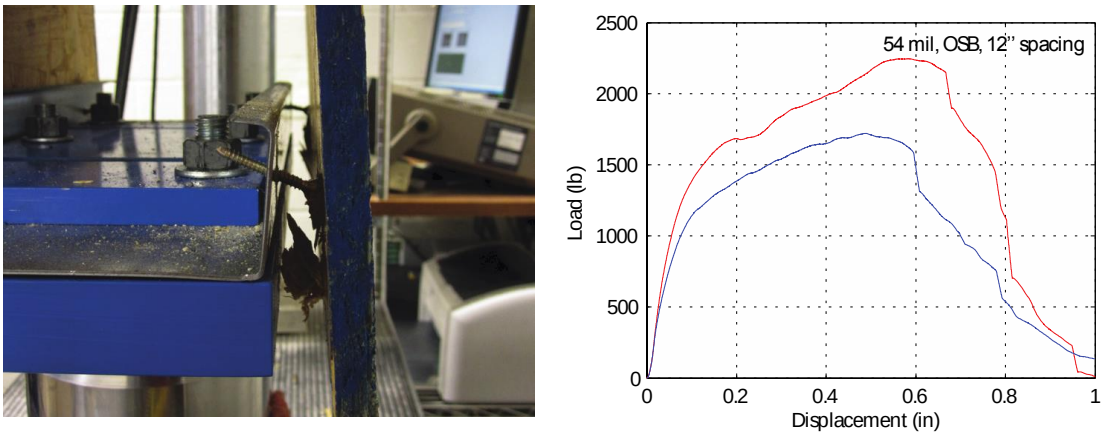
CHAPTER 2 LITERATURE REVIEW

2.1 Experimental Studies

In order to fully understand the behavior of cold-formed steel buildings under seismic excitation, a full-scale cold-formed steel building was tested on a shake table (Peterman et al. 2014) as shown in Fig. 2.1. The full-scale cold-formed steel building tests proved the building to be stiffer and stronger than what it was designed for. Even though the building response was only the combined behaviors of all building subsystems, the individual behaviors and their interactions were a challenge to characterize, highlighting the important need for performance-based design methods applicable to cold-formed steel structures.

Fig. 2.1. Full-scale CFS framed building seismic test. Peterman, K., Stehman, M., Buonopane, S., Nakata, N., Madsen, R., and Schafer, B. (2014). "SEISMIC PERFORMANCE OF FULL-SCALE COLD-FORMED STEEL BUILDINGS.", Tenth U.S. National Conference on Earthquake Engineering, Anchorage, Alaska. Used under fair use, 2015.

It has been shown with experiments and simulations that cold-formed steel to sheathing connections dictates shear wall behavior (Buonopane et al. 2014; Liu et al. 2012; Moen et al. 2014). Experimental research (Peterman and Schafer 2013) as shown in Fig. 2.2 was conducted on CFS-sheathing connections to characterize their hysteretic response. In this research, 24 cold-formed steel to sheathing connections were tested varying sheathing materials, steel ply thickness and fastener spacing to study their influences. The test results were fitted to Pinching4 material model. The fitted Pinching4 material model served as important input for shear wall numerical studies.



(a) **(b)**

Fig. 2.2. CFS-sheathing connection test and monotonic response

2.2 Numerical Studies

2.2.1 CASHEW model

CASHEW stands for "Cyclic Analysis of Shear Walls" (Folz and Filiatrault 2000). It is software written for wood framed shear wall. In this software, framing

members were modeled as rigid members with pin-ended connections. As result, the framing system deformed as a system and provided no lateral stiffness. It was also assumed that shear wall out-of-plane deformation could be ignored. From these assumptions, the equilibrium equation were formulated by the principle of virtual work. Only the virtual work contribution from sheathing and connections were considered.

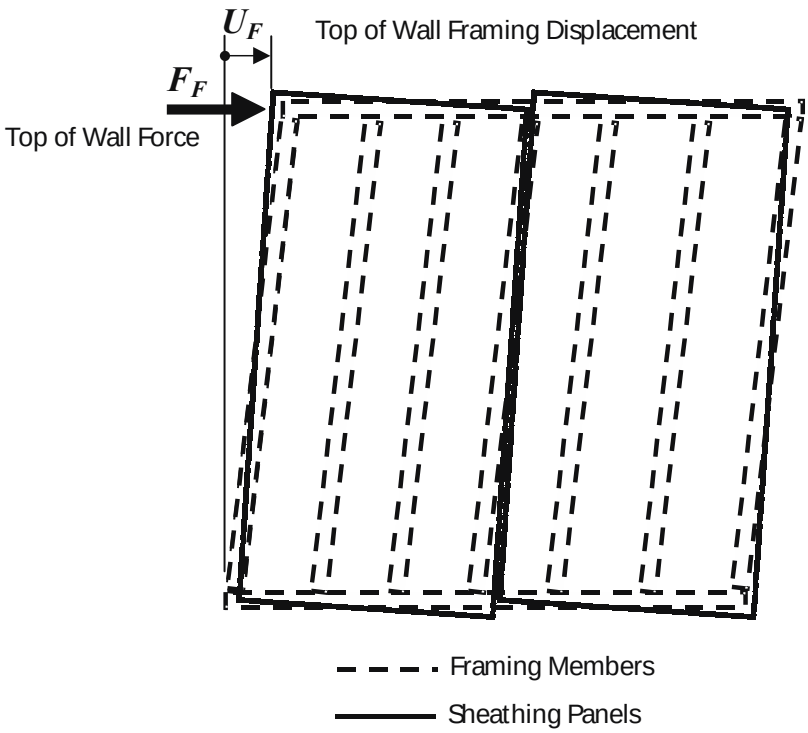


Fig. 2.3. Shear wall model deformation model in CASHEW

Framing-sheathing connection were defined with a hysteresis model originally proposed by (Foschi 1974). The hysteresis model can simulate pinching behavior with strength and stiffness degradation. Connections were modeled as a pair of orthogonal uncoupled springs both assigned with this hysteresis model. The reason behind this modeling approach results from the complexity of connector behavior. The deformation

trajectory of a connector under a monotonic analysis of the shear wall was found to be almost unidirectional and a single nonlinear spring was supposed to be suitable for monotonic analysis (Folz and Filiatrault 2000). However, under cyclic analysis, the connector displacement trajectory was bi-directional making it difficult to differentiate positive and negative connection displacement. To avoid this displacement sign issue, uncoupled spring pair model was adopted in CASHEW.

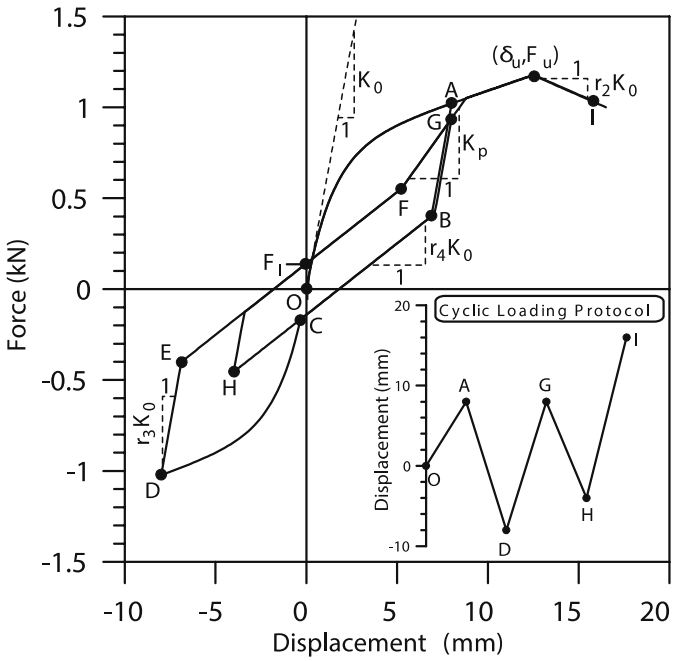
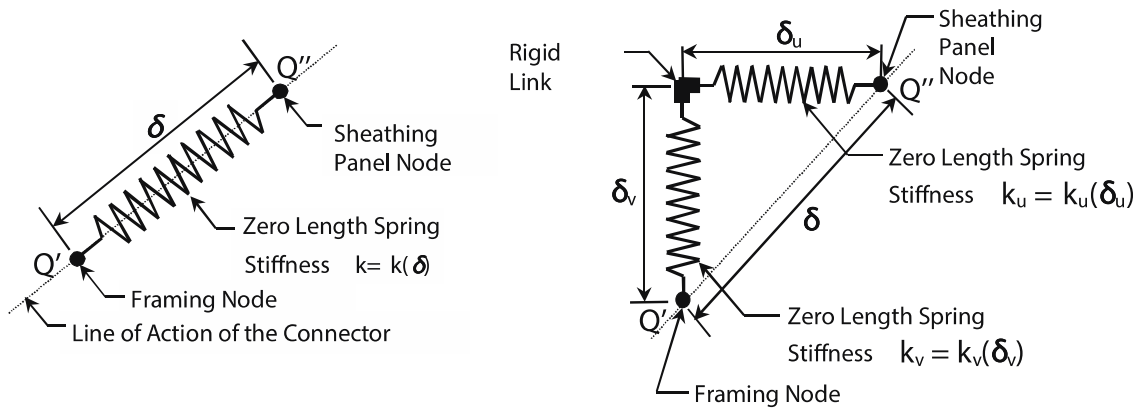


Fig. 2.4. Connection hysteresis model adopted in CASHEW

This modeling approach results in an overestimation of connection strength and stiffness. An internal adjustment strategy was adopted inside the program to overcome this obstacle. The strategy reduced the connector spacing, and therefore the number of connections, to match the energy absorbed in a monotonic analysis by the two-spring model with energy in the one-spring model (Folz and Filiatrault 2000). With this

adjustment, connection strength and stiffness overestimation was alleviated but not generally solved.



(a) **(b)**

Fig. 2.5. (a) Single spring model (b) Uncoupled spring pair model

CASHEW used displacement control and the Newton-Raphson method to find shear wall load-deformation response. It was found that the shear wall global tangent stiffness can become non-positive definite and the solution strategy would sometimes struggle to converge. To overcome this numerical issue, CASHEW internally added an axial spring at the top of shear wall to ensure that combine global tangent stiffness remained positive definite during analysis (Ramm 1981).

2.2.2 OpenSees model

Two CFS framing modeling approaches have been tried out in OpenSees. One approach is modeling CFS framed shear wall by X braces. This approach requires full-scale shear wall testing to provide parameter input for X braces. An incremental dynamic analysis model (Leng et al. 2013) was created in OpenSees that predicts time-history

response of CFS building under seismic executions. In this model, CFS framed shear walls were modeled as X braces. The braces were assigned with the Pinching4 material to simulate the hysteresis response of CFS framed shear walls. The Pinching4 material parameters were fitted from full-scale shear wall tests (Liu et al. 2012a).

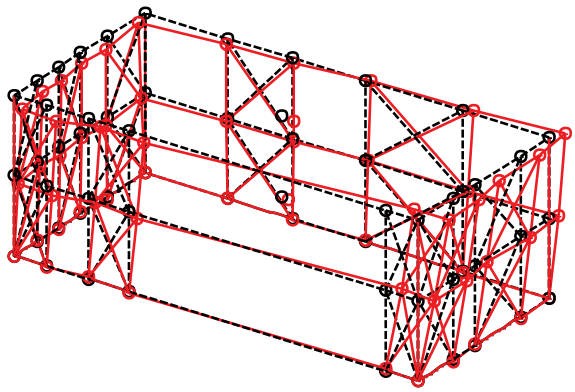


Fig. 2.6. OpenSees CFS framed building model

Another modeling approach is fastener-based modeling. This approach is inspired by the discovery that CFS framed shear wall load-deformation curves highly resemble CFS-sheathing connections. The principle is to include all CFS-sheathing connections on shear walls to the shear wall model. The total shear wall response is the combined behavior of CFS-sheathing connections, CFS framing and sheathing boards. One advantage of this approach is that only CFS-sheathing connection tests are needed to provide input for connection models. Models featuring monotonic and cyclic analysis have been well studied in OpenSees (Bian et al. 2014; Buonopane et al. 2014). In these OpenSees models (Fig.), the CFS-sheathing connections were modeled using CoupledZeroLength element (Fig.). Pinching4 material was assigned to the CoupleZeroLength elements to include connection hysteretic behaviors. Two features

make this element very suitable for modeling CFS-sheathing connections. CoupledZeroLength element is a single shear spring capable of rotating its orientation in the plane of the shear wall. Therefore, the connection strength and stiffness are not overestimated in comparison to the uncoupled spring pair model discussed in previous section. Also, CoupledZeroLength determines connection positive and negative displacement by element orientation. This ensures that positive and negative displacement can be differentiated for a bidirectional trajectory.

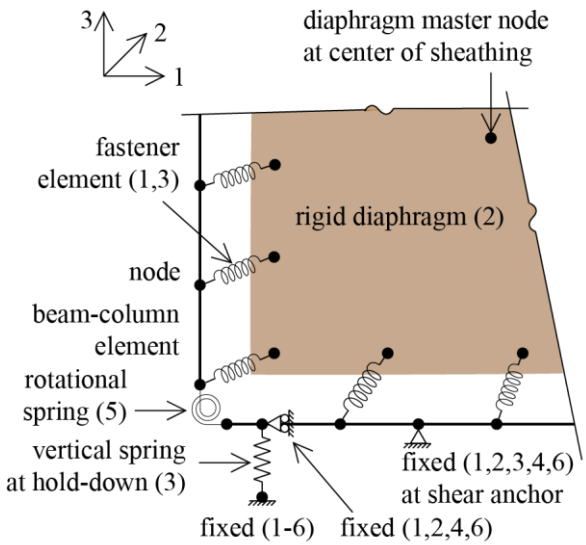


Fig. 2.7. CFS framed shear wall model in OpenSees

However, due to limitations of OpenSees, the behavior of CFS members cannot be directly included in the analysis and sheathing flexibility is not well simulated. In order to obtain more in-depth view of CFS shear wall behavior, a high-fidelity model with freedom to include all members is needed.

2.2.3 ABAQUS model

To study shear wall failure mechanisms, Ngo (2014) developed some high-fidelity models of CFS framed shear walls. Monotonic analysis were performed on shear wall models and results were verified against shear wall test data (Liu et al. 2012a).

One important breakthrough of these models is directly modeling CFS framing members and sheathing boards by shell elements. In these models, cold-formed steel framing members and sheathing boards were modeled using 4-node shell element S4R in ABAQUS. Finer meshing was applied to cold-formed steel members while wood-sheathing panels were coarsely meshed.

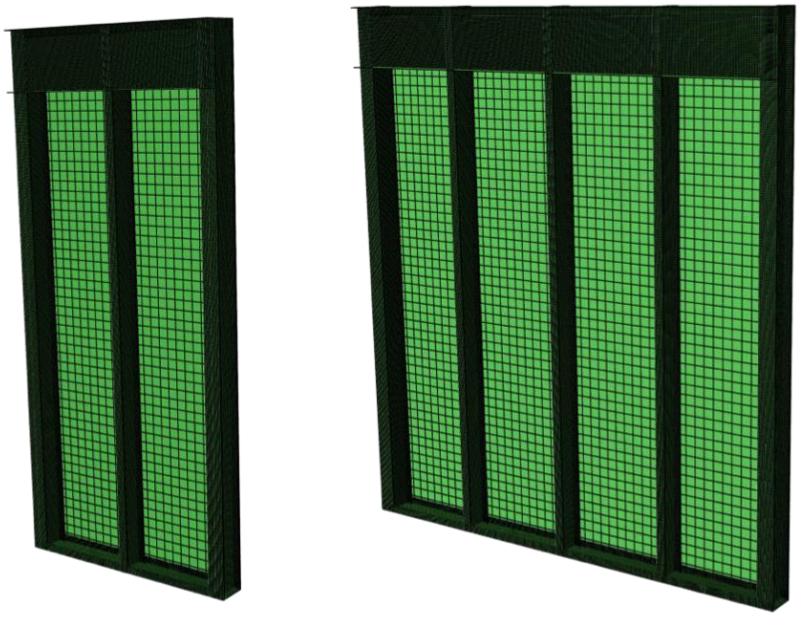


Fig. 2.8. High-fidelity model of CFS framed shear wall in ABAQUS

Another breakthrough is modeling the CFS-sheathing connections by SPRINGA elements (Fig.). SPRINGA is a 2-node axial spring element in ABAQUS. Two important features make it suitable for modeling CFS-sheathing connections. Unlike conventional spring elements, SPRINGA considers geometric nonlinearity. This means that its line of action can be rotated during analysis instead of being fixed to X, Y or Z directions. This feature avoids overestimation of connection strength and stiffness. Also, some level of material nonlinearity is included in this model (Fig. 2.9).

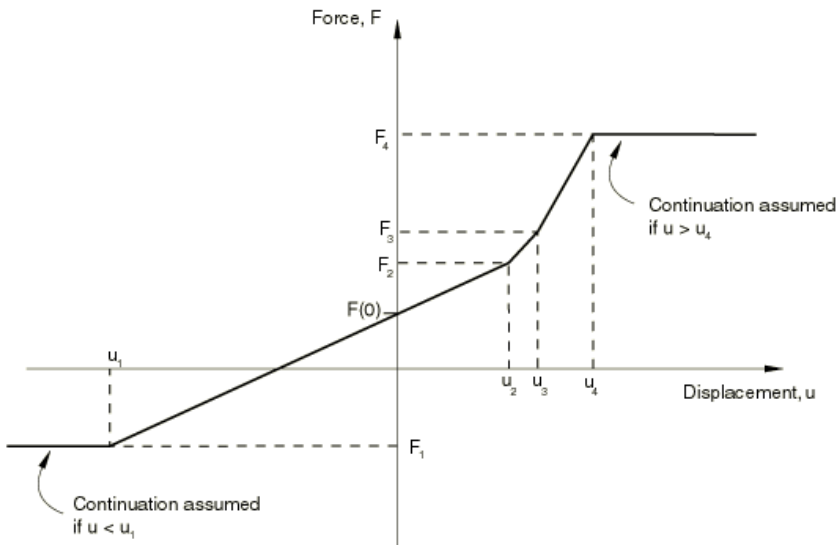


Fig. 2.9. Nonlinear spring force–relative displacement relationship

However, shear wall model with CFS-sheathing connections modeled by SPRINGA can only be used for monotonic analysis. Due to software limitations, complete CFS-sheathing connection hysteresis cannot be defined in SPRINGA. With no unloading and reloading paths defined, a shear wall model cannot achieve convergence under cyclic loading. Besides, CFS-sheathing connection is normally modeled by a single SPRINGA element (Ngo 2014). Therefore the SPRINGA displacement trajectory will be

bidirectional making it not possible to define positive and negative displacement. No special algorithm is provided in SPRINGA to address this issue. To achieve high-fidelity modeling applicable to both monotonic and cyclic analysis, ABAQUS needs an extension that incorporates complete CFS-sheathing connection hysteresis and algorithm resolving this bidirectional trajectory issue. The OpenSees Pinching4 model parameters and implementation are introduced in the next chapter to prepare the reader for its mapping to ABAQUS in Chapter 5.

CHAPTER 3 PINCHING4 FORMULATION IN OPENSEES

3.1 Pinching4 Material

Pinching4 is an OpenSees material model that some CFS researchers used for calibrating CFS-sheathing connection tests (Bian et al. 2014; Ngo 2014; Peterman and Schafer 2013). The calibrated Pinching4 material parameters can represent realistic CFS-sheathing hysteretic response curves (Fig.) which serve as a key input for computational modeling of CFS framed shear walls.

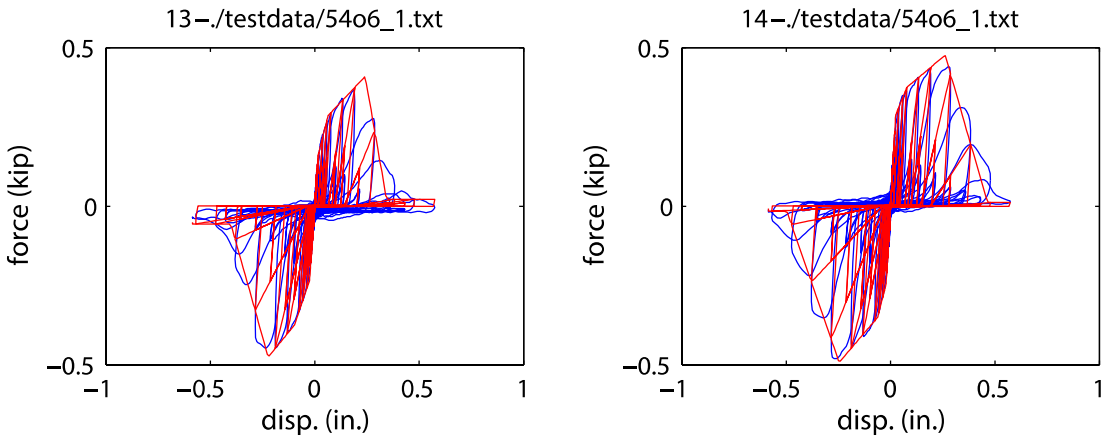


Fig. 3.1. CFS-sheathing connection test results against calibrated Pinching4 hysteresis

Pinching4 is a one-dimensional material model written by Lowes et al. (2003) and implemented in OpenSees (Mazzoni et al. 2006). Nonlinearity is included in this model by a set of rules that control the shape of hysteresis. This model is evolutionary in updating its strength envelope and unloading/reloading paths during analysis. These two features make Pinching4 very suitable for simulating CFS-sheathing connection behavior.

3.2 Backbone Curve and Pinching Path

The Pinching4 material backbone curve is multilinear. The multilinearity allows freedom for users to fully include the nonlinearity of CFS-sheathing connections hysteresis. Both positive and negative branches need to be defined which allows the Pinching4 backbone curve to be asymmetrical (Padilla-Llano et al. 2014). In total, 16 parameters are needed for defining a Pinching4 backbone curve. A typical Pinching4 backbone is shown in Fig. 3.2. The Pinching4 behavior is simulated by pinching paths. The pinching paths define material reloading and unloading paths. The pinching paths are not only controlled by user input parameters. Material loading history also affect the pinching path shapes. Depending on the material maximum deformation and minimum deformation, the pinching paths can be linear, bilinear or trilinear. There are six parameters required for defining pinching paths.

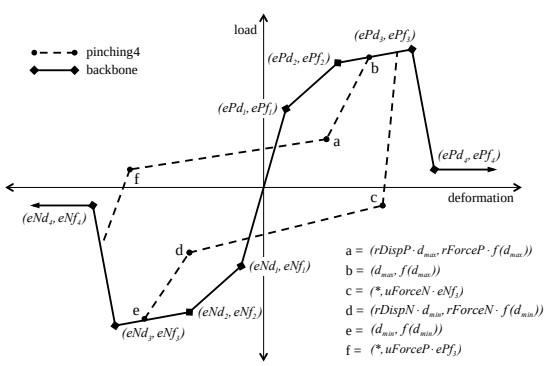


Fig. 3.2. Pinching4 material backbone curve and pinching paths

3.3 Pinching4 States

3.3.1 State definition

In Pinching4 material, there are four states, State 1, State 2, State 3 and State 4 (Fig. 3.3). Each state represents a set of material behavior. State 1 represents material being loaded in the way that follows the backbone positive branch and State 2 represents the backbone negative branch. The load path boundaries of State 1 and State 2 are two points on the backbone curve corresponding to maximum and minimum deformation respectively. State 3 and State 4 are reloading and unloading cases where all pinching and degradation behaviors occur. For State 3 and State 4, the load paths can be trilinear, bilinear or a straight line depending on load-deformation history. The boundaries of State 3 and State 4 are the maximum and minimum load-deformation points reached on backbone curve.

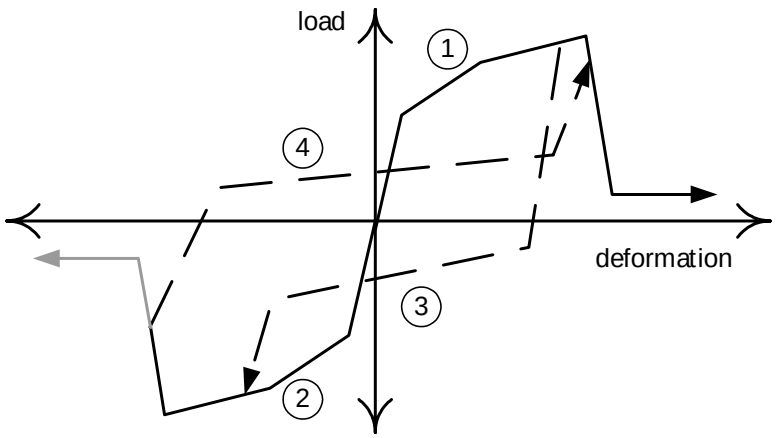


Fig. 3.3. Pinching4 material states

3.3.2 State change

It is unlikely that a material is always loaded in one state. State change will occur when loading direction is reversed or the material is loaded beyond the state boundaries. When a state change occurs, the material behaviors in the new state will be used in analysis. It is worth noting that certain state changes also trigger strength and stiffness degradation.

Different states have different conditions for triggering state change. For State 1 and State 2, state change can occur only when there is reverse in loading direction. For State 3 and State 4, both loading direction reversal and loading beyond state boundaries can trigger state change. The state after state change is determined by certain rules as shown in Fig. 3.4.

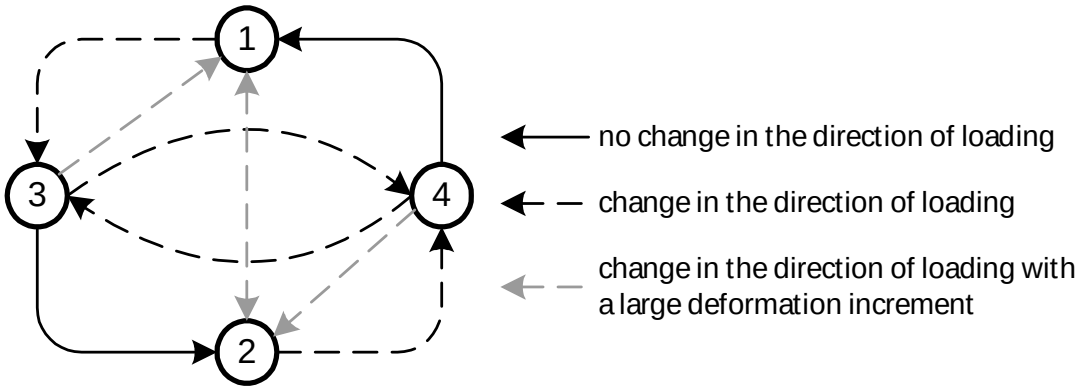


Fig. 3.4. State change rules

3.4 Degradation

In the Pinching4 material, damage rules were included to simulate material deterioration. The deterioration includes unloading/reloading stiffness degradation and

strength degradation. The amount of material degradation is determined by damage index as shown in Eq. 3.1.

$$\delta_i = \gamma_1 (d_{\max})^{\gamma_3} + \gamma_2 \left(\frac{E_i}{E_{monotonic}} \right)^{\gamma_4} < \gamma_{\lim} \tag{3.1}$$

i	=	current increment number
δ_i	=	degradation index at increment i
γ_1	=	degradation parameter 1
γ_2	=	degradation parameter 2
γ_3	=	degradation parameter 3
γ_4	=	degradation parameter 4
γ_{lim}	=	degradation parameter limit
d_{max}	=	maximum portion of failure displacement ever encountered
E_i	=	hysteretic energy at current increment i
$E_{monotonic}$	=	total energy achieved if loaded along backbone curve to failure
δ_{ki}	=	unloading stiffness degradation index at increment i
δ_{di}	=	reloading stiffness degradation index at increment i
δ_{fi}	=	strength degradation index at increment i

With damage index calculated, degradation can be easily applied to loading/unloading stiffness and strength degradation.

For unloading stiffness degradation:

$$k_i = k_0 \left(1 - \delta_{ki}\right) \tag{3.2}$$

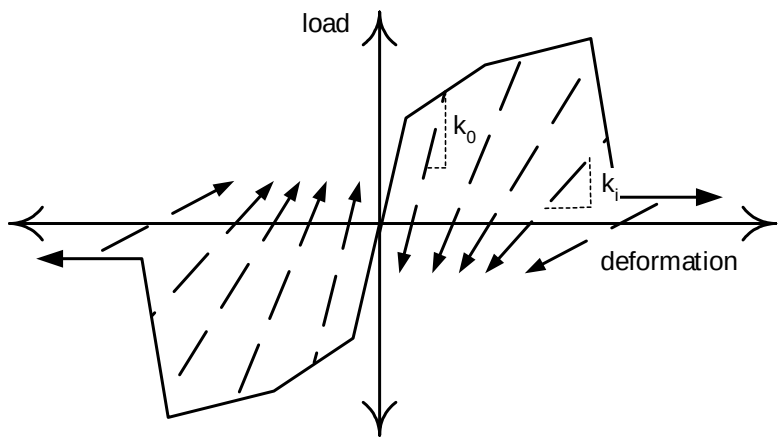


Fig. 3.5. Unloading stiffness degradation

For reloading stiffness degradation:

$$d_{\max i} = d_{\max 0} \left(1 + \delta_{di}\right) \tag{3.3}$$

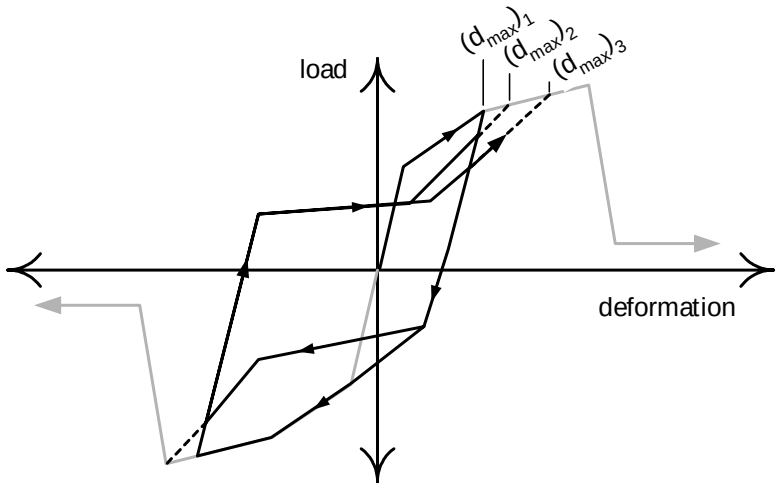


Fig. 3.6. Reloading stiffness degradation

For strength degradation:

$$f_{\max i} = f_{\max 0}\left(1-\delta_{fi}\right) \tag{3.4}$$

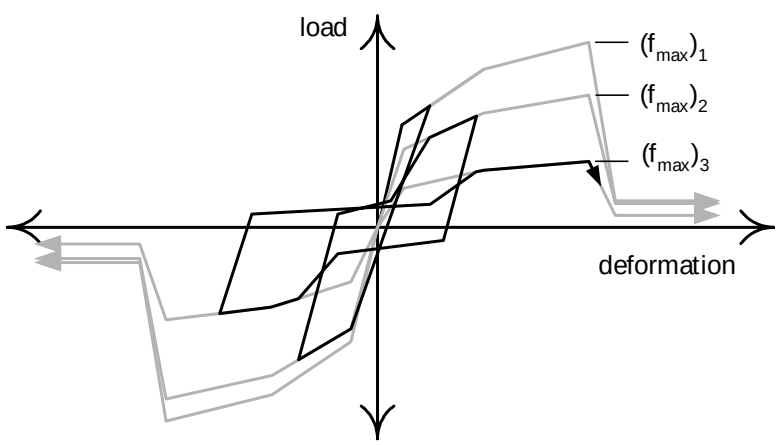


Fig. 3.7. Strength degradation

CHAPTER 4 CONVERTING PINCHING4 TO ABAQUS

4.1 General

As discussed in Chapter 2, current high-fidelity modeling of CFS framed shear walls in ABAQUS is inhibited by the fact that ABAQUS does not have suitable material or element for modeling CFS-sheathing connections. This chapter introduces a user element subroutine (UEL) which brings the Pinching4 material into ABAQUS.

4.2 ABAQUS User Element Subroutine (UEL)

4.2.1 Introduction to user element subroutine (UEL)

ABAQUS has a comprehensive element library. However, there are still some types of elements not available in its element library, especially elements with a special purpose. To overcome this limitation, ABAQUS allows users to define their own elements by programming a user element subroutine (UEL). A UEL is a FORTRAN program written specifically for ABAQUS. Like other ABAQUS elements, user elements can be defined and assigned from an input file. The only difference is that no visualization is provided for user elements in the ABAQUS Viewer.

4.2.2 Linking UEL to ABAQUS

A user element subroutine (UEL) is not a standalone program that can conduct finite element analysis. It needs to be linked to ABAQUS. Once linked, UEL will be called every time when ABAQUS needs information from the UEL (Fig. 4.1). In each call by ABAQUS, the UEL will be provided with element geometry information (coordinates, displacement and etc.), UEL properties, and solution-dependent variables

from the last increment and analysis procedures. By using the information provided by ABAQUS, the UEL calculates and returns to ABAQUS a Jacobian matrix and force residuals contributed by the UEL and the updated solution-dependent variables. Solution-dependent variables are carried in a vector where users can save data to be used in the next increment. It is the only way that element loading history can be retrieved.

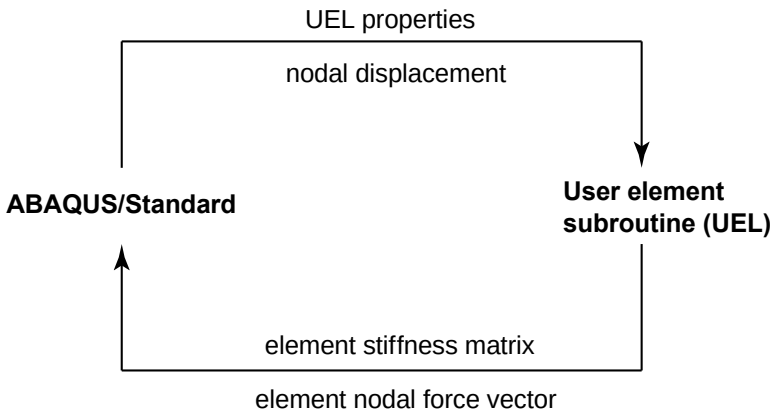


Fig. 4.1. Work flow of ABAQUS and UEL

4.3 Pinching4 Implementation in UEL

4.3.1 UEL framework

In order to model nonlinearity of screw-fastened connections, the Pinching4 model is implemented inside the UEL. The implementation is made possible by three important sections in the UEL (Fig. 4.2). A local subroutine is coded to calculate element deformation and orientation based on geometric information from ABAQUS. Given the element deformation, the Pinching4 model returns element force and stiffness. With the element force and stiffness, several local subroutines return element nodal force vector

and stiffness matrix. Table 4.1 lists the local subroutines responsible for the functions discussed above.

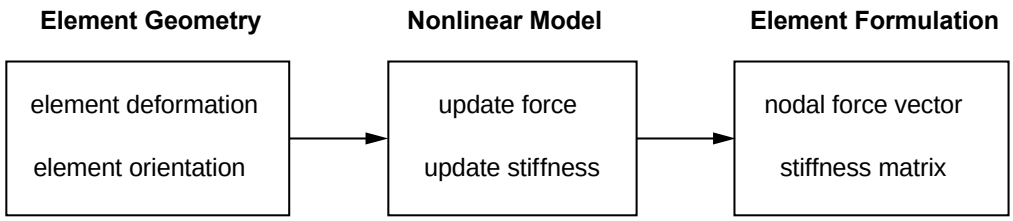


Fig. 4.2. Work flow of computation inside UEL

Table 4.1. Local subroutines used in the UEL

Subroutine	Output
SGEOM(…)	Return spring deformation, orientation
PINCHING4(…)	Return spring force and stiffness
SAMATRX(…)	Return element stiffness matrix
SNFORCE(…)	Return element nodal force vector

4.3.2 Pinching4 material implementation

As shown in Table 4.1, the local subroutine PINCHING4 is where the Pinching4 model is directly implemented. C++ source code of the Pinching4 model from OpenSees was translated into FORTRAN. A few modifications were made to fit ABAQUS coding style (implicit variable declaration).

As noted in Section 4.2, using solution-dependent variables is the only way to retrieve loading history. To implement the evolutionary load paths and damage rules, all Pinching4 variables are saved into solution-dependent variable vector (SVARS) at the end of each increment so that these parameters can be retrieved in the next increment.

Table 4.2. Local Pinching4 model subroutines

Subroutines	Output
SUEL2PIN(…)	Converts data from soultion-depedent variable vector to Pinching4 local variables
SPIN2UEL(…)	Converts data from Pinching4 local variables to solution-depedent variable vector
SetEnvelop(…)	Sets the initial backbone envelope for the material based upon the input by the user
revertToStart(…)	Initialization process for the material at start
revertToLastCommit(…)	Return back to its last committed state in case the analysis fails
setTrialStrain(…)	Sets a displacement demand of the material based upon its previous stiffness and also the residual force vector return
commitState(…)	Commits the history variables of the material model after the state-check has been done for the material model
getstate(…)	Determines the state of the material based upon the material history and current stress demand
posEnvlpStress(…) negEnvlpStress(…)	Returns positive/negative damaged stress of the material
posEnvlpTangent(…) negEnvlpTangent(…)	Returns positive/negative tangent of the material
Envlp3Stress (…) Envlp4Stress (…)	Determines the stress of the envelope at state 3 or state 4 of the material
Envlp3Tangent (…) Envlp4Tangent (…)	Determines the tangent of the envelope at state 3 or state 4 of the material
updateDmg(…)	Apply stiffness and strength degradations

4.3.3 Element formulation

Screw-fastened connections are idealized as axial springs. The shear behaviors of screw-fastened connections are simulated as tension or compression of axial springs. The complicated nonlinearity is condensed into the constitutive load-deformation relationship in the axial springs. There are many spring models proposed by researchers for simulating fastened connections. Some of them have already been utilized for fastener-based shear wall or diaphragm analysis. Based on these spring models, a new spring model is proposed here for simulating screw-fastened connections overcoming previous modeling limitations.

In total four spring models are implemented in the UEL as described in the following paragraphs. Any of these models can be selected for simulating screw-fastened connections. The objective is to provide users with flexibility in simulations. All these spring models are intended to only simulate connection shear behavior. Fastener withdrawal behaviors are not considered here and can be a topic for future study. Therefore, all of the spring models work in 2-dimensional plane – sheathing or diaphragm plane. Because ABAQUS allows user element to have 3D coordinates but only 2D degree-of-freedoms, the UEL proposed herein can still be used for 3D analysis in ABAQUS.

Model 1 - Uncoupled two-spring model

Uncoupled two-spring model is a model composed of two orthogonal springs aligned in the global X and Y directions. Each spring is assigned with Pinching4 material of the same properties.

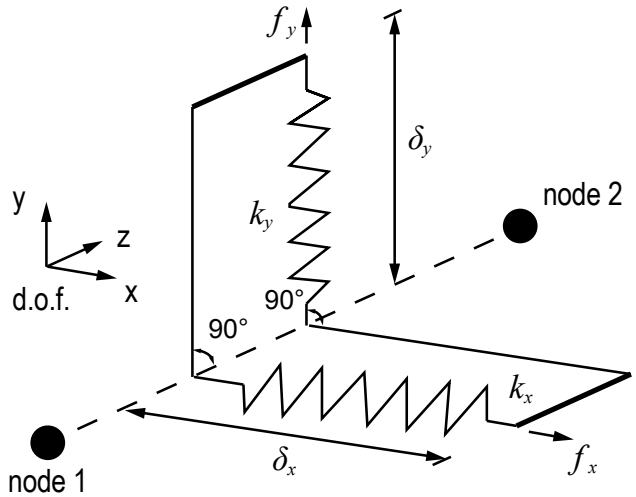


Fig. 4.3. Uncoupled two-spring model

The force resultant of two springs represents the connection resisting force. The stiffness matrix **K** and nodal force vector **F** are shown below.

$$\mathbf{K} = \begin{bmatrix} k_x & 0 & -k_x & 0 \\ 0 & k_y & 0 & -k_y \\ -k_x & 0 & k_y & 0 \\ 0 & -k_y & 0 & k_y \end{bmatrix} \tag{4.5}$$

$$\mathbf{F} = \begin{Bmatrix} -f_x \\ -f_y \\ f_x \\ f_y \end{Bmatrix} \tag{4.6}$$

The advantage of the two-spring model is that it is very “stable”. The spring orientations are fixed in global X and Y directions so that divergence induced by spring changing orientation is not a big concern. The disadvantage is overestimation of connection strength and stiffness.

Model 2 - Oriented spring pair model

Oriented spring pair model is an improved version of uncoupled two-spring model proposed by Judd (Judd and Fonseca 2005) to alleviate strength and stiffness overestimation. Still, each spring is assigned with the Pinching4 material model of the same properties. Compared to the uncoupled two-spring model, two orthogonal springs are not oriented towards the global X and Y directions. Instead, spring orientations are determined based on the initial spring deformation trajectory. In practice, in the 1st increment, uncoupled two-spring model is used. The spring deformation (δ_{x0}, δ_{y0}) from the 1st increment is then utilized to establish spring orientations for all the following increments.

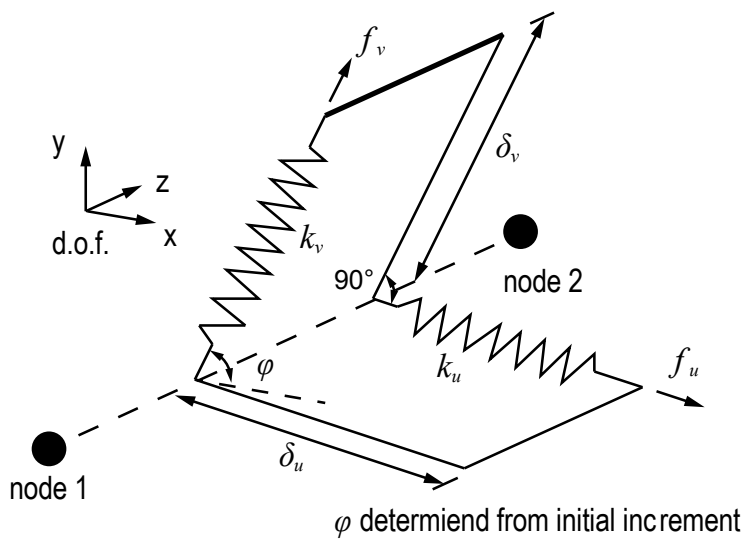


Fig. 4.4. Oriented spring pair model

With spring orientations established, the element stiffness matrix **K** and nodal force vector **F** can be written as

$$\mathbf{K} = \begin{bmatrix} K_{11} & K_{12} & -K_{11} & -K_{12} \\ K_{12} & K_{22} & -K_{12} & -K_{22} \\ -K_{11} & -K_{12} & K_{11} & K_{12} \\ -K_{12} & -K_{22} & K_{12} & K_{22} \end{bmatrix} \tag{4.7}$$

where

$$K_{11} = K_u \cos^2 \varphi + K_v \sin^2 \varphi \tag{4.8}$$

$$K_{12} = K_u \cos\varphi \sin\varphi - K_v \cos\varphi \sin\varphi \tag{4.9}$$

$$K_{22} = K_u \sin^2 \varphi + K_v \cos\varphi^2 \tag{4.10}$$

$$\mathbf{F} = \begin{Bmatrix} F_u \cos\varphi - F_v \sin\varphi \\ F_u \sin\varphi + F_v \cos\varphi \\ -F_u \cos\varphi + F_v \sin\varphi \\ -F_u \sin\varphi - F_v \cos\varphi \end{Bmatrix} \tag{4.11}$$

Model 3 - Coupled two-spring model

Coupled two-spring model is a spring model available in OpenSees named CoupledZeroLength. It is a pair of orthogonal coupled springs aligned in global X and Y directions. In contrast to uncoupled two-spring model and oriented spring pair, only a Pinching4 material model is assigned. Instead of spring deformation in global X and Y directions, the spring deformation resultant is input to the Pinching4 material model which outputs the spring force resultant. The coupling between X and Y directions are achieved by transforming spring force to X and Y directions as shown in equation (4.13). However, though with coupling, the spring stiffness matrix is in the uncoupled format as shown in equation (4.12).

$$\mathbf{K} = \begin{bmatrix} k & 0 & -k & 0 \\ 0 & k & 0 & -k \\ -k & 0 & k & 0 \\ 0 & -k & 0 & k \end{bmatrix} \tag{4.12}$$

$$\mathbf{F} = \begin{Bmatrix} -f\cos\varphi \\ -f\sin\varphi \\ f\cos\varphi \\ f\sin\varphi \end{Bmatrix} \tag{4.13}$$

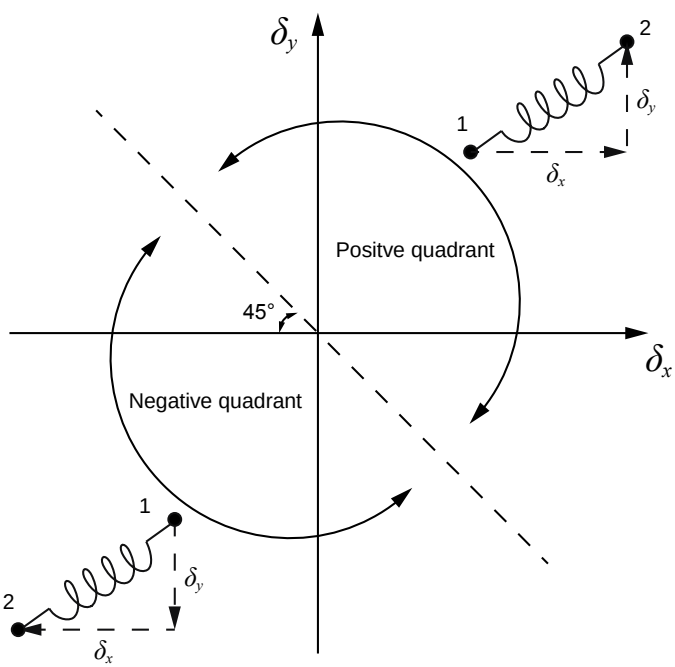


Fig. 4.5. Deformation quadrants of coupled two-spring model

Model 4 - Radial spring model

The radial spring model is a single spring model capable of updating its orientations in an analysis. Previous research indicated that single spring model is very suitable in simulating connection behavior.

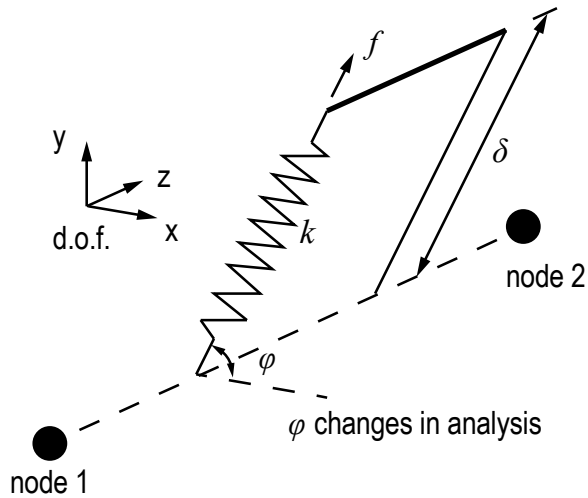


Fig. 4.6. Radial spring model

However, because single spring model cannot simulate "bi-directional" or cyclic deformation, this model is not applied to cyclic analysis. In order to simulate bi-directional deformation, a radial spring adopts a set of deformation quadrants so that "positive" and "negative" spring deformation can be differentiated. This set of deformation quadrants is an improved version of its counterpart in the coupled two-spring model. Instead of being divided by X+Y=0 line, deformation quadrants are divided based on spring initial deformation trajectory. Assuming that spring deformation trajectory does not change over a 90° angle, the quadrant division line is orthogonal to the initial spring deformation trajectory.

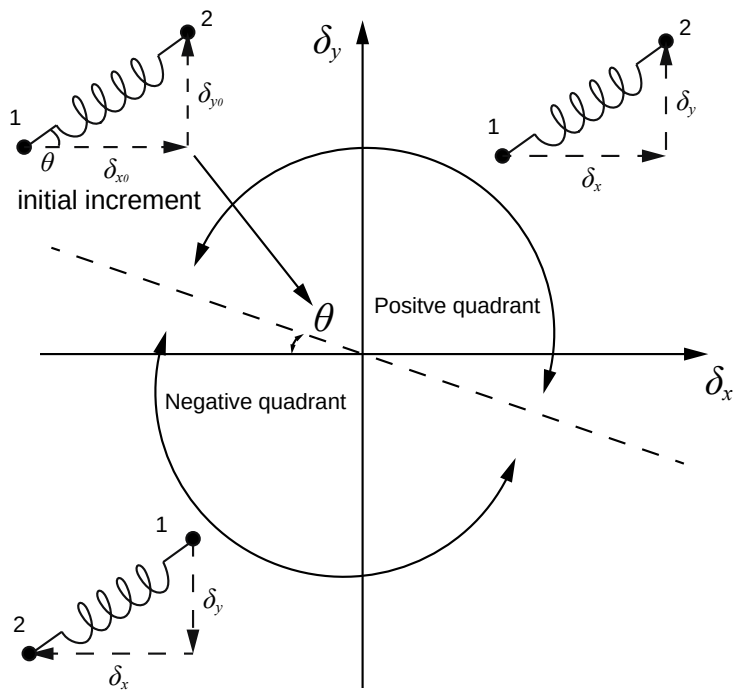


Fig. 4.7. Deformation quadrants of radial spring

Because geometric nonlinearity will be activated in high fidelity shear wall modeling, spring element geometric nonlinearity need to be included. This is accomplished by corotational formulation (De Borst et al. 2012). Corotational formulation allows the spring element to update its orientation at each increment.

The element stiffness matrix **K** is calculated as

$$\mathbf{K} = \mathbf{K_e} + \mathbf{K_g} \tag{4.14}$$

Conventional stiffness matrix $\mathbf{K_e}$ is calculated by

$$\mathbf{K_e} = \begin{bmatrix} k\cos^2\varphi & k\cos\varphi\sin\varphi & -k\cos^2\varphi & -k\cos\varphi\sin\varphi \\ k\cos\varphi\sin\varphi & k\sin^2\varphi & -k\cos\varphi\sin\varphi & -k\sin^2\varphi \\ -k\cos^2\varphi & -k\cos\varphi\sin\varphi & k\cos^2\varphi & k\cos\varphi\sin\varphi \\ -k\cos\varphi\sin\varphi & -k\sin^2\varphi & k\cos\varphi\sin\varphi & k\sin^2\varphi \end{bmatrix} \tag{4.15}$$

Geometric stiffness matrix [K_g] is calculated by

$$\mathbf{K_g} = \begin{bmatrix} f/l & 0 & -f/l & 0 \\ 0 & f/l & 0 & -f/l \\ -f/l & 0 & f/l & 0 \\ 0 & -f/l & 0 & f/l \end{bmatrix} \tag{4.16}$$

The nodal force vector **F** is calculated by

$$\mathbf{F} = \begin{Bmatrix} -f\cos\varphi \\ -f\sin\varphi \\ f\cos\varphi \\ f\sin\varphi \end{Bmatrix} \tag{4.17}$$

where

k	=	spring axial stiffness
f	=	spring axial force
l	=	spring current length
φ	=	angle between spring deformation and global X axis

The user element proposed here is a combination of Pinching4 nonlinear hysteretic model and spring element formulation. The four spring models described above are all attached with Pinching4 model. The only difference is spring element formulation, to be clear, element stiffness matrix and element nodal force vector. In the next chapter, the Model 4 (radial spring model) is selected to be attached with Pinching4 model for verification.

Model 5 – Modified radial spring model

It is found that allowing spring to change its orientation can create divergence issues in shear wall cyclic analysis. Changes in spring orientation combined with spring hysteretic model nonlinearity presents a numerical challenge. In order to solve the divergence issue, the element formulation in the original UEL is modified. Instead of being a zero length element free to rotate its orientation, the element orientation is "locked" in the prescribed direction. The direction is determined based on the orientation that element establish in elastic state. The spring orientation "locking" only occurs after connection begins yielding corresponding to Pinching4 backbone after the first curve "leg". This modification is based on the assumption that certain amount damage on the steel-to-sheathing connection will create a deformation path on the sheathing. Connection displacement along this deformation path has the lowest potential energy. Thus, any connection displacement is assumed to follow this deformation path. In summary, before connection begins yielding, the spring remains radial spring capable of rotating its orientation. After the connection begins yielding, the spring "locks" its orientation and changes into modified radial spring. Still only spring is used in order to avoid overestimation of strength and stiffness. It is assumed that screw during testing is relatively "locked" along the sheathing damaged trajectory.

The spring orientation is actually numerically "locked" by assigning a relatively large length in the spring orientation calculation as shown in Eq. 4.18 and Eq. 4.19.

$$\cos\varphi = (\delta_x + \delta_{x0}) / \sqrt{(\delta_x + \delta_{x0})^2 + (\delta_y + \delta_{y0})^2} \tag{4.18}$$

$$\sin\varphi = (\delta_y + \delta_0) / \sqrt{(\delta_x + \delta_{x0})^2 + (\delta_y + \delta_{y0})^2} \tag{4.19}$$

where

$$\delta = \sqrt{(\delta_x + \delta_{x0})^2 + (\delta_y + \delta_{y0})^2} - \sqrt{\delta_{x0}{}^2 + \delta_{y0}{}^2}$$

$$\delta_{x0} >> \delta_x, \ \delta_{y0} >> \delta_y$$

CHAPTER 5 ABAQUS CONNECTION UEL VERIFICATION

5.1 Verification Methodology

In order to ensure a successful implementation of the Pinching4 model in ABAQUS, the proposed ABAQUS user element (UEL) is verified against OpenSees. For this purpose, two sets of parameters are selected for validating backbone, pinching path and degradation features in Pinching4 model. The results from ABAQUS and OpenSees are compared at the end of the chapter.

5.2 Verification of Backbone and Pinching Path

5.2.1 Verification model

A screw-fastened steel to OSB connection is modeled to validate the backbone and the pinching path. The connection is modeled as Zerolength element in OpenSees and UEL (Model 4 - radial spring) in ABAQUS. In the OpenSees model, Pinching4 material is assigned as a Zerolength element. In ABAQUS, Pinching4 modeled is already included in the UEL. As shown in Fig. 5.1, for the spring element, the node 1 is restrained at the degree-of-freedoms of UX, UY. The node 2 is only restrained at UY allowing the cyclic loading protocol to be applied at UX.

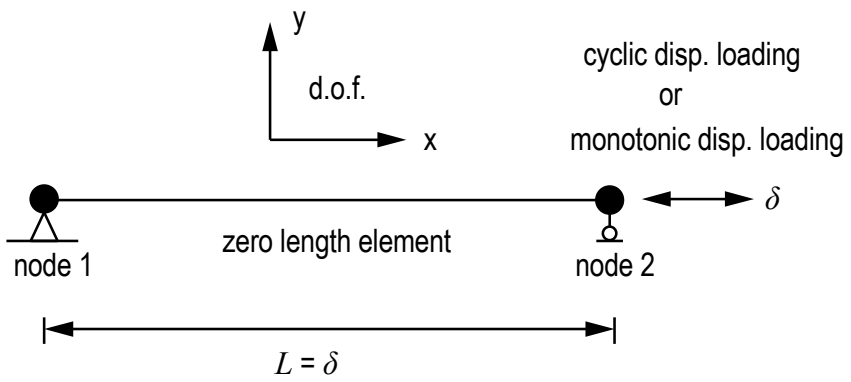


Fig. 5.1. UEL verification model

In total, 6 CFS-sheathing connection tests are simulated respectively in ABAQUS and OpenSees. All Pinching4 model parameters and loading protocols are taken from steel-to-OSB connection test data (Peterman and Schafer 2013). Pinching4 backbone and pinching path parameters used in the verification models can be found in Table A.1 and Table A.2. For this verification, degradation parameters are set to be zero. The cyclic loading protocol with unit peak displacement is shown in Fig. 5.2.

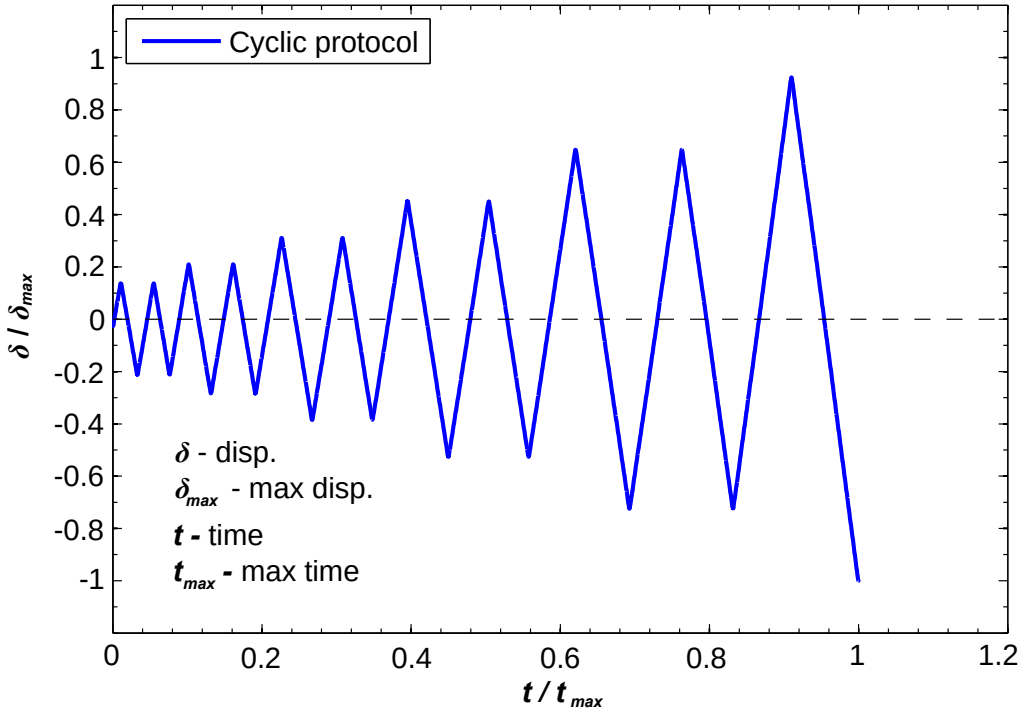
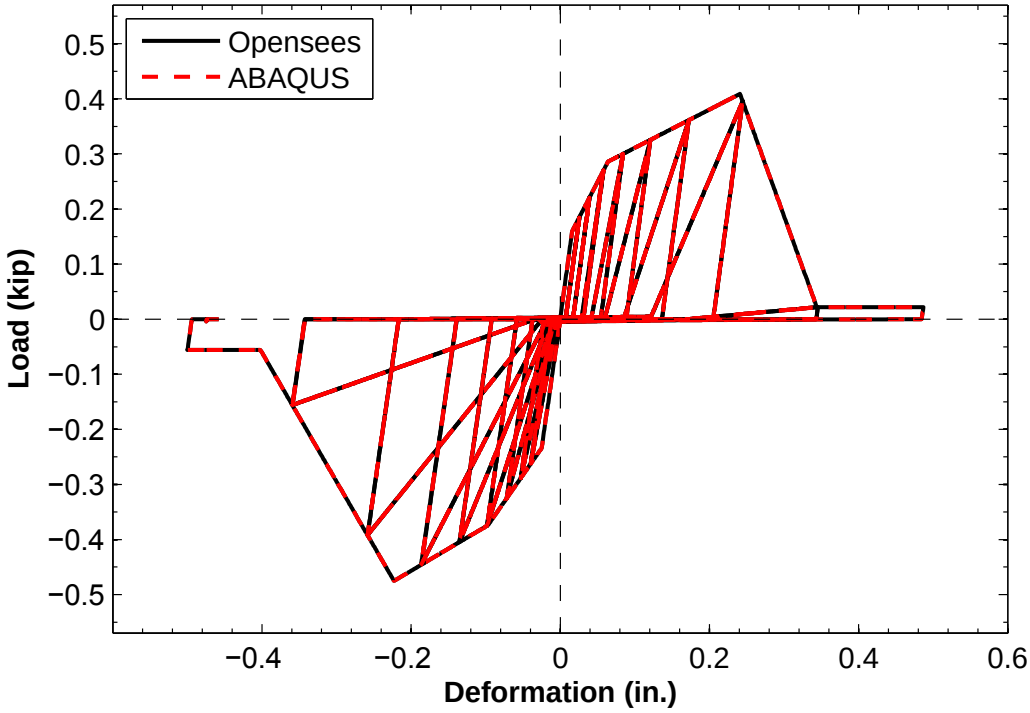


Fig. 5.2. Cyclic loading protocol

5.2.2 ABAQUS results against OpenSees

The simulation results from ABAQUS are compared to OpenSees.

Fig. 5.3 shows simulation of 54 mils to 7/16 in. OSB connection with 6 in. spacing. It can be shown that connection hysteresis ABAQUS closely match OpenSees. The energy-cycle curve is also shown to provide a closer look. The figures of remaining verification cases are listed in Appendix A. Therefore, Pinching4 model backbone and pinching paths are successfully implemented in ABAQUS.



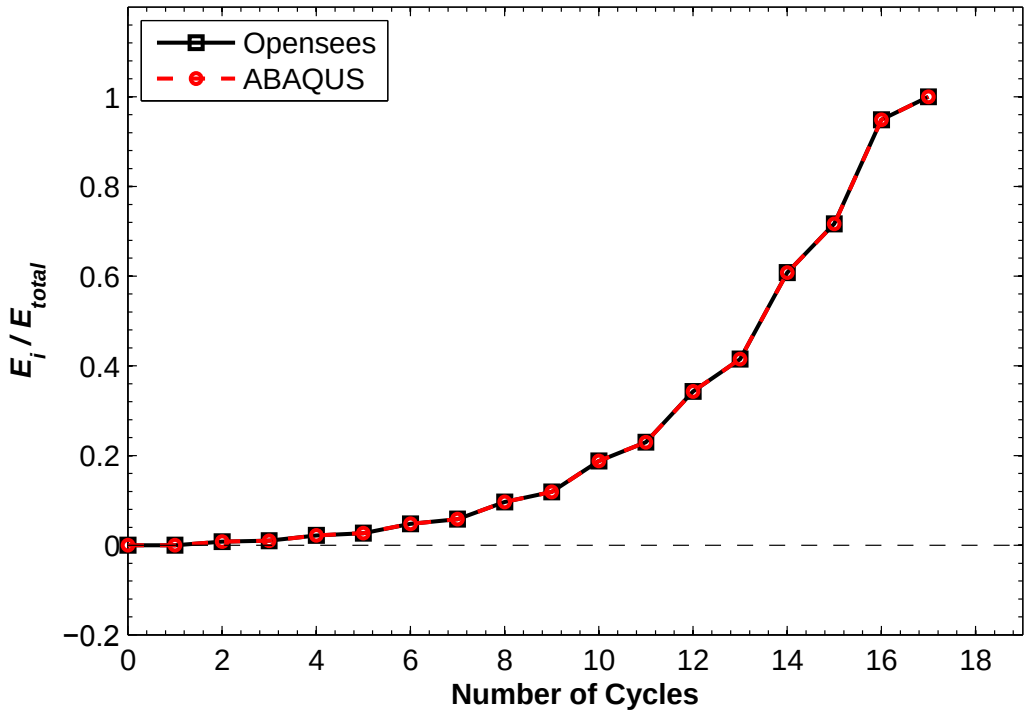


Fig. 5.3. Verification case c54o6_1 (a) Load-deformation (b) Energy-cycle

5.3 Verification of Degradation

5.3.1 Verification model

Because the degradation parameters are all zero in the previous section, another group of Pinching4 parameters are used here to validate the degradation features in UEL. The degradation parameters generated randomly instead of being fitted to specific connection tests. The newly added degradation parameters can be found in (Table A.5). For simplification, the verification model is still the same as the one in the previous section. The same loading protocols are used.

5.3.2 ABAQUS Results in Comparison to OpenSees

The figures below show hysteretic curves of 3 degradation cases, unloading stiffness degradation, reloading stiffness degradation and strength degradation. The ABAQUS simulation results are compared with OpenSees. As shown in Fig. 5.4, degradation cases are well simulated in ABAQUS. In each case, ABAQUS hysteretic curves overlap on OpenSees meaning that ABAQUS simulation results match OpenSees. Thus, Pinching4 degradation is successfully converted into ABAQUS.

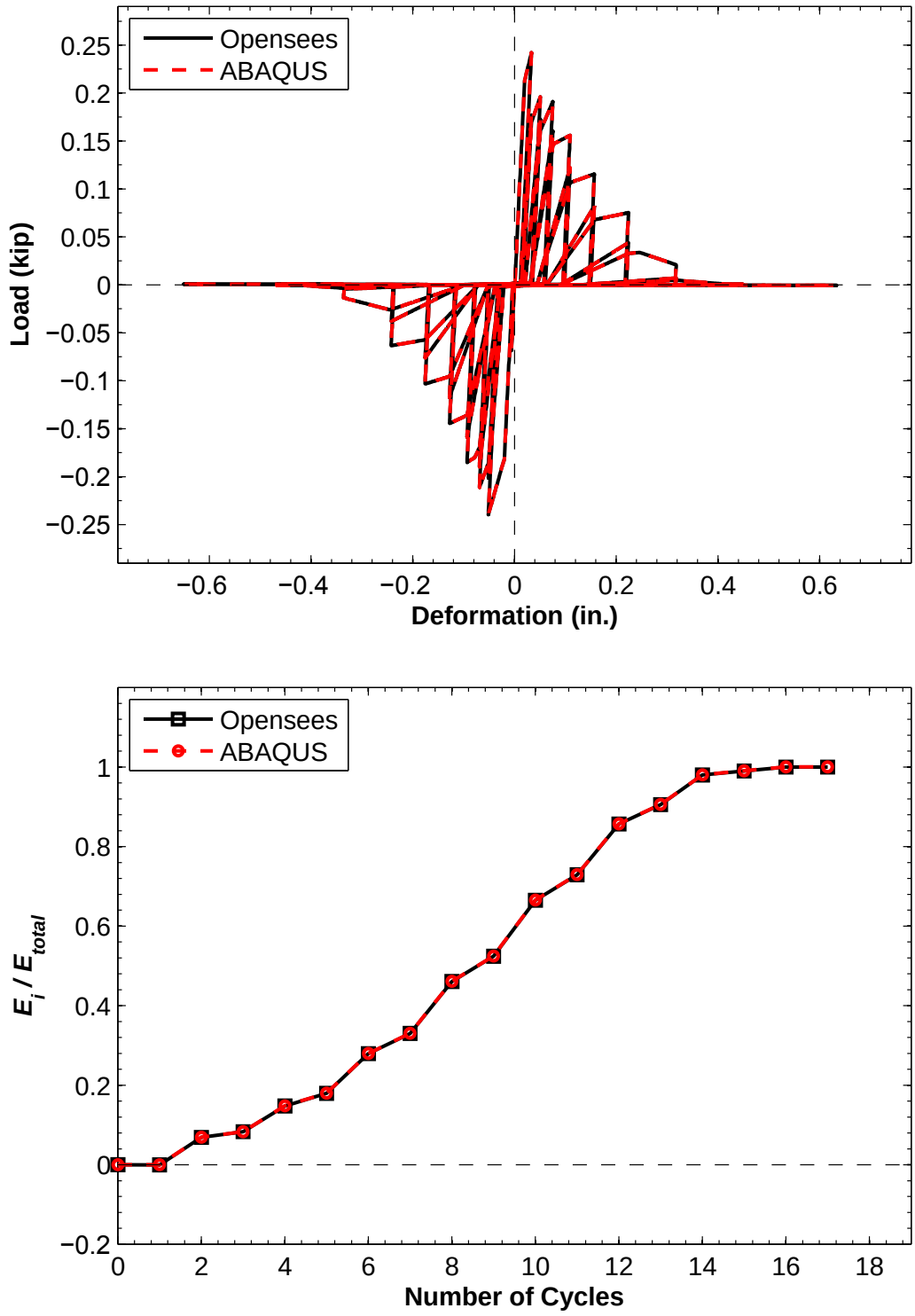


Fig. 5.4. Strength degradation verification case (a) Load-deformation (b) Cycle-energy

5.4 Simulations of Screw-Fastened Steel-to-OSB Connections

With Pinching4 model successfully converted into ABAQUS, the UEL proposed here can be applied to simulating any type of screw-fastened connections once given calibrated Pinching4 parameters. The connection nonlinearity can be represented by the hysteretic nonlinearity in Pinching4 model. And relative displacement at the connection can be simulated by reasonable spring element formulation. This allows the UEL to be utilized in fastener-based shear wall or diaphragm modeling. In this section, three types of screw-fastened steel-to-OSB connections with different configurations are simulated in ABAQUS by UEL. The single-element model from the previous sections are used.

Table 5.1. Positive backbone parameters of steel-to-OSB connections

Model	ePd_1	ePd_2	ePd_3	ePd_4	ePf_1	ePf_2	ePf_3	ePf_4
	(in.)				(kip)			
c33o6	0.020	0.084	0.254	0.493	0.160	0.300	0.380	0.026
c54o6	0.020	0.078	0.246	0.414	0.220	0.350	0.460	0.049
c97o6	0.011	0.039	0.082	0.158	0.200	0.390	0.450	0.028

Table 5.2. Negative backbone parameters of steel-to-OSB connections

Model	eNd_1	eNd_2	eNd_3	eNd_4	eNf_1	eNf_2	eNf_3	eNf_4
	(in.)				(kip)			
c33o6	-0.020	-0.084	-0.254	-0.493	-0.160	-0.300	-0.380	-0.026
c54o6	-0.020	-0.078	-0.246	-0.414	-0.220	-0.350	-0.460	-0.049
c97o6	-0.011	-0.039	-0.082	-0.158	-0.200	-0.390	-0.450	-0.028

Table 5.3. Pinching path parameters of steel-to-OSB connections

Model	*rDispP*	*rForceP*	*uForceP*	*rDispN*	*rForceN*	*uForceN*
c33o6	0.410	0.010	0.001	0.410	0.010	0.001
c54o6	0.420	0.010	0.001	0.420	0.010	0.001
c97o6	0.290	0.010	0.001	0.290	0.010	0.001

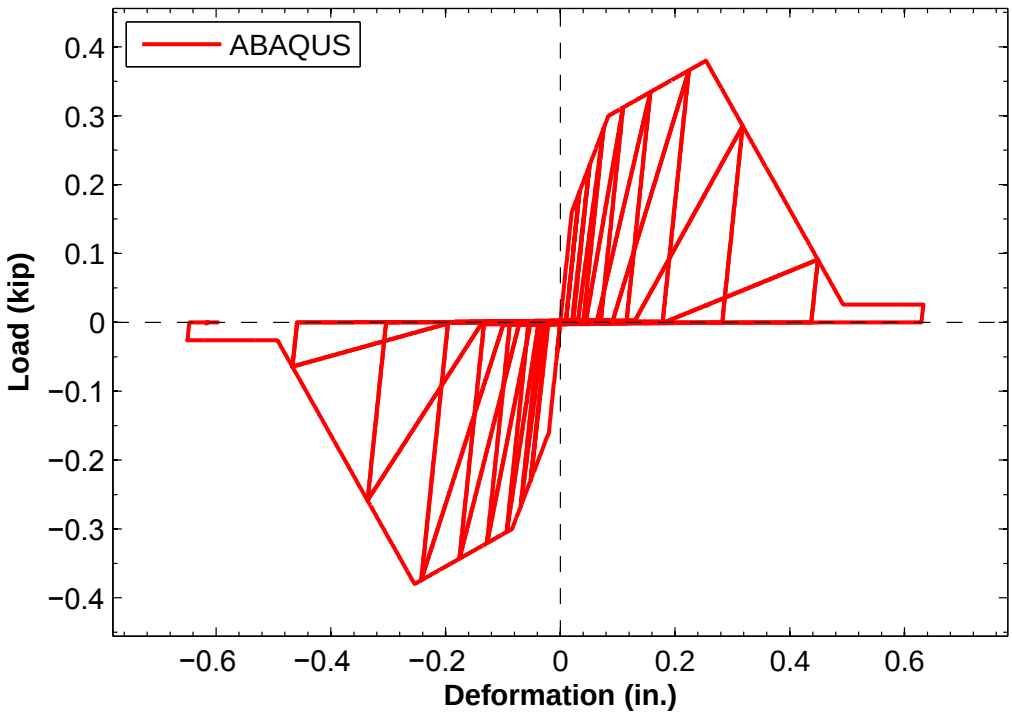


Fig. 5.5. Simulation of screw-fastened connections: 33 mils to 7/16'' OSB

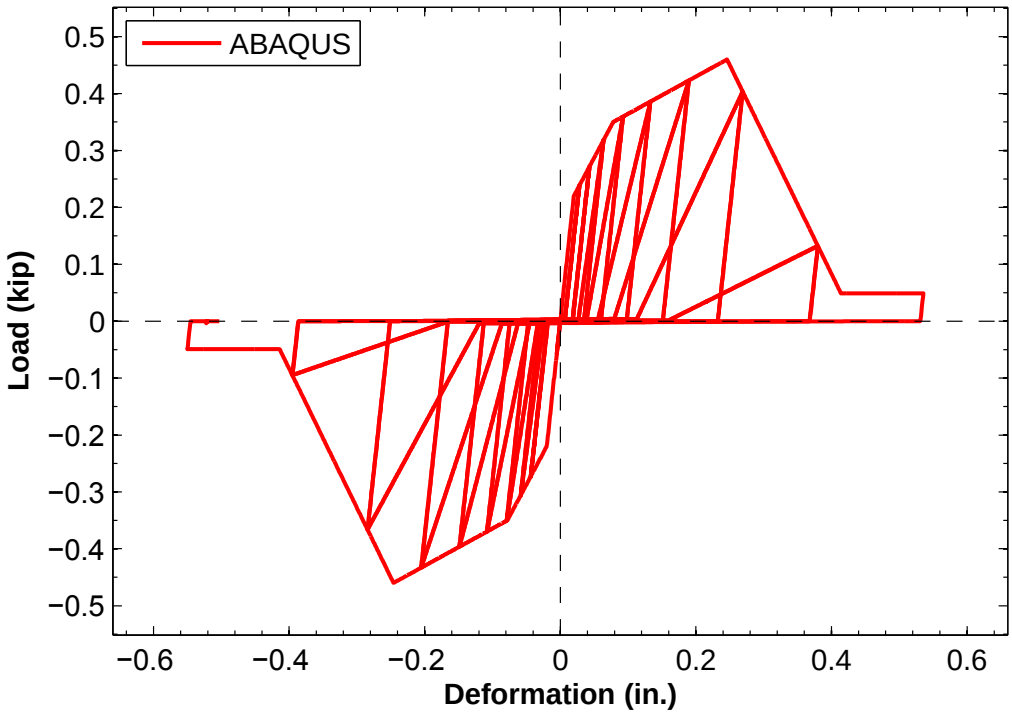


Fig. 5.6. Simulation of screw-fastened connections: 54 mils to 7/16'' OSB

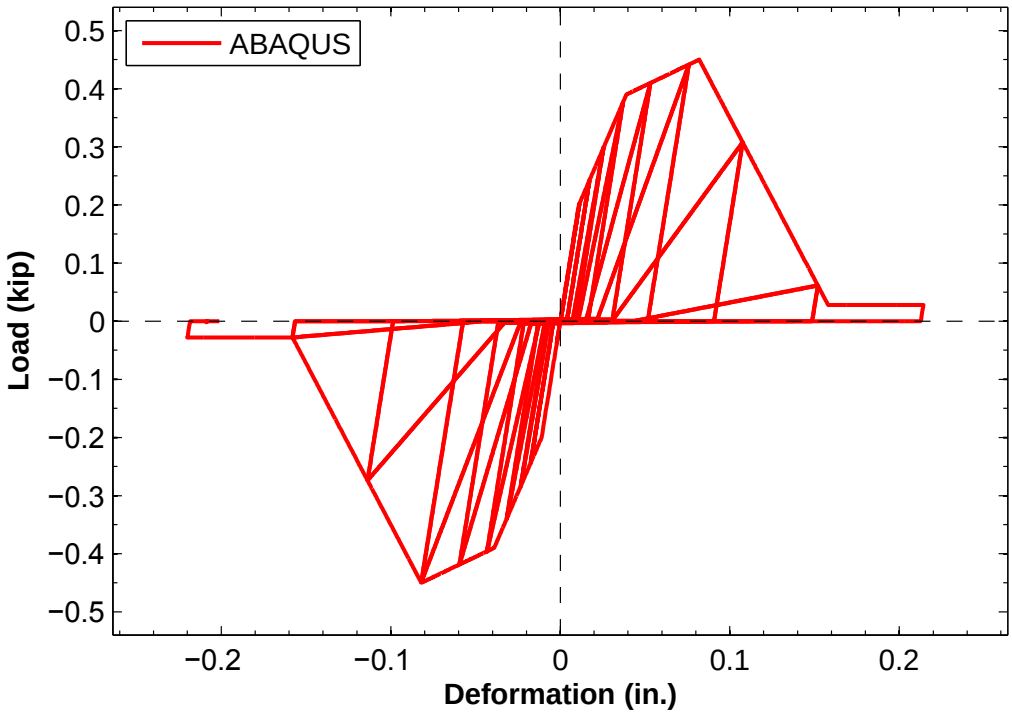


Fig. 5.7. Simulation of screw-fastened connections: 97 mils to 7/16'' OSB

The newly verified ABAQUS connection UEL is used in CFS sheathed shear wall simulations in the next chapter.

CHAPTER 6 NONLINEAR ANALYSIS OF SHEAR WALLS

6.1 Modeling methodology

This chapter applies the UEL proposed in the previous chapters to high-fidelity shear wall modeling. Due to the highly nonlinearity of these models, several nonlinear analysis procedures are discussed and compared herein. Recommendations are made towards the choice of nonlinear analysis procedures. Simulation results are also compared to experiments at both system level and fastener level.

6.2 Numerical Model

6.2.1 Model geometry

The 4x 9 shear wall test conducted by Liu et al. (2012a) is simulated in ABAQUS. The ABAQUS model is modified based on the model created by Ngo (2014) as shown in Fig. 6.4.

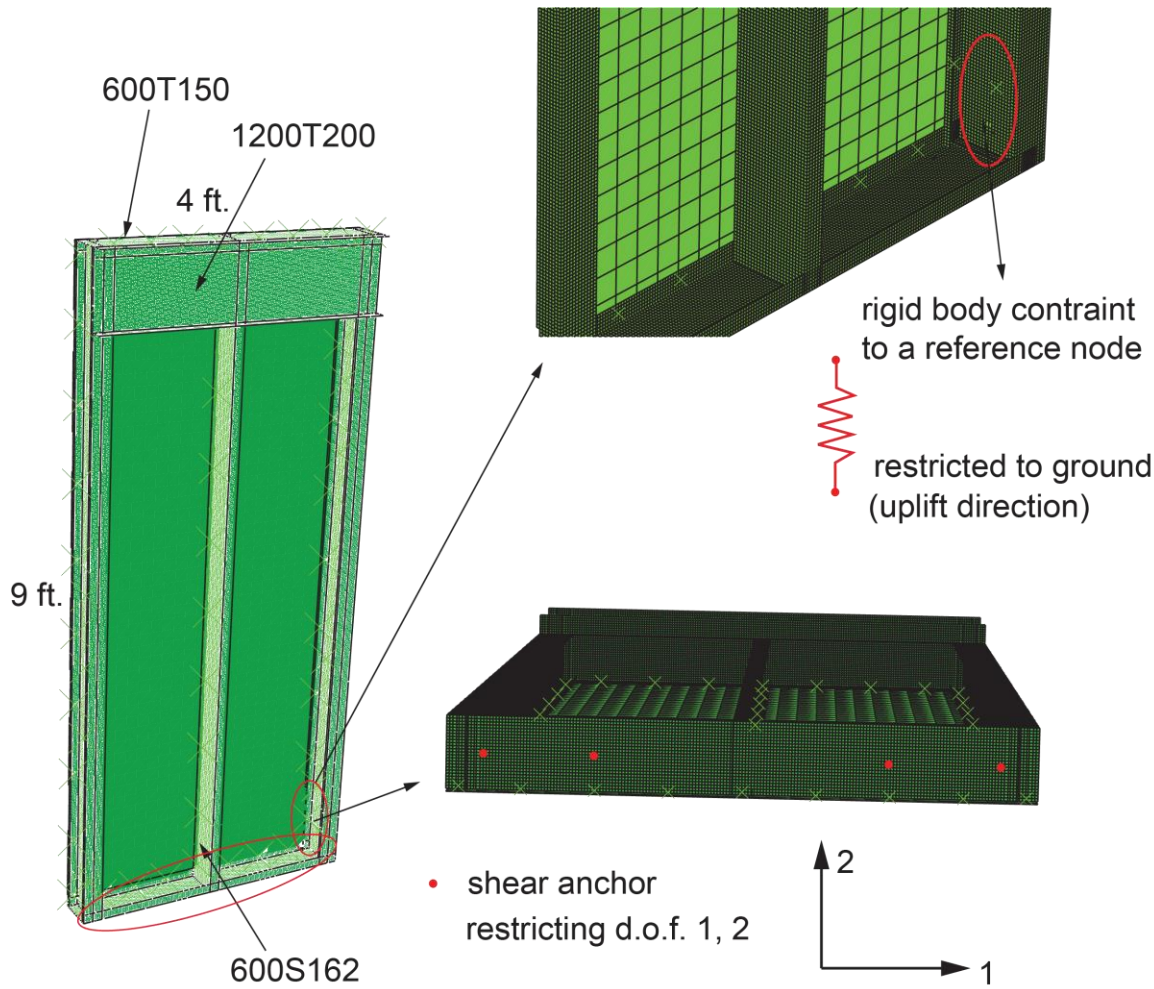


Fig. 6.1. Shear wall numerical model geometry

The wall dimension is 4 ft. by 9 ft. Only front sheathing (OSB) is installed and there is no gypsum sheathing. The rating of the OSB sheathing is APA 24/16 Exposure 1. The thickness is 7/16 in. The cold-formed steel frames consist of five studs, two tracks and one ledger. The dimension of studs is 600S162-54 mil (50 ksi). The dimension of track is 600T150-54 mil (50 ksi). The dimension of ledger is 1200T200-97 mil (50 ksi). Studs are fastened by #10 Hex head washer back to back on the left and right side of the

shear wall to form the chord studs. The tracks are fastened to studs by #10x3/4 in. flat head screws. The OSB are connected to CFS members by #8x1-15/16 in. flat head. Fastener spacing is 6 in. There is a seam existing between the two OSB sheathing boards. However, for simplicity, the seam and fastener connecting steel strap to OSB sheathing boards are not modeled.

6.2.2 OSB sheathing modeling

The shell element S4R in ABAQUS is used for modeling OSB sheathing boards. Instead of using the nominal thickness 7/16 in., the actual thickness of 0.4375 in. is used here. The original model created by Ngo (2014) assumes OSB sheathing as rigid diagrams by assuming very large modulus of elasticity to OSB material. In order to consider flexural and shear deformation of OSB sheathing board, the OSB material is modified based on panel strength from APA Panel Design Specification (APA 2008). With panel strength, the OSB material flexure and shear modulus is back calculated using the method adopted by Schafer et al. (2007).

For flexural modulus of elasticity,

$$E = 12EI_w / t_w^3 \tag{5.1}$$

For shear modulus of elasticity,

$$G = Et_w / t_w \tag{5.2}$$

OSB is an orthotropic material with differing stiffness in different directions. The APA Panel Design Specification (APA 2008) considers this by specifying panel strength in the direction parallel to the strength axis and perpendicular to the strength axis. The

panel strength is listed as flexure rigidity and shear rigidity (Table 6.1). By converting panel rigidity to modulus of elasticity, orthotropic OSB material parameters can be determined.

Table 6.1. OSB Panel flexural and shear rigidity

Plate bending stiffness (strength axis)	Plate bending stiffness (non-strength axis)	Shear rigidity (through thickness)
E_1I_w (lbf-in.^{2}/ft.)	E_2I_w (lbf-in.^{2}/ft.)	$G_{v1}t_v$ (lbf/in.)
78000	16000	83500

Table 6.2. Converted OSB material modulus of elasticity

Modulus of elasticity (strength axis)	Modulus of elasticity (non-strength axis)	Shear modulus (through thickness)
E_1 (ksi)	E_2 (ksi)	G_{12} (ksi)
1068	219	200

For orthotropic elastic material definition in ABAQUS, modulus of elasticity parameters and Poisson's ratio in 3-dimensions are required. The flexural modulus in the direction normal to the wall plane is not important in this analysis. The flexural modulus E_3 is assumed to be equal to E_2 as 219 ksi. Because out-of-plane shear deformation is not significant in shear wall analysis, the shear modulus corresponding to out-of-plane direction is taken to be the same as in-plane. Therefore, G_{13} is set be to 200 ksi. Poisson's ratio in all directions are taken as 0.30.

6.2.3 CFS members modeling

CFS member modeling (studs, tracks and ledger) is mainly based on the work done by Ngo (2014). The shell element S4R is utilized for modeling CFS members. Compared to meshing in the OSB sheathing, finer meshing is used for CFS members to better capture CFS member behaviors. The steel material is modeled with isotropic hardening. The choice of plastic or elastic material model has little effect on general shear wall load-deformation response. However, it affects simulation of CFS members' torsion and buckling behaviors. With elastic material model, it is found that unreasonably high stress concentration will occur at the bottom track close to hold-downs and anchor bolts. Comparison is made between monotonic shear wall analysis with elastic steel material and one with plastic material in Fig. 6.2 and Fig. 6.3.

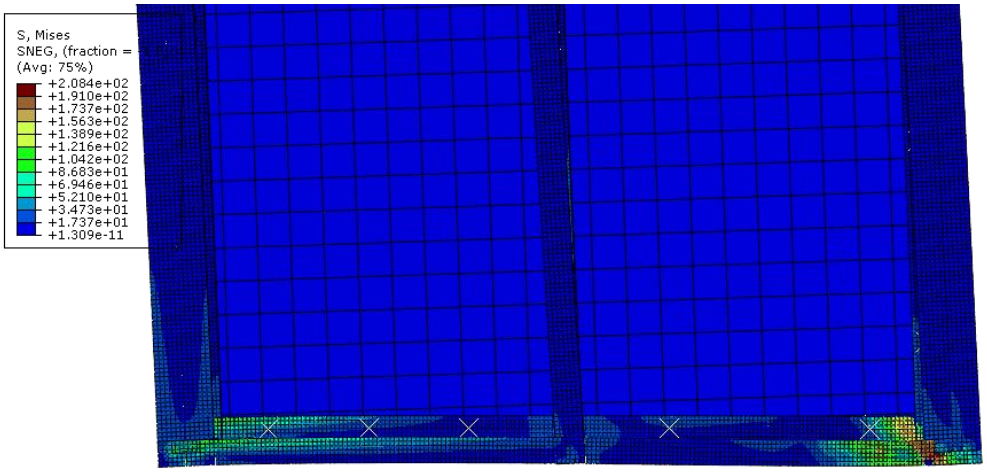


Fig. 6.2. Bottom track stress distribution at maximum deformation unde pushover analysis using elastic steel material

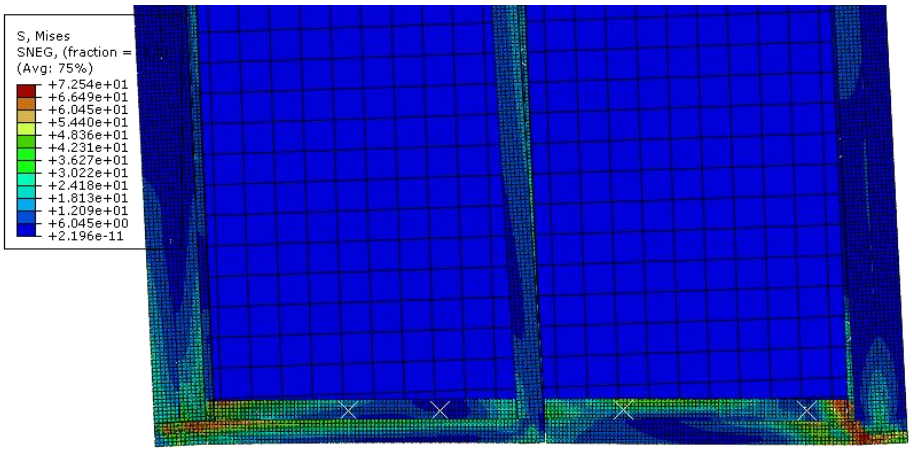


Fig. 6.3. Bottom track stress distribution at maximum deformation unde pushover analysis using plastic steel material

Therefore, it is recommend herein that plastic material model should be used to model cold-formed steel instead of only using elastic model. The steel elastic properties are 29,500 ksi (Young's modulus) and 0.3 (Poisson's Ratio). The isotropic hardening parameters are taken from the work by Moen (2009).

Table 6.3. Isotropic hardening parameters

Plastic Strain	**Stress** ksi
0	55.1
0.003	60.3
0.008	64.9
0.013	68.4
0.023	74
0.033	78.1
0.043	81.3
0.053	83.8
0.063	86.2

6.2.4 Fastened connections modeling

There are mainly two types of screw-fastened connections in the shear wall modeled here, steel-to-steel and steel-to-OSB. Steel-to-steel connections are relatively "rigid" compared to steel-to-OSB connections. From experiments, rarely were any steel-to-steel connections found to have failed. There, multi-point constraint pin type (MPC PIN) is used to simulate steel-to-steel connections.

The UEL proposed in the previous chapters are used for modeling steel-to-OSB connections. The configuration of these connection is 54 mils to 7/16'' OSB. Calibrated Pinching4 model (Peterman and Schafer 2013) is assigned to the UEL so that connection nonlinearity can be simulated. In order to consider changes in displacement trajectory, the radial spring model is used for the UEL. The distance between CFS node and OSB node is set to be 0.2373'' equal to the distance between CFS and OSB centerlines.

6.3 Pushover Analysis

6.3.1 Influence of analysis procedures

The cold-formed steel frame shear model modeled in this section was already tested in an experiment. It was found that the shear wall displayed a "brittle" loss of capacity after reaching its peak load (Fig. 6.4). Such sudden loss of capacity presents potential challenge for numerical analysis. In some cases, default Newton-Raphson method in ABAQUS may not be able to capture post-peak response of shear walls. In order to find a reliable solution procedure, several analysis procedure options are explored in this section. Their results are compared and discussed.

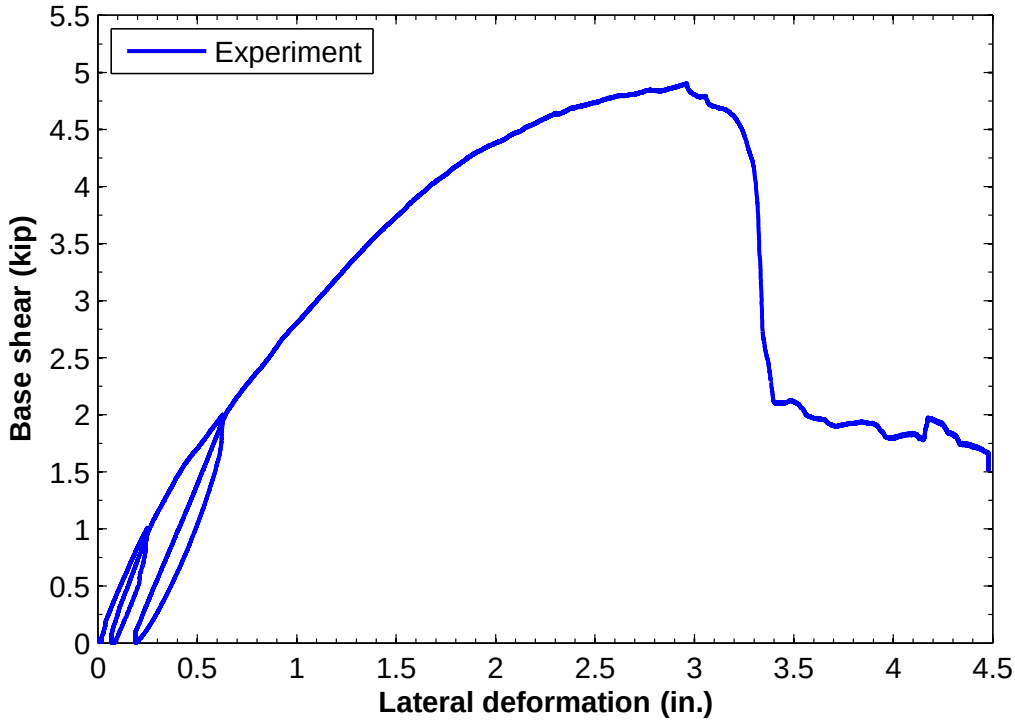


Fig. 6.4. Load-deformation response of shear wall under monotonic loading

The solution techniques applied are Newton-Raphson method, Riks method and implicit dynamic method. The Newton-Raphson method is the default nonlinear solution technique in ABAQUS/Standard. It needs the inverse Jacobian matrix in every iteration to calculate incremental displacement correction, which makes it sometimes numerically expensive for obtaining solution. It is an effective and accurate analysis procedure for most of problems. However, for problems tracing scenarios of unstable collapse or post-buckling, Newton-Raphson method sometimes fails to converge. For these problems, Riks method can be more reliable, especially for cases with geometric nonlinear collapse. Riks method iterates by the use of "arc length". Both displacement and load are unknown variables to be solved. However, because of the way that Riks method is formulated, it cannot be used for cyclic analysis.

The implicit dynamic analysis is also investigated here. Even though implicit dynamic method stills uses Newton-Raphson method, it considers damping and acceleration, which can potentially "dissipate" nodal residuals and improve convergence. The study also demonstrates the UEL's potential for dynamic analysis. The solution procedure and time incrementation input are based on the work done by Moen et al. (2014).

For implicit dynamic analysis, material mass is applied to cold-formed steel and OSB sheathing based on real material density. The UEL is only assigned with the mass of a fastener. Rayleigh mass proportional damping with α equal to 0.005 is assigned for energy dissipation. The loading rate is taken as 0.00004 in./sec to minimize inertia effects.

The cold-formed steel shear wall model introduced in this chapter is analyzed in ABAQUS using Newton-Raphson method, Riks method and implicit dynamic analysis. The shear wall load-deformation curves are shown in the Fig. 6.5. The results from three different analysis methods are compared. The horizontal axis "Displacement" corresponds to the drift at the top the shear wall. The vertical axis "Load" corresponds to the shear wall base shear.

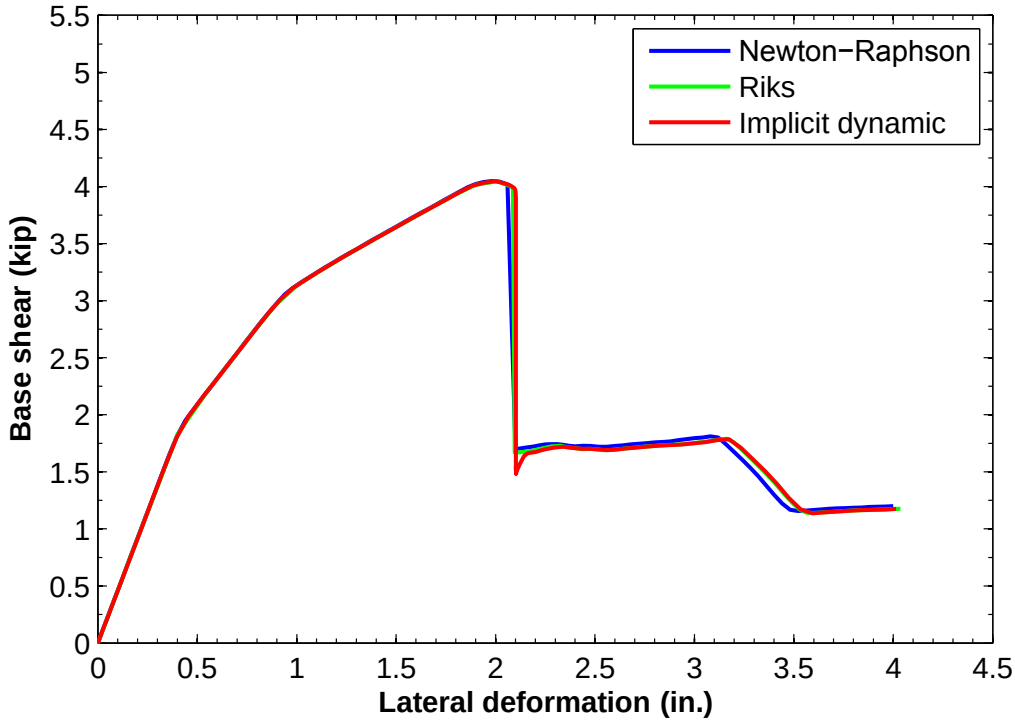


Fig. 6.5. Comparison of numerical analysis results using different solution procedures

All of the three analysis methods succeed in capturing post-peak response and eventually converge. As shown in the Fig. 6.5, the three analysis procedures predict basically the same peak load and corresponding displacement. Prior to reaching the peak load, same shear wall response is calculated by the three methods. After reaching the peak load, there is minimal difference between Newton-Raphson static method and Riks method. Implicit dynamic method creates slightly different post-peak behaviors with lower post-peak load immediately after loss of capacity. However, it gradually catches up with load-deformation paths of the other two methods. This means that the difference might be caused by acceleration induced by the “sharp” capacity loss since this difference is eventually dissipated.

From this comparison, it can be shown that Newton-Raphson method is sufficient for obtaining converged solution for shear wall pushover analysis. But for the case when Newton-Raphson method fails to converge, Riks method and implicit dynamic method are available.

6.3.2 Comparison to experiment

Shear wall numerical analysis result is compared to experiment in this section. In this analysis, radial spring model is selected for simulating screw-fastened connections and Newton-Raphson method is used for obtaining solution. The steel-to-sheathing connection Pinching4 parameters are taken from work by Padilla-Llano (2015). These Pinching4 parameters are shown in Table 6.4 and Table 6.5.

Table 6.4. Steel-to-sheathing Pinching4 backbone parameters

ePd₁	***ePd₂***	***ePd₃***	***ePd₄***	***ePf₁***	***ePf₂***	***ePf₃***	***ePf₄***
		(in.)				(kip.)	
0.022	0.124	0.462	0.815	0.192	0.384	0.5	0.049
ePd₁	***ePd₂***	***ePd₃***	***ePd₄***	***ePf₁***	***ePf₂***	***ePf₃***	***ePf₄***
		(in.)				(kip.)	
-0.022	-0.124	-0.462	-0.815	-0.192	-0.384	-0.5	-0.049

Table 6.5. Steel-to-sheathing Pinching4 pinching path parameters

rDispP	***rForceP***	***uForceP***	***rDispN***	***rForceN***	***uForceN***
0.42	0.01	0.001	0.42	0.01	0.001

The load-deformation curve of numerical analysis in comparison to experiment result is shown in Fig. 6.6. The numerical analysis gives very accurate prediction of shear wall response with slight inelasticity as shown in the first and second “legs” of the curve.

However, the shear wall stiffness is underestimated after the shear wall enters severe softening state as shown in the third “leg”. Regardless of the discrepancy caused by underestimated stiffness, the predicted post-peak response closely resembles experiment result.

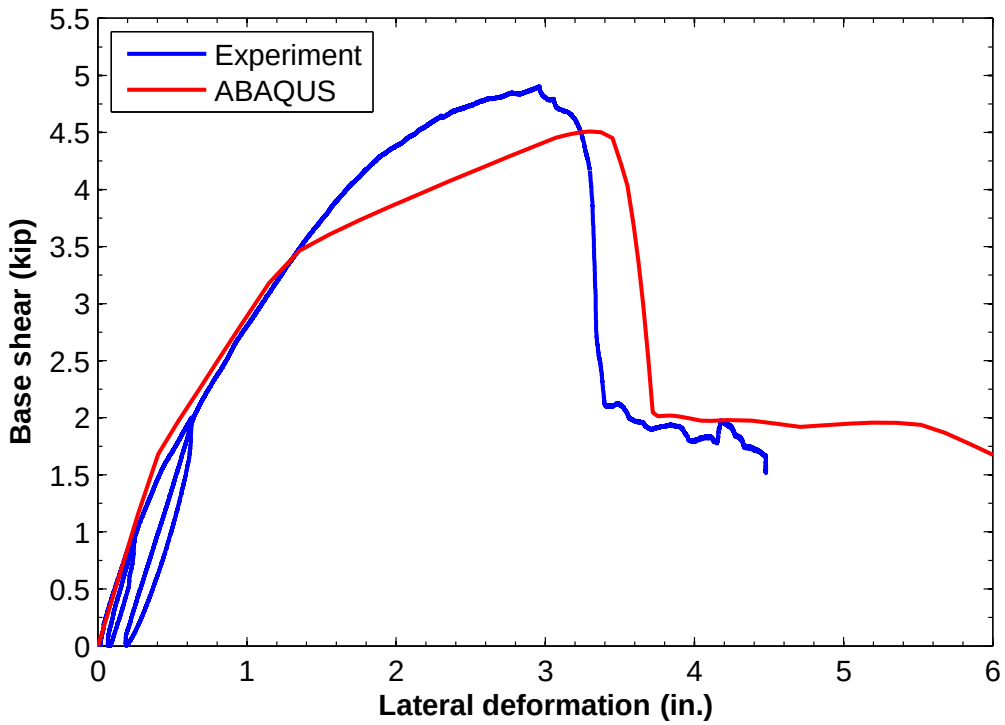


Fig. 6.6. Comparison of numerical analysis result to experiment

According to experiment data, the response of cold-formed steel frame shear wall under monotonic loading is controlled by screw-fastened connection failures where sequential connection failures lead to gradual softening of shear wall response until the number of failed connections is enough to lead to shear wall failure. Therefore, the input for connection Pinching4 parameters is critical for obtaining correct simulation. Curves of connection force with respect to shear wall lateral displacement are created in

Appendix B. It is found that the initiation and end of three pre-peak legs in these curves correspond to the three legs in the shear wall load-deformation curve. Thus, the third leg of connection Pinching4 backbone might be inappropriately chosen, which results into the difference between experiment results and numerical analysis. More study on single screw-fastened connection may need to be done in order to obtain closer simulation result.

The shear wall general deformed shear wall is shown in the Fig. 6.7. The shear wall as a whole deforms as a deep beam. The cold-formed steel frames is deformed as a parallelogram with slight bending. Torsion occurs on the middle stud as shown in Fig. 6.9, which is induced by fasteners connecting studs only on one side. The top portion of the cold-formed steel studs experience relatively high stress. This is possibly due the restraint created the ledger. The highest stress concentration on cold-formed steel studs occur at the hold-down areas, where steel around track-to-stud connections have entered hardening stage (Fig. 6.10). The OSB sheathing is found to rotate relative the cold-formed steel frame as shown in Fig. 6.11. It experiences much lower stress compared to cold-formed steel.

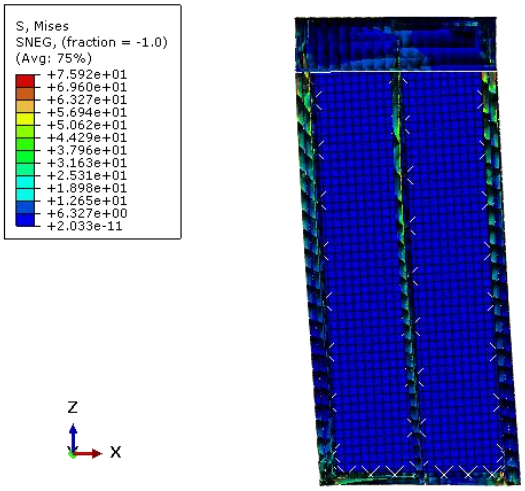


Fig. 6.7. Shear wall general deformed shape at maximum shear wall displacement

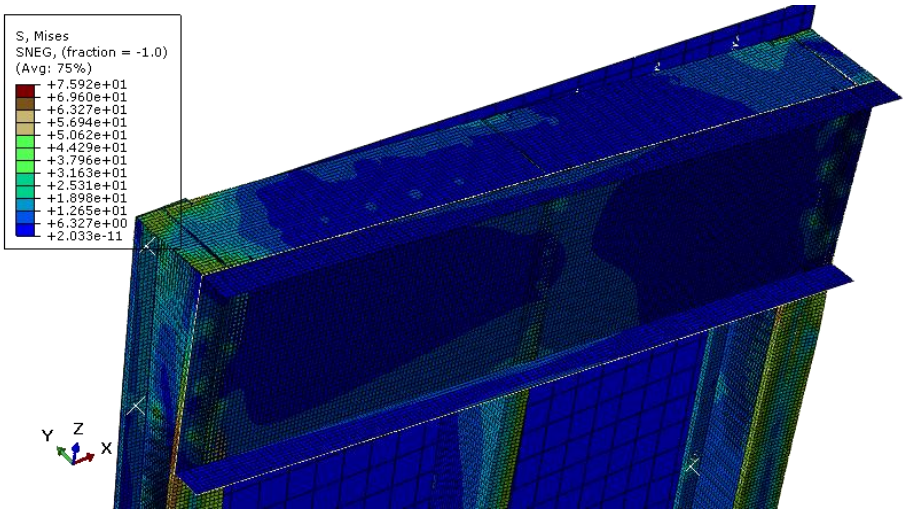


Fig. 6.8. Shear wall top track and ledger area Von Mises stress distribution at maximum shear wall displacement

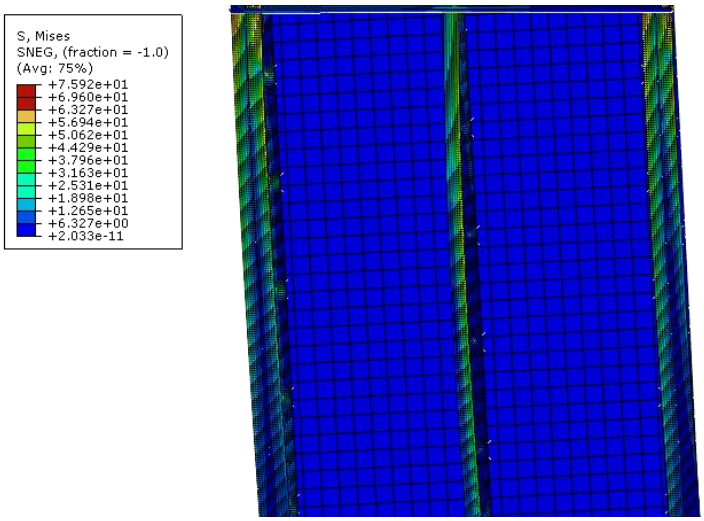


Fig. 6.9. Torsion of cold-formed steel studs of the shear wall at maximum lateral deformation

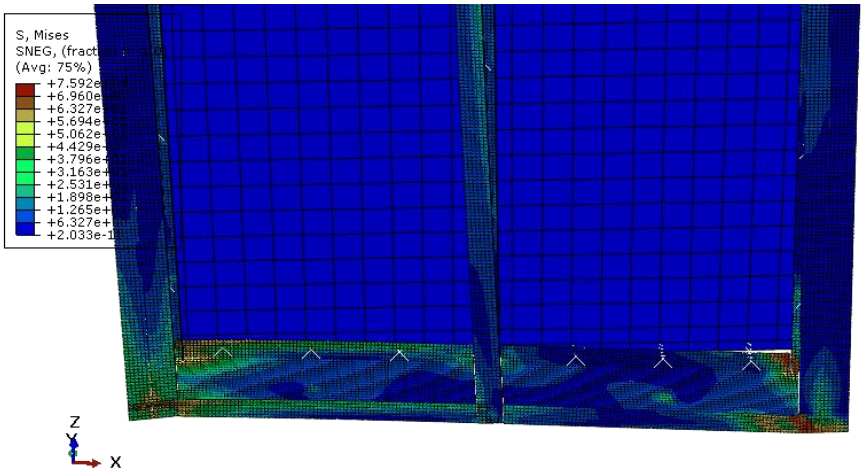


Fig. 6.10. Shear wall bottom track and stud Von Mises stress distribution at maximum shear wall deformation

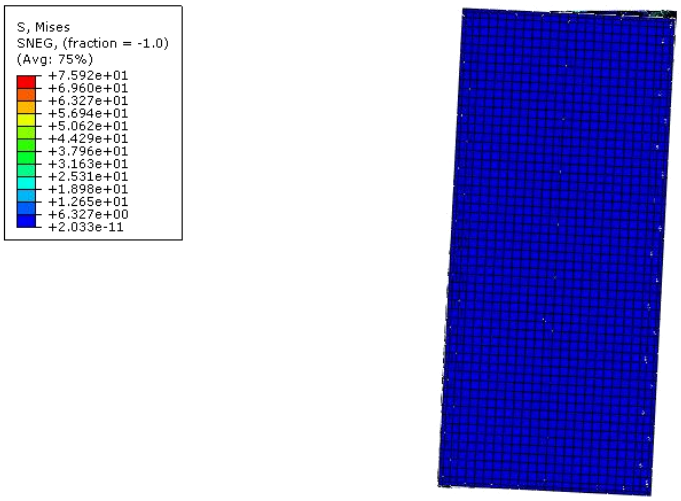


Fig. 6.11. Rotation of OSB sheathing at the maximum shear wall displacement

In terms of connection behavior, as shown in Fig. 6.12, the connections with distinctive failures during testing are labeled. Most of connection failures occurred at the bottom of the shear wall. Almost all track-to-sheathing connections failure by sheathing pull-through failure. Failures of stud-to-sheathing connections are mostly located at the stud lower part close to hold-downs. However, more connections failed on the right side than the left side. This might be explained by the difference between hold-down tension and compression stiffness.

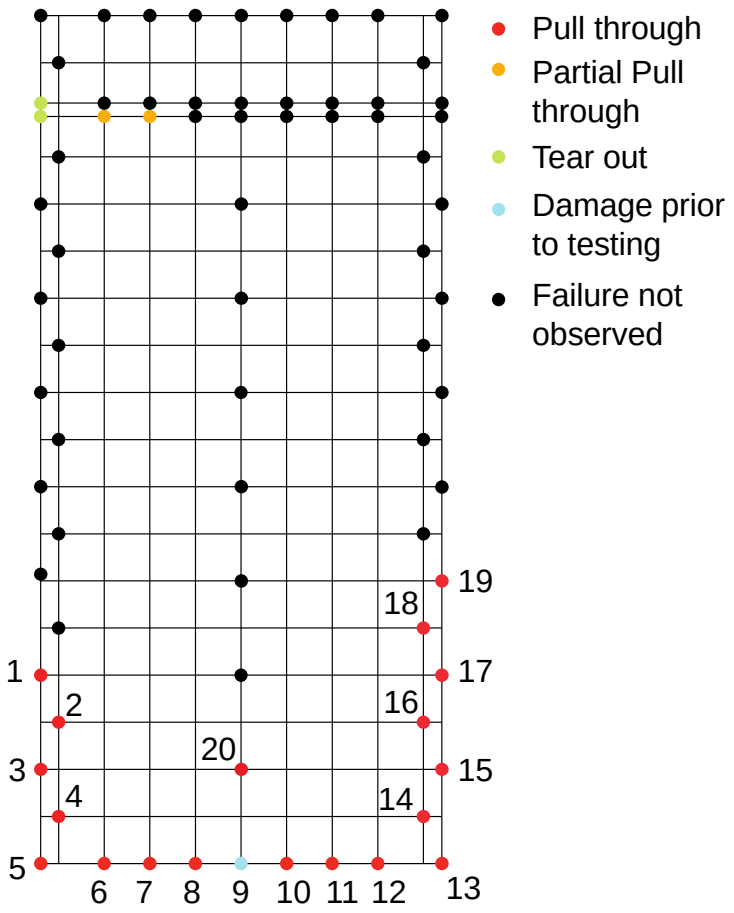


Fig. 6.12. Distribution of failed connections on the shear wall during testing

The Fig. 6.13, Fig. 6.14 and Fig. 6.15 are created showing respectively the response of the damaged connections on the left side, right side and the bottom. It can be seen that all connections shown here have been loaded past their strength, which agrees with experiment observation. However, connections post-peak behaviors are very different. Many connections on the left and bottom undergoes unloading after reaching peak load, while the right side connections continue being loaded along the backbone curves. This phenomenon may be caused by the difference of hold-down stiffness in compression and tension.

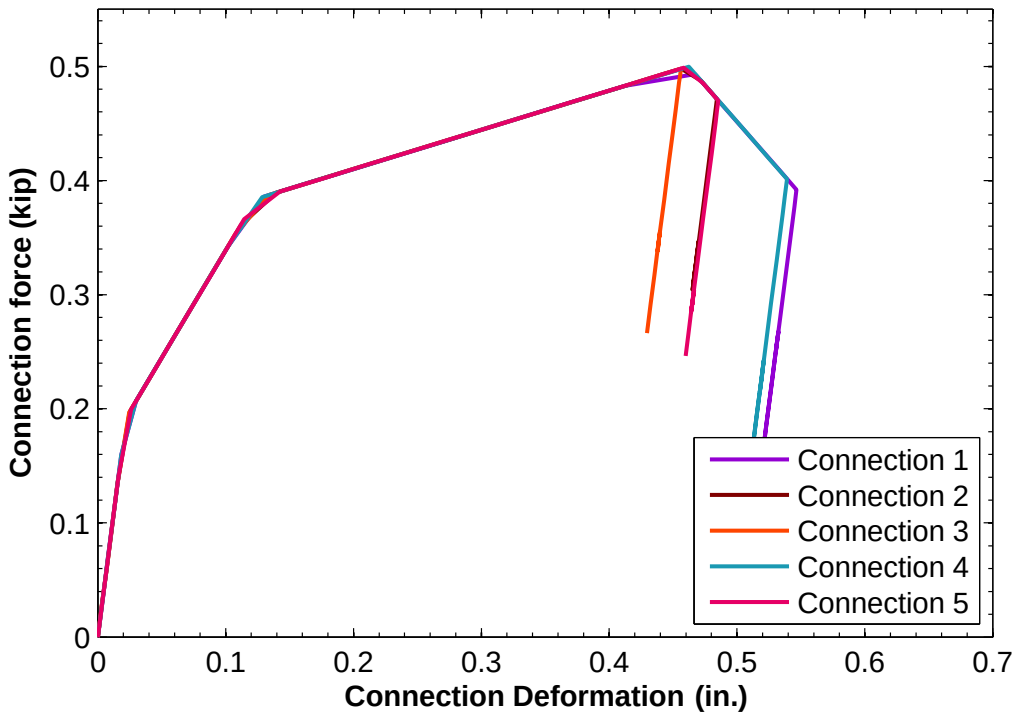


Fig. 6.13. Load-deformation response of the connections on the left stud bottom

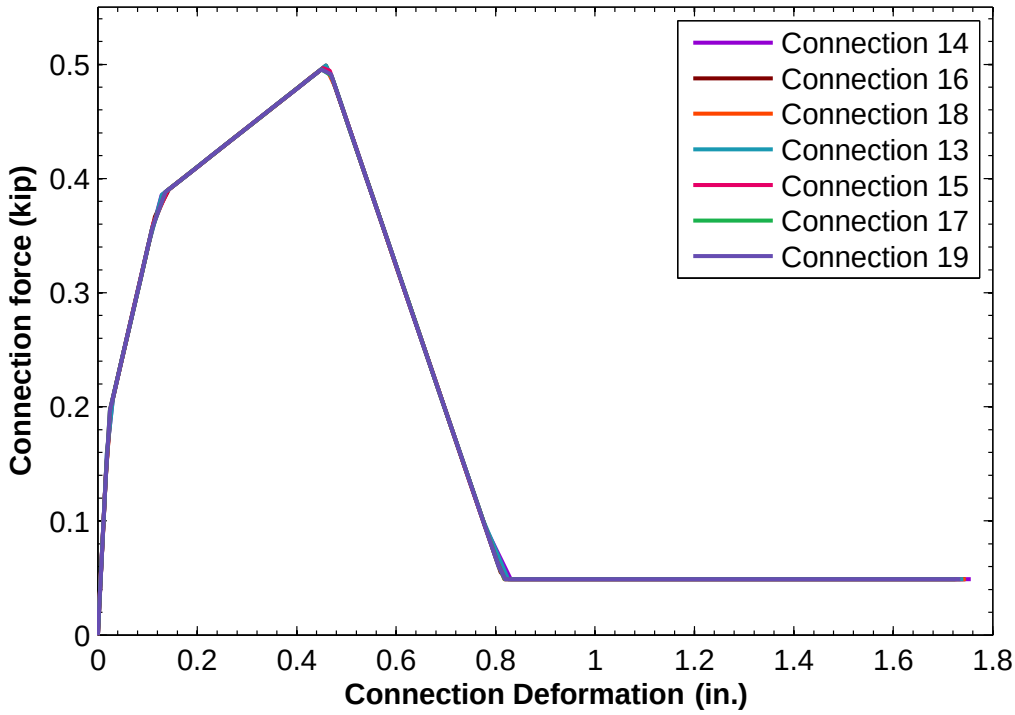


Fig. 6.14. Load-deformation response of the connections on the right stud bottom

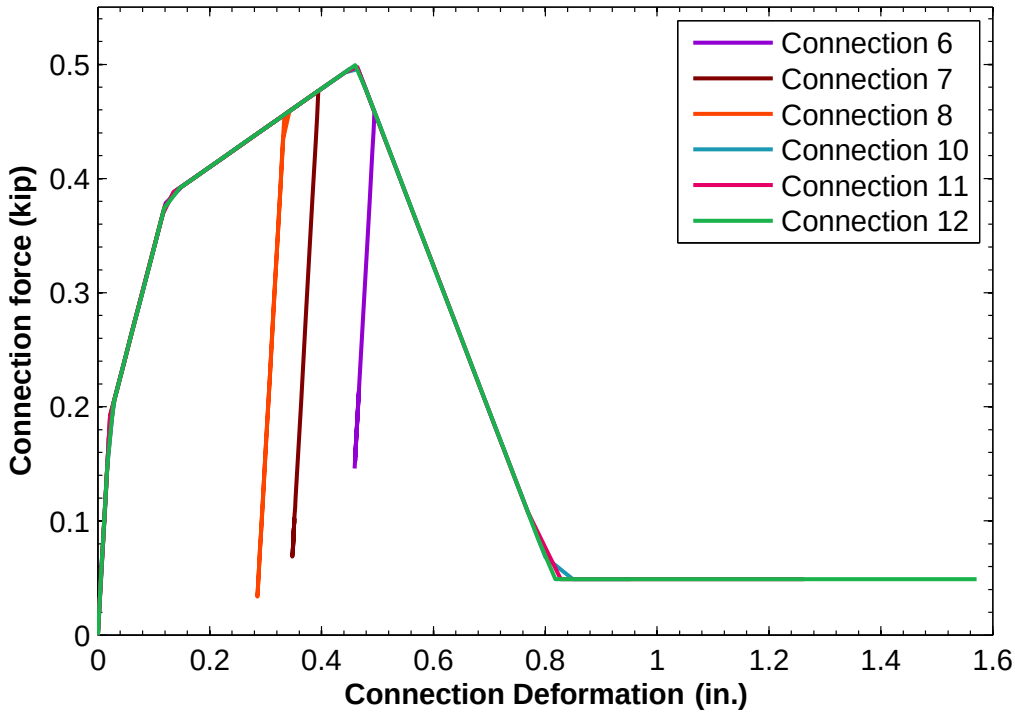


Fig. 6.15. Load-deformation response of the connections on the bottom track

6.4 Cyclic Analysis

6.4.1 Fastener-only model study

Compared to pushover analysis, loading and unloading in cyclic analysis adds more numerical difficulty for convergence. In order to settle on robust modeling technique, a fastener-only model (Fig. 6.16) is created by modifying original high-fidelity shear wall discussed in the last section. All the shell elements from the original shear wall model are discarded leaving only the screw-fastened connections modeled by the UEL. Rigid diaphragm assumption is assigned to the UEL nodes originally connected to sheathing shell elements. The other nodes on UEL are pinned to the ground. Cyclic displacement loading is prescribed on the reference node the top of the rigid diaphragm.

The cyclic loading protocol used in Chapter 5 is applied here with scale factor of 1.5. Under the cyclic displacement loading, the UEL will experience relative displacement between its two nodes and then establish resistance. Instead of trying to simplify original shear wall model, this fastener-only model is intended to mimic the relative displacement between CFS members and OSB sheathing which is the deformation of the UEL.

It is found that the model quickly divergences after two cycles when some fasteners enter inelastic state. The reason for this divergence is that change in stiffness of fasteners causes reestablishment of fastener orientation. Orientation reestablishment sometimes leads to change in element deformation. For radial spring model, the spring orientation is updated in each iteration. Combined with nonlinear model, the spring orientation can oscillate by a large amount and thusly create a cycle of reloading and unloading in one increment. This possibly contributes to divergence.

In order to solve the divergence issue, the element formulation in the original UEL is modified. Instead of being a zero length element free to rotate its orientation, the element orientation is “locked” in the prescribed direction. The direction is determined based on the orientation that element establish in elastic state. The spring orientation “locking” only occurs after connection begins yielding corresponding to Pinching4 backbone after the first curve “leg”. This modification is based on the assumption that certain amount damage on the steel-to-sheathing connection will create a deformation path on the sheathing. Connection displacement along this deformation path has the lowest potential energy. Thus, any connection displacement is assumed to follow this deformation path. In summary, before connection begins yielding, the spring remains

radial spring capable of rotating its orientation. After the connection begins yielding, the spring "locks" its orientation and changes into modified radial spring. Still only spring is used in order to avoid overestimation of strength and stiffness. It is assumed that screw during testing is relatively "locked" along the sheathing damaged trajectory.

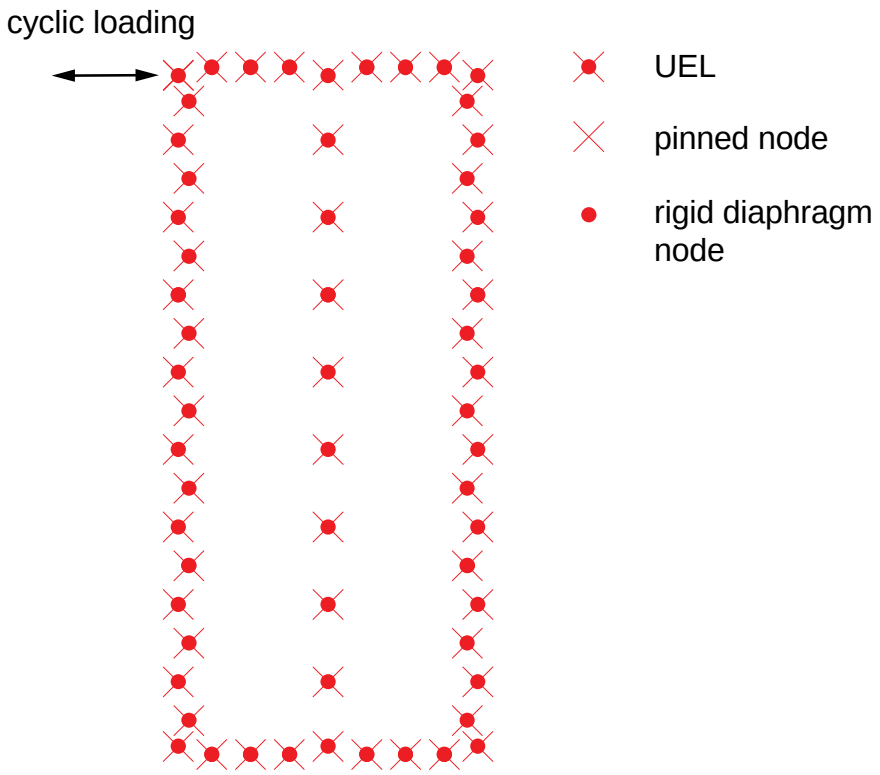


Fig. 6.16. Fastener-only model

With this modification, the fastener-models can converge. The fastener-only model response is shown in Fig. 6.17. It can be seen that the fastener-model result shows clear resemblance to fastener hysteretic response. Both peak load and pinching are simulated in this model.

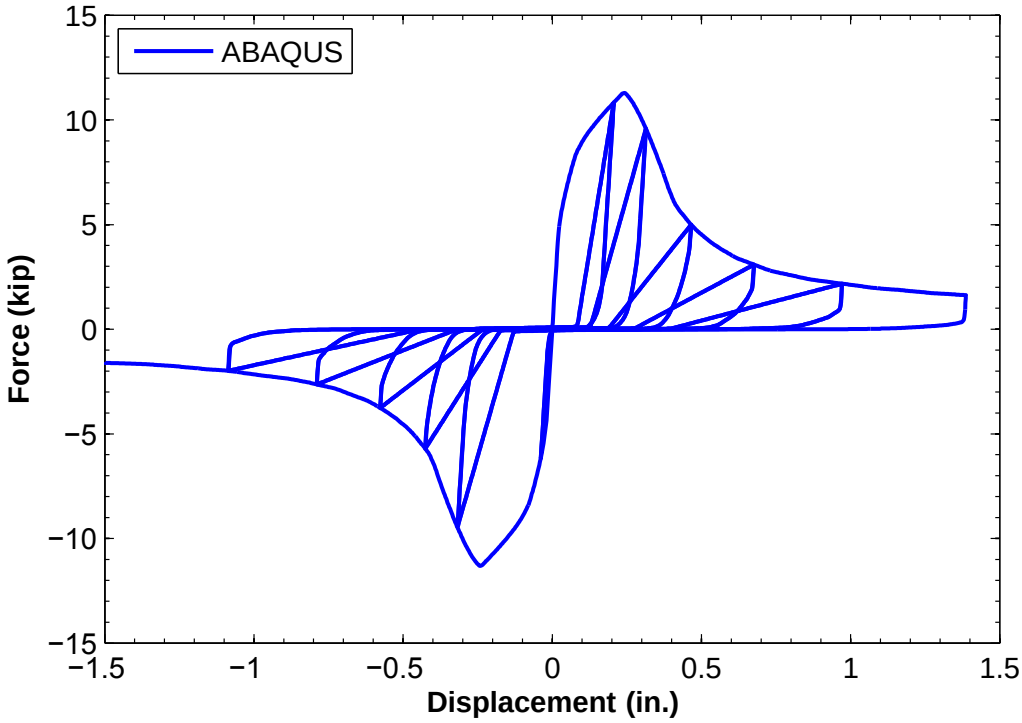


Fig. 6.17. Hysteretic response of fastener-only model

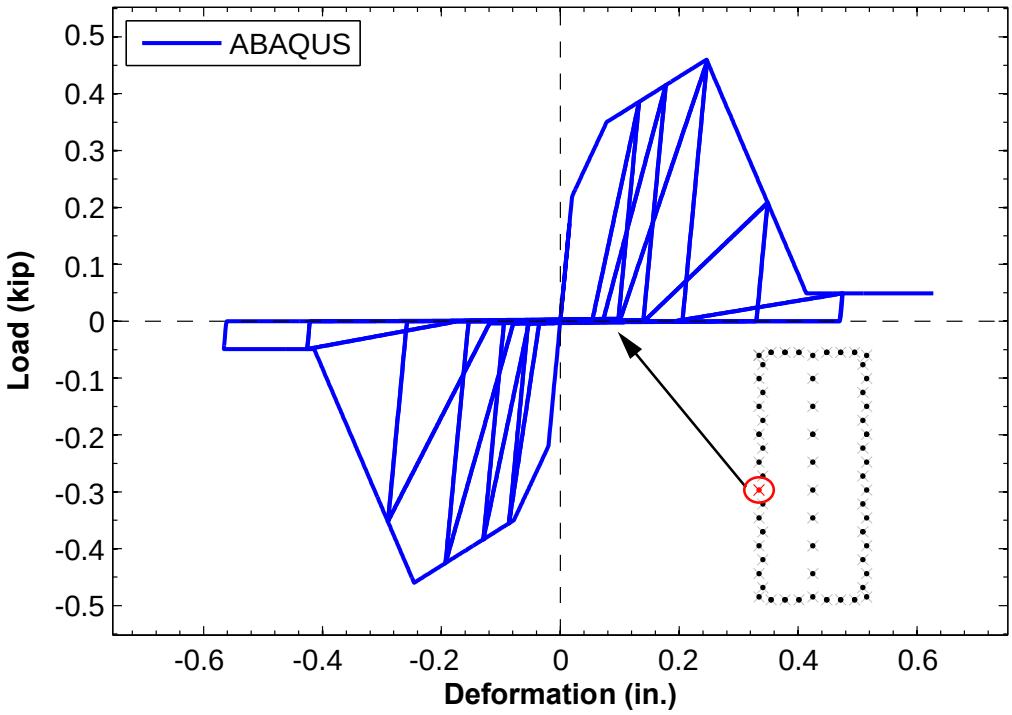


Fig. 6.18. Hysteretic response of one fastener in fastener-only model

6.4.2 High-fidelity model

With the convergent solution obtained in the fastener-only model, the high-fidelity shear wall model analyzed monotonically is assigned with cyclic displacement loading. Still, the modified UEL is used for analysis. Newton-Raphson method is used for obtaining the solution.

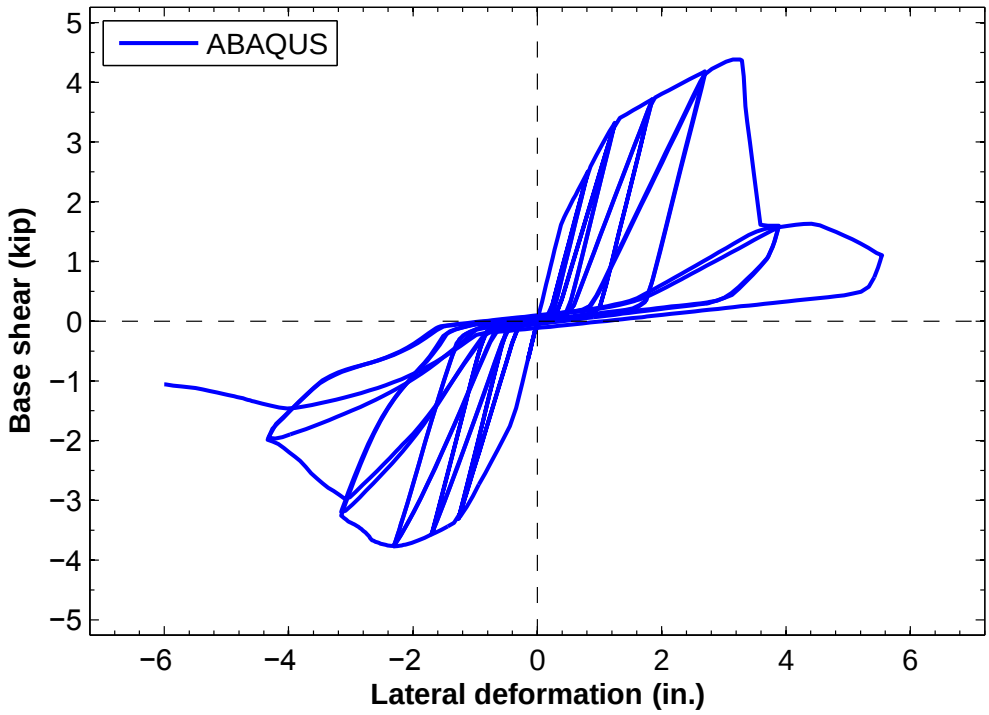


Fig. 6.19. Cyclic response of high-fidelity shear wall model

Shear wall cyclic response shows a nonlinear backbone and pinching. It can be seen that the shear wall cyclic response highly resembles the hysteretic behavior of individual fasteners. Because the shear wall hysteretic response is actually the combination of all individual fastener responses, the shear wall load-deformation curve is smoother than fastener. The response of one of the connections on the top track is shown in the Fig. 6.20.

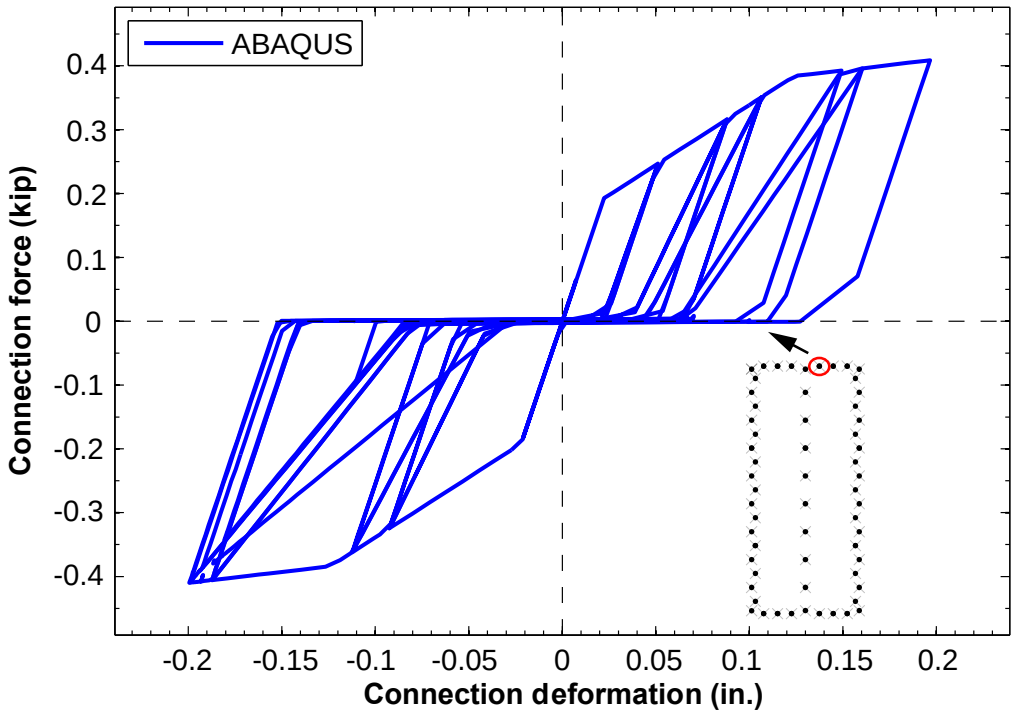


Fig. 6.20. Hysteretic response of one screw-fastened connection

Before the shear wall reaches its peak load, the total shear wall stiffness and strength is mostly provided by the steel-to-sheathing connections. As shown in Fig. 6.21, at shear wall peak load, there is no significant deformation on the CFS framing members except high stress concentration around hold-downs. The CFS steel frame is deformed as parallelogram providing little strength and stiffness. However, after most steel-to-sheathing connections fails, the lateral rigidity from OSB sheathing cannot be provided. In this condition, the CFS frame begins to resist the lateral displacement. This changes the failure mechanism. CFS frame in this period experiences very large deformation. The studs on the compression side experiences flexural-torsional buckling as shown in Fig. 6.22. Since steel-to-sheathing connections have already failed, the studs become unbraced along its full length making them susceptible to global buckling. Overall, this

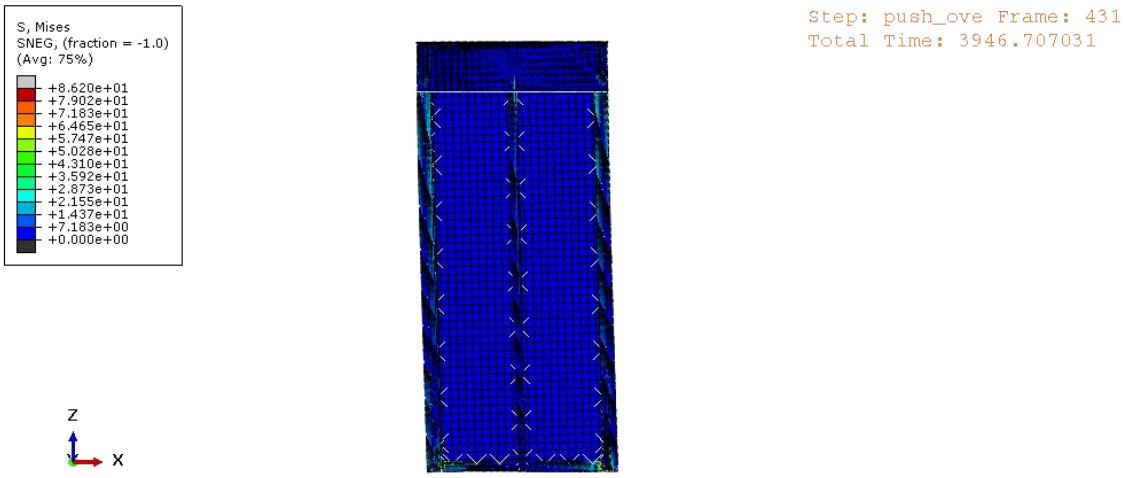


Fig. 6.21. Deformed shape of the shear wall at the maximum load

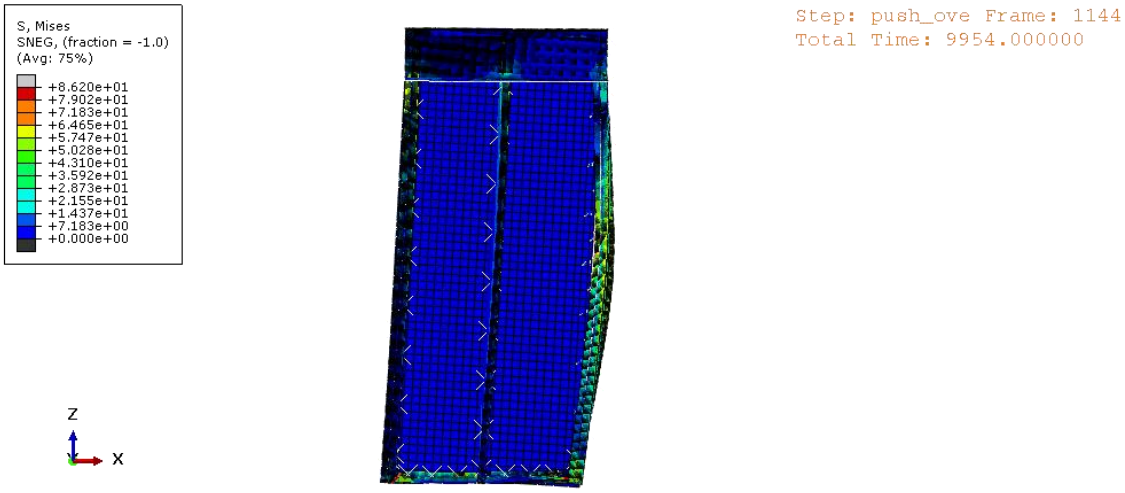


Fig. 6.22. Deformed shape of the shear wall at the maximum displacement

CHAPTER 7 CONCLUSIONS AND FUTURE WORK

The objective is of this thesis is to provide an approach for simulating screw-fastened connections in ABAQUS and make it applicable to shear wall numerical analysis. The difficulty lies in the fact that there is no suitable material or element type for simulating nonlinearity observed in connection tests. This objective is accomplished by creating a user element subroutine (UEL) for ABAQUS/Standard. This user element converts Pinching4 model from OpenSees to ABAQUS to provide ABAQUS with a suitable material type and to make use of latest research on screw-fastened connections. To represent the deformation trajectory of shear wall connections under loading, the radial spring model is proposed. However, to provide users with modeling flexibility, three other prevalent spring models are also included in the UEL here.

Pushover and cyclic of cold-formed steel framed shear walls are performed using the UEL proposed herein. Pushover analysis results are compared to experiments, which shows the potential of the UEL to be applied for high-fidelity modeling. Comparison are made to study the influence of solution procedures, spring model selection and connection input on predicted shear wall behaviors.

Overall, this research provides future researchers with numerical analysis tools to study cold-formed steel framed structures. Not only can cold-formed steel framed shear walls be studied numerically, studies can be also extended to any cold-formed steel subsystems with screw-fastened connections such as diaphragms or cold-formed steel built-up columns.

Still, future work is needed. Questions need to be answered whether connection deformation trajectory changes or keeps being relatively “locked” after damage occurs. To aid this effort, the real connection deformation trajectory in shear wall experiment might need to be monitored. Based on current UEL, with Pinching4 model successfully implemented in ABAQUS, only element formulation section needs to be modified. Besides, the monotonic and cyclic of cold-formed steel framed shear walls remains a preliminary attempt to study this important subsystem by using commercial finite element software. More in-depth work can be accomplished by using the proposed ABAQUS UEL herein, which hopefully can advance our understanding of cold-formed steel frame structures.

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APPENDIX A ANALYSIS CASES OF PINCHING4 MODEL VERIFICATION

A.1 Backbone and Pinching Paths Verification

Six verification cases are analyzed in ABAQUS by UEL and compared to OpenSees. Their parameter input are listed in the following tables.

Table A.1. Positive Pinching4 backbone parameters of verification cases

Model	***ePd₁***	***ePd₂***	***ePd₃***	***ePd₄***	***ePf₁***	***ePf₂***	***ePf₃***	***ePf₄***
	(in.)				(kip.)			
c33-o6-1	0.018	0.069	0.241	0.540	0.158	0.298	0.371	0.021
c33-o12-1	0.021	0.050	0.207	0.446	0.142	0.211	0.327	-0.013
c54-o6-1	0.016	0.064	0.241	0.344	0.160	0.286	0.409	0.022
c54-o12-1	0.019	0.077	0.230	0.427	0.207	0.381	0.475	0.054
c97-o6-1	0.011	0.041	0.084	0.229	0.164	0.313	0.359	0.015
c97-o12-1	0.011	0.036	0.067	0.121	0.218	0.405	0.475	0.049

Table A.2. Negative Pinching4 backbone parameters of verification cases

Model	***eNd₁***	***eNd₂***	***eNd₃***	***eNd₄***	***eNf₁***	***eNf₂***	***eNf₃***	***eNf₄***
	(in.)				(kip.)			
c33-o6-1	-0.024	-0.077	-0.267	-0.494	-0.211	-0.313	-0.427	-0.052
c33-o12-1	-0.019	-0.085	-0.266	-0.447	-0.123	-0.248	-0.324	-0.018
c54-o6-1	-0.025	-0.097	-0.223	-0.402	-0.234	-0.374	-0.475	-0.056
c54-o12-1	-0.019	-0.114	-0.258	-0.445	-0.204	-0.361	-0.466	-0.065
c97-o6-1	-0.012	-0.049	-0.112	-0.234	-0.194	-0.361	-0.380	-0.004
c97-o12-1	-0.010	-0.040	-0.088	-0.132	-0.197	-0.432	-0.494	-0.038

Table A.3. Pinching path parameters of verification cases

Model	***rDispP***	***rForceP***	***uForceP***	***rDispN***	***rForceN***	***uForceN***
c33-o6-1	0.481	0.011	0.001	0.333	0.011	0.001
c33-o12-1	0.506	0.016	0.001	-0.123	0.012	0.001
c54-o6-1	0.498	0.012	0.001	0.104	0.011	0.001
c54-o12-1	0.488	0.011	0.001	0.403	0.011	0.001
c97-o6-1	0.500	0.013	0.001	0.164	0.011	0.001
c97-o12-1	0.510	0.010	0.001	-0.198	0.014	0.001

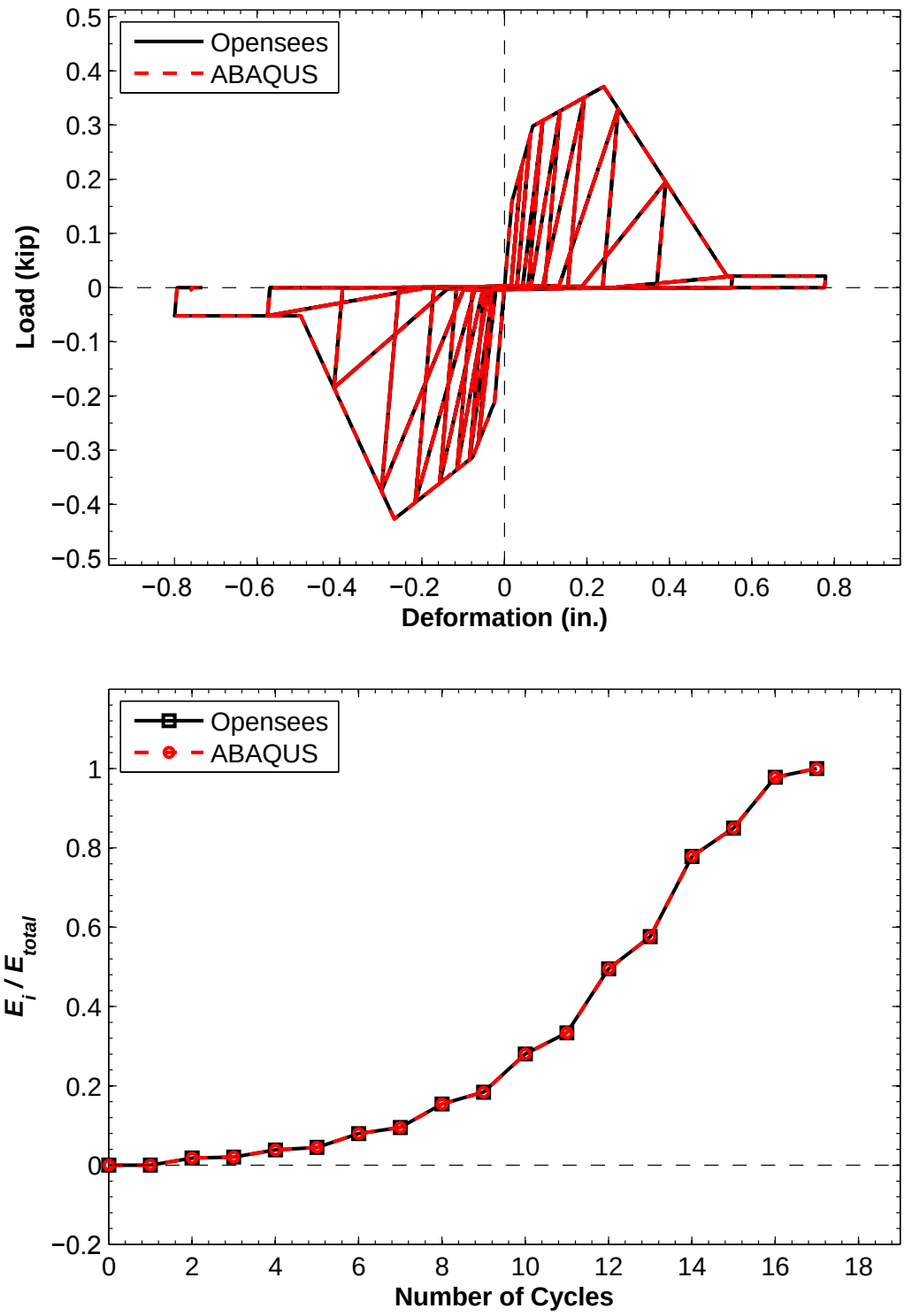

Fig. A.1. Verification case c33o6_1 (a) Load-deformation (b) Energy-cycle

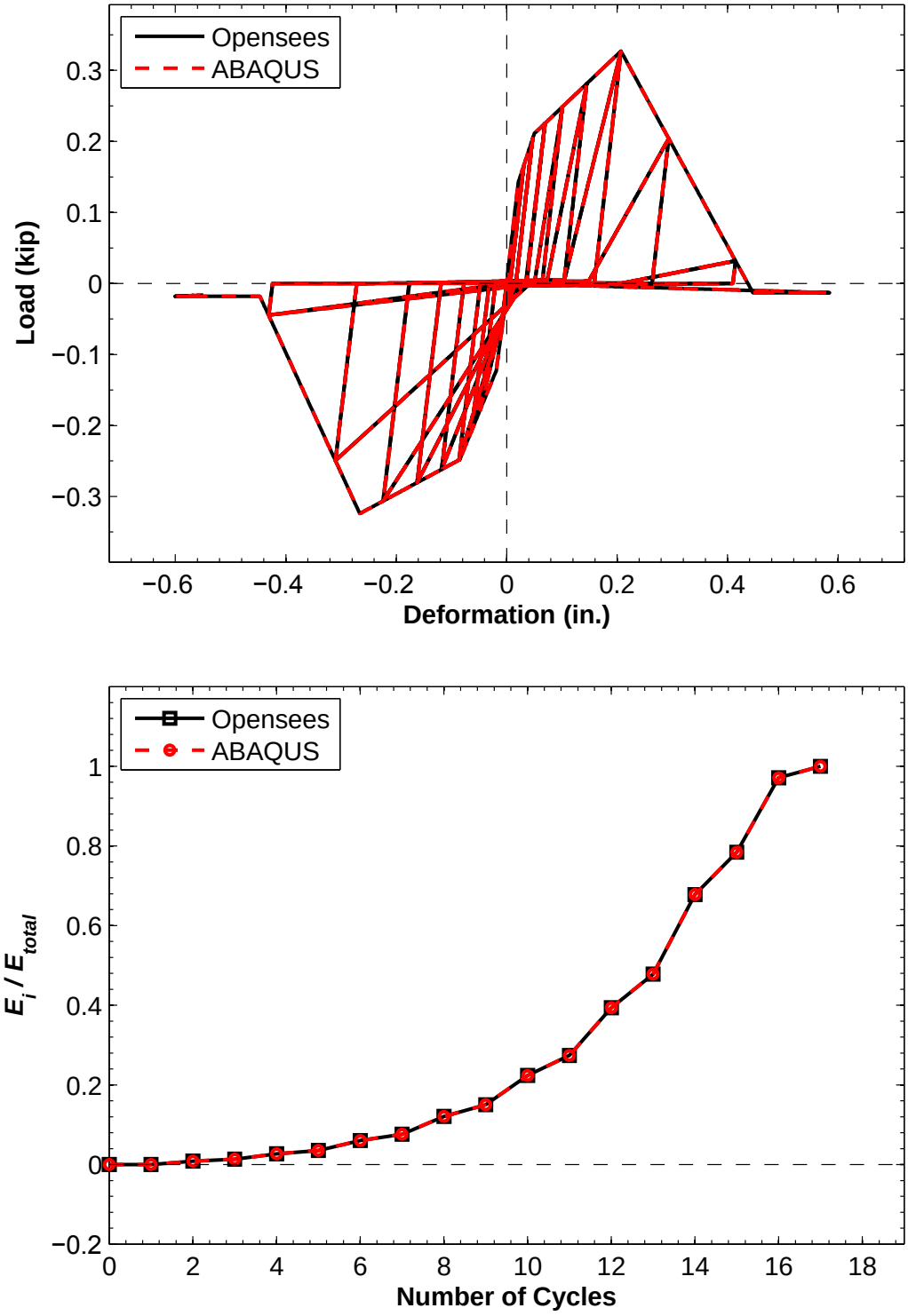

Fig. A.2. Verification case c33o12_1 (a) Load-deformation (b) Energy-cycle

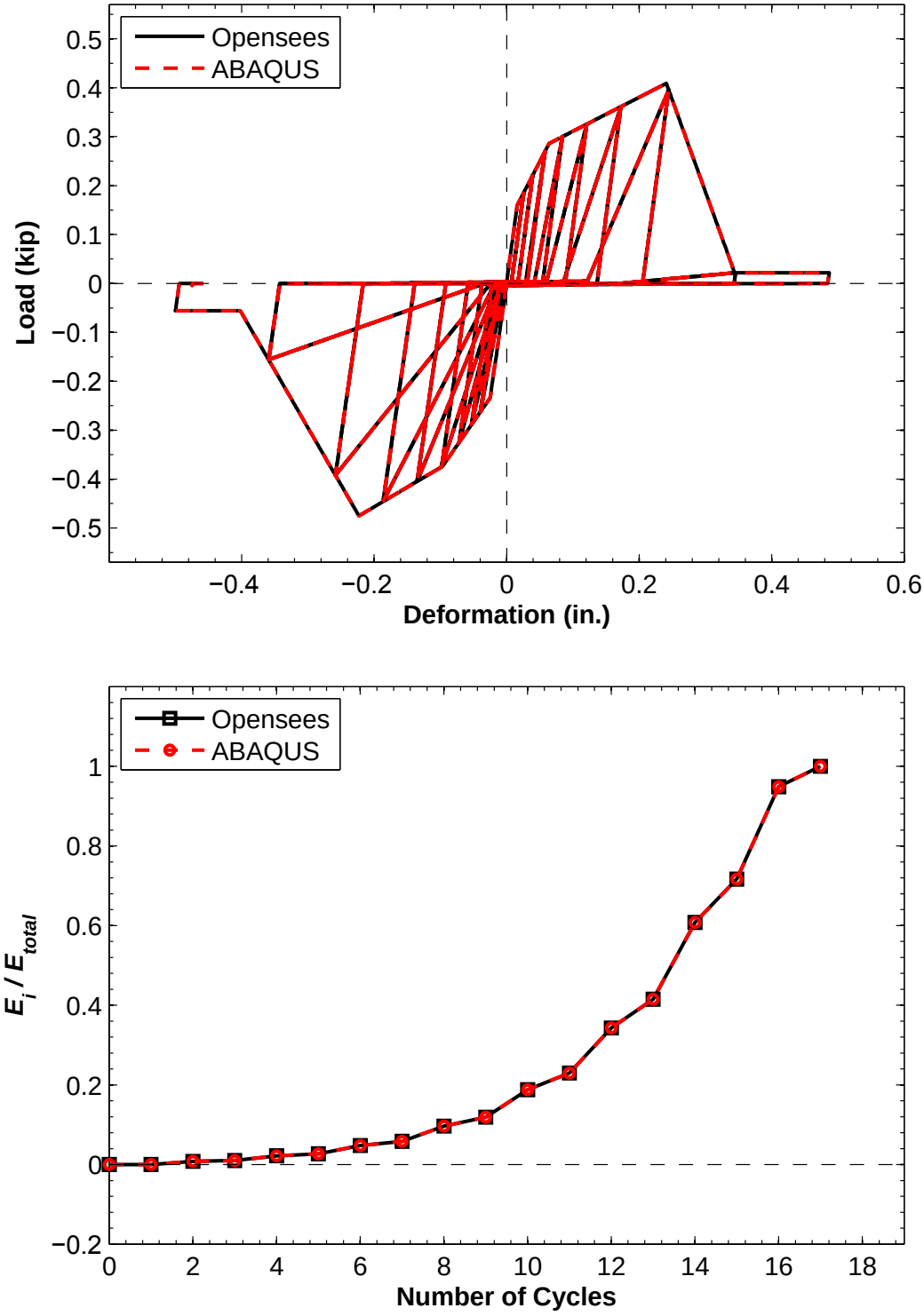

Fig. A.3. Verification case c54o6_1 (a) Load-deformation (b) Energy-cycle

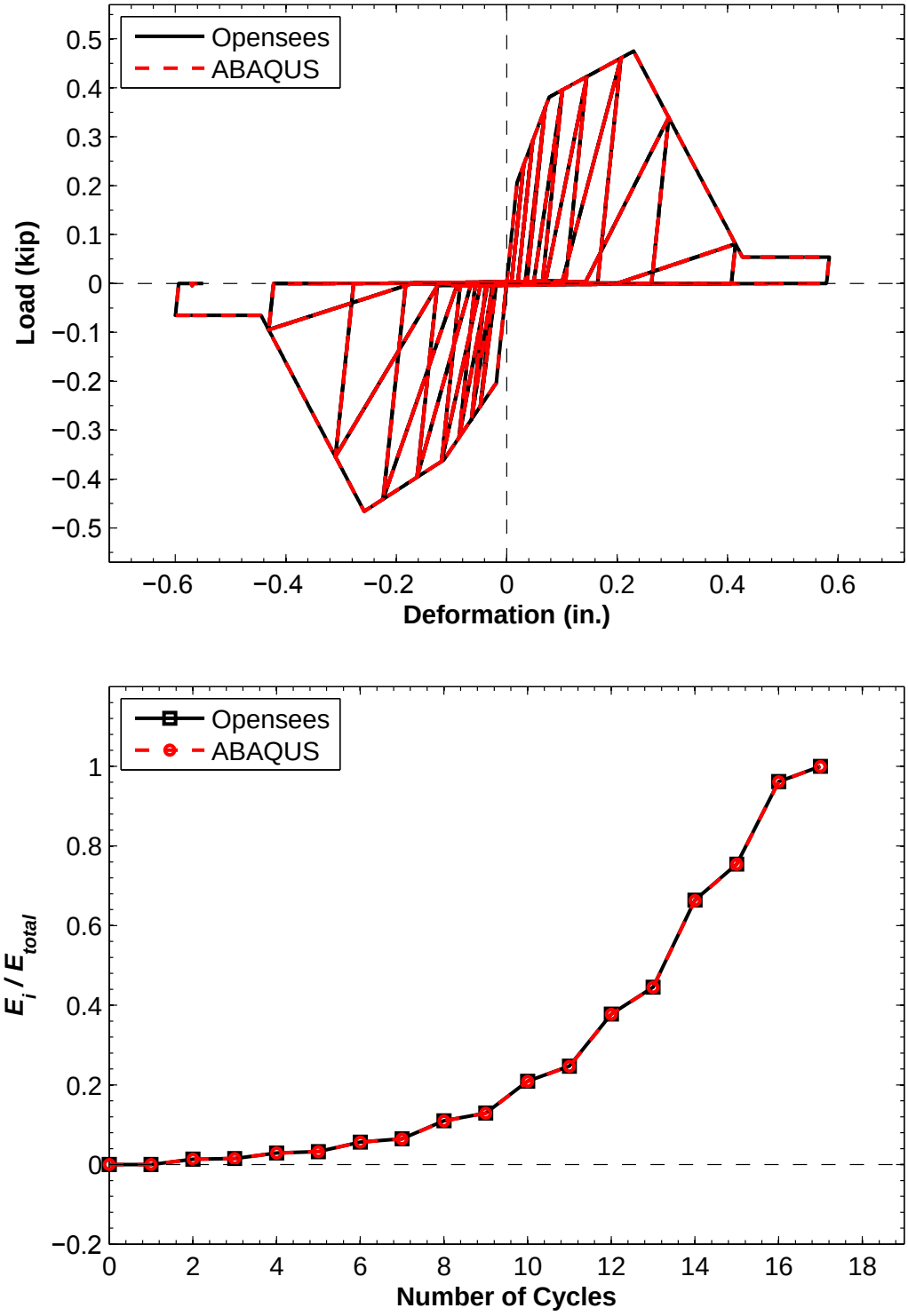

Fig. A.4. Verification case c54o12_1 (a) Load-deformation (b) Energy-cycle

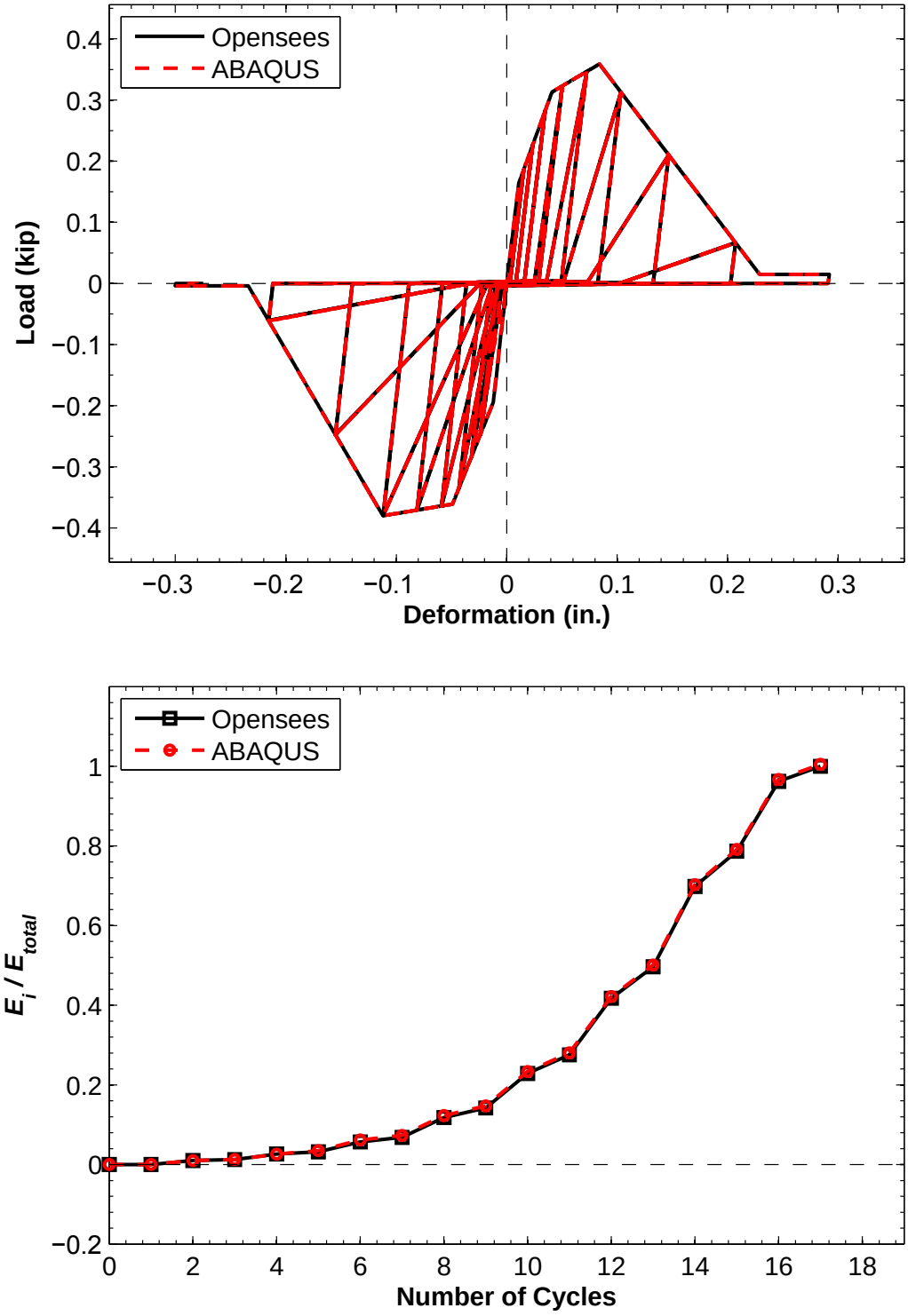

Fig. A.5. Verification case c97o6_1 (a) Load-deformation (b) Energy-cycle

A.2 Degradation Verification

Three verification cases are analyzed in ABAQUS studying respectively unloading stiffness degradation, reloading stiffness degradation and strength degradation. Pinching4 parameters of typical 54 mils to 7/16'' OSB connections are used. ABAQUS results are compared to OpenSees. The Pinching4 parameter input are listed in the following tables.

Table A.4. Backbone parameter of degradation verification cases

ePd_1	ePd_2	ePd_3	ePd_4	eNd_1	eNd_2	eNd_3	eNd_4
	(in.)				(in.)		
0.020	0.078	0.246	0.414	-0.020	-0.078	-0.246	-0.414
ePf_1	ePf_2	ePf_3	ePf_4	eNf_1	eNf_2	eNf_3	eNf_4
	(kip.)				(kip.)		
0.220	0.350	0.460	0.049	-0.220	-0.350	-0.460	-0.049

Table A.5. Degradation parameters of degradation verification cases

Degradation	γ_1	γ_2	γ_3	γ_4	γ_{lim}
Unloading stiffness	0.250	0.850	0.650	0.120	1000.000
Reloading stiffness	2.740	0.240	1.720	0.980	1000.000
Strength	0.160	1.170	0.530	0.460	1000.000

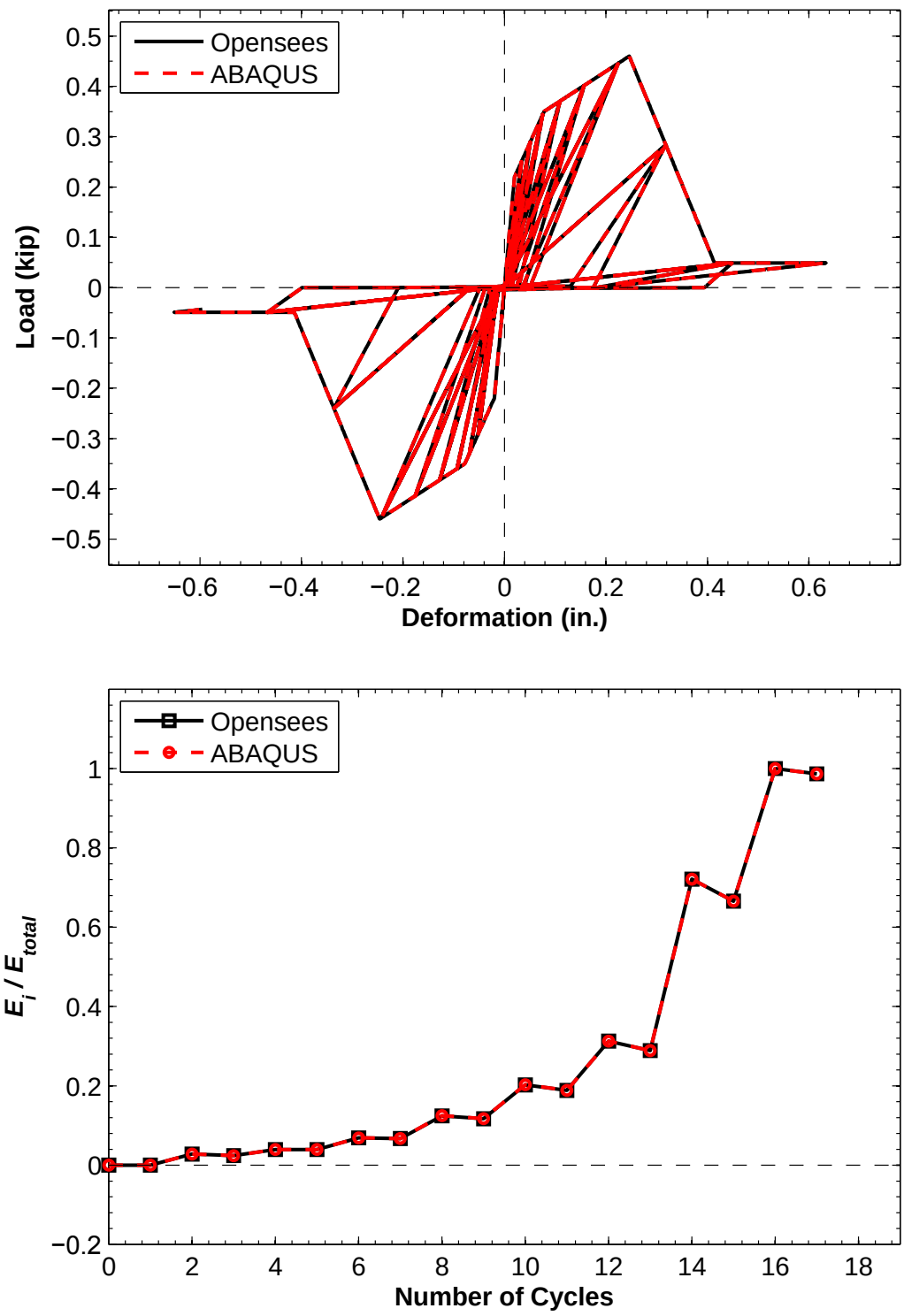

Fig. A.6. Unloading stiffness verification case: (a) Load-deformation (b) Cycle-energy

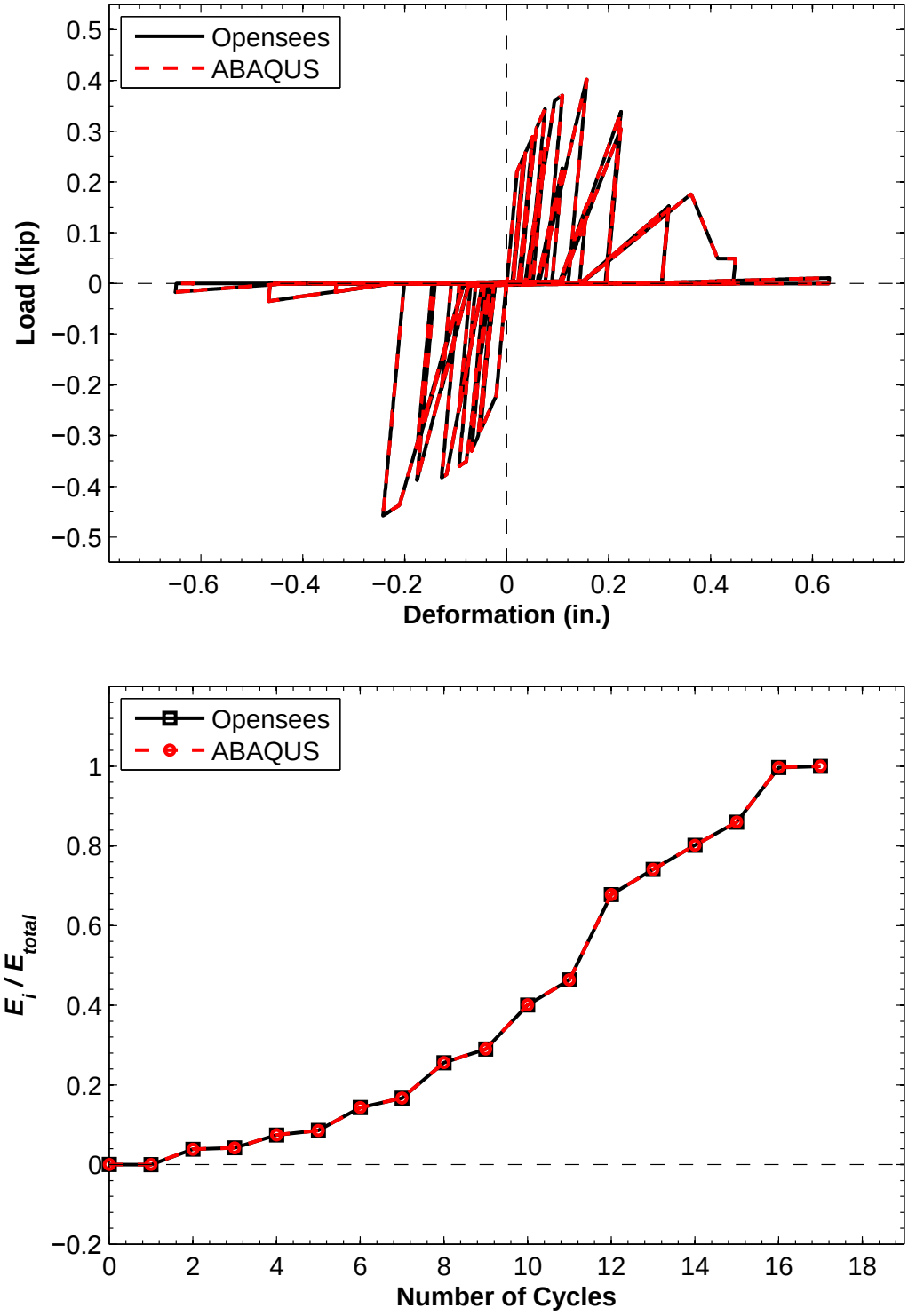

Fig. A.7. Reloading stiffness verification case: (a) Load-deformation (b) Cycle-energy

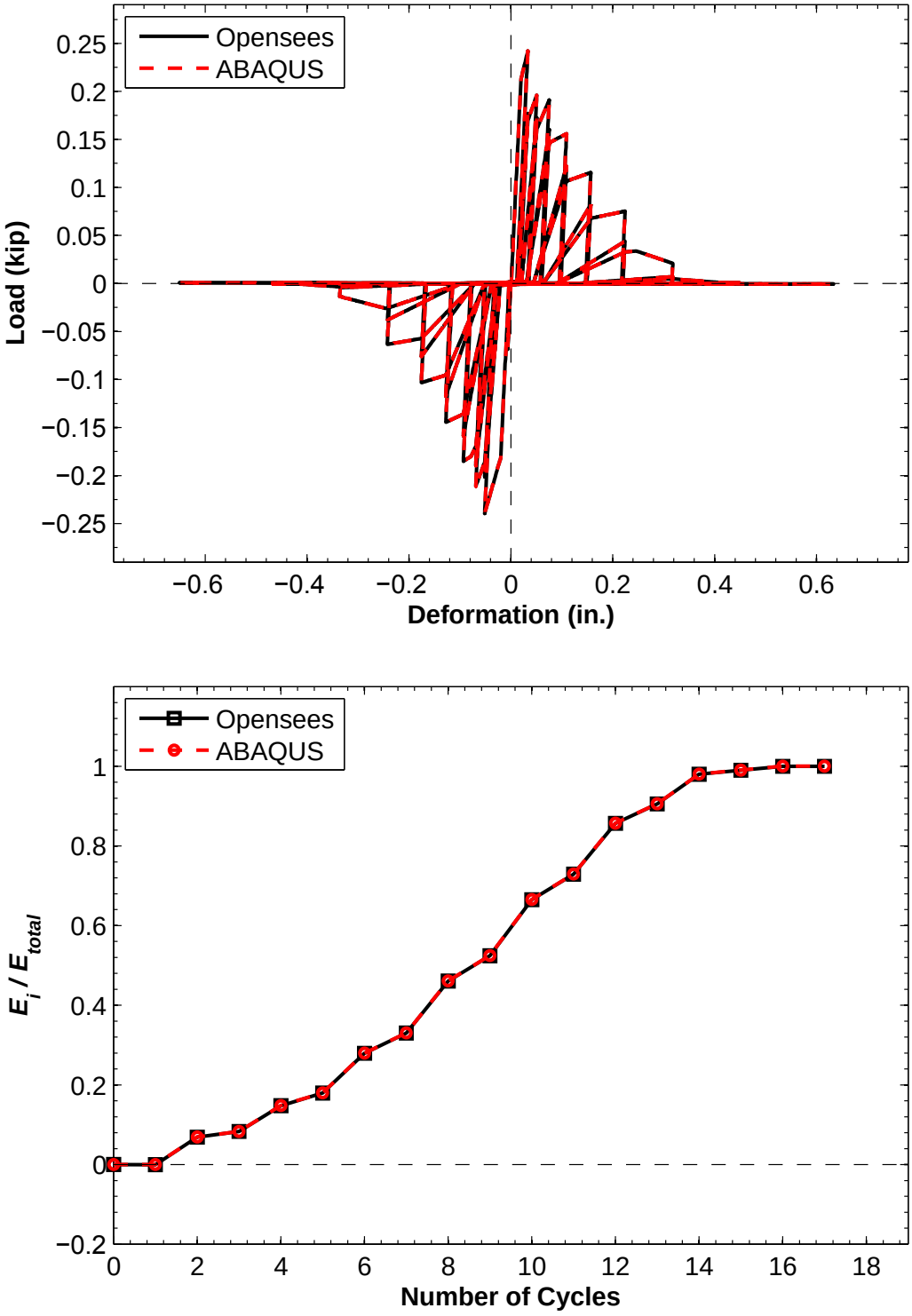

Fig. A.8. Strength stiffness verification case: (a) Load-deformation (b) Cycle-energY

APPENDIX B CONNECTION RESPONSE IN PUSHOVER ANALYSIS

The following figures shows screw-fastened connection force with respect to shear wall lateral displacement. Only those that are reported to have failed during shear experiment are shown here. The Fig. B.1, Fig. B.2 and Fig. B.3 shows failed connections at different locations, namely left stud bottom, right stud bottom and bottom track. The dashed lines in the these figures labels the specific shear wall lateral displacement corresponding to the initiation and end of shear wall load-deformation curve "legs".

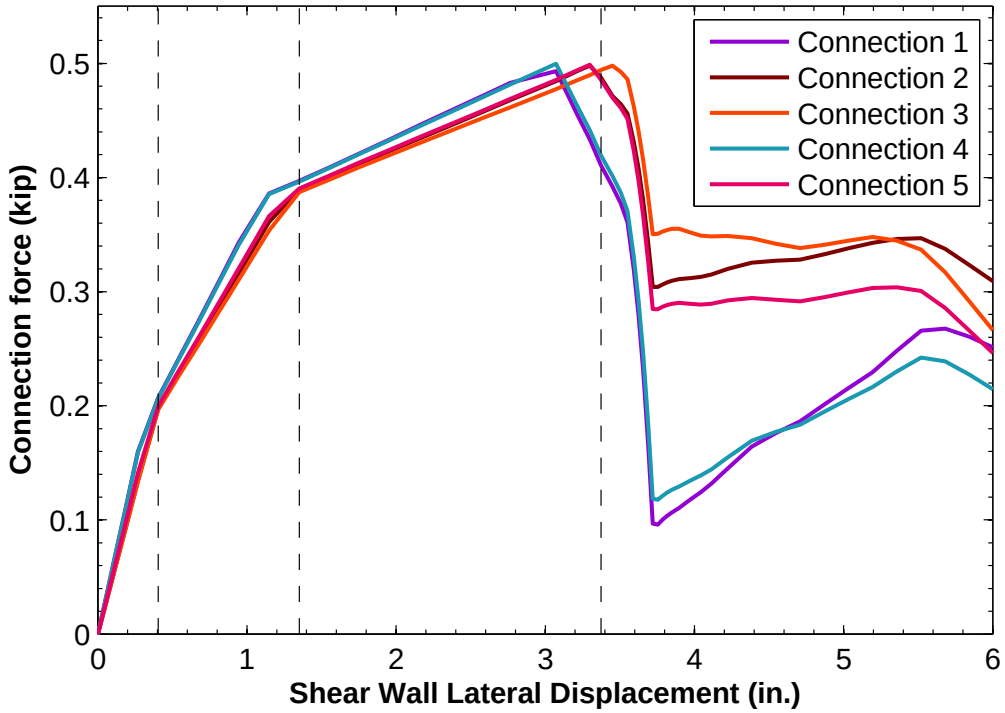

Fig. B.1. Force of left stud bottom connections a shear wall lateral displacement

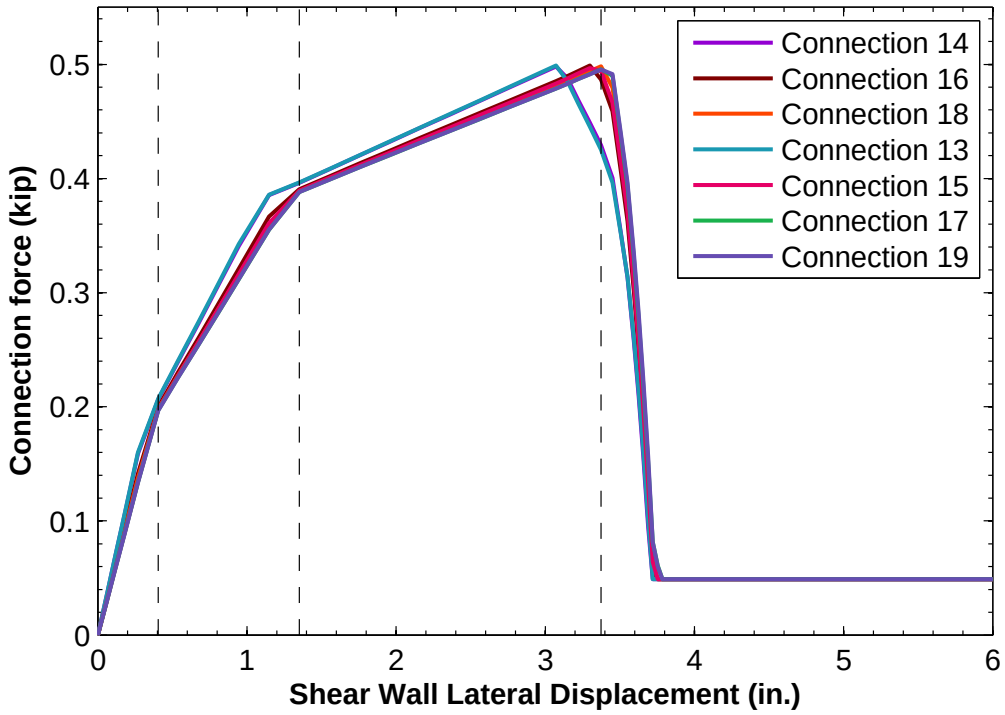

Fig. B.2. Force of right stud bottom connections against shear wall lateral displacement

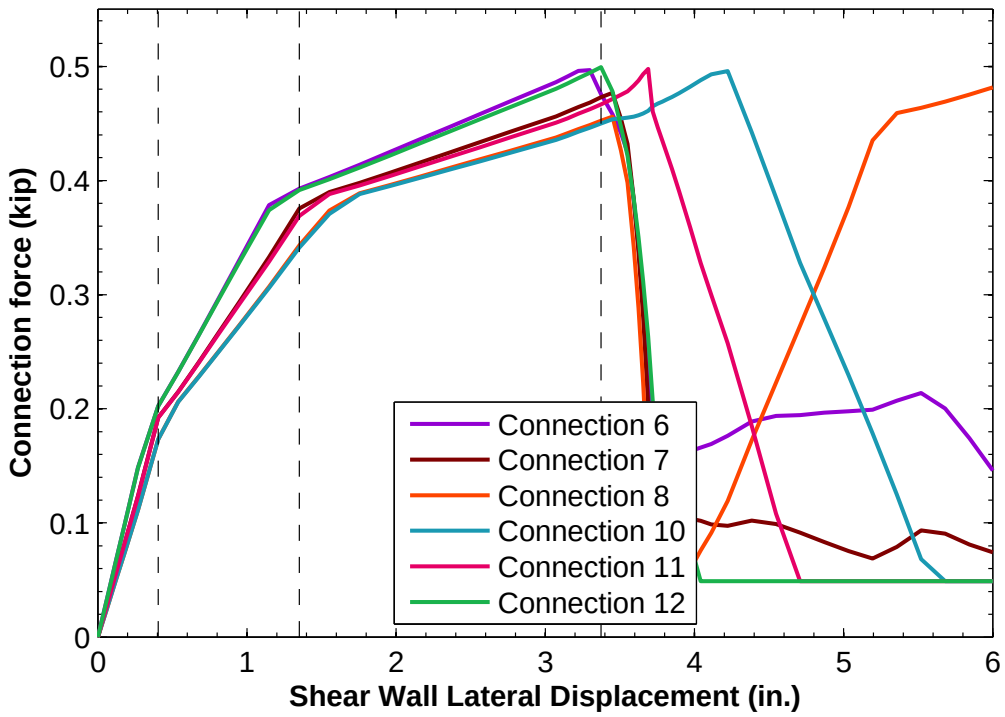

Fig. B.3. Force of bottom track connections against shear wall lateral displacement

APPENDIX C USER ELEMENT SUBROUTINE IMPLICIT CODE (UEL)

```
C
C
*****************************************************************************************
*******
C                        ABAQUS USER ELEMENT SUBROUTINE (UEL)
C                  --- FOR FASTENER-BASED SHEAR WALL/DIAPHRAGM ANALYSIS  ---
C             ------------------------------------------------------------------
C                                          AUTHOR:  Chu Ding
(chud91@vt.edu)
C                                          ADVISOR: Dr. Cristopher D. Moen
(cmoen@vt.edu)
C                                          RESEARCH GROUP:
http://www.moen.cee.vt.edu/
C
*****************************************************************************************
*******
C
      SUBROUTINE UEL(RHS,AMATRX,SVARS,ENERGY,NDOFEL,NRHS,NSVARS,
     +    PROPS,NPROPS,COORDS,MCRD,NNODE,U,DU,V,A,JTYPE,TIME,DTIME,
     +    KSTEP,KINC,JELEM,PARAMS,NDLOAD,JDLTYP,ADLMAG,PREDEF,
     +    NPREDF,LFLAGS,MLVARX,DDLMAG,MDLOAD,PNEWDT,JPROPS,NJPROP,
     +    PERIOD)
C
C
C     ************************************************************
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0, TWO = 2.D0)
C
C
      DIMENSION RHS(MLVARX,*),AMATRX(NDOFEL,NDOFEL),PROPS(*),
     1 SVARS(*),ENERGY(8),COORDS(MCRD,NNODE),U(NDOFEL),
     2 DU(MLVARX,*),V(NDOFEL),A(NDOFEL),TIME(2),PARAMS(*),
     3 JDLTYP(MDLOAD,*),ADLMAG(MDLOAD,*),DDLMAG(MDLOAD,*),
     4 PREDEF(2,NPREDF,NNODE),LFLAGS(*),JPROPS(*)
C
      DIMENSION SRESID(4)
      DIMENSION SPR_AMATRX(4,4), SPR_SRESID(4)
C
      DOUBLE PRECISION SPR_LEN, SPR_DISP
```

```
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
      DOUBLE PRECISION SPR_DISP_X, SPR_DISP_Y
      DOUBLE PRECISION SPR_K, SPR_F
      DOUBLE PRECISION SPR_SGN
      DOUBLE PRECISION SPR_K_X, SPR_K_Y
      DOUBLE PRECISION SPR_F_X, SPR_F_Y
      DOUBLE PRECISION SPR_DISP_U, SPR_DISP_V
      DOUBLE PRECISION SPR_K_U, SPR_K_V
      DOUBLE PRECISION SPR_F_U, SPR_F_V
C
      DOUBLE PRECISION SPR_K_SEC, SPR_K_SEC_X, SPR_K_SEC_Y
      DOUBLE PRECISION SPR_K_SEC_U, SPR_K_SEC_V
C
      DOUBLE PRECISION SPR_ORIENT_1, SPR_ORIENT_2
C
      DOUBLE PRECISION SPR_DISP1, SPR_DISP2, SPR_F1, SPR_F2,
SPR_ENERGY
C
      DOUBLE PRECISION SPR_YD
C
      INTEGER I_SPR_NUM
      INTEGER KPNT, KSEC, KORIENT
C
      CHARACTER FILENAME*200
      CHARACTER*(*) FILEPATH
C
C
C     --------------                Choose spring data output path                --------------
C     ***********************************************************************************************
      PARAMETER (FILEPATH = 'E:\Onedrive\VT_RESEARCH\UEL
work\uel_upgrade\add all springs\modified radial spring\check\')
C     ***********************************************************************************************
C
C
C     --------------                Select your spring type                       --------------
C     ***********************************************************************************************
C     * 1: Radial spring, 2: Coupled spring pair, 3: Uncoupled spring pair, 4: Oriented
spring pair
C     * 5: Modified radial spring
      KPNT = 5
C     * 0: Tangent stiffness, 1: Secant stiffness
      KSEC = 0
C     * 0: Default deformation quadrants, 1: Displacement-based deformation quadrants
      KORIENT = 1
C     * 0:  Forbid spring data output, 1: Permit spring data output
      KOUTPUT = 1
C     ***********************************************************************************************
C
C
```

```
C     Specify fastener mass
      AM   = 4.5D-5
C
C     Initialize vector variables
      DO K1 = 1, NDOFEL
         SRESID(K1) = ZERO
         SPR_SRESID(K1) = ZERO
         DO KRHS = 1, NRHS
            RHS(K1,KRHS) = ZERO
         END DO
         DO K2 = 1, NDOFEL
            AMATRX(K1, K2) = ZERO
            SPR_AMATRX(K1,K2) = ZERO
         END DO
      END DO
C
C     Initialize scalar variables
      SPR_DISP_X = ZERO
      SPR_DISP_Y = ZERO
      SPR_K_X = ZERO
      SPR_K_Y = ZERO
      SPR_F_X = ZERO
      SPR_F_Y = ZERO
C
C
C     **************** Generate spring geometry info. ****************
      IF (KPNT .EQ. 1) THEN
C     * Radial-spring model
         CALL
SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,
SPR_DISP_Y,PROPS,SVARS)
      ELSE IF (KPNT. EQ. 2) THEN
C     * Coupled-spring model
         CALL
SGEOM_CUP(U,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,SPR_DISP_Y)
      ELSE IF (KPNT .EQ. 4) THEN
C     * Oriented spring pair
         CALL SGEOM_ORN(U, SPR_DISP_X, SPR_DISP_Y, SPR_COS_X,
SPR_COS_Y, SPR_DISP_U, SPR_DISP_V, SVARS)
      ELSE IF (KPNT .EQ. 5) THEN
         IF (SVARS(180) .EQ. ZERO) THEN
            CALL
SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,
SPR_DISP_Y,PROPS,SVARS)
         ELSE
            CALL
SGEOM_MDRD(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_D
ISP_X,SPR_DISP_Y,PROPS,SVARS)
         END IF
```

```
      ELSE
C      * 2-spring model
         CALL
SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,
SPR_DISP_Y,PROPS,SVARS)
      END IF
C
C
C      **************** Record connection yielding ****************
      IF (KPNT .EQ. 1 .OR. KPNT .EQ. 2 .OR. KPNT. EQ. 5) THEN
         IF (SVARS(180) .EQ. ZERO) THEN
            IF (DABS(SPR_DISP) .GE. DABS(PROPS(1))) THEN
               SPR_YD = ONE
               SVARS(180) = ONE
               SVARS(181) = SPR_COS_X
               SVARS(182) = SPR_COS_Y
            ELSE
               SPR_YD = ZERO
               SVARS(180) = ZERO
            END IF
         END IF
      END IF
C
C
C      **************** Save spring original orientation ****************
*      * Set up spring positive/negative deformation rule
C      * Only applicable to radial spring/coupled spring/modified radial spring
      IF (KPNT .EQ. 1 .OR. KPNT .EQ. 2 .OR. KPNT .EQ. 5) THEN
C         * Deformation quadrant based on initial displacement
         IF (KORIENT .EQ. 1) THEN
            IF (SVARS(128) .NE. ONE) THEN
C               * Use default deformation quadrant when deformation is "zero"
               IF (DABS(SPR_DISP) .LE. TWO * TOL) THEN
                  SVARS(129) = 1.D0/DSQRT(2.D0)
                  SVARS(130) = 1.D0/DSQRT(2.D0)
               ELSE
C               * Now use displacement-based quadrant
C                  * Save spring orientation
                  SVARS(129) = SPR_COS_X
                  SVARS(130) = SPR_COS_Y
C                  * Keep spring orientation quadrant fixed now
                  SVARS(128) = SVARS(128) + ONE
               END IF
            END IF
C            * Retrieve spring orientation
            SPR_ORIENT_1 = SVARS(129)
            SPR_ORIENT_2 = SVARS(130)
C         * Default deformation quadrant
         ELSE
```

```
            SPR_ORIENT_1 = 1.D0/DSQRT(2.D0)
            SPR_ORIENT_2 = 1.D0/DSQRT(2.D0)
         END IF
      END IF
C
C
C     **************** Adjust spring deformation sign ****************
C     * Only applicable to radial spring/coupled spring model
      IF (KPNT .EQ. 1 .OR. KPNT .EQ. 2 .OR. (KPNT .EQ. 5 .AND. SVARS(180) .EQ.
ZERO)) THEN
         SPR_SGN = ONE
C         * For the case of "real compression"
         IF (SPR_DISP .LT. ZERO) THEN
            SPR_SGN = ONE
C         * For the case of "fake compression" determined by deformation quadrants
         ELSE IF (SPR_DISP_X .NE. ZERO .AND. SPR_DISP_Y .NE. ZERO) THEN
            IF (SPR_ORIENT_1 * SPR_DISP_X + SPR_ORIENT_2 * SPR_DISP_Y .LT.
ZERO) THEN
               SPR_SGN = -ONE
            END IF
         END IF
C         * Spring deformation is assinged with positive or negative sign
         SPR_DISP = SPR_SGN * SPR_DISP
      ELSE
         SPR_SGN = ONE
      END IF
!C
C
C     **************** Get spring stiffness and force from nonlinear model ****************
C     * Apply to radial spring, coupled two-spring, modified radial spring *
      IF (KPNT .EQ. 1 .OR. KPNT. EQ. 2 .OR. KPNT .EQ. 5) THEN
C         Use tangent stiffness definition
         I_SPR_NUM = 1
         CALL
PINCHING4(PROPS,SVARS,SPR_DISP,SPR_K,SPR_F,KINC,I_SPR_NUM)
C
C         Use secant stiffness definition
         IF (KSEC .EQ. 1 .AND. DABS(SPR_DISP) .GE. TOL) THEN
            SPR_K_SEC = SPR_F / SPR_DISP
            SPR_K = SPR_K_SEC
         END IF
C     * Apply to oriented spring pair *
      ELSE IF (KPNT .EQ. 4) THEN
C
         IF (KINC .EQ. 0 .OR. KINC .EQ. 1) THEN
            SPR_DISP_U = SPR_DISP_X
            SPR_DISP_V = SPR_DISP_Y
         END IF
C
```

```
      I_SPR_NUM = 1
      CALL
PINCHING4(PROPS,SVARS,SPR_DISP_U,SPR_K_U,SPR_F_U,KINC,I_SPR_NUM)
C
      I_SPR_NUM = 2
      CALL
PINCHING4(PROPS,SVARS,SPR_DISP_V,SPR_K_V,SPR_F_V,KINC,I_SPR_NUM)
C
C       Use secant stiffness definition
      IF (KSEC .EQ. 1. AND. DABS(SPR_DISP_U) .GE. TOL .AND.
DABS(SPR_DISP_V) .GE. TOL) THEN
         SPR_K_SEC_U = SPR_F_U / SPR_DISP_U
         SPR_K_SEC_V = SPR_F_V / SPR_DISP_V
         SPR_K_U = SPR_K_SEC_U
         SPR_K_V = SPR_K_SEC_V
      END IF
C
      IF (KINC .EQ. 0 .OR. KINC .EQ. 1) THEN
         SPR_K_X = SPR_K_U
         SPR_F_X = SPR_F_U
         SPR_K_Y = SPR_K_V
         SPR_F_Y = SPR_F_V
      END IF
C
C    * Apply two-spring model
    ELSE
C       Use tangent stiffness definition
      I_SPR_NUM = 1
      CALL
PINCHING4(PROPS,SVARS,SPR_DISP_X,SPR_K_X,SPR_F_X,KINC,I_SPR_NUM)
C
      I_SPR_NUM = 2
      CALL
PINCHING4(PROPS,SVARS,SPR_DISP_Y,SPR_K_Y,SPR_F_Y,KINC,I_SPR_NUM)
C
C       Use secant stiffness definition
      IF (KSEC .EQ. 1. AND. DABS(SPR_DISP_X) .GE. TOL .AND.
DABS(SPR_DISP_Y) .GE. TOL) THEN
         SPR_K_SEC_X = SPR_F_X / SPR_DISP_X
         SPR_K_SEC_Y = SPR_F_Y / SPR_DISP_Y
         SPR_K_X = SPR_K_SEC_X
         SPR_K_Y = SPR_K_SEC_Y
      END IF
    END IF
C
C
C    **************** Generate stiffness matrix and residual force vector ****************
C    * Radial spring model
    IF (KPNT .EQ. 1 .OR. KPNT .EQ. 5) THEN
```

```
      CALL SAMATRX(SPR_AMATRX, SPR_K, SPR_F, SPR_LEN, SPR_COS_X,
SPR_COS_Y, SPR_SGN)
      CALL SNFORCE(SPR_F, SPR_COS_X, SPR_COS_Y, SPR_SRESID,
SPR_SGN)
C     * Coupled spring model
    ELSE IF (KPNT .EQ. 2) THEN
      CALL SAMATRX_CUP(SPR_AMATRX, SPR_K)
      CALL SNFORCE(SPR_F, SPR_COS_X, SPR_COS_Y, SPR_SRESID,
SPR_SGN)
C     * Oriented spring pair model
    ELSE IF (KPNT .EQ. 4) THEN
      IF (KINC. EQ. 1 .OR. KINC .EQ. 0) THEN
        CALL SAMATRX_2(SPR_AMATRX, SPR_K_X, SPR_K_Y)
        CALL SFORCE_2(SPR_SRESID, SPR_F_X, SPR_F_Y)
      ELSE
        CALL SAMATRX_ORNT(SPR_AMATRX, SPR_K_U, SPR_K_V, SVARS)
        CALL SNFORCE_ORNT(SPR_F_U, SPR_F_V, SVARS, SPR_SRESID,
SPR_F_X, SPR_F_Y)
      END IF
C     * Uncoupled 2-spring model
    ELSE
      CALL SAMATRX_2(SPR_AMATRX, SPR_K_X, SPR_K_Y)
      CALL SFORCE_2(SPR_SRESID, SPR_F_X, SPR_F_Y)
    END IF
C
C
C     **************** Update energy ****************
    IF (KPNT .EQ. 1 .OR. KPNT .EQ. 2 .OR. KPNT .EQ. 5) THEN
      SVARS(141) = SVARS(142)        ! Deformation for last increment
      SVARS(142) = SPR_DISP          ! Deformation at current increment
      SVARS(143) = SVARS(144)        ! Spring force from last increment
      SVARS(144) = SPR_F             ! Spring force at current increment
C
      SPR_DISP1 = SVARS(141)
      SPR_DISP2 = SVARS(142)
      SPR_F1 = SVARS(143)
      SPR_F2 = SVARS(144)
      SPR_ENERGY = HALF * (SPR_F2 + SPR_F1) * (SPR_DISP2 - SPR_DISP1)
      SVARS(145) = SVARS(145) + SPR_ENERGY
    ELSE
      SVARS(141) = SVARS(142)
      SVARS(142) = SPR_DISP_X
      SVARS(143) = SVARS(144)
      SVARS(144) = SPR_DISP_Y
      SVARS(146) = SVARS(147)
      SVARS(147) = SPR_F_X
      SVARS(148) = SVARS(149)
      SVARS(149) = SPR_F_Y
C
```

```
      SPR_DISP_X1 = SVARS(141)
      SPR_DISP_X2 = SVARS(142)
      SPR_DISP_Y1 = SVARS(143)
      SPR_DISP_Y2 = SVARS(144)
      SPR_F_X1 = SVARS(146)
      SPR_F_X2 = SVARS(147)
      SPR_F_Y1 = SVARS(148)
      SPR_F_Y2 = SVARS(149)
      SPR_ENERGY_X = HALF * (SPR_F_X2 + SPR_F_X1) * (SPR_DISP_X2 -
SPR_DISP_X1)
      SPR_ENERGY_Y = HALF * (SPR_F_Y2 + SPR_F_Y1) * (SPR_DISP_Y2 -
SPR_DISP_Y1)
      SPR_ENERGY = SPR_ENERGY_X + SPR_ENERGY_Y
      SVARS(145) = SVARS(145) + SPR_ENERGY
    END IF
C
C
C    *************** ABAQUS/Standar analysis procedures ***************
    IF (LFLAGS(3) .EQ. 1) THEN
C       * General static analysis
      IF (LFLAGS(1) .EQ.1 .OR. LFLAGS(1) .EQ. 2) THEN
        DO K1 = 1, 4
          DO K2 = 1,4
            AMATRX(K1,K2) = SPR_AMATRX(K1,K2)
          END DO
          SRESID(K1) = SPR_SRESID(K1)
          RHS(K1,1) = RHS(K1,1) - SRESID(K1)
          ENERGY(2) = SVARS(145)
        END DO
C       * Dynamic analysis (implicit)
      ELSE IF (LFLAGS(1).EQ.11 .OR. LFLAGS(1).EQ.12) THEN
        ALPHA = PARAMS(1)
        BETA  = PARAMS(2)
        GAMMA = PARAMS(3)
        DADU = ONE/(BETA*DTIME**2)
        DVDU = GAMMA/(BETA*DTIME)
C
        DO K1 = 1, NDOFEL
          AMATRX(K1,K1) = AM*DADU
          RHS(K1,1) = RHS(K1,1)-AM*A(K1)
        END DO
C
        DO K1 = 1, NDOFEL
          DO K2 = 1, NDOFEL
            AMATRX(K1,K2) = AMATRX(K1,K2) +
SPR_AMATRX(K1,K2)*(ONE+ALPHA)
          END DO
          SRESID(K1) = SPR_SRESID(K1)
        END DO
```

```
C
          DO K1 = 1, NDOFEL
             RHS(K1,1) = RHS(K1,1) - ((ONE+ALPHA)*SRESID(K1)-
ALPHA*SVARS(150+K1))
          END DO
C
          ENERGY(1) = ZERO
          DO K1 = 1, NDOFEL
             SVARS(K1+154) = SVARS(K1+150)
             SVARS(K1+150) = SRESID(K1)
             ENERGY(1) = ENERGY(1)+HALF*V(K1)*AM*V(K1)
          END DO
C
          ENERGY(2) = SVARS(145)
       END IF
C    * Define stiffness matrix only
    ELSE IF (LFLAGS(3) .EQ. 2) THEN
       DO K1 = 1, 4
          DO K2 = 1,4
             AMATRX(K1,K2) = SPR_AMATRX(K1,K2)
          END DO
       END DO
C    * Define mass matrix
    ELSE IF (LFLAGS(3) .EQ. 4) THEN
       DO K1 = 1, NDOFEL
          DO K2 = 1, NDOFEL
             AMATRX(K1,K2) = ZERO
          END DO
       END DO
       DO K1 = 1, NDOFEL
          AMATRX(K1,K1) = AM
       END DO
C    * Half-step residual calculation
    ELSE IF (LFLAGS(3) .EQ. 5) THEN
       ALPHA = PARAMS(1)
       DO K1 = 1, NDOFEL
          SRESID(K1) = SPR_SRESID(K1)
       END DO
       DO K1 = 1, NDOFEL
          RHS(K1,1) = RHS(K1,1)-AM*A(K1)-(ONE+ALPHA)*SRESID(K1) +
   + HALF*ALPHA*(SVARS(K1+150)+SVARS(K1+154))
       END DO
C    * Initial acceleration calculation
    ELSE IF (LFLAGS(3) .EQ. 6) THEN
       DO K1 = 1, NDOFEL
          AMATRX(K1,K1) = AM
          SRESID(K1) = SPR_SRESID(K1)
       END DO
       DO K1 = 1, NDOFEL
```

```
            RHS(K1,1) = RHS(K1,1)-SRESID(K1)
         END DO
         ENERGY(1) = ZERO
         DO K1 = 1, NDOFEL
            SVARS(K1+150) = SRESID(K1)
            ENERGY(1) = ENERGY(1)+HALF*V(K1)*AM*V(K1)
         END DO
         ENERGY(2) = SVARS(145)
      END IF
C
C
C     **************** Ouput spring data ****************
C     * Uncoupled two-spring model
800   FORMAT(I10, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8)
C
C     * Radial spring/coupled spring model
900   FORMAT(I10, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8,
F20.8)
C
C     * Oriented spring model
700   FORMAT(I10, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8,
F20.8, F20.8, F20.8)
C
C     * Modified radial spring
950   FORMAT(I10, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8, F20.8,
F20.8,
     +F20.8, F20.8, F20.8)
C
C
      IF (KOUTPUT .EQ. 1) THEN
         IF (KINC .GE. 1) THEN
            WRITE(FILENAME, fmt='(a, I0, a)') FILEPATH, JELEM, ".txt"
            OPEN(300, FILE=FILENAME, STATUS='UNKNOWN', POSITION='APPEND')
C            * Radial spring/coupled two-spring model
            IF (KPNT .EQ. 1 .OR. KPNT .EQ. 2) THEN
               WRITE(300, 900) KINC, TIME(2), SPR_DISP, SPR_F, SPR_K, ENERGY(2),
     +SPR_SGN, SPR_COS_X, SPR_COS_Y, SPR_DISP_X, SPR_DISP_Y
C            * Oriented spring pair model
            ELSE IF (KPNT .EQ. 4) THEN
               WRITE(300, 700) KINC, TIME(2), SPR_DISP_U, SPR_K_U, SPR_F_U,
SPR_DISP_V,
     +SPR_K_V, SPR_F_V, SVARS(171), SVARS(172), SPR_DISP_X, SPR_DISP_Y
C            * Modified radial spring
            ELSE IF (KPNT .EQ. 5) THEN
               WRITE(300, 950) KINC, TIME(2), SPR_DISP, SPR_F, SPR_K, ENERGY(2),
     +SPR_SGN, SPR_COS_X, SPR_COS_Y, SPR_DISP_X, SPR_DISP_Y,
SVARS(180), SVARS(181), SVARS(182)
C            * Uncoupled two-spring model
            ELSE
```

```
            WRITE(300, 800) KINC, TIME(2), SPR_DISP_X, SPR_K_X, SPR_F_X,
SPR_DISP_Y, SPR_K_Y, SPR_F_Y
          END IF
          CLOSE(300)
        END IF
      END IF
C
C
      RETURN
      END
C
C
      SUBROUTINE
SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,
SPR_DISP_Y,PROPS,SVARS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION U(4), COORDS(3,2), PROPS(41), SVARS(200)
C
C
      DOUBLE PRECISION SPR_COORD_X, SPR_COORD_Y
      DOUBLE PRECISION SPR_DISP_X, SPR_DISP_Y
      DOUBLE PRECISION SPR_LEN_X, SPR_LEN_Y
      DOUBLE PRECISION SPR_LEN0, SPR_LEN
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
C
      INTEGER ISPR_DIR_1, ISPR_DIR_2
C
C
      ISPR_DIR_1 = INT(PROPS(40))
      ISPR_DIR_2 = INT(PROPS(41))
C
      SPR_COORD_X = COORDS(ISPR_DIR_1,2) - COORDS(ISPR_DIR_1,1)
      SPR_COORD_Y = COORDS(ISPR_DIR_2,2) - COORDS(ISPR_DIR_2,1)
C
      SPR_LEN0 =
DSQRT(SPR_COORD_X*SPR_COORD_X+SPR_COORD_Y*SPR_COORD_Y)
C
      SPR_DISP_X = U(3) - U(1)
      SPR_DISP_Y = U(4) - U(2)
C
C     Adjust spring deformation and orientation for 'zero'' deformation case
      IF (DABS(SPR_DISP_X) .LE. TOL .OR. DABS(SPR_DISP_Y) .LE. TOL) THEN
        SPR_DISP_X = SPR_DISP_X + TOL * 1.D0/DSQRT(2.D0)
```

```
      SPR_DISP_Y = SPR_DISP_Y + TOL * 1.D0/DSQRT(2.D0)
    END IF
C
    SPR_LEN_X = SPR_COORD_X + SPR_DISP_X
    SPR_LEN_Y = SPR_COORD_Y + SPR_DISP_Y
C
C    * Radial spring length should not be zero!
    SPR_LEN = DSQRT(SPR_LEN_X*SPR_LEN_X+SPR_LEN_Y*SPR_LEN_Y)
C
    SPR_DISP = SPR_LEN - SPR_LEN0
C
    SPR_COS_X = SPR_LEN_X/SPR_LEN
    SPR_COS_Y = SPR_LEN_Y/SPR_LEN
C
C    Record spring orientation
C    * Discard if unrealistically huge, zero or one
    IF (DABS(SPR_COS_X * SPR_COS_Y) .LT. ONE) THEN
      IF (DABS(SPR_COS_X * SPR_COS_Y) .GT. ZERO) THEN
        SVARS(124) = SPR_COS_X
        SVARS(125) = SPR_COS_Y
      END IF
    END IF
C
C
    RETURN
    END
C
C
    SUBROUTINE
SGEOM_MDRD(U,COORDS,SPR_LEN,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_D
ISP_X,SPR_DISP_Y,PROPS,SVARS)
C
C
    INCLUDE 'ABA_PARAM.INC'
C
    PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
   + ONE = 1.D0)
C
    DIMENSION U(4), COORDS(3,2), PROPS(41), SVARS(200)
C
C
    DOUBLE PRECISION SPR_COORD_X, SPR_COORD_Y
    DOUBLE PRECISION SPR_DISP_X, SPR_DISP_Y
    DOUBLE PRECISION SPR_LEN_X, SPR_LEN_Y
    DOUBLE PRECISION SPR_LEN0, SPR_LEN
    DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
C
    INTEGER ISPR_DIR_1, ISPR_DIR_2
C
```

```
C
      ISPR_DIR_1 = INT(PROPS(40))
      ISPR_DIR_2 = INT(PROPS(41))
C
      SPR_COORD_X = COORDS(ISPR_DIR_1,2) - COORDS(ISPR_DIR_1,1)
      SPR_COORD_Y = COORDS(ISPR_DIR_2,2) - COORDS(ISPR_DIR_2,1)
C
      IF (SVARS(180) .EQ. ONE) THEN
         SPR_ORIENT_1 = SVARS(181)
         SPR_ORIENT_2 = SVARS(182)
      END IF
C
      SPR_COORD_X = SPR_ORIENT_1 * 1.D1
      SPR_COORD_Y = SPR_ORIENT_2 * 1.D1
C
      SPR_LEN0 =
DSQRT(SPR_COORD_X*SPR_COORD_X+SPR_COORD_Y*SPR_COORD_Y)
C
      SPR_DISP_X = U(3) - U(1)
      SPR_DISP_Y = U(4) - U(2)
C
C     Adjust spring deformation and orientation for 'zero'' deformation case
      IF (DABS(SPR_DISP_X) .LE. TOL .OR. DABS(SPR_DISP_Y) .LE. TOL) THEN
         SPR_DISP_X = SPR_DISP_X + TOL * 1.D0/DSQRT(2.D0)
         SPR_DISP_Y = SPR_DISP_Y + TOL * 1.D0/DSQRT(2.D0)
      END IF
C
      SPR_LEN_X = SPR_COORD_X + SPR_DISP_X
      SPR_LEN_Y = SPR_COORD_Y + SPR_DISP_Y
C
C     * Radial spring length should not be zero!
      SPR_LEN = DSQRT(SPR_LEN_X*SPR_LEN_X+SPR_LEN_Y*SPR_LEN_Y)
C
      SPR_DISP = SPR_LEN - SPR_LEN0
C
      SPR_COS_X = SPR_LEN_X/SPR_LEN
      SPR_COS_Y = SPR_LEN_Y/SPR_LEN
C
C     Record spring orientation
C     * Discard if unrealistically huge, zero or one
      IF (DABS(SPR_COS_X * SPR_COS_Y) .LT. ONE) THEN
         IF (DABS(SPR_COS_X * SPR_COS_Y) .GT. ZERO) THEN
            SVARS(124) = SPR_COS_X
            SVARS(125) = SPR_COS_Y
         END IF
      END IF
C
C
      RETURN
```

```
      END
C
C
      SUBROUTINE
SGEOM_CUP(U,SPR_DISP,SPR_COS_X,SPR_COS_Y,SPR_DISP_X,SPR_DISP_Y)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION U(4)
C
C
      DOUBLE PRECISION SPR_DISP_X, SPR_DISP_Y
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
      DOUBLE PRECISION SPR_DISP
C
C
      SPR_DISP_X = U(3) - U(1)
      SPR_DISP_Y = U(4) - U(2)
C
      SPR_DISP = DSQRT(SPR_DISP_X*SPR_DISP_X + SPR_DISP_Y*SPR_DISP_Y)
C
      SPR_COS_X = SPR_DISP_X/SPR_DISP
      SPR_COS_Y = SPR_DISP_Y/SPR_DISP
C
C
      RETURN
      END
C
C
      SUBROUTINE SGEOM_ORN(U, SPR_DISP_X, SPR_DISP_Y, SPR_COS_X,
SPR_COS_Y, SPR_DISP_U, SPR_DISP_V, SVARS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION U(4), SVARS(200)
C
C
      DOUBLE PRECISION SPR_DISP_X, SPR_DISP_Y
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
      DOUBLE PRECISION SPR_DISP_U, SPR_DISP_V
      DOUBLE PRECISION SPR_DISP
```

```
C
C
      SPR_DISP_X = U(3) - U(1)
      SPR_DISP_Y = U(4) - U(2)
      SPR_DISP = DSQRT(SPR_DISP_X*SPR_DISP_X + SPR_DISP_Y*SPR_DISP_Y)
C
C     Adjust spring deformation and orientation for 'zero" deformation case
      IF (DABS(SPR_DISP_X) .LE. TOL .OR. DABS(SPR_DISP_Y) .LE. TOL) THEN
         SPR_COS_X = 1.D0/DSQRT(2.D0)
         SPR_COS_Y = 1.D0/DSQRT(2.D0)
      ELSE
         SPR_COS_X = SPR_DISP_X/SPR_DISP
         SPR_COS_Y = SPR_DISP_Y/SPR_DISP
      END IF
C
C     Save spring orientation
      IF (SVARS(173) .NE. ONE) THEN
         IF (SPR_DISP_X .NE. 1.D0/DSQRT(2.D0) .AND. SPR_DISP_X
     +         .NE. 1.D0/DSQRT(2.D0)) THEN
            SVARS(171) = SPR_COS_X
            SVARS(172) = SPR_COS_Y
            SVARS(173) = ONE
         END IF
      END IF

C     Retrieve spring orientation
      IF (SVARS(173) .EQ. ONE) THEN
         SPR_COS_X = SVARS(171)
         SPR_COS_Y = SVARS(172)
      END IF
C
      SPR_DISP_U = SPR_DISP_X * SPR_COS_X + SPR_DISP_Y * SPR_COS_Y
      SPR_DISP_V = -SPR_DISP_X * SPR_COS_Y + SPR_DISP_Y * SPR_COS_X
C
C
      RETURN
      END
C
C
      SUBROUTINE  SAMATRX_2(AMATRX, SPR_K_X, SPR_K_Y)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION AMATRX(4,4)
C
```

```
      DOUBLE PRECISION SPR_K_X, SPR_K_Y
C
C
C     STIFFNESS MATRIX
      AMATRX(1,1) = SPR_K_X
      AMATRX(3,3) = SPR_K_X
      AMATRX(1,3) = -SPR_K_X
      AMATRX(3,1) = -SPR_K_X
      AMATRX(2,2) = SPR_K_Y
      AMATRX(4,4) = SPR_K_Y
      AMATRX(2,4) = -SPR_K_Y
      AMATRX(4,2) = -SPR_K_Y
C
C
      RETURN
      END
C
C
      SUBROUTINE SFORCE_2(SRESID, SPR_F_X, SPR_F_Y)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION SRESID(4)
C
      DOUBLE PRECISION SPR_F_X, SPR_F_Y
C
C
      SRESID(1) = -SPR_F_X
      SRESID(2) = -SPR_F_Y
      SRESID(3) = SPR_F_X
      SRESID(4) = SPR_F_Y
C
C
      RETURN
      END
C
C
      SUBROUTINE  SAMATRX_CUP(AMATRX, SPR_K)
C
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
```

```
C
      DIMENSION AMATRX(4,4)
C
      DOUBLE PRECISION SPR_K
C
C
      AMATRX(1,1) = SPR_K
      AMATRX(3,3) = SPR_K
      AMATRX(1,3) = -SPR_K
      AMATRX(3,1) = -SPR_K
      AMATRX(2,2) = SPR_K
      AMATRX(4,4) = SPR_K
      AMATRX(4,2) = -SPR_K
      AMATRX(2,4) = -SPR_K
C
C
      RETURN
      END
C
C
      SUBROUTINE  SAMATRX(AMATRX, SPR_K, SPR_F, SPR_LEN, SPR_COS_X,
SPR_COS_Y, SPR_SGN)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION AMATRX(4,4)
C
C
      DOUBLE PRECISION SPR_K, SPR_F
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
      DOUBLE PRECISION SPR_LEN
C
      DOUBLE PRECISION SPR_SGN
C
C     ELASTIC STIFFNESS MATRIX
C
       AMATRX(1,1) = SPR_K * (SPR_COS_X * SPR_COS_X)
       AMATRX(1,2) = SPR_K * (SPR_COS_X * SPR_COS_Y)
       AMATRX(1,3) = SPR_K * (-SPR_COS_X * SPR_COS_X)
       AMATRX(1,4) = SPR_K * (-SPR_COS_X * SPR_COS_Y)
C
       AMATRX(2,1) = SPR_K * (SPR_COS_X * SPR_COS_Y)
       AMATRX(2,2) = SPR_K * (SPR_COS_Y * SPR_COS_Y)
       AMATRX(2,3) = SPR_K * (-SPR_COS_X * SPR_COS_Y)
       AMATRX(2,4) = SPR_K * (-SPR_COS_Y * SPR_COS_Y)
```

```
C
      AMATRX(3,1) = SPR_K * (-SPR_COS_X * SPR_COS_X)
      AMATRX(3,2) = SPR_K * (-SPR_COS_X * SPR_COS_Y)
      AMATRX(3,3) = SPR_K * (SPR_COS_X * SPR_COS_X)
      AMATRX(3,4) = SPR_K * (SPR_COS_X * SPR_COS_Y)
C
      AMATRX(4,1) = SPR_K * (-SPR_COS_X * SPR_COS_Y)
      AMATRX(4,2) = SPR_K * (-SPR_COS_Y * SPR_COS_Y)
      AMATRX(4,3) = SPR_K * (SPR_COS_X * SPR_COS_Y)
      AMATRX(4,4) = SPR_K * (SPR_COS_Y * SPR_COS_Y)
C

C
C     ADD GEOMETRIC STIFFNESS MATRIX COMPONENT
      AMATRX(1,1) = AMATRX(1,1) + SPR_F / SPR_LEN * SPR_SGN
      AMATRX(1,3) = AMATRX(1,3) - SPR_F / SPR_LEN * SPR_SGN
      AMATRX(2,2) = AMATRX(2,2) + SPR_F / SPR_LEN * SPR_SGN
      AMATRX(2,4) = AMATRX(2,4) - SPR_F / SPR_LEN * SPR_SGN
      AMATRX(3,1) = AMATRX(3,1) - SPR_F / SPR_LEN * SPR_SGN
      AMATRX(3,3) = AMATRX(3,3) + SPR_F / SPR_LEN * SPR_SGN
      AMATRX(4,2) = AMATRX(4,2) - SPR_F / SPR_LEN * SPR_SGN
      AMATRX(4,4) = AMATRX(4,4) + SPR_F / SPR_LEN * SPR_SGN
C
C
      RETURN
      END
C
C
      SUBROUTINE SNFORCE(SPR_F, SPR_COS_X, SPR_COS_Y, SRESID,
SPR_SGN)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
C
      DIMENSION SRESID(4)
C
      DOUBLE PRECISION SPR_F
      DOUBLE PRECISION SPR_F_X, SPR_F_Y
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
C
      DOUBLE PRECISION SPR_SGN
C
C     NODAL FORCE COMPONENTS
      SPR_F_X = SPR_F * SPR_COS_X * SPR_SGN
      SPR_F_Y = SPR_F * SPR_COS_Y * SPR_SGN
```

```
C
C     UPDATE NODAL FORCE VECTOR
      SRESID(1) = -SPR_F_X
      SRESID(2) = -SPR_F_Y
      SRESID(3) = SPR_F_X
      SRESID(4) = SPR_F_Y
C
C
      RETURN
      END
C
C
      SUBROUTINE  SAMATRX_ORNT(AMATRX, SPR_K_U, SPR_K_V, SVARS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION AMATRX(4,4), SVARS(200)
C
C
      DOUBLE PRECISION SPR_K_U, SPR_K_V
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
C
C
      DOUBLE PRECISION K11, K12, K22
C
C
      SPR_COS_X = SVARS(171)
      SPR_COS_Y = SVARS(172)
C
      K11 = SPR_K_U * SPR_COS_X * SPR_COS_X + SPR_K_V * SPR_COS_Y *
SPR_COS_Y
      K12 = SPR_K_U * SPR_COS_X * SPR_COS_Y - SPR_K_V * SPR_COS_X *
SPR_COS_Y
      K22 = SPR_K_U * SPR_COS_Y * SPR_COS_Y + SPR_K_V * SPR_COS_X *
SPR_COS_X
C
      AMATRX(1,1) = K11
      AMATRX(1,2) = K12
      AMATRX(1,3) = -K11
      AMATRX(1,4) = -K12
      AMATRX(2,1) = K12
      AMATRX(2,2) = K22
      AMATRX(2,3) = -K12
      AMATRX(2,4) = -K22
      AMATRX(3,1) = -K11
```

```
      AMATRX(3,2) = -K12
      AMATRX(3,3) = K11
      AMATRX(3,4) = K12
      AMATRX(4,1) = -K12
      AMATRX(4,2) = -K22
      AMATRX(4,3) = K12
      AMATRX(4,4) = K22
C
C
      RETURN
      END
C
C
      SUBROUTINE SNFORCE_ORNT(SPR_F_U, SPR_F_V, SVARS, SRESID,
SPR_F_X, SPR_F_Y)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION SRESID(4), SVARS(200)
C
      DOUBLE PRECISION SPR_F_X, SPR_F_Y
      DOUBLE PRECISION SPR_F_U, SPR_F_V
      DOUBLE PRECISION SPR_COS_X, SPR_COS_Y
C
C
      SPR_COS_X = SVARS(171)
      SPR_COS_Y = SVARS(172)
C
C     NODAL FORCE COMPONENTS
      SPR_F_X = SPR_F_U * SPR_COS_X - SPR_F_V * SPR_COS_Y
      SPR_F_Y = SPR_F_U * SPR_COS_Y + SPR_F_V * SPR_COS_X
C
C     UPDATE NODAL FORCE VECTOR
      SRESID(1) = -SPR_F_X
      SRESID(2) = -SPR_F_Y
      SRESID(3) = SPR_F_X
      SRESID(4) = SPR_F_Y
C
C
      RETURN
      END
C
C
C     ****************************************************************
C                          PINCHING4 ROUTINE
```

```
C     ***************************************************************
      SUBROUTINE
PINCHING4(PROPS,SVARS,SPR_DISP,SPR_K,SPR_F,KINC,I_SPR_NUM)
C
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41), SVARS(200),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
      INTEGER I_Cstate, I_Tstate
      INTEGER I_DmgCyc
      DOUBLE PRECISION strain, dstrain
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION Tstrain, Tstress, TstrainRate
      DOUBLE PRECISION P_lowI_CstateStrain, P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain, hghI_CstateStress
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION TminStrainDmnd,TmaxStrainDmnd
      DOUBLE PRECISION elasticStrainEnergy, energyCapacity
      DOUBLE PRECISION Cenergy, CnCycle
      DOUBLE PRECISION Tenergy, TnCycle
      DOUBLE PRECISION CgammaK, CgammaD, CgammaF
      DOUBLE PRECISION TgammaD, TgammaK, TgammaF
      DOUBLE PRECISION gammaKUsed, gammaFUsed
      DOUBLE PRECISION Ttangent, P_kunload
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
      DOUBLE PRECISION P_kElasticPos,P_kElasticNeg
      DOUBLE PRECISION uMaxDamgd, uMinDamgd
C
      DOUBLE PRECISION SPR_K, SPR_F, SPR_DISP
C
      INTEGER I_SPR_NUM

C
C     ASSIGN SVARS VALUES TO PINCHING4 LOCAL VARIABLES
      CALL SUEL2PIN(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
```

```
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy,
     +SPR_F, SPR_K, SVARS, I_SPR_NUM)
C
C    CONVERT UEL VARIABLES TO PINCHING4 LOCAL VARIABLES
      strain = SPR_DISP
C
C    ***************************************************************
      CALL SetEnvelop(PROPS, envlpPosStrain,
     +          envlpPosStress, envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,energyCapacity)
C
C
      IF (KINC .EQ. 1 .OR. KINC .EQ. 0) THEN
         CALL revertToStart(envlpPosStrain, envlpPosStress,
     +          envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,
     +          I_Cstate,Cstrain,Cstress,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,CgammaK,CgammaD,CgammaF,CnCycle,
     +          Ttangent,dstrain,gammaKUsed,gammaFUsed,
     +          P_kElasticPosDamgd,P_kElasticNegDamgd,
     +          uMaxDamgd,uMinDamgd,
     +          envlpPosDamgdStress, envlpNegDamgdStress)
C
C
      ELSE
         CALL revertToLastCommit(I_Cstate,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,Cstrain,Cstress,
     +          CgammaD,CgammaK,CgammaF,CnCycle,
     +          I_Tstate,TstrainRate,
     +          P_lowI_TstateStrain,P_lowI_TstateStress,
     +          hghI_TstateStrain,hghI_TstateStress,
     +          TminStrainDmnd,TmaxStrainDmnd,
     +          Tenergy,Tstrain,Tstress,
     +          TgammaD,TgammaK,TgammaF,TnCycle)
      END IF
C
C
      CALL setTrialStrain(strain,CstrainRate,I_Cstate,Cenergy,
     +                P_lowI_CstateStrain,hghI_CstateStrain,
     +                P_lowI_CstateStress,hghI_CstateStress,
     +                CminStrainDmnd,CmaxStrainDmnd,
```

```
     +                CgammaF,CgammaK,CgammaD,
     +                envlpPosStress,envlpPosStrain,
     +                P_kElasticPosDamgd,P_kElasticNegDamgd,
     +                state3Strain,state3Stress,
     +                P_kunload,state4Strain,state4Stress,Cstrain,
     +                uMaxDamgd,uMinDamgd,
     +                envlpNegStrain,envlpNegStress,
     +                P_kElasticPos,P_kElasticNeg,Cstress,I_DmgCyc,
     +                CnCycle,energyCapacity,
     +                I_Tstate,Tenergy,Tstrain,
     +                P_lowI_TstateStrain,hghI_TstateStrain,
     +                P_lowI_TstateStress,hghI_TstateStress,
     +                TgammaF,TgammaK,TgammaD,
     +                dstrain,Ttangent,Tstress,elasticStrainEnergy,
     +                TminStrainDmnd,TmaxStrainDmnd,
     +                gammaKUsed,gammaFUsed,
     +                envlpPosDamgdStress,envlpNegDamgdStress,
     +                TnCycle, PROPS)
C
C
      CALL commitState(I_Tstate,dstrain,TstrainRate,
     +            P_lowI_TstateStrain,P_lowI_TstateStress,
     +            hghI_TstateStrain,hghI_TstateStress,
     +            TminStrainDmnd,TmaxStrainDmnd,
     +            Tenergy,Tstress,Tstrain,
     +            TgammaK,TgammaD,TgammaF,
     +            P_kElasticPos,P_kElasticNeg,
     +            gammaKUsed,gammaFUsed,
     +            envlpPosStress,envlpNegStress,TnCycle,
     +            I_Cstate,CstrainRate,
     +            P_lowI_CstateStrain,P_lowI_CstateStress,
     +            hghI_CstateStrain,hghI_CstateStress,
     +            CminStrainDmnd,CmaxStrainDmnd,
     +            Cenergy,Cstress,Cstrain,
     +            CgammaK,CgammaD,CgammaF,
     +            P_kElasticPosDamgd,P_kElasticNegDamgd,
     +            uMaxDamgd,uMinDamgd,
     +            envlpPosDamgdStress,envlpNegDamgdStress,CnCycle)
C     ****************************************************************
C
C     CONVERT PINCHING4 LOCAL VARIABELS TO UEL VARAIBLES
      SPR_F = Cstress
      SPR_K = Ttangent
C
C     SAVE PINCHING4 LOCAL VARIABLES TO SVARS
      CALL SPIN2UEL(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
```

```
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy, strain, dstrain,
     +SPR_DISP, SPR_F, SPR_K, SVARS, I_SPR_NUM)
C
C
      RETURN
      END
C
C
C      ****************************************
C         PINCHING4 FUNCTION: SetEnvelop()
C      ****************************************
      SUBROUTINE SetEnvelop(PROPS, envlpPosStrain,
     +          envlpPosStress, envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,energyCapacity)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6)
C
      DOUBLE PRECISION strain1p, strain2p, strain3p, strain4p
      DOUBLE PRECISION stress1p, stress2p, stress3p, stress4p
      DOUBLE PRECISION strain1n, strain2n, strain3n, strain4n
      DOUBLE PRECISION stress1n, stress2n, stress3n, stress4n
      DOUBLE PRECISION gE
      DOUBLE PRECISION P_kPos, P_kNeg, P_k
      DOUBLE PRECISION u
      DOUBLE PRECISION P_k1, P_k2
      DOUBLE PRECISION P_kElasticPos, P_kElasticNeg
      DOUBLE PRECISION energypos, energyneg
      DOUBLE PRECISION P_max_energy, energyCapacity
C
C      UNZIP PROPS(*) VALUES
      strain1p = PROPS(1)
      strain2p = PROPS(2)
      strain3p = PROPS(3)
      strain4p = PROPS(4)
      stress1p = PROPS(5)
      stress2p = PROPS(6)
      stress3p = PROPS(7)
      stress4p = PROPS(8)
```

```
C
      strain1n = PROPS(9)
      strain2n = PROPS(10)
      strain3n = PROPS(11)
      strain4n = PROPS(12)
      stress1n = PROPS(13)
      stress2n = PROPS(14)
      stress3n = PROPS(15)
      stress4n = PROPS(16)

C      ************************************
      gE = PROPS(38)
C
      P_kPos = stress1p/strain1p
      P_kNeg = stress1n/strain1n
      P_k = MAX(P_kPos, P_kNeg)
C
      IF (strain1p > -ONE*strain1n) THEN
         u = (1.0D-8)*strain1p
      ELSE
         u = (-1.0D-8)*strain1n
      END IF
C
      envlpPosStrain(1) = u
      envlpPosStress(1) = u*P_k
      envlpNegStrain(1) = -u
      envlpNegStress(1) = -u*P_k
C
      envlpPosStrain(2) = strain1p
      envlpPosStrain(3) = strain2p
      envlpPosStrain(4) = strain3p
      envlpPosStrain(5) = strain4p
C
      envlpNegStrain(2) = strain1n
      envlpNegStrain(3) = strain2n
      envlpNegStrain(4) = strain3n
      envlpNegStrain(5) = strain4n
C
      envlpPosStress(2) = stress1p
      envlpPosStress(3) = stress2p
      envlpPosStress(4) = stress3p
      envlpPosStress(5) = stress4p
C
      envlpNegStress(2) = stress1n
      envlpNegStress(3) = stress2n
      envlpNegStress(4) = stress3n
      envlpNegStress(5) = stress4n
C
      P_k1 = (stress4p - stress3p)/(strain4p - strain3p)
```

```
      P_k2 = (stress4n - stress3n)/(strain4n - strain3n)
C
      envlpPosStrain(6) = 1.0D+6*strain4p
      IF (P_k1 .GT. ZERO) THEN
         envlpPosStress(6) = stress4p+P_k1*(envlpPosStrain(6)-strain4p)
      ELSE
         envlpPosStress(6) = stress4p*(ONE+PONE)
      END IF
      envlpNegStrain(6) = 1.0D+6*strain4n
      IF (P_k2 .GT. ZERO) THEN
         envlpNegStress(6) = stress4n+P_k2*(envlpNegStrain(6)-strain4n)
      ELSE
          envlpNegStress(6) = stress4n*(ONE+PONE)
      END IF
C
C     define crtical material properties
      P_kElasticPos = envlpPosStress(2)/envlpPosStrain(2)
      P_kElasticNeg = envlpNegStress(2)/envlpNegStrain(2)
C
      energypos = HALF*envlpPosStrain(1)*envlpPosStress(1)
      DO J = 1, 4
          energypos = energypos+HALF*(envlpPosStress(J) +
     +        envlpPosStress(J+1))*(envlpPosStrain(J+1) -
     +        envlpPosStrain(J))
      END DO
C
      energyneg = HALF*envlpNegStrain(1)*envlpNegStress(1)
      DO J = 1, 4
         energyneg = energyneg+HALF*(envlpNegStress(J) +
     +        envlpNegStress(J+1))*(envlpNegStrain(J+1) -
     +        envlpNegStrain(J))
      END DO
C
C
      P_max_energy = MAX(energypos, energyneg)
      energyCapacity = gE*P_max_energy
C
C
      RETURN
      END
C
C
C     ****************************************
C        PINCHING4: revertToStart
C     ****************************************
      SUBROUTINE revertToStart(envlpPosStrain, envlpPosStress,
     +           envlpNegStrain, envlpNegStress,
     +           P_kElasticPos,P_kElasticNeg,
     +           I_Cstate,Cstrain,Cstress,CstrainRate,
```

```
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,CgammaK,CgammaD,CgammaF,CnCycle,
     +          Ttangent,dstrain,gammaKUsed,gammaFUsed,
     +          P_kElasticPosDamgd,P_kElasticNegDamgd,
     +          uMaxDamgd,uMinDamgd,
     +          envlpPosDamgdStress, envlpNegDamgdStress)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6)
C
      INTEGER I_Cstate
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION dstrain
      DOUBLE PRECISION P_lowI_CstateStrain, P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain, hghI_CstateStress
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION Cenergy
      DOUBLE PRECISION CnCycle
      DOUBLE PRECISION CgammaK, CgammaD, CgammaF
      DOUBLE PRECISION gammaKUsed, gammaFUsed
      DOUBLE PRECISION Ttangent
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
      DOUBLE PRECISION P_kElasticPos, P_kElasticNeg
      DOUBLE PRECISION uMaxDamgd, uMinDamgd

C
      I_Cstate = 0
      Cstrain = ZERO
      Cstress = ZERO
      CstrainRate = ZERO
      P_lowI_CstateStrain = envlpNegStrain(1)
      P_lowI_CstateStress = envlpNegStress(1)
      hghI_CstateStrain = envlpPosStrain(1)
      hghI_CstateStress = envlpPosStress(1)
      CminStrainDmnd = envlpNegStrain(2)
      CmaxStrainDmnd = envlpPosStrain(2)
      Cenergy = ZERO
      CgammaK = ZERO
      CgammaD = ZERO
      CgammaF = ZERO
```

```
      CnCycle = ZERO
C
      Ttangent = envlpPosStress(1)/envlpPosStrain(1)
      dstrain = ZERO
      gammaKUsed = ZERO
      gammaFUsed = ZERO
C
      P_kElasticPosDamgd = P_kElasticPos
      P_kElasticNegDamgd = P_kElasticNeg
      uMaxDamgd = CmaxStrainDmnd
      uMinDamgd = CminStrainDmnd
C
C     INITIALIZE DAMAGED BACKBONE - envlpPosDamgdStress,
envlpNegDamgdStress
      DO I = 1, 6
         envlpPosDamgdStress(I) = envlpPosStress(I)
         envlpNegDamgdStress(I) = envlpNegStress(I)
      END DO
C
C
      RETURN
      END
C
C
C     ****************************************
C        PINCHING4: revertToLastCommit
C     ****************************************
      SUBROUTINE revertToLastCommit(I_Cstate,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,Cstrain,Cstress,
     +          CgammaD,CgammaK,CgammaF,CnCycle,
     +          I_Tstate,TstrainRate,
     +          P_lowI_TstateStrain,P_lowI_TstateStress,
     +          hghI_TstateStrain,hghI_TstateStress,
     +          TminStrainDmnd,TmaxStrainDmnd,
     +          Tenergy,Tstrain,Tstress,
     +          TgammaD,TgammaK,TgammaF,TnCycle)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6)
C
```

```
      INTEGER I_Tstate, I_Cstate
      DOUBLE PRECISION TstrainRate
      DOUBLE PRECISION CstrainRate
      DOUBLE PRECISION P_lowI_TstateStrain, P_lowI_TstateStress
      DOUBLE PRECISION hghI_TstateStrain, hghI_TstateStress
      DOUBLE PRECISION P_lowI_CstateStrain, P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain, hghI_CstateStress
      DOUBLE PRECISION TminStrainDmnd, TmaxStrainDmnd
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION Tenergy
      DOUBLE PRECISION Cenergy
      DOUBLE PRECISION Tstrain, Tstress
      DOUBLE PRECISION Cstrain, Cstress
      DOUBLE PRECISION TgammaD, Tgamma, TgammaF
      DOUBLE PRECISION CgammaD, CgammaK, CgammaF
      DOUBLE PRECISION TnCycle
      DOUBLE PRECISION CnCycle
C
      I_Tstate = I_Cstate
C
      TstrainRate = CstrainRate
C
      P_lowI_TstateStrain = P_lowI_CstateStrain
      P_lowI_TstateStress = P_lowI_CstateStress
      hghI_TstateStrain = hghI_CstateStrain
      hghI_TstateStress = hghI_CstateStress
      TminStrainDmnd = CminStrainDmnd
      TmaxStrainDmnd = CmaxStrainDmnd
      Tenergy = Cenergy
C
      Tstrain = Cstrain
      Tstress = Cstress
C
      TgammaD = CgammaD
      TgammaK = CgammaK
      TgammaF = CgammaF
C
      TnCycle = CnCycle
C
C
      RETURN
      END
C
C
C     ****************************************
C          PINCHING4: setTrialStrain
C     ****************************************
      SUBROUTINE setTrialStrain(strain,CstrainRate,I_Cstate,Cenergy,
     +                  P_lowI_CstateStrain,hghI_CstateStrain,
```

```
     +              P_lowI_CstateStress,hghI_CstateStress,
     +              CminStrainDmnd,CmaxStrainDmnd,
     +              CgammaF,CgammaK,CgammaD,
     +              envlpPosStress,envlpPosStrain,
     +              P_kElasticPosDamgd,P_kElasticNegDamgd,
     +              state3Strain,state3Stress,
     +              P_kunload,state4Strain,state4Stress,Cstrain,
     +              uMaxDamgd,uMinDamgd,
     +              envlpNegStrain,envlpNegStress,
     +              P_kElasticPos,P_kElasticNeg,Cstress,I_DmgCyc,
     +              CnCycle,energyCapacity,
     +              I_Tstate,Tenergy,Tstrain,
     +              P_lowI_TstateStrain,hghI_TstateStrain,
     +              P_lowI_TstateStress,hghI_TstateStress,
     +              TgammaF,TgammaK,TgammaD,
     +              dstrain,Ttangent,Tstress,elasticStrainEnergy,
     +              TminStrainDmnd,TmaxStrainDmnd,
     +              gammaKUsed,gammaFUsed,
     +              envlpPosDamgdStress,envlpNegDamgdStress,
     +              TnCycle, PROPS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41),
     +        envlpPosStrain(6), envlpPosStress(6),
     +        envlpNegStrain(6), envlpNegStress(6),
     +        envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +        state3Strain(4), state3Stress(4),
     +        state4Strain(4), state4Stress(4)
C
      INTEGER I_Tstate, I_Cstate
      INTEGER I_DmgCyc
      DOUBLE PRECISION Tenergy
      DOUBLE PRECISION Cenergy
      DOUBLE PRECISION strain, dstrain
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION Tstrain, Tstress
      DOUBLE PRECISION Ttangent, P_kunload
      DOUBLE PRECISION P_lowI_TstateStrain, hghI_TstateStrain
      DOUBLE PRECISION P_lowI_CstateStrain, hghI_CstateStrain
      DOUBLE PRECISION P_lowI_TstateStress, hghI_TstateStress
      DOUBLE PRECISION P_lowI_CstateStress, hghI_CstateStress
      DOUBLE PRECISION TminStrainDmnd, TmaxStrainDmnd
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION TgammaF, TgammaK, TgammaD
```

```
      DOUBLE PRECISION CgammaF, CgammaK, CgammaD
      DOUBLE PRECISION uMaxDamgd, uMinDamgd
      DOUBLE PRECISION P_kElasticPos, P_kElasticNeg
      DOUBLE PRECISION gammaFUsed, gammaKUsed
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
      DOUBLE PRECISION denergy, elasticStrainEnergy
      DOUBLE PRECISION CnCycle, TnCycle
C
      DOUBLE PRECISION EXTSTRESS
      DOUBLE PRECISION P_k, f

C
C     INITIALIZE TRIAL PARAMETERS AS THE LAST CONVERGED ONES
      I_Tstate = I_Cstate
      Tenergy = Cenergy
      Tstrain = strain
      P_lowI_TstateStrain = P_lowI_CstateStrain
      hghI_TstateStrain = hghI_CstateStrain
      P_lowI_TstateStress = P_lowI_CstateStress
      hghI_TstateStress = hghI_CstateStress
      TminStrainDmnd = CminStrainDmnd
      TmaxStrainDmnd = CmaxStrainDmnd
      TgammaF = CgammaF
      TgammaK = CgammaK
      TgammaD = CgammaD
C
C
      dstrain = Tstrain - Cstrain
      IF (dstrain  .LT. 1.0D-12 .AND. dstrain .GT.-1.0D-12) THEN
         dstrain = ZERO
      END IF
C
C     DETERMINE IF THERE IS A CAHNGE IN STATE
      CALL getstate(Tstrain,dstrain, CstrainRate, Cstrain, Cstress,
     +              envlpPosStrain, envlpPosStress,
     +              envlpNegStrain, envlpNegStress,
     +              uMaxDamgd, uMinDamgd, CgammaF, CgammaK,
     +              P_kElasticPos, P_kElasticNeg,
     +              P_lowI_TstateStrain, P_lowI_TstateStress,
     +              hghI_TstateStrain, hghI_TstateStress,
     +              TmaxStrainDmnd, TminStrainDmnd,
     +              gammaFUsed, gammaKUsed,
     +              envlpNegDamgdStress, envlpPosDamgdStress,
     +              P_kElasticPosDamgd, P_kElasticNegDamgd,I_Tstate)
C
C
C
      IF (I_Tstate .GE. 0) THEN
         IF (I_Tstate .EQ. 0) THEN
```

```
          Ttangent = envlpPosStress(1)/envlpPosStrain(1)
          Tstress = Ttangent*Tstrain
        ELSE IF (I_Tstate .EQ. 1) THEN
          CALL posEnvlpTangent(strain,envlpPosDamgdStress,
     +      envlpPosStrain, P_k)
          Ttangent = P_k
          CALL posEnvlpStress(strain,envlpPosDamgdStress,
     +     envlpPosStrain, EXTSTRESS)
          Tstress = EXTSTRESS
       ELSE IF (I_Tstate .EQ. 2) THEN
          CALL negEnvlpTangent(strain,envlpNegDamgdStress,
     +      envlpNegStrain, P_k)
          Ttangent = P_k
          CALL negEnvlpStress(strain,envlpNegDamgdStress,
     +     envlpNegStrain, EXTSTRESS)
          Tstress = EXTSTRESS
C          DEFINITELY WRONG HERE
        ELSE IF (I_Tstate .EQ. 3) THEN
          IF (hghI_TstateStrain .LT. ZERO) THEN
             P_kunload = P_kElasticNegDamgd
          ELSE
             P_kunload = P_kElasticPosDamgd
          END IF
          state3Strain(1) = P_lowI_TstateStrain
          state3Strain(4) = hghI_TstateStrain
          state3Stress(1) = P_lowI_TstateStress
          state3Stress(4) = hghI_TstateStress
          CALL getstate3(state3Strain, state3Stress, P_kunload,
     +   P_kElasticNegDamgd, P_lowI_TstateStrain, P_lowI_TstateStress,
     +   hghI_TstateStrain, hghI_TstateStress, TminStrainDmnd,
     +   envlpNegStrain, envlpNegDamgdStress, PROPS)
          CALL Envlp3Tangent(state3Strain,state3Stress,strain, P_k)
          Ttangent = P_k
          CALL Envlp3Stress(state3Strain,state3Stress,strain, f)
          Tstress = f
        ELSE IF (I_Tstate .EQ. 4) THEN
          IF (P_lowI_TstateStrain .LT. ZERO) THEN
             P_kunload = P_kElasticNegDamgd
          ELSE
             P_kunload = P_kElasticPosDamgd
          END IF
          state4Strain(1) = P_lowI_TstateStrain
          state4Strain(4) = hghI_TstateStrain
          state4Stress(1) = P_lowI_TstateStress
          state4Stress(4) = hghI_TstateStress
          CALL getstate4(state4Strain, state4Stress, P_kunload,
     +       P_kElasticPosDamgd, P_lowI_TstateStrain,P_lowI_TstateStress,
     +       hghI_TstateStrain, hghI_TstateStress, TmaxStrainDmnd,
     +       envlpPosStrain, envlpPosDamgdStress, PROPS)
```

```
            CALL Envlp4Tangent(state4Strain,state4Stress, strain, P_k)
            Ttangent = P_k
            CALL Envlp4Stress(state4Strain,state4Stress, strain, f)
            Tstress = f
         END IF
      END IF
C
C     UPDATE ENERGY DISSIPATION
      denergy = HALF*(Tstress+Cstress)*dstrain
      IF (Tstrain .GT. ZERO) THEN
         elasticStrainEnergy = HALF*Tstress/P_kElasticPosDamgd*Tstress
      ELSE
         elasticStrainEnergy = HALF*Tstress/P_kElasticNegDamgd*Tstress
      END IF
      Tenergy = Cenergy + denergy
C
C     UPDATE DAMAGE
      CALL updateDmg(Tstrain,dstrain,
     +          TmaxStrainDmnd, TminStrainDmnd,
     +          envlpPosStrain, envlpNegStrain,
     +          envlpPosDamgdStress,envlpNegDamgdStress,
     +          CnCycle,Tenergy,energyCapacity,
     +          I_DmgCyc, elasticStrainEnergy,
     +          P_kElasticPos,P_kElasticNeg,
     +          TnCycle,TgammaK,TgammaD,TgammaF,
     +          PROPS)
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: getstate
C     ****************************************
      SUBROUTINE getstate(SU, SDU, CstrainRate, Cstrain, Cstress,
     +                envlpPosStrain, envlpPosStress,
     +                envlpNegStrain, envlpNegStress,
     +                uMaxDamgd, uMinDamgd, CgammaF, CgammaK,
     +                P_kElasticPos, P_kElasticNeg,
     +                P_lowI_TstateStrain, P_lowI_TstateStress,
     +                hghI_TstateStrain, hghI_TstateStress,
     +                TmaxStrainDmnd, TminStrainDmnd,
     +                gammaFUsed, gammaKUsed,
     +                envlpNegDamgdStress, envlpPosDamgdStress,
     +                P_kElasticPosDamgd, P_kElasticNegDamgd, I_Tstate)
C
C
      INCLUDE 'ABA_PARAM.INC'
```

```
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
      LOGICAL cid, cis
C
      INTEGER I_Cstate, I_Tstate
      INTEGER newState
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION P_lowI_TstateStrain, hghI_TstateStrain
      DOUBLE PRECISION P_lowI_TstateStress, hghI_TstateStress
      DOUBLE PRECISION TmaxStrainDmnd, TminStrainDmnd
      DOUBLE PRECISION uMaxDamgd, uMinDamgd
      DOUBLE PRECISION CgammaF, CgammaK
      DOUBLE PRECISION gammaFUsed, gammaKUsed
      DOUBLE PRECISION P_kElasticPos, P_kElasticNeg
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
C
      DOUBLE PRECISION SU, SDU
      DOUBLE PRECISION EXTSTRESS
C
C        INITIALIZE LOCAL VARIABLES
         cid = .false.                        ! CHANGE IN DIRECTION
      cis = .false.          ! CHANGE IN STATE
         newState = 0          ! NEW SPRING STATE DETERMINED
C
C     INITIALIZE VARIABLES FOR CALLING EXTERNAL SUBROUTINES
      EXTSTRESS = ZERO
C
         IF (SDU * CstrainRate .LE. ZERO) THEN
                 cid = .true.
         END IF
C
      IF (SU .LT. P_lowI_TstateStrain .OR. SU .GT. hghI_TstateStrain .OR.
     +              cid) THEN
         IF (I_Tstate .EQ. 0) THEN
            IF (SU .GT. hghI_TstateStrain) THEN
               cis = .true.
               newstate = 1
               P_lowI_TstateStrain = envlpPosStrain(1)
               P_lowI_TstateStress = envlpPosStress(1)
               hghI_TstateStrain = envlpPosStrain(6)
```

```
            hghI_TstateStress = envlpPosStress(6)
         ELSE IF (SU .LT. P_lowI_TstateStrain) THEN
            cis = .true.
            newstate = 2
            P_lowI_TstateStrain = envlpNegStrain(6)
            P_lowI_TstateStress = envlpNegStress(6)
            hghI_TstateStrain = envlpNegStrain(1)
            hghI_TstateStress = envlpNegStress(1)
         END IF
      ELSE IF (I_Tstate .EQ. 1 .AND. SDU .LT. ZERO) THEN
         cis = .true.
         IF (Cstrain .GT. TmaxStrainDmnd) THEN
            TmaxStrainDmnd = SU - SDU
         END IF
         IF (TmaxStrainDmnd .LT. uMaxDamgd) THEN
            TmaxStrainDmnd = uMaxDamgd
         END IF
         IF (SU .LT. uMinDamgd) THEN
            newState = 2
            gammaFUsed = CgammaF
            DO I = 1, 6
               envlpNegDamgdStress(I) = envlpNegStress(I) *
+                 (ONE - gammaFUsed)
            END DO
            P_lowI_TstateStrain = envlpNegStrain(6)
            P_lowI_TstateStress = envlpNegStress(6)
            hghI_TstateStrain = envlpNegStrain(1)
            hghI_TstateStress = envlpNegStress(1)
         ELSE
            newstate = 3
            gammaFUsed = CgammaF
            DO I = 1, 6
               envlpNegDamgdStress(I) = envlpNegStress(I) *
+                 (ONE - gammaFUsed)
            END DO
            P_lowI_TstateStrain = uMinDamgd
            CALL negEnvlpStress(uMinDamgd, envlpNegDamgdStress,
+                          envlpNegStrain, EXTSTRESS)
            P_lowI_TstateStress = EXTSTRESS
            hghI_TstateStrain = Cstrain
            hghI_TstateStress = Cstress
            gammaKUsed = CgammaK
            P_kElasticPosDamgd = P_kElasticPos * (ONE-gammaKUsed)
         END IF
      ELSE IF (I_Tstate .EQ. 2 .AND. SDU .GT. ZERO) THEN
         cis = .true.
         IF (Cstrain .LT. TminStrainDmnd) THEN
            TminStrainDmnd = Cstrain
         END IF
```

```
      IF (TminStrainDmnd .GT. uMinDamgd) THEN
         TminStrainDmnd = uMinDamgd
      END IF
      IF (SU .GT. uMaxDamgd) THEN
         newState = 1
         gammaFUsed = CgammaF
         DO I = 1, 6
            envlpPosDamgdStress(I) = envlpPosStress(I) *
+                (ONE - gammaFUsed)
         END DO
         P_lowI_TstateStrain = envlpPosStrain(1)
         P_lowI_TstateStress = envlpPosStress(1)
         hghI_TstateStrain = envlpPosStrain(6)
         hghI_TstateStress = envlpPosStress(6)
      ELSE
         newState = 4
         gammaFUsed = CgammaF
         DO I = 1, 6
            envlpPosDamgdStress(I) = envlpPosStress(I) *
+                (ONE - gammaFUsed)
         END DO
         P_lowI_TstateStrain = Cstrain
         P_lowI_TstateStress = Cstress
         hghI_TstateStrain = uMaxDamgd
         CALL posEnvlpStress(uMaxDamgd, envlpPosDamgdStress,
+                        envlpPosStrain, EXTSTRESS)
         hghI_TstateStress = EXTSTRESS
         gammaKUsed = CgammaK;
         P_kElasticNegDamgd = P_kElasticNeg * (ONE- gammaKUsed)
      END IF
   ELSE IF (I_Tstate .EQ. 3) THEN
      IF (SU .LT. P_lowI_TstateStrain) THEN
         cis = .true.
         newState = 2
         P_lowI_TstateStrain = envlpNegStrain(6)
         P_lowI_TstateStress = envlpNegDamgdStress(6)
         hghI_TstateStrain = envlpNegStrain(1)
         hghI_TstateStress = envlpNegDamgdStress(1)
      ELSE IF (SU .GT. uMaxDamgd .AND. SDU .GT. ZERO) THEN
         cis = .true.
         newState = 1
         P_lowI_TstateStrain = envlpPosStrain(1)
         P_lowI_TstateStress = envlpPosStress(1)
         hghI_TstateStrain = envlpPosStrain(6)
         hghI_TstateStress = envlpPosStress(6)
      ELSE IF (SDU .GT. ZERO) THEN
         cis = .true.
         newState = 4
         gammaFUsed = CgammaF
```

```
            P_lowI_TstateStrain = Cstrain
            P_lowI_TstateStress = Cstress
            hghI_TstateStrain = uMaxDamgd
            DO I = 1, 6
               envlpPosDamgdStress(I) = envlpPosStress(I) *
     +              (ONE - gammaFUsed)
            END DO
            CALL posEnvlpStress(uMaxDamgd, envlpPosDamgdStress,
     +envlpPosStrain, EXTSTRESS)
            hghI_TstateStress = EXTSTRESS
            gammaKUsed = CgammaK
            P_kElasticNegDamgd = P_kElasticNeg *(ONE - gammaKUsed)
         END IF
      ELSE IF (I_Tstate .EQ. 4) THEN
         IF (SU .GT. hghI_TstateStrain) THEN
            cis = .true.
            newState = 1
            P_lowI_TstateStrain = envlpPosStrain(1)
            P_lowI_TstateStress = envlpPosDamgdStress(1)
            hghI_TstateStrain = envlpPosStrain(6)
            hghI_TstateStress = envlpPosDamgdStress(6)
         ELSE IF (SU .LT. uMinDamgd .AND. SDU .LT. ZERO) THEN
            cis = .true.
            newState = 2
            P_lowI_TstateStrain = envlpNegStrain(6)
            P_lowI_TstateStress = envlpNegDamgdStress(6)
            hghI_TstateStrain = envlpNegStrain(1)
            hghI_TstateStress = envlpNegDamgdStress(1)
         ELSE IF (SDU .LT. ZERO) THEN
            cis = .true.
            newState = 3
            gammaFUsed = CgammaF
            DO I = 1, 6
               envlpNegDamgdStress(I) = envlpNegStress(I) *
     +              (ONE - gammaFUsed)
            END DO
            P_lowI_TstateStrain = uMinDamgd
            CALL negEnvlpStress(uMinDamgd, envlpNegDamgdStress,
     +                     envlpNegStrain, EXTSTRESS)
            P_lowI_TstateStress = EXTSTRESS
C             SOME BUG HERE
            hghI_TstateStrain = Cstrain
            hghI_TstateStress = Cstress
            gammaKUsed = CgammaK
            P_kElasticPosDamgd = P_kElasticPos * (ONE-gammaKUsed)
         END IF
      END IF
   END IF
C
```

```
      IF (cis) THEN
         I_Tstate = newState
      END IF
C
      RETURN
      END
C
C
C     ***************************************
C           PINCHING4: posEnvlpStress
C     ***************************************
      SUBROUTINE posEnvlpStress(SU, envlpPosDamgdStress,
     +envlpPosStrain, EXTSTRESS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpPosStrain(6), envlpPosDamgdStress(6)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k, F
      DOUBLE PRECISION EXTSTRESS
C
C
      P_k = ZERO
      F = ZERO
      I = 1
      EXTSTRESS = ZERO
C
      DO WHILE (P_k .EQ. ZERO .AND. I .LE. 5)
         IF (SU .LE. envlpPosStrain(I+1)) THEN
            P_k = (envlpPosDamgdStress(I+1)-envlpPosDamgdStress(I)) /
     +          (envlpPosStrain(I+1)-envlpPosStrain(I))
            F = envlpPosDamgdStress(I) + (SU-envlpPosStrain(I)) * P_k
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. ZERO) THEN
         P_k = (envlpPosDamgdStress(6) - envlpPosDamgdStress(5)) /
     +       (envlpPosStrain(6) - envlpPosStrain(5))
         F = envlpPosDamgdStress(6) + P_k * (SU - envlpPosStrain(6))
      END IF
C
      EXTSTRESS = F
```

```
C
C
      RETURN
      END
C
C
C     ***************************************
C           PINCHING4: posEnvlpTangent
C     ***************************************
      SUBROUTINE posEnvlpTangent(SU,envlpPosDamgdStress,envlpPosStrain,
     +                           P_k)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpPosDamgdStress(6), envlpPosStrain(6)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k
C
      P_k = ZERO
      I = 1
      DO WHILE (P_k .EQ. ZERO .AND. I .LT. 5)
         IF (SU .LE. envlpPosStrain(I+1)) THEN
            P_k = (envlpPosDamgdStress(I+1)-envlpPosDamgdStress(I))/
     +            (envlpPosStrain(I+1)-envlpPosStrain(I))
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. ZERO) THEN
         P_k = (envlpPosDamgdStress(6) - envlpPosDamgdStress(5))/
     +     (envlpPosStrain(6) - envlpPosStrain(5))
      END IF
C
C
      RETURN
      END
C
C
C     ***************************************
C           PINCHING4: negEnvlpStress
C     ***************************************
      SUBROUTINE negEnvlpStress(SU, envlpNegDamgdStress, envlpNegStrain,
     +                          EXTSTRESS)
```

```
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpNegStrain(6), envlpNegDamgdStress(6)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k, F
      DOUBLE PRECISION EXTSTRESS
C
      P_k = ZERO
      F = ZERO
      I = 1
      EXTSTRESS = ZERO
C
C
      DO WHILE (P_k .EQ. ZERO .AND. I .LE. 5)
         IF (SU .GE. envlpNegStrain(I+1)) THEN
            P_k = (envlpNegDamgdStress(I) - envlpNegDamgdStress(I+1))/
     +          (envlpNegStrain(I) - envlpNegStrain(I+1))
            F = envlpNegDamgdStress(I+1) +
     +          (SU - envlpNegStrain(I+1)) * P_k
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. ZERO) THEN
         P_k = (envlpNegDamgdStress(5) - envlpNegDamgdStress(6)) /
     +      (envlpNegStrain(5) - envlpNegStrain(6))
         F = envlpNegDamgdStress(6) + P_k * (SU - envlpNegStrain(6))
      END IF
C
      EXTSTRESS = F
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: negEnvlpTangent
C     ****************************************
      SUBROUTINE  negEnvlpTangent(SU,envlpNegDamgdStress,envlpNegStrain,
     +                            P_k)
C
```

```
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpNegDamgdStress(6), envlpNegStrain(6)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k
C
      P_k = ZERO
      I = 1
      DO WHILE (P_k .EQ. ZERO .AND. I .LT. 5)
         IF (SU .GE. envlpNegStrain(i+1)) THEN
            P_k = (envlpNegDamgdStress(i)-envlpNegDamgdStress(i+1))/
     +          (envlpNegStrain(i)-envlpNegStrain(i+1))
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. ZERO) THEN
         P_k = (envlpNegDamgdStress(5) - envlpNegDamgdStress(6))/
     +       (envlpNegStrain(5)-envlpNegStrain(6))
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: getstate3
C     ****************************************
      SUBROUTINE getstate3(state3Strain, state3Stress, P_kunload,
     +    P_kElasticNegDamgd, P_lowI_TstateStrain, P_lowI_TstateStress,
     +    hghI_TstateStrain, hghI_TstateStress, TminStrainDmnd,
     +    envlpNegStrain, envlpNegDamgdStress, PROPS)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
```

```
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
C
      LOGICAL cid, cis
C
      INTEGER I
      DOUBLE PRECISION P_kunload
      DOUBLE PRECISION P_kElasticNegDamgd
      DOUBLE PRECISION P_lowI_TstateStrain, P_lowI_TstateStress
      DOUBLE PRECISION hghI_TstateStrain, hghI_TstateStress
      DOUBLE PRECISION TminStrainDmnd
      DOUBLE PRECISION rDispN, rForceN, uForceN
C
      DOUBLE PRECISION P_kmax
      DOUBLE PRECISION st1, st2
      DOUBLE PRECISION STDU, STDF, STDFR
      DOUBLE PRECISION avgforce
      DOUBLE PRECISION slope12, slope34, checkSlope, slope
C
C
C    PARAMETERS TAKEN FROM PROPS
      rDispN = PROPS(20)
      rForceN = PROPS(21)
      uForceN = PROPS(22)
C
      P_kmax = MAX(P_kunload, P_kElasticNegDamgd)
C
      IF (state3Strain(1) * state3Strain(4) .LT. ZERO) THEN
         state3Strain(2) = P_lowI_TstateStrain * rDispN
         IF ((rForceN - uForceN) .GT. 1E-8) THEN
            state3Stress(2) = P_lowI_TstateStress * rForceN
         ELSE
            IF (TminStrainDmnd .LT. envlpNegStrain(4)) THEN
               st1 = P_lowI_TstateStress * uForceN * (ONE+TOL)
               st2 = envlpNegDamgdStress(5) * (ONE+TOL)
               state3Stress(2) = MIN(st1, st2)
            ELSE
               st1 = envlpNegDamgdStress(4) * uForceN * (ONE+TOL)
               st2 = envlpNegDamgdStress(5) * (ONE+TOL)
               state3Stress(2) = MIN(st1, st2)
            END IF
         END IF
         IF ((state3Stress(2) - state3Stress(1)) / (state3Strain(2) -
     +       state3Strain(1)) .GT. P_kElasticNegDamgd) THEN
            state3Strain(2) = P_lowI_TstateStrain +
     +       (state3Stress(2)-state3Stress(1))/P_kElasticNegDamgd
         END IF
```

```
      IF (state3Strain(2) .GT. state3Strain(4)) THEN
         STDU = state3Strain(4) - state3Strain(1)
         STDF = state3Stress(4) - state3Stress(1)
         state3Strain(2) = state3Strain(1) + 0.33D0*STDU
         state3Strain(3) = state3Strain(1) + 0.67D0*STDU
         state3Stress(2) = state3Stress(1) + 0.33D0*STDF
         state3Stress(3) = state3Stress(1) + 0.67D0*STDF
      ELSE
C          PATH:
         IF (TminStrainDmnd .LT. envlpNegStrain(4)) THEN
            state3Stress(3) = uForceN * envlpNegDamgdStress(5)
         ELSE
            state3Stress(3) = uForceN * envlpNegDamgdStress(4)
C             PATH:
         END IF
         state3Strain(3) = hghI_TstateStrain -
     +    (hghI_TstateStress-state3Stress(3))/P_kunload
         IF (state3Strain(3) .GT. state3Strain(4)) THEN
            STDU = state3Strain(4) - state3Strain(2)
            STDF = state3Stress(4) - state3Stress(2)
            state3Strain(3) = state3Strain(2) + HALF*STDU
            state3Stress(3) = state3Stress(2) + HALF*STDF
         ELSE IF ((state3Stress(3) - state3Stress(2))/
     +       (state3Strain(3) -state3Strain(2)) .GT. P_kmax) THEN
C               PATH:
               STDU = state3Strain(4) - state3Strain(1)
               STDF = state3Stress(4) - state3Stress(1)
               state3Strain(2) = state3Strain(1) + 0.33D0*STDU
               state3Strain(3) = state3Strain(1) + 0.67D0*STDU
               state3Stress(2) = state3Stress(1) + 0.33D0*STDF
               state3Stress(3) = state3Stress(1) + 0.67D0*STDF
         ELSE IF ((state3Strain(3) .LT. state3Strain(2)) .OR.
     +       ((state3Stress(3)-state3Stress(2))/
     +       (state3Strain(3)-state3Strain(2)) .LT. 0)) THEN
                  IF (state3Strain(3) .LT. ZERO) THEN
                     STDU = state3Strain(4)-state3Strain(2)
                     STDF = state3Stress(4)-state3Stress(2)
                     state3Strain(3)=state3Strain(2)+HALF*STDU
                     state3Stress(3)= state3Stress(2)+HALF*STDF
                  ELSE IF (state3Strain(2) .GT. ZERO) THEN
                     STDU = state3Strain(3)-state3Strain(1)
                     STDF = state3Stress(3)-state3Stress(1)
                     state3Strain(2)=state3Strain(1)+HALF*STDU
                     state3Stress(2)=state3Stress(1)+HALF*STDF
                  ELSE
                     avgforce = HALF*(state3Stress(3) +
     +                 state3Stress(2))
                     STDFR = ZERO
                     IF (avgforce .LT. ZERO) THEN
```

```
                    STDFR = -avgforce/100.0D0
                 ELSE
                    STDFR = avgforce/100.0D0
                 END IF
                 slope12 = (state3Stress(2) -
     +        state3Stress(1))/(state3Strain(2) - state3Strain(1))
                 slope34 = (state3Stress(4) -
     +        state3Stress(3))/(state3Strain(4) - state3Strain(3))
                 state3Stress(2) = avgforce - STDFR
                 state3Stress(3) = avgforce + STDFR
                 state3Strain(2) = state3Strain(1) +
     +        (state3Stress(2) - state3Stress(1))/slope12
                 state3Strain(3) = state3Strain(4) -
     +        (state3Stress(4) - state3Stress(3))/slope34
              END IF
          END IF
       END IF
    ELSE
       STDU = state3Strain(4)-state3Strain(1)
       STDF = state3Stress(4)-state3Stress(1)
       state3Strain(2) = state3Strain(1) + 0.33D0*STDU;
       state3Strain(3) = state3Strain(1) + 0.67D0*STDU;
          state3Stress(2) = state3Stress(1) + 0.33D0*STDF;
          state3Stress(3) = state3Stress(1) + 0.67D0*STDF;
    END IF
C
    checkSlope = state3Stress(1)/state3Strain(1)
    slope = ZERO
C
C    FINAL CHECK
    I = 1
    DO WHILE (I .LT. 4)
       STDU = state3Strain(i+1)-state3Strain(i)
       STDF = state3Stress(i+1)-state3Stress(i)
       IF (STDU .LT. ZERO .OR. STDF .LT. ZERO) THEN
          STDU = state3Strain(4)-state3Strain(1)
          STDF = state3Stress(4)-state3Stress(1)
                 state3Strain(2) = state3Strain(1) + 0.33D0*STDU
                 state3Strain(3) = state3Strain(1) + 0.67D0*STDU
                 state3Stress(2) = state3Stress(1) + 0.33D0*STDF
                 state3Stress(3) = state3Stress(1) + 0.67D0*STDF
          slope = STDF / STDU
          I = 4
       END IF
       IF (slope .GT. 1.0D-8 .AND. slope .LT. checkSlope) THEN
          state3Strain(2) = ZERO;
          state3Stress(2) = ZERO;
                 state3Strain(3) = state3Strain(4)*HALF
          state3Stress(3) = state3Stress(4)*HALF
```

```
      END IF
      I = I + 1
    END DO
C
C
    RETURN
    END
C
C
C    ****************************************
C          PINCHING4: getstate4
C    ****************************************
    SUBROUTINE getstate4(state4Strain, state4Stress, P_kunload,
   +   P_kElasticPosDamgd, P_lowI_TstateStrain,P_lowI_TstateStress,
   +   hghI_TstateStrain, hghI_TstateStress, TmaxStrainDmnd,
   +   envlpPosStrain, envlpPosDamgdStress, PROPS)
C
C
    INCLUDE 'ABA_PARAM.INC'
C
    PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
   + ONE = 1.D0)
C
    DIMENSION PROPS(41),
   +          envlpPosStrain(6), envlpPosStress(6),
   +          envlpNegStrain(6), envlpNegStress(6),
   +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
   +          state4Strain(4), state4Stress(4)
C
C
    LOGICAL cid, cis
C
    INTEGER I
    DOUBLE PRECISION P_kunload
    DOUBLE PRECISION P_kElasticPosDamgd
    DOUBLE PRECISION P_lowI_TstateStrain,P_lowI_TstateStress
    DOUBLE PRECISION hghI_TstateStrain, hghI_TstateStress
    DOUBLE PRECISION TmaxStrainDmnd
    DOUBLE PRECISION rDispP, rForceP, uForceP
C
    DOUBLE PRECISION P_kmax
    DOUBLE PRECISION st1, st2
    DOUBLE PRECISION STDU, STDF, STDFR
    DOUBLE PRECISION avgforce
    DOUBLE PRECISION slope12, slope34, checkSlope, slope

C
C
C
```

```
C     PARAMETERS TAKEN FROM PROPS
      rDispP = PROPS(17)
      rForceP = PROPS(18)
      uForceP = PROPS(19)
C
      P_kmax = MAX(P_kunload, P_kElasticPosDamgd)
C
      IF (state4Strain(1) * state4Strain(4) .LT. ZERO) THEN
         state4Strain(3) = hghI_TstateStrain * rDispP
         IF (uForceP .EQ. ZERO) THEN
            state4Stress(3) = hghI_TstateStress * rForceP
         ELSE IF (rForceP-uForceP .GT. 1.0D-8) THEN
            state4Stress(3) = hghI_TstateStress * rForceP
         ELSE
            IF (TmaxStrainDmnd .GT. envlpPosStrain(4)) THEN
               st1 = hghI_TstateStress * uForceP * (ONE+TOL)
               st2 = envlpNegDamgdStress(5) * (ONE+TOL)
               state4Stress(3) = MAX(st1, st2)
            ELSE
               st1 = envlpPosDamgdStress(4)*uForceP*(ONE+TOL)
               st2 = envlpPosDamgdStress(5)*(ONE+TOL)
               state4Stress(3) = MIN(st1, st2)
            END IF
         END IF
         IF ((state4Stress(4) - state4Stress(3)) / (state4Strain(4) -
     +       state4Strain(3)) .GT. P_kElasticPosDamgd) THEN
            state4Strain(3) = hghI_TstateStrain -
     +       (state4Stress(4)-state4Stress(3))/P_kElasticPosDamgd
         END IF
         IF (state4Strain(3) .LT. state4Strain(1)) THEN
            STDU = state4Strain(4) - state4Strain(1)
            STDF = state4Stress(4) - state4Stress(1)
            state4Strain(2) = state4Strain(1) + 0.33D0*STDU
            state4Strain(3) = state4Strain(1) + 0.67D0*STDU
            state4Stress(2) = state4Stress(1) + 0.33D0*STDF
            state4Stress(3) = state4Stress(1) + 0.67D0*STDF
         ELSE
C           PATH:
            IF (TmaxStrainDmnd .GT. envlpPosStrain(4)) THEN
               state4Stress(2) = uForceP * envlpPosDamgdStress(5)
            ELSE
               state4Stress(2) = uForceP * envlpPosDamgdStress(4)
C              PATH:
            END IF
            state4Strain(2) = P_lowI_TstateStrain +
     +       (-P_lowI_TstateStress + state4Stress(2))/P_kunload
            IF (state4Strain(2) .LT. state4Strain(1)) THEN
               STDU = state4Strain(3) - state4Strain(1)
               STDF = state4Stress(3) - state4Stress(1)
```

```
            state4Strain(2) = state4Strain(1) + HALF*STDU
            state4Stress(2) = state4Stress(1) + HALF*STDF
         ELSE IF ((state4Stress(3) - state4Stress(2))/
     +      (state4Strain(3) -state4Strain(2)) .GT. P_kmax) THEN
C              PATH:
              STDU = state4Strain(4) - state4Strain(1)
              STDF = state4Stress(4) - state4Stress(1)
              state4Strain(2) = state4Strain(1) + 0.33D0*STDU
              state4Strain(3) = state4Strain(1) + 0.67D0*STDU
              state4Stress(2) = state4Stress(1) + 0.33D0*STDF
              state4Stress(3) = state4Stress(1) + 0.67D0*STDF
         ELSE IF ((state4Strain(3) .LT. state4Strain(2)) .OR.
     +      ((state4Stress(3)-state4Stress(2))/
     +      (state4Strain(3)-state4Strain(2)) .LT. ZERO)) THEN
                IF (state4Strain(2) .GT. ZERO) THEN
                   STDU = state4Strain(3)-state4Strain(1)
                   STDF = state4Stress(3)-state4Stress(1)
                   state4Strain(2)=state4Strain(1)+HALF*STDU
                   state4Stress(2)=state4Stress(1)+HALF*STDF
                ELSE IF (state4Strain(3) .LT. ZERO) THEN
                   STDU = state4Strain(4)-state4Strain(2)
                   STDF = state4Stress(4)-state4Stress(2)
                   state4Strain(3)=state4Strain(2)+HALF*STDU
                   state4Stress(3)=state4Stress(2)+HALF*STDF
                ELSE
                   avgforce = HALF*(state4Stress(3) +
     +              state4Stress(2))
                   STDFR = ZERO
                   IF (avgforce .LT. ZERO) THEN
                      STDFR = -avgforce/100.0D0
                   ELSE
                      STDFR = avgforce/100.0D0
                   END IF
                   slope12 = (state4Stress(2) -
     +      state4Stress(1))/(state4Strain(2) - state4Strain(1))
                   slope34 = (state4Stress(4) -
     +      state4Stress(3))/(state4Strain(4) - state4Strain(3))
                   state4Stress(2) = avgforce - STDFR
                   state4Stress(3) = avgforce + STDFR
                   state4Strain(2) = state4Strain(1) +
     +      (state4Stress(2) - state4Stress(1))/slope12
                   state4Strain(3) = state4Strain(4) -
     +      (state4Stress(4) - state4Stress(3))/slope34
                END IF
         END IF
      END IF
    ELSE
      STDU = state4Strain(4)-state4Strain(1)
      STDF = state4Stress(4)-state4Stress(1)
```

```
      state4Strain(2) = state4Strain(1) + 0.33D0*STDU;
      state4Strain(3) = state4Strain(1) + 0.67D0*STDU;
          state4Stress(2) = state4Stress(1) + 0.33D0*STDF;
          state4Stress(3) = state4Stress(1) + 0.67D0*STDF;
    END IF
C
    checkSlope = state4Stress(1)/state4Strain(1)
    slope = ZERO
C
C    FINAL CHECK
    I = 1
    DO WHILE (I .LT. 4)
      STDU = state4Strain(I+1)-state4Strain(I)
      STDF = state4Stress(I+1)-state4Stress(I)
      IF (STDU .LT. ZERO .OR. STDF .LT. ZERO) THEN
        STDU = state4Strain(4)-state4Strain(1)
        STDF = state4Stress(4)-state4Stress(1)
                 state4Strain(2) = state4Strain(1) + 0.33D0*STDU
                 state4Strain(3) = state4Strain(1) + 0.67D0*STDU
                 state4Stress(2) = state4Stress(1) + 0.33D0*STDF
                 state4Stress(3) = state4Stress(1) + 0.67D0*STDF
        slope = STDF / STDU
        I = 4
      END IF
      IF (slope .GT. 1.0D-8 .AND. slope .LT. checkSlope) THEN
        state4Strain(2) = ZERO;
        state4Stress(2) = ZERO;
                 state4Strain(3) = state4Strain(4)*HALF
        state4Stress(3) = state4Stress(4)*HALF
      END IF
      I = I + 1
    END DO
C
C
    RETURN
    END
C
C
C    ****************************************
C          PINCHING4: Envlp3Stress
C    ****************************************
    SUBROUTINE Envlp3Stress(s3Strain,s3Stress,SU, f)
C
C
    INCLUDE 'ABA_PARAM.INC'
C
    PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
   + ONE = 1.D0)
C
```

```
      DIMENSION s3Strain(4), s3Stress(4)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k, f
C
      P_k = ZERO
      I = 1
      f = ZERO
      DO WHILE ((P_k .EQ. ZERO .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s3Strain(i)) THEN
            P_k = (s3Stress(i+1)-s3Stress(i))/
     +          (s3Strain(i+1)-s3Strain(i))
            f =  s3Stress(i)+(SU-s3Strain(i))*P_k
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. ZERO) THEN
         IF (SU .LT. s3Strain(1)) THEN
            I = 1
         ELSE
            I = 3
         END IF
             P_k = (s3Stress(i+1)-s3Stress(i))/(s3Strain(i+1)-s3Strain(i))
             f = s3Stress(i)+(SU-s3Strain(i))*P_k
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C            PINCHING4: Envlp3Tangent
C     ****************************************
      SUBROUTINE Envlp3Tangent(s3Strain,s3Stress,SU, P_k)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION s3Strain(4), s3Stress(4)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k
C
```

```
      P_k = ZERO
      I = 1
      DO WHILE ((P_k .EQ. ZERO .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s3Strain(i)) THEN
            P_k = (s3Stress(i+1)-s3Stress(i))/
     +          (s3Strain(i+1)-s3Strain(i))
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. ZERO) THEN
         IF (SU .LT. s3Strain(1)) THEN
            I = 1
         ELSE
            I = 3
         END IF
         P_k = (s3Stress(i+1)-s3Stress(i))/(s3Strain(i+1)-s3Strain(i))
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: Envlp4Stress
C     ****************************************
      SUBROUTINE Envlp4Stress(s4Strain,s4Stress,SU, f)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION s4Strain(4), s4Stress(4)
C
      INTEGER I
      DOUBLE PRECISION SU
      DOUBLE PRECISION P_k, f
C
      P_k = ZERO
      I = 1
      f = ZERO
      DO WHILE ((P_k .EQ. ZERO .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s4Strain(i)) THEN
            P_k = (s4Stress(i+1)-s4Stress(i))/
     +          (s4Strain(i+1)-s4Strain(i))
            f =  s4Stress(i)+(SU-s4Strain(i))*P_k
         END IF
```

```
      I = I + 1
    END DO
    IF (P_k .EQ. ZERO) THEN
      IF (SU .LT. s4Strain(1)) THEN
        I = 1
      ELSE
        I = 3
      END IF
          P_k = (s4Stress(i+1)-s4Stress(i))/(s4Strain(i+1)-s4Strain(i))
          f = s4Stress(i)+(SU-s4Strain(i))*P_k
    END IF
C
C
    RETURN
    END
C
C
C    ****************************************
C          PINCHING4: Envlp4Tangent
C    ****************************************
    SUBROUTINE Envlp4Tangent(s4Strain,s4Stress, SU, P_k)
C
C
    INCLUDE 'ABA_PARAM.INC'
C
    PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
   + ONE = 1.D0)
C
    DIMENSION s4Strain(4), s4Stress(4)
C
    INTEGER I
    DOUBLE PRECISION SU
    DOUBLE PRECISION P_k
C
    P_k = ZERO
    I = 1
    DO WHILE ((P_k .EQ. ZERO .OR. i .LE. 3) .AND. (i .LE. 3))
      IF (SU .GE. s4Strain(i)) THEN
        P_k = (s4Stress(i+1)-s4Stress(i))/
   +          (s4Strain(i+1)-s4Strain(i))
      END IF
      I = I + 1
    END DO
    IF (P_k .EQ. ZERO) THEN
      IF (SU .LT. s4Strain(1)) THEN
        I = 1
      ELSE
        I = 3
      END IF
```

```
      P_k = (s4Stress(i+1)-s4Stress(i))/(s4Strain(i+1)-s4Strain(i))
    END IF
C
C
    RETURN
    END
C
C
C    ****************************************
C            PINCHING4: updateDmg
C    ****************************************
    SUBROUTINE updateDmg(strain, dstrain,
   +          TmaxStrainDmnd, TminStrainDmnd,
   +          envlpPosStrain, envlpNegStrain,
   +          envlpPosDamgdStress,envlpNegDamgdStress,
   +          CnCycle,Tenergy,energyCapacity,
   +          I_DmgCyc, elasticStrainEnergy,
   +          P_kElasticPos,P_kElasticNeg,
   +          TnCycle,TgammaK,TgammaD,TgammaF,
   +          PROPS)
C
C
    INCLUDE 'ABA_PARAM.INC'
C
    PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
   + ONE = 1.D0)
C
    DIMENSION PROPS(41),
   +          envlpPosStrain(6), envlpPosStress(6),
   +          envlpNegStrain(6), envlpNegStress(6),
   +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
   +          state3Strain(4), state3Stress(4),
   +          state4Strain(4), state4Stress(4)
C
    INTEGER I_DmgCyc
    DOUBLE PRECISION strain, dstrain
    DOUBLE PRECISION TmaxStrainDmnd, TminStrainDmnd
    DOUBLE PRECISION P_kElasticPos,P_kElasticNeg
    DOUBLE PRECISION CnCycle, TnCycle
    DOUBLE PRECISION Tenergy, energyCapacity, elasticStrainEnergy
    DOUBLE PRECISION TgammaK,TgammaD,TgammaF
C
    DOUBLE PRECISION gammaK1, gammaK2, gammaK3, gammaK4, gammaKLimit
    DOUBLE PRECISION gammaD1, gammaD2, gammaD3, gammaD4, gammaDLimit
    DOUBLE PRECISION gammaF1, gammaF2, gammaF3, gammaF4, gammaFLimit
C
    DOUBLE PRECISION tes
    DOUBLE PRECISION umaxAbs, uultAbs
    DOUBLE PRECISION gammaKLimEnv
```

```
C
      DOUBLE PRECISION EXTSTRESS
      DOUBLE PRECISION P_kminP, P_kminN, P_kmin
      DOUBLE PRECISION P_k1

C
C     UNZIP PARAMETERS FROM PROPS()
      gammaK1 = PROPS(23)
      gammaK2 = PROPS(24)
      gammaK3 = PROPS(25)
      gammaK4 = PROPS(26)
      gammaKLimit = PROPS(27)
      gammaD1 = PROPS(28)
      gammaD2 = PROPS(29)
      gammaD3 = PROPS(30)
      gammaD4 = PROPS(31)
      gammaDLimit = PROPS(32)
      gammaF1 = PROPS(33)
      gammaF2 = PROPS(34)
      gammaF3 = PROPS(35)
      gammaF4 = PROPS(36)
      gammaFLimit = PROPS(37)
      I_DmgCyc = INT(PROPS(39))
C
      tes = ZERO
      umaxAbs = MAX(TmaxStrainDmnd, -TminStrainDmnd)
      uultAbs = MAX(envlpPosStrain(5), -envlpNegStrain(5))
      TnCycle = CnCycle + DABS(dstrain)/(4.0D0*umaxAbs)
C
      IF ((strain .LT. uultAbs .AND. strain .GT. -uultAbs) .AND.
     + Tenergy .LT. energyCapacity) THEN
         TgammaK = gammaK1 * ((umaxAbs/uultAbs) ** gammaK3)
         TgammaD = gammaD1 * ((umaxAbs/uultAbs) ** gammaD3)
         TgammaF = gammaF1 * ((umaxAbs/uultAbs) ** gammaF3)
C
         IF (Tenergy .GT. elasticStrainEnergy
     + .AND. I_DmgCyc .EQ. 0) THEN
            tes = (Tenergy-elasticStrainEnergy)/energyCapacity
            TgammaK = TgammaK + gammaK2 * (tes ** gammaK4)
            TgammaD = TgammaD + gammaD2 * (tes ** gammaD4)
            TgammaF = TgammaF + gammaF2 * (tes ** gammaF4)
         ELSE IF (I_DmgCyc .EQ. 1) THEN
            TgammaK = TgammaK + gammaK2 * (TnCycle ** gammaK4)
            TgammaD = TgammaD + gammaD2 * (TnCycle ** gammaD4)
            TgammaF = TgammaF + gammaF2 * (TnCycle ** gammaF4)
         END IF
C
         CALL posEnvlpStress(TmaxStrainDmnd, envlpPosDamgdStress,
     +       envlpPosStrain, EXTSTRESS)
```

```
      P_kminP = EXTSTRESS/TmaxStrainDmnd
      CALL negEnvlpStress(TminStrainDmnd, envlpNegDamgdStress,
     +     envlpNegStrain, EXTSTRESS)
      P_kminN = EXTSTRESS/TminStrainDmnd
      P_kmin = MAX(P_kminP/P_kElasticPos, P_kminN/P_kElasticNeg)
      gammaKLimEnv = MAX(ZERO, (ONE-P_kmin))
C
      P_k1 = MIN(TgammaK, gammaKLimit)
      TgammaK = MIN(P_k1, gammaKLimEnv)
      TgammaD = MIN(TgammaD, gammaDLimit)
      TgammaF = MIN(TgammaF, gammaFLimit)
    ELSE IF (strain .LT. uultAbs .AND. strain .GT.-uultAbs) THEN
      CALL posEnvlpStress(TmaxStrainDmnd, envlpPosDamgdStress,
     +     envlpPosStrain, EXTSTRESS)
      P_kminP = EXTSTRESS/TmaxStrainDmnd
      CALL negEnvlpStress(TminStrainDmnd, envlpNegDamgdStress,
     +     envlpNegStrain, EXTSTRESS)
      P_kminN = EXTSTRESS/TminStrainDmnd
      P_kmin = MAX(P_kminP/P_kElasticPos, P_kminN/P_kElasticNeg)
      gammaKLimEnv = MAX(ZERO, (ONE-P_kmin))
C
      TgammaK = MIN(gammaKLimit, gammaKLimEnv)
      TgammaD = MIN(TgammaD, gammaDLimit)
      TgammaF = MIN(TgammaF, gammaFLimit)
C
    END IF
C
C
    RETURN
    END
C
C
C    ****************************************
C          PINCHING4: commitState
C    ****************************************
    SUBROUTINE commitState(I_Tstate,dstrain,TstrainRate,
     +           P_lowI_TstateStrain,P_lowI_TstateStress,
     +           hghI_TstateStrain,hghI_TstateStress,
     +           TminStrainDmnd,TmaxStrainDmnd,
     +           Tenergy,Tstress,Tstrain,
     +           TgammaK,TgammaD,TgammaF,
     +           P_kElasticPos,P_kElasticNeg,
     +           gammaKUsed,gammaFUsed,
     +           envlpPosStress,envlpNegStress,TnCycle,
     +           I_Cstate,CstrainRate,
     +           P_lowI_CstateStrain,P_lowI_CstateStress,
     +           hghI_CstateStrain,hghI_CstateStress,
     +           CminStrainDmnd,CmaxStrainDmnd,
     +           Cenergy,Cstress,Cstrain,
```

```
     +            CgammaK,CgammaD,CgammaF,
     +            P_kElasticPosDamgd,P_kElasticNegDamgd,
     +            uMaxDamgd,uMinDamgd,
     +            envlpPosDamgdStress,envlpNegDamgdStress,CnCycle)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION PROPS(41),
     +        envlpPosStrain(6), envlpPosStress(6),
     +        envlpNegStrain(6), envlpNegStress(6),
     +        envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +        state3Strain(4), state3Stress(4),
     +        state4Strain(4), state4Stress(4)
C
C
      INTEGER I_Cstate, I_Tstate
      DOUBLE PRECISION dstrain
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION Tstrain, Tstress, TstrainRate
      DOUBLE PRECISION P_lowI_TstateStrain, P_lowI_TstateStress
      DOUBLE PRECISION hghI_TstateStrain, hghI_TstateStress
      DOUBLE PRECISION P_lowI_CstateStrain,P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain,hghI_CstateStress
      DOUBLE PRECISION TminStrainDmnd,TmaxStrainDmnd
      DOUBLE PRECISION CminStrainDmnd,CmaxStrainDmnd
      DOUBLE PRECISION Cenergy, Tenergy
      DOUBLE PRECISION CnCycle, TnCycle
      DOUBLE PRECISION TgammaK,TgammaD,TgammaF
      DOUBLE PRECISION CgammaK,CgammaD,CgammaF
      DOUBLE PRECISION gammaKUsed,gammaFUsed
      DOUBLE PRECISION P_kElasticPos,P_kElasticNeg
      DOUBLE PRECISION P_kElasticPosDamgd,P_kElasticNegDamgd
      DOUBLE PRECISION uMaxDamgd,uMinDamgd
C
      I_Cstate = I_Tstate
C
      IF (dstrain .GT. 1.0D-12 .OR. dstrain<-(1.0D-12)) THEN
         CstrainRate = dstrain
      ELSE
         CstrainRate = TstrainRate
      END IF
C
      P_lowI_CstateStrain = P_lowI_TstateStrain
      P_lowI_CstateStress = P_lowI_TstateStress
      hghI_CstateStrain = hghI_TstateStrain
```

```
      hghI_CstateStress = hghI_TstateStress
      CminStrainDmnd = TminStrainDmnd
      CmaxStrainDmnd = TmaxStrainDmnd
      Cenergy = Tenergy
C
      Cstress = Tstress
      Cstrain = Tstrain
C
      CgammaK = TgammaK
      CgammaD = TgammaD
      CgammaF = TgammaF
C
      P_kElasticPosDamgd = P_kElasticPos*(1 - gammaKUsed)
      P_kElasticNegDamgd = P_kElasticNeg*(1 - gammaKUsed)
C
      uMaxDamgd = TmaxStrainDmnd*(1 + CgammaD)
      uMinDamgd = TminStrainDmnd*(1 + CgammaD)
C
      envlpPosDamgdStress = envlpPosStress*(1-gammaFUsed)
      envlpNegDamgdStress = envlpNegStress*(1-gammaFUsed)
C
      CnCycle = TnCycle
C
C
      RETURN
      END
C
C
C
C
C     ****************************************
C        PINCHING4 INTERFACE:SPIN2UEL
C     ****************************************
      SUBROUTINE SPIN2UEL(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy, strain, dstrain,
     +SPR_DISP, SPR_F, SPR_K, SVARS, I_SPR_NUM)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
```

```
      DIMENSION envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4),
     +          SVARS(200)
C
      DOUBLE PRECISION strain, dstrain
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION P_lowI_CstateStrain, P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain, hghI_CstateStress
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION Cenergy
      DOUBLE PRECISION CgammaK, CgammaD, CgammaF
      DOUBLE PRECISION Ttangent
      DOUBLE PRECISION gammaKUsed, gammaFUsed
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
      DOUBLE PRECISION uMaxDamgd,uMinDamgd
      DOUBLE PRECISION P_kunload
      DOUBLE PRECISION CnCycle
      DOUBLE PRECISION elasticStrainEnergy
      DOUBLE PRECISION SPR_DISP, SPR_K, SPR_F
C
      INTEGER I_Cstate
C
      INTEGER I_SPR_NUM
C
C
      IF (I_SPR_NUM .EQ. 1) THEN
         SVARS(1) = envlpPosDamgdStress(1)
         SVARS(2) = envlpPosDamgdStress(2)
         SVARS(3) = envlpPosDamgdStress(3)
         SVARS(4) = envlpPosDamgdStress(4)
         SVARS(5) = envlpPosDamgdStress(5)
         SVARS(6) = envlpPosDamgdStress(6)
         SVARS(7) = envlpNegDamgdStress(1)
         SVARS(8) = envlpNegDamgdStress(2)
         SVARS(9) = envlpNegDamgdStress(3)
         SVARS(10) = envlpNegDamgdStress(4)
         SVARS(11) = envlpNegDamgdStress(5)
         SVARS(12) = envlpNegDamgdStress(6)
         SVARS(13) = state3Strain(1)
         SVARS(14) = state3Strain(2)
         SVARS(15) = state3Strain(3)
         SVARS(16) = state3Strain(4)
         SVARS(17) = state3Stress(1)
         SVARS(18) = state3Stress(2)
         SVARS(19) = state3Stress(3)
         SVARS(20) = state3Stress(4)
         SVARS(21) = state4Strain(1)
         SVARS(22) = state4Strain(2)
```

```
    SVARS(23) = state4Strain(3)
    SVARS(24) = state4Strain(4)
    SVARS(25) = state4Stress(1)
    SVARS(26) = state4Stress(2)
    SVARS(27) = state4Stress(3)
    SVARS(28) = state4Stress(4)
    SVARS(29) = DBLE(I_Cstate)
    SVARS(30) = Cstrain
    SVARS(31) = Cstress
    SVARS(32) = CstrainRate
    SVARS(33) = P_lowI_CstateStrain
    SVARS(34) = P_lowI_CstateStress
    SVARS(35) = hghI_CstateStrain
    SVARS(36) = hghI_CstateStress
    SVARS(37) = CminStrainDmnd
    SVARS(38) = CmaxStrainDmnd
    SVARS(39) = Cenergy
    SVARS(40) = CgammaK
    SVARS(41) = CgammaD
    SVARS(42) = CgammaF
    SVARS(43) = gammaKUsed
    SVARS(44) = gammaFUsed
    SVARS(45) = Ttangent
    SVARS(46) = P_kElasticPosDamgd
    SVARS(47) = P_kElasticNegDamgd
    SVARS(48) = uMaxDamgd
    SVARS(49) = uMinDamgd
    SVARS(50) = P_kunload
    SVARS(51) = CnCycle
    SVARS(52) = elasticStrainEnergy
    SVARS(53) = strain
    SVARS(54) = dstrain
    SVARS(55) = SPR_DISP
    SVARS(56) = SPR_F
    SVARS(57) = SPR_K
ELSE IF (I_SPR_NUM .EQ. 2) THEN
    SVARS(58) = envlpPosDamgdStress(1)
    SVARS(59) = envlpPosDamgdStress(2)
    SVARS(60) = envlpPosDamgdStress(3)
    SVARS(61) = envlpPosDamgdStress(4)
    SVARS(62) = envlpPosDamgdStress(5)
    SVARS(63) = envlpPosDamgdStress(6)
    SVARS(64) = envlpNegDamgdStress(1)
    SVARS(65) = envlpNegDamgdStress(2)
    SVARS(66) = envlpNegDamgdStress(3)
    SVARS(67) = envlpNegDamgdStress(4)
    SVARS(68) = envlpNegDamgdStress(5)
    SVARS(69) = envlpNegDamgdStress(6)
    SVARS(70) = state3Strain(1)
```

```
      SVARS(71) = state3Strain(2)
      SVARS(72) = state3Strain(3)
      SVARS(73) = state3Strain(4)
      SVARS(74) = state3Stress(1)
      SVARS(75) = state3Stress(2)
      SVARS(76) = state3Stress(3)
      SVARS(77) = state3Stress(4)
      SVARS(78) = state4Strain(1)
      SVARS(79) = state4Strain(2)
      SVARS(80) = state4Strain(3)
      SVARS(81) = state4Strain(4)
      SVARS(82) = state4Stress(1)
      SVARS(83) = state4Stress(2)
      SVARS(84) = state4Stress(3)
      SVARS(85) = state4Stress(4)
      SVARS(86) = DBLE(I_Cstate)
      SVARS(87) = Cstrain
      SVARS(88) = Cstress
      SVARS(89) = CstrainRate
      SVARS(90) = P_lowI_CstateStrain
      SVARS(91) = P_lowI_CstateStress
      SVARS(92) = hghI_CstateStrain
      SVARS(93) = hghI_CstateStress
      SVARS(94) = CminStrainDmnd
      SVARS(95) = CmaxStrainDmnd
      SVARS(96) = Cenergy
      SVARS(97) = CgammaK
      SVARS(98) = CgammaD
      SVARS(99) = CgammaF
      SVARS(100) = gammaKUsed
      SVARS(101) = gammaFUsed
      SVARS(102) = Ttangent
      SVARS(103) = P_kElasticPosDamgd
      SVARS(104) = P_kElasticNegDamgd
      SVARS(105) = uMaxDamgd
      SVARS(106) = uMinDamgd
      SVARS(107) = P_kunload
      SVARS(108) = CnCycle
      SVARS(109) = elasticStrainEnergy
      SVARS(110) = strain
      SVARS(111) = dstrain
      SVARS(112) = SPR_DISP
      SVARS(113) = SPR_F
      SVARS(114) = SPR_K
    END IF
C
C
    RETURN
    END
```

```
C
C
C     ****************************************
C        PINCHING4 INTERFACE:SUEL2PIN
C     ****************************************
      SUBROUTINE SUEL2PIN(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy,
     +SPR_F, SPR_K, SVARS, I_SPR_NUM)
C
C
      INCLUDE 'ABA_PARAM.INC'
C
      PARAMETER (TOL = 1.D-128, ZERO = 0.D0, PONE = 0.1D0, HALF = 0.5D0,
     + ONE = 1.D0)
C
      DIMENSION envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4), SVARS(200)
C
      DOUBLE PRECISION strain, dstrain
      DOUBLE PRECISION Cstrain, Cstress, CstrainRate
      DOUBLE PRECISION P_lowI_CstateStrain, P_lowI_CstateStress
      DOUBLE PRECISION hghI_CstateStrain, hghI_CstateStress
      DOUBLE PRECISION CminStrainDmnd, CmaxStrainDmnd
      DOUBLE PRECISION Cenergy
      DOUBLE PRECISION CgammaK, CgammaD, CgammaF
      DOUBLE PRECISION Ttangent
      DOUBLE PRECISION gammaKUsed, gammaFUsed
      DOUBLE PRECISION P_kElasticPosDamgd, P_kElasticNegDamgd
      DOUBLE PRECISION uMaxDamgd,uMinDamgd
      DOUBLE PRECISION P_kunload
      DOUBLE PRECISION CnCycle
      DOUBLE PRECISION elasticStrainEnergy
      DOUBLE PRECISION SPR_DISP, SPR_K, SPR_F
C
      INTEGER I_Cstate
C
      INTEGER I_SPR_NUM
C
      IF (I_SPR_NUM .EQ. 1) THEN
         envlpPosDamgdStress(1) = SVARS(1)
         envlpPosDamgdStress(2) = SVARS(2)
         envlpPosDamgdStress(3) = SVARS(3)
```

```
envlpPosDamgdStress(4) = SVARS(4)
envlpPosDamgdStress(5) = SVARS(5)
envlpPosDamgdStress(6) = SVARS(6)
envlpNegDamgdStress(1) = SVARS(7)
envlpNegDamgdStress(2) = SVARS(8)
envlpNegDamgdStress(3) = SVARS(9)
envlpNegDamgdStress(4) = SVARS(10)
envlpNegDamgdStress(5) = SVARS(11)
envlpNegDamgdStress(6) = SVARS(12)
state3Strain(1) = SVARS(13)
state3Strain(2) = SVARS(14)
state3Strain(3) = SVARS(15)
state3Strain(4) = SVARS(16)
state3Stress(1) = SVARS(17)
state3Stress(2) = SVARS(18)
state3Stress(3) = SVARS(19)
state3Stress(4) = SVARS(20)
state4Strain(1) = SVARS(21)
state4Strain(2) = SVARS(22)
state4Strain(3) = SVARS(23)
state4Strain(4) = SVARS(24)
state4Stress(1) = SVARS(25)
state4Stress(2) = SVARS(26)
state4Stress(3) = SVARS(27)
state4Stress(4) = SVARS(28)
I_Cstate = INT(SVARS(29))
Cstrain = SVARS(30)
Cstress = SVARS(31)
CstrainRate = SVARS(32)
P_lowI_CstateStrain = SVARS(33)
P_lowI_CstateStress = SVARS(34)
hghI_CstateStrain = SVARS(35)
hghI_CstateStress = SVARS(36)
CminStrainDmnd = SVARS(37)
CmaxStrainDmnd = SVARS(38)
Cenergy = SVARS(39)
CgammaK = SVARS(40)
CgammaD = SVARS(41)
CgammaF = SVARS(42)
gammaKUsed = SVARS(43)
gammaFUsed = SVARS(44)
Ttangent = SVARS(45)
P_kElasticPosDamgd = SVARS(46)
P_kElasticNegDamgd = SVARS(47)
uMaxDamgd = SVARS(48)
uMinDamgd = SVARS(49)
P_kunload = SVARS(50)
CnCycle = SVARS(51)
elasticStrainEnergy = SVARS(52)
```

```
    SPR_F = SVARS(56)
    SPR_K = SVARS(57)
ELSE IF (I_SPR_NUM .EQ. 2) THEN
    envlpPosDamgdStress(1) = SVARS(58)
    envlpPosDamgdStress(2) = SVARS(59)
    envlpPosDamgdStress(3) = SVARS(60)
    envlpPosDamgdStress(4) = SVARS(61)
    envlpPosDamgdStress(5) = SVARS(62)
    envlpPosDamgdStress(6) = SVARS(63)
    envlpNegDamgdStress(1) = SVARS(64)
    envlpNegDamgdStress(2) = SVARS(65)
    envlpNegDamgdStress(3) = SVARS(66)
    envlpNegDamgdStress(4) = SVARS(67)
    envlpNegDamgdStress(5) = SVARS(68)
    envlpNegDamgdStress(6) = SVARS(69)
    state3Strain(1) = SVARS(70)
    state3Strain(2) = SVARS(71)
    state3Strain(3) = SVARS(72)
    state3Strain(4) = SVARS(73)
    state3Stress(1) = SVARS(74)
    state3Stress(2) = SVARS(75)
    state3Stress(3) = SVARS(76)
    state3Stress(4) = SVARS(77)
    state4Strain(1) = SVARS(78)
    state4Strain(2) = SVARS(79)
    state4Strain(3) = SVARS(80)
    state4Strain(4) = SVARS(81)
    state4Stress(1) = SVARS(82)
    state4Stress(2) = SVARS(83)
    state4Stress(3) = SVARS(84)
    state4Stress(4) = SVARS(85)
    I_Cstate = INT(SVARS(86))
    Cstrain = SVARS(87)
    Cstress = SVARS(88)
    CstrainRate = SVARS(89)
    P_lowI_CstateStrain = SVARS(90)
    P_lowI_CstateStress = SVARS(91)
    hghI_CstateStrain = SVARS(92)
    hghI_CstateStress = SVARS(93)
    CminStrainDmnd = SVARS(94)
    CmaxStrainDmnd = SVARS(95)
    Cenergy = SVARS(96)
    CgammaK = SVARS(97)
    CgammaD = SVARS(98)
    CgammaF = SVARS(99)
    gammaKUsed = SVARS(100)
    gammaFUsed = SVARS(101)
    Ttangent = SVARS(102)
    P_kElasticPosDamgd = SVARS(103)
```

```
      P_kElasticNegDamgd = SVARS(104)
      uMaxDamgd = SVARS(105)
      uMinDamgd = SVARS(106)
      P_kunload = SVARS(107)
      CnCycle = SVARS(108)
      elasticStrainEnergy = SVARS(109)
      SPR_F = SVARS(113)
      SPR_K = SVARS(114)
    END IF
C
C
    RETURN
    END
C
C
C
*****************************************************************************************
*******
```

APPENDIX D USER ELEMENT SUBROUTINE EXPLICIT CODE (VUEL)

```
C
*****************************************************************************************************
*******
C                        ABAQUS/Explicit User Element Subroutine (VUEL)
C                    --- for Fasterner-Based Shear Wall/Diaphragm Analysis  ---
C               ----------------------------------------------------------------
C                                          author:  Chu Ding                (chud91@vt.edu)
C                                          advior: Dr. Cristopher D. Moen
(cmoen@vt.edu)
C                                          website: http://www.moen.cee.vt.edu/
C
*****************************************************************************************************
*******subroutine vuel(
    *     nblock,
c         to be defined
    *     rhs,amass,dtimeStable,
    *     svars,nsvars,
    *     energy,
c
    *     nnode,ndofel,
    *     props,nprops,
    *     jprops,njprops,
    *     coords,ncrd,
    *     u,du,v,a,
    *     jtype,jelem,
    *     time,period,dtimeCur,dtimePrev,kstep,kinc,lflags,
    *     dMassScaleFactor,
    *     predef,npredef,
    *     jdltyp,adlmag)


     include 'vaba_param.inc'

     parameter ( zero = 0.d0, half = 0.5d0, one = 1.d0, two=2.d0 )

c     operation code
     parameter ( jMassCalc            = 1,
    *           jIntForceAndDtStable = 2,
    *           jExternForce         = 3)
c
c     flags
     parameter (iProcedure = 1,
    *           iNlgeom    = 2,
```

```
     *          iOpCode    = 3,
     *          nFlags     = 3)

c     time
      parameter (iStepTime  = 1,
     *          iTotalTime = 2,
     *          nTime      = 2)

c     procedure flags
      parameter ( jDynExplicit = 17 )

c     energies
      parameter ( iElPd = 1,
     *           iElCd = 2,
     *           iElIe = 3,
     *           iElTs = 4,
     *           iElDd = 5,
     *           iElBv = 6,
     *           iElDe = 7,
     *           iElHe = 8,
     *           iElKe = 9,
     *           iElTh = 10,
     *           iElDmd = 11,
     *           iElDc = 12,
     *           nElEnergy = 12)

c     predefined variables
      parameter ( iPredValueNew = 1,
     *           iPredValueOld = 2,
     *           nPred         = 2)

c     indexing in a 3-long vector

      parameter (factorStable = 0.99d0)
**-----------------------------------
C
      dimension rhs(nblock,ndofel), amass(nblock,ndofel,ndofel),
     *     dtimeStable(nblock),
     *     svars(nblock,nsvars), energy(nblock,nElEnergy),
     *     props(nprops), jprops(njprops),
     *     jelem(nblock), time(nTime), lflags(nFlags),
     *     coords(nblock,nnode,ncrd), u(nblock,ndofel),
     *     du(nblock,ndofel), v(nblock,ndofel), a(nblock, ndofel),
     *     dMassScaleFactor(nblock),
     *     predef(nblock, nnode, npredef, nPred), adlmag(nblock)


      DIMENSION SRESID(6)
      REAL SPR_DISP, SPR_F, SPR_K
```

```
      REAL SPR_LEN, SPR_COS_X, SPR_COS_Y, SPR_SGN
      REAL SPR_DISP_X, SPR_DISP_Y
      REAL SPR_F_WD, SPR_K_WD
      REAL SPR_ORIENT_1, SPR_ORIENT_2
      INTEGER KORIENT
      CHARACTER FILENAME*200
      CHARACTER*(*) FILEPATH


C     --------------                Choose spring data output path                --------------
C     ***********************************************************************************************
      PARAMETER (FILEPATH = 'E:\Onedrive\VT_RESEARCH\UEL work\vuel
construction\test elem formu\test_energy\vuel_method\')
C     ***********************************************************************************************
C     --------------                Select your spring type                       --------------
C     ***********************************************************************************************
c     * 0: Default deformation quadrants, 1: Displacement-based deformation quadrants
      KORIENT = 1
C     ***********************************************************************************************
c
c
      if (jtype .eq. 2 .and.
     *    lflags(iProcedure).eq.jDynExplicit) then

c       initialize default dynamics parameters
        eDampTra = zero
        am0 = 4.5D-5

c       use original distance to compute mass
        if ( lflags(iOpCode).eq.jMassCalc ) then
          ! loop over every user element
          do kblock = 1, nblock
            amass(kblock,1,1) = am0
            amass(kblock,2,2) = am0
            amass(kblock,3,3) = am0
            amass(kblock,4,4) = am0
            amass(kblock,5,5) = am0
            amass(kblock,6,6) = am0
          end do

c       update right-hand side vetor and stable time increment
        else if ( lflags(iOpCode) .eq.
     *            jIntForceAndDtStable) then
          ! loop over every user element
          do kblock = 1, nblock
            amElem0 = two * am0
            area   = vol0/alen
**-----------------------------------
c             * -------- update spring geometry -------- *
```

```
          call SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_DISP_WD,
     +SPR_COS_X,SPR_COS_Y, SPR_DISP_X,SPR_DISP_Y,PROPS,SVARS,kblock)
          alen = SPR_DISP
**-----------------------------------
*         * -------- generate deformation quadrant -------- *
          IF (KORIENT .EQ. 1) THEN
             IF (SVARS(kblock,128) .EQ. 0.0) THEN
C             * Use default deformation quadrant when deformation is "zero"
               IF (ABS(SPR_DISP) .LE. 2.0 * TOL) THEN
                  SVARS(kblock,129) = 1.D0/SQRT(2.0)
                  SVARS(kblock,130) = 1.D0/SQRT(2.0)
               ELSE
C             * Now use displacement-based quadrant
C                * Save spring orientation
                  SVARS(kblock,129) = SPR_COS_X
                  SVARS(kblock,130) = SPR_COS_Y
                  SVARS(kblock,128) = SVARS(kblock,128)+1.0
               END IF
             END IF
C          * Retrieve spring orientation
             SPR_ORIENT_1 = SVARS(kblock,129)
             SPR_ORIENT_2 = SVARS(kblock,130)
C       * Default deformation quadrant
          ELSE
             SPR_ORIENT_1 = 1.D0/SQRT(2.0)
             SPR_ORIENT_2 = 1.D0/SQRT(2.0)
          END IF
**-----------------------------------
C          * -------- adjust spring deformation sign -------- *
          SPR_SGN = 1.0
C          * For the case of "real compression"
          IF (SPR_DISP .LT. 0.0) THEN
             SPR_SGN = 1.0
C          * For the case of "fake compression" determined by deformation quadrants
          ELSE IF (SPR_DISP_X .NE. 0. .AND. SPR_DISP_Y .NE. 0.) THEN
             IF (SPR_ORIENT_1 * SPR_DISP_X + SPR_ORIENT_2 *
     +SPR_DISP_Y .LT. 0.) THEN
             SPR_SGN = -1.0
             END IF
          END IF
C          * Spring deformation is assinged with positive or negative sign
          SPR_DISP = SPR_SGN * SPR_DISP
**-----------------------------------
c          * -------- update radial spring force and stifness -------- *
          I_SPR_NUM = 1
          call PINCHING4(PROPS,SVARS,SPR_DISP,SPR_K,SPR_F,KINC,
     +I_SPR_NUM,kblock)
          ak = SPR_K
          fElasTra = SPR_F
```

```
            forceTra = fElasTra
**-----------------------------------
c            * -------- update withdrawl spring force -------- *
            SPR_K_WD = 1.E8
            SPR_F_WD = SPR_DISP_WD * SPR_K_WD
**-----------------------------------
c            * -------- update spring nodal force vector -------- *
            DO K1 = 1, 6
               SRESID(K1) = ZERO
            END DO
            call SNFORCE(PROPS, SPR_F, SPR_COS_X, SPR_COS_Y, SRESID,
    +SPR_SGN, SPR_F_WD)
            RHS(kblock,1) = SRESID(1)
            RHS(kblock,2) = SRESID(2)
            RHS(kblock,3) = SRESID(3)
            RHS(kblock,4) = SRESID(4)
            RHS(kblock,5) = SRESID(5)
            RHS(kblock,6) = SRESID(6)
**-----------------------------------
c            * -------- undamped stable time increment for translations -------- *
            dtTrialTransl = sqrt(amElem0/ak)
c            damped stable time increment; since eDampTra=0, the
c            stable time increment does not change because of damping
            critDampTransl = two*sqrt(amElem0*ak)
            csiTra = eDampTra/critDampTransl
            factDamp = sqrt(one+csiTra*csiTra) - csiTra
            dtTrialTransl = dtTrialTransl*factDamp*factorStable
            dtimeStable(kblock) = dtTrialTransl
**-----------------------------------
c            * -------- update internal energy -------- *
            SVARS(kblock,141) = SVARS(kblock,142)
            SVARS(kblock,142) = SPR_DISP
            SVARS(kblock,143) = SVARS(kblock,144)
            SVARS(kblock,144) = SPR_F
            SPR_DISP1 = SVARS(kblock,141)
            SPR_DISP2 = SVARS(kblock,142)
            SPR_F1 = SVARS(kblock,143)
            SPR_F2 = SVARS(kblock,144)
            SPR_ENERGY = half*(SPR_F2+SPR_F1)*(SPR_DISP2-SPR_DISP1)
            SVARS(kblock,145) = SVARS(kblock,145) + SPR_ENERGY
            energy(kblock, iElIe) = SVARS(kblock,145)
**-----------------------------------
c           * -------- output spring load history -------- *
900   FORMAT(I10, F20.8, F20.8, F20.8, F20.8)
c
     WRITE(FILENAME, fmt='(a, I0, a)') FILEPATH, jelem(nblock), ".txt"
     OPEN(300, FILE=FILENAME, STATUS='UNKNOWN', POSITION='APPEND')
     WRITE(300, 900) KINC, SPR_DISP, SPR_F, SPR_K, energy(kblock, iElIe)
     CLOSE(300)
```

```
**-----------------------------------
          end do
        else if ( lflags(iOpCode) .eq.
     *            jExternForce) then
          if (jdltyp.eq.123) then
            do kblock = 1, nblock
              rhs(kblock,4) = adlmag(kblock)
            end do
          end if
        end if
      end if
c
      return
      end
c
c
C     ****************************************************************
C                          PINCHING4 ROUTINE
C     ****************************************************************
      SUBROUTINE PINCHING4(PROPS,SVARS,SPR_DISP,SPR_K,SPR_F,KINC,
     +I_SPR_NUM,kblock)
C
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41), SVARS(kblock,200),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
      INTEGER I_Cstate, I_Tstate
      INTEGER I_DmgCyc
      REAL strain, dstrain
      REAL Cstrain, Cstress, CstrainRate
      REAL Tstrain, Tstress, TstrainRate
      REAL P_lowI_CstateStrain, P_lowI_CstateStress
      REAL hghI_CstateStrain, hghI_CstateStress
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL TminStrainDmnd,TmaxStrainDmnd
      REAL elasticStrainEnergy, energyCapacity
      REAL Cenergy, CnCycle
      REAL Tenergy, TnCycle
      REAL CgammaK, CgammaD, CgammaF
      REAL TgammaD, TgammaK, TgammaF
```

```
      REAL gammaKUsed, gammaFUsed
      REAL Ttangent, P_kunload
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
      REAL P_kElasticPos,P_kElasticNeg
      REAL uMaxDamgd, uMinDamgd
C
      REAL SPR_K, SPR_F, SPR_DISP
C
      INTEGER I_SPR_NUM
C
C
C     ASSIGN SVARS VALUES TO PINCHING4 LOCAL VARIABLES
      CALL SUEL2PIN(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy,
     +SPR_F, SPR_K, SVARS, I_SPR_NUM, kblock)
C
C     CONVERT UEL VARIABLES TO PINCHING4 LOCAL VARIABLES
      strain = SPR_DISP
C
C     ****************************************************************
      CALL SetEnvelop(PROPS, SVARS, envlpPosStrain,
     +          envlpPosStress, envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg, energyCapacity,kblock)
C
C
      IF (KINC .EQ. 1 .OR. KINC .EQ. 0) THEN
         CALL revertToStart(envlpPosStrain, envlpPosStress,
     +          envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,
     +          I_Cstate,Cstrain,Cstress,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,CgammaK,CgammaD,CgammaF,CnCycle,
     +          Ttangent,dstrain,gammaKUsed,gammaFUsed,
     +          P_kElasticPosDamgd,P_kElasticNegDamgd,
     +          uMaxDamgd,uMinDamgd,
     +          envlpPosDamgdStress, envlpNegDamgdStress)
C
C
      ELSE
         CALL revertToLastCommit(I_Cstate,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
```

```
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,Cstrain,Cstress,
     +          CgammaD,CgammaK,CgammaF,CnCycle,
     +          I_Tstate,TstrainRate,
     +          P_lowI_TstateStrain,P_lowI_TstateStress,
     +          hghI_TstateStrain,hghI_TstateStress,
     +          TminStrainDmnd,TmaxStrainDmnd,
     +          Tenergy,Tstrain,Tstress,
     +          TgammaD,TgammaK,TgammaF,TnCycle)
      END IF
C
C
      CALL setTrialStrain(strain,CstrainRate,I_Cstate,Cenergy,
     +                P_lowI_CstateStrain,hghI_CstateStrain,
     +                P_lowI_CstateStress,hghI_CstateStress,
     +                CminStrainDmnd,CmaxStrainDmnd,
     +                CgammaF,CgammaK,CgammaD,
     +                envlpPosStress,envlpPosStrain,
     +                P_kElasticPosDamgd,P_kElasticNegDamgd,
     +                state3Strain,state3Stress,
     +                P_kunload,state4Strain,state4Stress,Cstrain,
     +                uMaxDamgd,uMinDamgd,
     +                envlpNegStrain,envlpNegStress,
     +                P_kElasticPos,P_kElasticNeg,Cstress,I_DmgCyc,
     +                CnCycle,energyCapacity,
     +                I_Tstate,Tenergy,Tstrain,
     +                P_lowI_TstateStrain,hghI_TstateStrain,
     +                P_lowI_TstateStress,hghI_TstateStress,
     +                TgammaF,TgammaK,TgammaD,
     +                dstrain,Ttangent,Tstress,elasticStrainEnergy,
     +                TminStrainDmnd,TmaxStrainDmnd,
     +                gammaKUsed,gammaFUsed,
     +                envlpPosDamgdStress,envlpNegDamgdStress,
     +                TnCycle, PROPS)
C
C
      CALL commitState(I_Tstate,dstrain,TstrainRate,
     +            P_lowI_TstateStrain,P_lowI_TstateStress,
     +            hghI_TstateStrain,hghI_TstateStress,
     +            TminStrainDmnd,TmaxStrainDmnd,
     +            Tenergy,Tstress,Tstrain,
     +            TgammaK,TgammaD,TgammaF,
     +            P_kElasticPos,P_kElasticNeg,
     +            gammaKUsed,gammaFUsed,
     +            envlpPosStress,envlpNegStress,TnCycle,
     +            I_Cstate,CstrainRate,
     +            P_lowI_CstateStrain,P_lowI_CstateStress,
     +            hghI_CstateStrain,hghI_CstateStress,
```

```
     +            CminStrainDmnd,CmaxStrainDmnd,
     +            Cenergy,Cstress,Cstrain,
     +            CgammaK,CgammaD,CgammaF,
     +            P_kElasticPosDamgd,P_kElasticNegDamgd,
     +            uMaxDamgd,uMinDamgd,
     +            envlpPosDamgdStress,envlpNegDamgdStress,CnCycle)
C     ***************************************************************
C
C     CONVERT PINCHING4 LOCAL VARIABELS TO UEL VARAIBLES
      SPR_F = Cstress
      SPR_K = Ttangent
C
C     SAVE PINCHING4 LOCAL VARIABLES TO SVARS
      CALL SPIN2UEL(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy, strain, dstrain,
     +SPR_DISP, SPR_F, SPR_K, SVARS, I_SPR_NUM, kblock)
C
C
      RETURN
      END
C
C
C     ***************************************
C        PINCHING4 FUNCTION: SetEnvelop()
C     ***************************************
      SUBROUTINE SetEnvelop(PROPS, SVARS, envlpPosStrain,
     +          envlpPosStress, envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,energyCapacity,kblock)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41), SVARS(kblock,200),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6)
C
      REAL strain1p, strain2p, strain3p, strain4p
      REAL stress1p, stress2p, stress3p, stress4p
      REAL strain1n, strain2n, strain3n, strain4n
      REAL stress1n, stress2n, stress3n, stress4n
      REAL gE
```

```
      REAL P_kPos, P_kNeg, P_k
      REAL u
      REAL P_k1, P_k2
      REAL P_kElasticPos, P_kElasticNeg
      REAL energypos, energyneg
      REAL P_max_energy, energyCapacity
C
C     UNZIP PROPS(*) VALUES
      strain1p = PROPS(1)
      strain2p = PROPS(2)
      strain3p = PROPS(3)
      strain4p = PROPS(4)
      stress1p = PROPS(5)
      stress2p = PROPS(6)
      stress3p = PROPS(7)
      stress4p = PROPS(8)
C
      strain1n = PROPS(9)
      strain2n = PROPS(10)
      strain3n = PROPS(11)
      strain4n = PROPS(12)
      stress1n = PROPS(13)
      stress2n = PROPS(14)
      stress3n = PROPS(15)
      stress4n = PROPS(16)

C     ************************************
      gE = PROPS(38)
C
      P_kPos = stress1p/strain1p
      P_kNeg = stress1n/strain1n
      P_k = MAX(P_kPos, P_kNeg)
C
      IF (strain1p > -1.0*strain1n) THEN
         u = (1.0E-8)*strain1p
      ELSE
         u = (-1.0E-8)*strain1n
      END IF
C
      envlpPosStrain(1) = u
      envlpPosStress(1) = u*P_k
      envlpNegStrain(1) = -u
      envlpNegStress(1) = -u*P_k
C
      envlpPosStrain(2) = strain1p
      envlpPosStrain(3) = strain2p
      envlpPosStrain(4) = strain3p
      envlpPosStrain(5) = strain4p
C
```

```
      envlpNegStrain(2) = strain1n
      envlpNegStrain(3) = strain2n
      envlpNegStrain(4) = strain3n
      envlpNegStrain(5) = strain4n
C
      envlpPosStress(2) = stress1p
      envlpPosStress(3) = stress2p
      envlpPosStress(4) = stress3p
      envlpPosStress(5) = stress4p
C
      envlpNegStress(2) = stress1n
      envlpNegStress(3) = stress2n
      envlpNegStress(4) = stress3n
      envlpNegStress(5) = stress4n
C
      P_k1 = (stress4p - stress3p)/(strain4p - strain3p)
      P_k2 = (stress4n - stress3n)/(strain4n - strain3n)
C
      envlpPosStrain(6) = 1.0E+6*strain4p
      IF (P_k1 .GT. 0.0) THEN
         envlpPosStress(6) = stress4p+P_k1*(envlpPosStrain(6)-strain4p)
      ELSE
         envlpPosStress(6) = stress4p*(1.0+0.1)
      END IF
      envlpNegStrain(6) = 1.0E+6*strain4n
      IF (P_k2 .GT. 0.0) THEN
         envlpNegStress(6) = stress4n+P_k2*(envlpNegStrain(6)-strain4n)
      ELSE
          envlpNegStress(6) = stress4n*(1.0+0.1)
      END IF
C
C     define crtical material properties
      P_kElasticPos = envlpPosStress(2)/envlpPosStrain(2)
      P_kElasticNeg = envlpNegStress(2)/envlpNegStrain(2)
C
      energypos = 0.5*envlpPosStrain(1)*envlpPosStress(1)
      DO J = 1, 4
          energypos = energypos+0.5*(envlpPosStress(J) +
     +        envlpPosStress(J+1))*(envlpPosStrain(J+1) -
     +        envlpPosStrain(J))
      END DO
C
      energyneg = 0.5*envlpNegStrain(1)*envlpNegStress(1)
      DO J = 1, 4
         energyneg = energyneg+0.5*(envlpNegStress(J) +
     +        envlpNegStress(J+1))*(envlpNegStrain(J+1) -
     +        envlpNegStrain(J))
      END DO
C
```

```
C
      P_max_energy = MAX(energypos, energyneg)
      energyCapacity = gE*P_max_energy
C
C
      RETURN
      END
C
C
C     ****************************************
C        PINCHING4: revertToStart
C     ****************************************
      SUBROUTINE revertToStart(envlpPosStrain, envlpPosStress,
     +          envlpNegStrain, envlpNegStress,
     +          P_kElasticPos,P_kElasticNeg,
     +          I_Cstate,Cstrain,Cstress,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,CgammaK,CgammaD,CgammaF,CnCycle,
     +          Ttangent,dstrain,gammaKUsed,gammaFUsed,
     +          P_kElasticPosDamgd,P_kElasticNegDamgd,
     +          uMaxDamgd,uMinDamgd,
     +          envlpPosDamgdStress, envlpNegDamgdStress)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6)
C
      INTEGER I_Cstate
      REAL Cstrain, Cstress, CstrainRate
      REAL dstrain
      REAL P_lowI_CstateStrain, P_lowI_CstateStress
      REAL hghI_CstateStrain, hghI_CstateStress
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL Cenergy
      REAL CnCycle
      REAL CgammaK, CgammaD, CgammaF
      REAL gammaKUsed, gammaFUsed
      REAL Ttangent
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
      REAL P_kElasticPos, P_kElasticNeg
      REAL uMaxDamgd, uMinDamgd
```

```
C
      I_Cstate = 0
      Cstrain = 0.0
      Cstress = 0.0
      CstrainRate = 0.0
      P_lowI_CstateStrain = envlpNegStrain(1)
      P_lowI_CstateStress = envlpNegStress(1)
      hghI_CstateStrain = envlpPosStrain(1)
      hghI_CstateStress = envlpPosStress(1)
      CminStrainDmnd = envlpNegStrain(2)
      CmaxStrainDmnd = envlpPosStrain(2)
      Cenergy = 0.0
      CgammaK = 0.0
      CgammaD = 0.0
      CgammaF = 0.0
      CnCycle = 0.0
C
      Ttangent = envlpPosStress(1)/envlpPosStrain(1)
      dstrain = 0.0
      gammaKUsed = 0.0
      gammaFUsed = 0.0
C
      P_kElasticPosDamgd = P_kElasticPos
      P_kElasticNegDamgd = P_kElasticNeg
      uMaxDamgd = CmaxStrainDmnd
      uMinDamgd = CminStrainDmnd
C
C     INITIALIZE DAMAGED BACKBONE - envlpPosDamgdStress,
envlpNegDamgdStress
      DO I = 1, 6
         envlpPosDamgdStress(I) = envlpPosStress(I)
         envlpNegDamgdStress(I) = envlpNegStress(I)
      END DO
C
C
      RETURN
      END
C
C
C     ****************************************
C        PINCHING4: revertToLastCommit
C     ****************************************
      SUBROUTINE revertToLastCommit(I_Cstate,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,Cstrain,Cstress,
     +          CgammaD,CgammaK,CgammaF,CnCycle,
     +          I_Tstate,TstrainRate,
```

```
     +          P_lowI_TstateStrain,P_lowI_TstateStress,
     +          hghI_TstateStrain,hghI_TstateStress,
     +          TminStrainDmnd,TmaxStrainDmnd,
     +          Tenergy,Tstrain,Tstress,
     +          TgammaD,TgammaK,TgammaF,TnCycle)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6)
C
      INTEGER I_Tstate, I_Cstate
      REAL TstrainRate
      REAL CstrainRate
      REAL P_lowI_TstateStrain, P_lowI_TstateStress
      REAL hghI_TstateStrain, hghI_TstateStress
      REAL P_lowI_CstateStrain, P_lowI_CstateStress
      REAL hghI_CstateStrain, hghI_CstateStress
      REAL TminStrainDmnd, TmaxStrainDmnd
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL Tenergy
      REAL Cenergy
      REAL Tstrain, Tstress
      REAL Cstrain, Cstress
      REAL TgammaD, Tgamma, TgammaF
      REAL CgammaD, CgammaK, CgammaF
      REAL TnCycle
      REAL CnCycle
C
      I_Tstate = I_Cstate
C
      TstrainRate = CstrainRate
C
      P_lowI_TstateStrain = P_lowI_CstateStrain
      P_lowI_TstateStress = P_lowI_CstateStress
      hghI_TstateStrain = hghI_CstateStrain
      hghI_TstateStress = hghI_CstateStress
      TminStrainDmnd = CminStrainDmnd
      TmaxStrainDmnd = CmaxStrainDmnd
      Tenergy = Cenergy
C
      Tstrain = Cstrain
      Tstress = Cstress
C
      TgammaD = CgammaD
      TgammaK = CgammaK
```

```
      TgammaF = CgammaF
C
      TnCycle = CnCycle
C
C
      RETURN
      END
C
C
C     ****************************************
C          PINCHING4: setTrialStrain
C     ****************************************
      SUBROUTINE setTrialStrain(strain,CstrainRate,I_Cstate,Cenergy,
     +                P_lowI_CstateStrain,hghI_CstateStrain,
     +                P_lowI_CstateStress,hghI_CstateStress,
     +                CminStrainDmnd,CmaxStrainDmnd,
     +                CgammaF,CgammaK,CgammaD,
     +                envlpPosStress,envlpPosStrain,
     +                P_kElasticPosDamgd,P_kElasticNegDamgd,
     +                state3Strain,state3Stress,
     +                P_kunload,state4Strain,state4Stress,Cstrain,
     +                uMaxDamgd,uMinDamgd,
     +                envlpNegStrain,envlpNegStress,
     +                P_kElasticPos,P_kElasticNeg,Cstress,I_DmgCyc,
     +                CnCycle,energyCapacity,
     +                I_Tstate,Tenergy,Tstrain,
     +                P_lowI_TstateStrain,hghI_TstateStrain,
     +                P_lowI_TstateStress,hghI_TstateStress,
     +                TgammaF,TgammaK,TgammaD,
     +                dstrain,Ttangent,Tstress,elasticStrainEnergy,
     +                TminStrainDmnd,TmaxStrainDmnd,
     +                gammaKUsed,gammaFUsed,
     +                envlpPosDamgdStress,envlpNegDamgdStress,
     +                TnCycle, PROPS)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
      INTEGER I_Tstate, I_Cstate
      INTEGER I_DmgCyc
```

```
      REAL Tenergy
      REAL Cenergy
      REAL strain, dstrain
      REAL Cstrain, Cstress, CstrainRate
      REAL Tstrain, Tstress
      REAL Ttangent, P_kunload
      REAL P_lowI_TstateStrain, hghI_TstateStrain
      REAL P_lowI_CstateStrain, hghI_CstateStrain
      REAL P_lowI_TstateStress, hghI_TstateStress
      REAL P_lowI_CstateStress, hghI_CstateStress
      REAL TminStrainDmnd, TmaxStrainDmnd
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL TgammaF, TgammaK, TgammaD
      REAL CgammaF, CgammaK, CgammaD
      REAL uMaxDamgd, uMinDamgd
      REAL P_kElasticPos, P_kElasticNeg
      REAL gammaFUsed, gammaKUsed
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
      REAL denergy, elasticStrainEnergy
      REAL CnCycle, TnCycle
C
      REAL EXTSTRESS
      REAL P_k, f

C
C     INITIALIZE TRIAL PARAMETERS AS THE LAST CONVERGED ONES
      I_Tstate = I_Cstate
      Tenergy = Cenergy
      Tstrain = strain
      P_lowI_TstateStrain = P_lowI_CstateStrain
      hghI_TstateStrain = hghI_CstateStrain
      P_lowI_TstateStress = P_lowI_CstateStress
      hghI_TstateStress = hghI_CstateStress
      TminStrainDmnd = CminStrainDmnd
      TmaxStrainDmnd = CmaxStrainDmnd
      TgammaF = CgammaF
      TgammaK = CgammaK
      TgammaD = CgammaD
C
C
      dstrain = Tstrain - Cstrain
      IF (dstrain  .LT. 1.0E-12 .AND. dstrain .GT.-1.0E-12) THEN
         dstrain = 0.0
      END IF
C
C     DETERMINE IF THERE IS A CAHNGE IN STATE
      CALL getstate(Tstrain,dstrain, CstrainRate, Cstrain, Cstress,
     +envlpPosStrain, envlpPosStress,
     +envlpNegStrain, envlpNegStress,
```

```
     +uMaxDamgd, uMinDamgd, CgammaF, CgammaK,
     +P_kElasticPos, P_kElasticNeg,
     +P_lowI_TstateStrain, P_lowI_TstateStress,
     +hghI_TstateStrain, hghI_TstateStress,
     +TmaxStrainDmnd, TminStrainDmnd,
     +gammaFUsed, gammaKUsed,
     +envlpNegDamgdStress, envlpPosDamgdStress,
     +P_kElasticPosDamgd, P_kElasticNegDamgd,I_Tstate)
C
C
C
      IF (I_Tstate .GE. 0) THEN
         IF (I_Tstate .EQ. 0) THEN
            Ttangent = envlpPosStress(1)/envlpPosStrain(1)
            Tstress = Ttangent*Tstrain
         ELSE IF (I_Tstate .EQ. 1) THEN
            CALL posEnvlpTangent(strain,envlpPosDamgdStress,
     +        envlpPosStrain, P_k)
            Ttangent = P_k
            CALL posEnvlpStress(strain,envlpPosDamgdStress,
     +       envlpPosStrain, EXTSTRESS)
            Tstress = EXTSTRESS
          ELSE IF (I_Tstate .EQ. 2) THEN
            CALL negEnvlpTangent(strain,envlpNegDamgdStress,
     +        envlpNegStrain, P_k)
            Ttangent = P_k
            CALL negEnvlpStress(strain,envlpNegDamgdStress,
     +       envlpNegStrain, EXTSTRESS)
            Tstress = EXTSTRESS
C            DEFINITELY WRONG HERE
         ELSE IF (I_Tstate .EQ. 3) THEN
            IF (hghI_TstateStrain .LT. 0.0) THEN
               P_kunload = P_kElasticNegDamgd
            ELSE
               P_kunload = P_kElasticPosDamgd
            END IF
            state3Strain(1) = P_lowI_TstateStrain
            state3Strain(4) = hghI_TstateStrain
            state3Stress(1) = P_lowI_TstateStress
            state3Stress(4) = hghI_TstateStress
            CALL getstate3(state3Strain, state3Stress, P_kunload,
     +    P_kElasticNegDamgd, P_lowI_TstateStrain, P_lowI_TstateStress,
     +    hghI_TstateStrain, hghI_TstateStress, TminStrainDmnd,
     +    envlpNegStrain, envlpNegDamgdStress, PROPS)
            CALL Envlp3Tangent(state3Strain,state3Stress,strain, P_k)
            Ttangent = P_k
            CALL Envlp3Stress(state3Strain,state3Stress,strain, f)
            Tstress = f
         ELSE IF (I_Tstate .EQ. 4) THEN
```

```
          IF (P_lowI_TstateStrain .LT. 0.0) THEN
             P_kunload = P_kElasticNegDamgd
          ELSE
             P_kunload = P_kElasticPosDamgd
          END IF
          state4Strain(1) = P_lowI_TstateStrain
          state4Strain(4) = hghI_TstateStrain
          state4Stress(1) = P_lowI_TstateStress
          state4Stress(4) = hghI_TstateStress
          CALL getstate4(state4Strain, state4Stress, P_kunload,
     +P_kElasticPosDamgd, P_lowI_TstateStrain,P_lowI_TstateStress,
     +hghI_TstateStrain, hghI_TstateStress, TmaxStrainDmnd,
     +envlpPosStrain, envlpPosDamgdStress, PROPS)
          CALL Envlp4Tangent(state4Strain,state4Stress, strain, P_k)
          Ttangent = P_k
          CALL Envlp4Stress(state4Strain,state4Stress, strain, f)
          Tstress = f
       END IF
    END IF
C
C    UPDATE ENERGY DISSIPATION
    denergy = 0.5*(Tstress+Cstress)*dstrain
    IF (Tstrain .GT. 0.0) THEN
       elasticStrainEnergy = 0.5*Tstress/P_kElasticPosDamgd*Tstress
    ELSE
       elasticStrainEnergy = 0.5*Tstress/P_kElasticNegDamgd*Tstress
    END IF
    Tenergy = Cenergy + denergy
C
C    UPDATE DAMAGE
    CALL updateDmg(Tstrain,dstrain,
     +          TmaxStrainDmnd, TminStrainDmnd,
     +          envlpPosStrain, envlpNegStrain,
     +          envlpPosDamgdStress,envlpNegDamgdStress,
     +          CnCycle,Tenergy,energyCapacity,
     +          I_DmgCyc, elasticStrainEnergy,
     +          P_kElasticPos,P_kElasticNeg,
     +          TnCycle,TgammaK,TgammaD,TgammaF,
     +          PROPS)
C
C
    RETURN
    END
C
C
C    ****************************************
C           PINCHING4: getstate
C    ****************************************
    SUBROUTINE getstate(SU, SDU, CstrainRate, Cstrain, Cstress,
```

```
     +envlpPosStrain, envlpPosStress,
     +envlpNegStrain, envlpNegStress,
     +uMaxDamgd, uMinDamgd, CgammaF, CgammaK,
     +P_kElasticPos, P_kElasticNeg,
     +P_lowI_TstateStrain, P_lowI_TstateStress,
     +hghI_TstateStrain, hghI_TstateStress,
     +TmaxStrainDmnd, TminStrainDmnd,
     +gammaFUsed, gammaKUsed,
     +envlpNegDamgdStress, envlpPosDamgdStress,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, I_Tstate)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
      LOGICAL cid, cis
C
      INTEGER I_Cstate, I_Tstate
      INTEGER newState
      REAL Cstrain, Cstress, CstrainRate
      REAL P_lowI_TstateStrain, hghI_TstateStrain
      REAL P_lowI_TstateStress, hghI_TstateStress
      REAL TmaxStrainDmnd, TminStrainDmnd
      REAL uMaxDamgd, uMinDamgd
      REAL CgammaF, CgammaK
      REAL gammaFUsed, gammaKUsed
      REAL P_kElasticPos, P_kElasticNeg
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
C
      REAL SU, SDU
      REAL EXTSTRESS
C
C        INITIALIZE LOCAL VARIABLES
         cid = .false.                    ! CHANGE IN DIRECTION
      cis = .false.          ! CHANGE IN STATE
         newState = 0          ! NEW SPRING STATE DETERMINED
C
C     INITIALIZE VARIABLES FOR CALLING EXTERNAL SUBROUTINES
      EXTSTRESS = 0.0
C
         IF (SDU * CstrainRate .LE. 0.0) THEN
```

```
                cid = .true.
        END IF
C
     IF (SU .LT. P_lowI_TstateStrain .OR. SU .GT. hghI_TstateStrain
    +.OR. cid) THEN
        IF (I_Tstate .EQ. 0) THEN
           IF (SU .GT. hghI_TstateStrain) THEN
              cis = .true.
              newstate = 1
              P_lowI_TstateStrain = envlpPosStrain(1)
              P_lowI_TstateStress = envlpPosStress(1)
              hghI_TstateStrain = envlpPosStrain(6)
              hghI_TstateStress = envlpPosStress(6)
           ELSE IF (SU .LT. P_lowI_TstateStrain) THEN
              cis = .true.
              newstate = 2
              P_lowI_TstateStrain = envlpNegStrain(6)
              P_lowI_TstateStress = envlpNegStress(6)
              hghI_TstateStrain = envlpNegStrain(1)
              hghI_TstateStress = envlpNegStress(1)
           END IF
        ELSE IF (I_Tstate .EQ. 1 .AND. SDU .LT. 0.0) THEN
           cis = .true.
           IF (Cstrain .GT. TmaxStrainDmnd) THEN
              TmaxStrainDmnd = SU - SDU
           END IF
           IF (TmaxStrainDmnd .LT. uMaxDamgd) THEN
              TmaxStrainDmnd = uMaxDamgd
           END IF
           IF (SU .LT. uMinDamgd) THEN
              newState = 2
              gammaFUsed = CgammaF
              DO I = 1, 6
                 envlpNegDamgdStress(I) = envlpNegStress(I) *
    +                (1.0 - gammaFUsed)
              END DO
              P_lowI_TstateStrain = envlpNegStrain(6)
              P_lowI_TstateStress = envlpNegStress(6)
              hghI_TstateStrain = envlpNegStrain(1)
              hghI_TstateStress = envlpNegStress(1)
           ELSE
              newstate = 3
              gammaFUsed = CgammaF
              DO I = 1, 6
                 envlpNegDamgdStress(I) = envlpNegStress(I) *
    +                (1.0 - gammaFUsed)
              END DO
              P_lowI_TstateStrain = uMinDamgd
              CALL negEnvlpStress(uMinDamgd, envlpNegDamgdStress,
```

```
+                         envlpNegStrain, EXTSTRESS)
          P_lowI_TstateStress = EXTSTRESS
          hghI_TstateStrain = Cstrain
          hghI_TstateStress = Cstress
          gammaKUsed = CgammaK
          P_kElasticPosDamgd = P_kElasticPos * (1.0-gammaKUsed)
       END IF
    ELSE IF (I_Tstate .EQ. 2 .AND. SDU .GT. 0.0) THEN
       cis = .true.
       IF (Cstrain .LT. TminStrainDmnd) THEN
          TminStrainDmnd = Cstrain
       END IF
       IF (TminStrainDmnd .GT. uMinDamgd) THEN
          TminStrainDmnd = uMinDamgd
       END IF
       IF (SU .GT. uMaxDamgd) THEN
          newState = 1
          gammaFUsed = CgammaF
          DO I = 1, 6
             envlpPosDamgdStress(I) = envlpPosStress(I) *
+                (1.0 - gammaFUsed)
          END DO
          P_lowI_TstateStrain = envlpPosStrain(1)
          P_lowI_TstateStress = envlpPosStress(1)
          hghI_TstateStrain = envlpPosStrain(6)
          hghI_TstateStress = envlpPosStress(6)
       ELSE
          newState = 4
          gammaFUsed = CgammaF
          DO I = 1, 6
             envlpPosDamgdStress(I) = envlpPosStress(I) *
+                (1.0 - gammaFUsed)
          END DO
          P_lowI_TstateStrain = Cstrain
          P_lowI_TstateStress = Cstress
          hghI_TstateStrain = uMaxDamgd
          CALL posEnvlpStress(uMaxDamgd, envlpPosDamgdStress,
+                         envlpPosStrain, EXTSTRESS)
          hghI_TstateStress = EXTSTRESS
          gammaKUsed = CgammaK;
          P_kElasticNegDamgd = P_kElasticNeg * (1.0- gammaKUsed)
       END IF
    ELSE IF (I_Tstate .EQ. 3) THEN
       IF (SU .LT. P_lowI_TstateStrain) THEN
          cis = .true.
          newState = 2
          P_lowI_TstateStrain = envlpNegStrain(6)
          P_lowI_TstateStress = envlpNegDamgdStress(6)
          hghI_TstateStrain = envlpNegStrain(1)
```

```
          hghI_TstateStress = envlpNegDamgdStress(1)
       ELSE IF (SU .GT. uMaxDamgd .AND. SDU .GT. 0.0) THEN
          cis = .true.
          newState = 1
          P_lowI_TstateStrain = envlpPosStrain(1)
          P_lowI_TstateStress = envlpPosStress(1)
          hghI_TstateStrain = envlpPosStrain(6)
          hghI_TstateStress = envlpPosStress(6)
       ELSE IF (SDU .GT. 0.0) THEN
          cis = .true.
          newState = 4
          gammaFUsed = CgammaF
          P_lowI_TstateStrain = Cstrain
          P_lowI_TstateStress = Cstress
          hghI_TstateStrain = uMaxDamgd
          DO I = 1, 6
             envlpPosDamgdStress(I) = envlpPosStress(I) *
+                 (1.0 - gammaFUsed)
          END DO
          CALL posEnvlpStress(uMaxDamgd, envlpPosDamgdStress,
+envlpPosStrain, EXTSTRESS)
          hghI_TstateStress = EXTSTRESS
          gammaKUsed = CgammaK
          P_kElasticNegDamgd = P_kElasticNeg *(1.0 - gammaKUsed)
       END IF
    ELSE IF (I_Tstate .EQ. 4) THEN
       IF (SU .GT. hghI_TstateStrain) THEN
          cis = .true.
          newState = 1
          P_lowI_TstateStrain = envlpPosStrain(1)
          P_lowI_TstateStress = envlpPosDamgdStress(1)
          hghI_TstateStrain = envlpPosStrain(6)
          hghI_TstateStress = envlpPosDamgdStress(6)
       ELSE IF (SU .LT. uMinDamgd .AND. SDU .LT. 0.0) THEN
          cis = .true.
          newState = 2
          P_lowI_TstateStrain = envlpNegStrain(6)
          P_lowI_TstateStress = envlpNegDamgdStress(6)
          hghI_TstateStrain = envlpNegStrain(1)
          hghI_TstateStress = envlpNegDamgdStress(1)
       ELSE IF (SDU .LT. 0.0) THEN
          cis = .true.
          newState = 3
          gammaFUsed = CgammaF
          DO I = 1, 6
             envlpNegDamgdStress(I) = envlpNegStress(I) *
+                 (1.0 - gammaFUsed)
          END DO
          P_lowI_TstateStrain = uMinDamgd
```

```
            CALL negEnvlpStress(uMinDamgd, envlpNegDamgdStress,
     +                          envlpNegStrain, EXTSTRESS)
            P_lowI_TstateStress = EXTSTRESS
            hghI_TstateStrain = Cstrain
            hghI_TstateStress = Cstress
            gammaKUsed = CgammaK
            P_kElasticPosDamgd = P_kElasticPos * (1.0-gammaKUsed)
          END IF
        END IF
      END IF
C
      IF (cis) THEN
        I_Tstate = newState
      END IF
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: posEnvlpStress
C     ****************************************
      SUBROUTINE posEnvlpStress(SU, envlpPosDamgdStress,
     +envlpPosStrain, EXTSTRESS)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpPosStrain(6), envlpPosDamgdStress(6)
C
      INTEGER I
      REAL SU
      REAL P_k, F
      REAL EXTSTRESS
C
C
      P_k = 0.0
      F = 0.0
      I = 1
      EXTSTRESS = 0.0
C
      DO WHILE (P_k .EQ. 0.0 .AND. I .LE. 5)
        IF (SU .LE. envlpPosStrain(I+1)) THEN
          P_k = (envlpPosDamgdStress(I+1)-envlpPosDamgdStress(I)) /
     +          (envlpPosStrain(I+1)-envlpPosStrain(I))
          F = envlpPosDamgdStress(I) + (SU-envlpPosStrain(I)) * P_k
        END IF
```

```
      I = I + 1
    END DO
C
    IF (P_k .EQ. 0.0) THEN
      P_k = (envlpPosDamgdStress(6) - envlpPosDamgdStress(5)) /
     +      (envlpPosStrain(6) - envlpPosStrain(5))
      F = envlpPosDamgdStress(6) + P_k * (SU - envlpPosStrain(6))
    END IF
C
    EXTSTRESS = F
C
C
    RETURN
    END
C
C
C    ***************************************
C          PINCHING4: posEnvlpTangent
C    ***************************************
    SUBROUTINE posEnvlpTangent(SU,envlpPosDamgdStress,envlpPosStrain,
     +                         P_k)
C
C
    include 'vaba_param.inc'
C
    PARAMETER (TOL = 1.E-32)
C
    DIMENSION envlpPosDamgdStress(6), envlpPosStrain(6)
C
    INTEGER I
    REAL SU
    REAL P_k
C
    P_k = 0.0
    I = 1
    DO WHILE (P_k .EQ. 0.0 .AND. I .LT. 5)
      IF (SU .LE. envlpPosStrain(I+1)) THEN
        P_k = (envlpPosDamgdStress(I+1)-envlpPosDamgdStress(I))/
     +          (envlpPosStrain(I+1)-envlpPosStrain(I))
      END IF
      I = I + 1
    END DO
C
    IF (P_k .EQ. 0.0) THEN
      P_k = (envlpPosDamgdStress(6) - envlpPosDamgdStress(5))/
     +    (envlpPosStrain(6) - envlpPosStrain(5))
    END IF
C
C
```

```
      RETURN
      END
C
C
C     ***************************************
C           PINCHING4: negEnvlpStress
C     ***************************************
      SUBROUTINE negEnvlpStress(SU, envlpNegDamgdStress, envlpNegStrain,
     +                          EXTSTRESS)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpNegStrain(6), envlpNegDamgdStress(6)
C
      INTEGER I
      REAL SU
      REAL P_k, F
      REAL EXTSTRESS
C
      P_k = 0.0
      F = 0.0
      I = 1
      EXTSTRESS = 0.0
C
C
      DO WHILE (P_k .EQ. 0.0 .AND. I .LE. 5)
         IF (SU .GE. envlpNegStrain(I+1)) THEN
            P_k = (envlpNegDamgdStress(I) - envlpNegDamgdStress(I+1))/
     +          (envlpNegStrain(I) - envlpNegStrain(I+1))
            F = envlpNegDamgdStress(I+1) +
     +          (SU - envlpNegStrain(I+1)) * P_k
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. 0.0) THEN
         P_k = (envlpNegDamgdStress(5) - envlpNegDamgdStress(6)) /
     +       (envlpNegStrain(5) - envlpNegStrain(6))
         F = envlpNegDamgdStress(6) + P_k * (SU - envlpNegStrain(6))
      END IF
C
      EXTSTRESS = F
C
C
      RETURN
      END
```

```
C
C
C     ****************************************
C           PINCHING4: negEnvlpTangent
C     ****************************************
      SUBROUTINE  negEnvlpTangent(SU,envlpNegDamgdStress,envlpNegStrain,
     +                            P_k)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpNegDamgdStress(6), envlpNegStrain(6)
C
      INTEGER I
      REAL SU
      REAL P_k
C
      P_k = 0.0
      I = 1
      DO WHILE (P_k .EQ. 0.0 .AND. I .LT. 5)
         IF (SU .GE. envlpNegStrain(i+1)) THEN
            P_k = (envlpNegDamgdStress(i)-envlpNegDamgdStress(i+1))/
     +          (envlpNegStrain(i)-envlpNegStrain(i+1))
         END IF
         I = I + 1
      END DO
C
      IF (P_k .EQ. 0.0) THEN
         P_k = (envlpNegDamgdStress(5) - envlpNegDamgdStress(6))/
     +       (envlpNegStrain(5)-envlpNegStrain(6))
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: getstate3
C     ****************************************
      SUBROUTINE getstate3(state3Strain, state3Stress, P_kunload,
     +    P_kElasticNegDamgd, P_lowI_TstateStrain, P_lowI_TstateStress,
     +    hghI_TstateStrain, hghI_TstateStress, TminStrainDmnd,
     +    envlpNegStrain, envlpNegDamgdStress, PROPS)
C
C
      include 'vaba_param.inc'
```

```
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41),
     +          envlpPosStrain(6), envlpPosStress(6),
     +          envlpNegStrain(6), envlpNegStress(6),
     +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4)
C
C
      LOGICAL cid, cis
C
      INTEGER I
      REAL P_kunload
      REAL P_kElasticNegDamgd
      REAL P_lowI_TstateStrain, P_lowI_TstateStress
      REAL hghI_TstateStrain, hghI_TstateStress
      REAL TminStrainDmnd
      REAL rDispN, rForceN, uForceN
C
      REAL P_kmax
      REAL st1, st2
      REAL STDU, STDF, STDFR
      REAL avgforce
      REAL slope12, slope34, checkSlope, slope
C
C
C     PARAMETERS TAKEN FROM PROPS
      rDispN = PROPS(20)
      rForceN = PROPS(21)
      uForceN = PROPS(22)
C
      P_kmax = MAX(P_kunload, P_kElasticNegDamgd)
C
      IF (state3Strain(1) * state3Strain(4) .LT. 0.0) THEN
         state3Strain(2) = P_lowI_TstateStrain * rDispN
         IF ((rForceN - uForceN) .GT. 1E-8) THEN
            state3Stress(2) = P_lowI_TstateStress * rForceN
         ELSE
            IF (TminStrainDmnd .LT. envlpNegStrain(4)) THEN
               st1 = P_lowI_TstateStress * uForceN * (1.0+TOL)
               st2 = envlpNegDamgdStress(5) * (1.0+TOL)
               state3Stress(2) = MIN(st1, st2)
            ELSE
               st1 = envlpNegDamgdStress(4) * uForceN * (1.0+TOL)
               st2 = envlpNegDamgdStress(5) * (1.0+TOL)
               state3Stress(2) = MIN(st1, st2)
            END IF
```

```
      END IF
      IF ((state3Stress(2) - state3Stress(1)) / (state3Strain(2) -
     +     state3Strain(1)) .GT. P_kElasticNegDamgd) THEN
         state3Strain(2) = P_lowI_TstateStrain +
     +     (state3Stress(2)-state3Stress(1))/P_kElasticNegDamgd
      END IF
      IF (state3Strain(2) .GT. state3Strain(4)) THEN
         STDU = state3Strain(4) - state3Strain(1)
         STDF = state3Stress(4) - state3Stress(1)
         state3Strain(2) = state3Strain(1) + 0.33D0*STDU
         state3Strain(3) = state3Strain(1) + 0.67D0*STDU
         state3Stress(2) = state3Stress(1) + 0.33D0*STDF
         state3Stress(3) = state3Stress(1) + 0.67D0*STDF
      ELSE
C          PATH:
         IF (TminStrainDmnd .LT. envlpNegStrain(4)) THEN
            state3Stress(3) = uForceN * envlpNegDamgdStress(5)
         ELSE
            state3Stress(3) = uForceN * envlpNegDamgdStress(4)
C             PATH:
         END IF
         state3Strain(3) = hghI_TstateStrain -
     +     (hghI_TstateStress-state3Stress(3))/P_kunload
         IF (state3Strain(3) .GT. state3Strain(4)) THEN
            STDU = state3Strain(4) - state3Strain(2)
            STDF = state3Stress(4) - state3Stress(2)
            state3Strain(3) = state3Strain(2) + 0.5*STDU
            state3Stress(3) = state3Stress(2) + 0.5*STDF
         ELSE IF ((state3Stress(3) - state3Stress(2))/
     +         (state3Strain(3) -state3Strain(2)) .GT. P_kmax) THEN
C                PATH:
               STDU = state3Strain(4) - state3Strain(1)
               STDF = state3Stress(4) - state3Stress(1)
               state3Strain(2) = state3Strain(1) + 0.33D0*STDU
               state3Strain(3) = state3Strain(1) + 0.67D0*STDU
               state3Stress(2) = state3Stress(1) + 0.33D0*STDF
               state3Stress(3) = state3Stress(1) + 0.67D0*STDF
         ELSE IF ((state3Strain(3) .LT. state3Strain(2)) .OR.
     +         ((state3Stress(3)-state3Stress(2))/
     +         (state3Strain(3)-state3Strain(2)) .LT. 0)) THEN
                  IF (state3Strain(3) .LT. 0.0) THEN
                     STDU = state3Strain(4)-state3Strain(2)
                     STDF = state3Stress(4)-state3Stress(2)
                     state3Strain(3)=state3Strain(2)+0.5*STDU
                     state3Stress(3)= state3Stress(2)+0.5*STDF
                  ELSE IF (state3Strain(2) .GT. 0.0) THEN
                     STDU = state3Strain(3)-state3Strain(1)
                     STDF = state3Stress(3)-state3Stress(1)
                     state3Strain(2)=state3Strain(1)+0.5*STDU
```

```
                    state3Stress(2)=state3Stress(1)+0.5*STDF
                 ELSE
                    avgforce = 0.5*(state3Stress(3) +
     +               state3Stress(2))
                    STDFR = 0.0
                    IF (avgforce .LT. 0.0) THEN
                       STDFR = -avgforce/100.0D0
                    ELSE
                       STDFR = avgforce/100.0D0
                    END IF
                    slope12 = (state3Stress(2) -
     +          state3Stress(1))/(state3Strain(2) - state3Strain(1))
                    slope34 = (state3Stress(4) -
     +          state3Stress(3))/(state3Strain(4) - state3Strain(3))
                    state3Stress(2) = avgforce - STDFR
                    state3Stress(3) = avgforce + STDFR
                    state3Strain(2) = state3Strain(1) +
     +          (state3Stress(2) - state3Stress(1))/slope12
                    state3Strain(3) = state3Strain(4) -
     +          (state3Stress(4) - state3Stress(3))/slope34
                 END IF
          END IF
       END IF
    ELSE
       STDU = state3Strain(4)-state3Strain(1)
       STDF = state3Stress(4)-state3Stress(1)
       state3Strain(2) = state3Strain(1) + 0.33D0*STDU;
       state3Strain(3) = state3Strain(1) + 0.67D0*STDU;
            state3Stress(2) = state3Stress(1) + 0.33D0*STDF;
            state3Stress(3) = state3Stress(1) + 0.67D0*STDF;
    END IF
C
    checkSlope = state3Stress(1)/state3Strain(1)
    slope = 0.0
C
C    FINAL CHECK
    I = 1
    DO WHILE (I .LT. 4)
       STDU = state3Strain(i+1)-state3Strain(i)
       STDF = state3Stress(i+1)-state3Stress(i)
       IF (STDU .LT. 0.0 .OR. STDF .LT. 0.0) THEN
          STDU = state3Strain(4)-state3Strain(1)
          STDF = state3Stress(4)-state3Stress(1)
                  state3Strain(2) = state3Strain(1) + 0.33D0*STDU
                  state3Strain(3) = state3Strain(1) + 0.67D0*STDU
                  state3Stress(2) = state3Stress(1) + 0.33D0*STDF
                  state3Stress(3) = state3Stress(1) + 0.67D0*STDF
          slope = STDF / STDU
          I = 4
```

```
      END IF
      IF (slope .GT. 1.0E-8 .AND. slope .LT. checkSlope) THEN
         state3Strain(2) = 0.0;
         state3Stress(2) = 0.0;
                  state3Strain(3) = state3Strain(4)*0.5
         state3Stress(3) = state3Stress(4)*0.5
      END IF
      I = I + 1
   END DO
C
C
   RETURN
   END
C
C
C    ***************************************
C          PINCHING4: getstate4
C    ***************************************
   SUBROUTINE getstate4(state4Strain, state4Stress, P_kunload,
  +   P_kElasticPosDamgd, P_lowI_TstateStrain,P_lowI_TstateStress,
  +   hghI_TstateStrain, hghI_TstateStress, TmaxStrainDmnd,
  +   envlpPosStrain, envlpPosDamgdStress, PROPS)
C
C
   include 'vaba_param.inc'
C
   PARAMETER (TOL = 1.E-32)
C
   DIMENSION PROPS(41),
  +         envlpPosStrain(6), envlpPosStress(6),
  +         envlpNegStrain(6), envlpNegStress(6),
  +         envlpPosDamgdStress(6), envlpNegDamgdStress(6),
  +         state4Strain(4), state4Stress(4)
C
C
   LOGICAL cid, cis
C
   INTEGER I
   REAL P_kunload
   REAL P_kElasticPosDamgd
   REAL P_lowI_TstateStrain,P_lowI_TstateStress
   REAL hghI_TstateStrain, hghI_TstateStress
   REAL TmaxStrainDmnd
   REAL rDispP, rForceP, uForceP
C
   REAL P_kmax
   REAL st1, st2
   REAL STDU, STDF, STDFR
   REAL avgforce
```

```
      REAL slope12, slope34, checkSlope, slope

C
C
C
C     PARAMETERS TAKEN FROM PROPS
      rDispP = PROPS(17)
      rForceP = PROPS(18)
      uForceP = PROPS(19)
C
      P_kmax = MAX(P_kunload, P_kElasticPosDamgd)
C
      IF (state4Strain(1) * state4Strain(4) .LT. 0.0) THEN
         state4Strain(3) = hghI_TstateStrain * rDispP
         IF (uForceP .EQ. 0.0) THEN
            state4Stress(3) = hghI_TstateStress * rForceP
         ELSE IF (rForceP-uForceP .GT. 1.0E-8) THEN
            state4Stress(3) = hghI_TstateStress * rForceP
         ELSE
            IF (TmaxStrainDmnd .GT. envlpPosStrain(4)) THEN
               st1 = hghI_TstateStress * uForceP * (1.0+TOL)
               st2 = envlpNegDamgdStress(5) * (1.0+TOL)
               state4Stress(3) = MAX(st1, st2)
            ELSE
               st1 = envlpPosDamgdStress(4)*uForceP*(1.0+TOL)
               st2 = envlpPosDamgdStress(5)*(1.0+TOL)
               state4Stress(3) = MIN(st1, st2)
            END IF
         END IF
         IF ((state4Stress(4) - state4Stress(3)) / (state4Strain(4) -
     +       state4Strain(3)) .GT. P_kElasticPosDamgd) THEN
            state4Strain(3) = hghI_TstateStrain -
     +       (state4Stress(4)-state4Stress(3))/P_kElasticPosDamgd
         END IF
         IF (state4Strain(3) .LT. state4Strain(1)) THEN
            STDU = state4Strain(4) - state4Strain(1)
            STDF = state4Stress(4) - state4Stress(1)
            state4Strain(2) = state4Strain(1) + 0.33D0*STDU
            state4Strain(3) = state4Strain(1) + 0.67D0*STDU
            state4Stress(2) = state4Stress(1) + 0.33D0*STDF
            state4Stress(3) = state4Stress(1) + 0.67D0*STDF
         ELSE
C           PATH:
            IF (TmaxStrainDmnd .GT. envlpPosStrain(4)) THEN
               state4Stress(2) = uForceP * envlpPosDamgdStress(5)
            ELSE
               state4Stress(2) = uForceP * envlpPosDamgdStress(4)
C              PATH:
            END IF
```

```
      state4Strain(2) = P_lowI_TstateStrain +
     +  (-P_lowI_TstateStress + state4Stress(2))/P_kunload
      IF (state4Strain(2) .LT. state4Strain(1)) THEN
         STDU = state4Strain(3) - state4Strain(1)
         STDF = state4Stress(3) - state4Stress(1)
         state4Strain(2) = state4Strain(1) + 0.5*STDU
         state4Stress(2) = state4Stress(1) + 0.5*STDF
      ELSE IF ((state4Stress(3) - state4Stress(2))/
     +    (state4Strain(3) -state4Strain(2)) .GT. P_kmax) THEN
C           PATH:
            STDU = state4Strain(4) - state4Strain(1)
            STDF = state4Stress(4) - state4Stress(1)
            state4Strain(2) = state4Strain(1) + 0.33D0*STDU
            state4Strain(3) = state4Strain(1) + 0.67D0*STDU
            state4Stress(2) = state4Stress(1) + 0.33D0*STDF
            state4Stress(3) = state4Stress(1) + 0.67D0*STDF
      ELSE IF ((state4Strain(3) .LT. state4Strain(2)) .OR.
     +    ((state4Stress(3)-state4Stress(2))/
     +    (state4Strain(3)-state4Strain(2)) .LT. 0.0)) THEN
            IF (state4Strain(2) .GT. 0.0) THEN
               STDU = state4Strain(3)-state4Strain(1)
               STDF = state4Stress(3)-state4Stress(1)
               state4Strain(2)=state4Strain(1)+0.5*STDU
               state4Stress(2)=state4Stress(1)+0.5*STDF
            ELSE IF (state4Strain(3) .LT. 0.0) THEN
               STDU = state4Strain(4)-state4Strain(2)
               STDF = state4Stress(4)-state4Stress(2)
               state4Strain(3)=state4Strain(2)+0.5*STDU
               state4Stress(3)=state4Stress(2)+0.5*STDF
            ELSE
               avgforce = 0.5*(state4Stress(3) +
     +          state4Stress(2))
               STDFR = 0.0
               IF (avgforce .LT. 0.0) THEN
                  STDFR = -avgforce/100.0D0
               ELSE
                  STDFR = avgforce/100.0D0
               END IF
               slope12 = (state4Stress(2) -
     +    state4Stress(1))/(state4Strain(2) - state4Strain(1))
               slope34 = (state4Stress(4) -
     +    state4Stress(3))/(state4Strain(4) - state4Strain(3))
               state4Stress(2) = avgforce - STDFR
               state4Stress(3) = avgforce + STDFR
               state4Strain(2) = state4Strain(1) +
     +    (state4Stress(2) - state4Stress(1))/slope12
               state4Strain(3) = state4Strain(4) -
     +    (state4Stress(4) - state4Stress(3))/slope34
            END IF
```

```
            END IF
         END IF
      ELSE
         STDU = state4Strain(4)-state4Strain(1)
         STDF = state4Stress(4)-state4Stress(1)
         state4Strain(2) = state4Strain(1) + 0.33D0*STDU;
         state4Strain(3) = state4Strain(1) + 0.67D0*STDU;
              state4Stress(2) = state4Stress(1) + 0.33D0*STDF;
              state4Stress(3) = state4Stress(1) + 0.67D0*STDF;
      END IF
C
      checkSlope = state4Stress(1)/state4Strain(1)
      slope = 0.0
C
C     FINAL CHECK
      I = 1
      DO WHILE (I .LT. 4)
         STDU = state4Strain(I+1)-state4Strain(I)
         STDF = state4Stress(I+1)-state4Stress(I)
         IF (STDU .LT. 0.0 .OR. STDF .LT. 0.0) THEN
            STDU = state4Strain(4)-state4Strain(1)
            STDF = state4Stress(4)-state4Stress(1)
                     state4Strain(2) = state4Strain(1) + 0.33D0*STDU
                     state4Strain(3) = state4Strain(1) + 0.67D0*STDU
                     state4Stress(2) = state4Stress(1) + 0.33D0*STDF
                     state4Stress(3) = state4Stress(1) + 0.67D0*STDF
            slope = STDF / STDU
            I = 4
         END IF
         IF (slope .GT. 1.0E-8 .AND. slope .LT. checkSlope) THEN
            state4Strain(2) = 0.0;
            state4Stress(2) = 0.0;
                     state4Strain(3) = state4Strain(4)*0.5
            state4Stress(3) = state4Stress(4)*0.5
         END IF
         I = I + 1
      END DO
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: Envlp3Stress
C     ****************************************
      SUBROUTINE Envlp3Stress(s3Strain,s3Stress,SU, f)
C
C
```

```
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION s3Strain(4), s3Stress(4)
C
      INTEGER I
      REAL SU
      REAL P_k, f
C
      P_k = 0.0
      I = 1
      f = 0.0
      DO WHILE ((P_k .EQ. 0.0 .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s3Strain(i)) THEN
            P_k = (s3Stress(i+1)-s3Stress(i))/
     +          (s3Strain(i+1)-s3Strain(i))
            f =  s3Stress(i)+(SU-s3Strain(i))*P_k
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. 0.0) THEN
         IF (SU .LT. s3Strain(1)) THEN
            I = 1
         ELSE
            I = 3
         END IF
             P_k = (s3Stress(i+1)-s3Stress(i))/(s3Strain(i+1)-s3Strain(i))
             f = s3Stress(i)+(SU-s3Strain(i))*P_k
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: Envlp3Tangent
C     ****************************************
      SUBROUTINE Envlp3Tangent(s3Strain,s3Stress,SU, P_k)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION s3Strain(4), s3Stress(4)
C
      INTEGER I
```

```
      REAL SU
      REAL P_k
C
      P_k = 0.0
      I = 1
      DO WHILE ((P_k .EQ. 0.0 .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s3Strain(i)) THEN
            P_k = (s3Stress(i+1)-s3Stress(i))/
     +          (s3Strain(i+1)-s3Strain(i))
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. 0.0) THEN
         IF (SU .LT. s3Strain(1)) THEN
            I = 1
         ELSE
            I = 3
         END IF
         P_k = (s3Stress(i+1)-s3Stress(i))/(s3Strain(i+1)-s3Strain(i))
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C           PINCHING4: Envlp4Stress
C     ****************************************
      SUBROUTINE Envlp4Stress(s4Strain,s4Stress,SU, f)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION s4Strain(4), s4Stress(4)
C
      INTEGER I
      REAL SU
      REAL P_k, f
C
      P_k = 0.0
      I = 1
      f = 0.0
      DO WHILE ((P_k .EQ. 0.0 .OR. i .LE. 3) .AND. i .LE. 3)
         IF (SU .GE. s4Strain(i)) THEN
            P_k = (s4Stress(i+1)-s4Stress(i))/
     +          (s4Strain(i+1)-s4Strain(i))
```

```
            f =  s4Stress(i)+(SU-s4Strain(i))*P_k
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. 0.0) THEN
         IF (SU .LT. s4Strain(1)) THEN
            I = 1
         ELSE
            I = 3
         END IF
             P_k = (s4Stress(i+1)-s4Stress(i))/(s4Strain(i+1)-s4Strain(i))
             f = s4Stress(i)+(SU-s4Strain(i))*P_k
      END IF
C
C
      RETURN
      END
C
C
C     ****************************************
C            PINCHING4: Envlp4Tangent
C     ****************************************
      SUBROUTINE Envlp4Tangent(s4Strain,s4Stress, SU, P_k)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION s4Strain(4), s4Stress(4)
C
      INTEGER I
      REAL SU
      REAL P_k
C
      P_k = 0.0
      I = 1
      DO WHILE ((P_k .EQ. 0.0 .OR. i .LE. 3) .AND. (i .LE. 3))
         IF (SU .GE. s4Strain(i)) THEN
            P_k = (s4Stress(i+1)-s4Stress(i))/
     +          (s4Strain(i+1)-s4Strain(i))
         END IF
         I = I + 1
      END DO
      IF (P_k .EQ. 0.0) THEN
         IF (SU .LT. s4Strain(1)) THEN
            I = 1
         ELSE
            I = 3
```

```
      END IF
      P_k = (s4Stress(i+1)-s4Stress(i))/(s4Strain(i+1)-s4Strain(i))
    END IF
C
C
    RETURN
    END
C
C
C    ****************************************
C            PINCHING4: updateDmg
C    ****************************************
    SUBROUTINE updateDmg(strain, dstrain,
   +          TmaxStrainDmnd, TminStrainDmnd,
   +          envlpPosStrain, envlpNegStrain,
   +          envlpPosDamgdStress,envlpNegDamgdStress,
   +          CnCycle,Tenergy,energyCapacity,
   +          I_DmgCyc, elasticStrainEnergy,
   +          P_kElasticPos,P_kElasticNeg,
   +          TnCycle,TgammaK,TgammaD,TgammaF,
   +          PROPS)
C
C
    include 'vaba_param.inc'
C
    PARAMETER (TOL = 1.E-32)
C
    DIMENSION PROPS(41),
   +          envlpPosStrain(6), envlpPosStress(6),
   +          envlpNegStrain(6), envlpNegStress(6),
   +          envlpPosDamgdStress(6), envlpNegDamgdStress(6),
   +          state3Strain(4), state3Stress(4),
   +          state4Strain(4), state4Stress(4)
C
    INTEGER I_DmgCyc
    REAL strain, dstrain
    REAL TmaxStrainDmnd, TminStrainDmnd
    REAL P_kElasticPos,P_kElasticNeg
    REAL CnCycle, TnCycle
    REAL Tenergy, energyCapacity, elasticStrainEnergy
    REAL TgammaK,TgammaD,TgammaF
C
    REAL gammaK1, gammaK2, gammaK3, gammaK4, gammaKLimit
    REAL gammaD1, gammaD2, gammaD3, gammaD4, gammaDLimit
    REAL gammaF1, gammaF2, gammaF3, gammaF4, gammaFLimit
C
    REAL tes
    REAL umaxAbs, uultAbs
    REAL gammaKLimEnv
```

```
C
      REAL EXTSTRESS
      REAL P_kminP, P_kminN, P_kmin
      REAL P_k1

C
C     UNZIP PARAMETERS FROM PROPS()
      gammaK1 = PROPS(23)
      gammaK2 = PROPS(24)
      gammaK3 = PROPS(25)
      gammaK4 = PROPS(26)
      gammaKLimit = PROPS(27)
      gammaD1 = PROPS(28)
      gammaD2 = PROPS(29)
      gammaD3 = PROPS(30)
      gammaD4 = PROPS(31)
      gammaDLimit = PROPS(32)
      gammaF1 = PROPS(33)
      gammaF2 = PROPS(34)
      gammaF3 = PROPS(35)
      gammaF4 = PROPS(36)
      gammaFLimit = PROPS(37)
      I_DmgCyc = INT(PROPS(39))
C
      tes = 0.0
      umaxAbs = MAX(TmaxStrainDmnd, -TminStrainDmnd)
      uultAbs = MAX(envlpPosStrain(5), -envlpNegStrain(5))
      TnCycle = CnCycle + ABS(dstrain)/(4.0D0*umaxAbs)
C
      IF ((strain .LT. uultAbs .AND. strain .GT. -uultAbs) .AND.
     + Tenergy .LT. energyCapacity) THEN
         TgammaK = gammaK1 * ((umaxAbs/uultAbs) ** gammaK3)
         TgammaD = gammaD1 * ((umaxAbs/uultAbs) ** gammaD3)
         TgammaF = gammaF1 * ((umaxAbs/uultAbs) ** gammaF3)
C
         IF (Tenergy .GT. elasticStrainEnergy
     + .AND. I_DmgCyc .EQ. 0) THEN
            tes = (Tenergy-elasticStrainEnergy)/energyCapacity
            TgammaK = TgammaK + gammaK2 * (tes ** gammaK4)
            TgammaD = TgammaD + gammaD2 * (tes ** gammaD4)
            TgammaF = TgammaF + gammaF2 * (tes ** gammaF4)
         ELSE IF (I_DmgCyc .EQ. 1) THEN
            TgammaK = TgammaK + gammaK2 * (TnCycle ** gammaK4)
            TgammaD = TgammaD + gammaD2 * (TnCycle ** gammaD4)
            TgammaF = TgammaF + gammaF2 * (TnCycle ** gammaF4)
         END IF
C
         CALL posEnvlpStress(TmaxStrainDmnd, envlpPosDamgdStress,
     +       envlpPosStrain, EXTSTRESS)
```

```
      P_kminP = EXTSTRESS/TmaxStrainDmnd
      CALL negEnvlpStress(TminStrainDmnd, envlpNegDamgdStress,
     +     envlpNegStrain, EXTSTRESS)
      P_kminN = EXTSTRESS/TminStrainDmnd
      P_kmin = MAX(P_kminP/P_kElasticPos, P_kminN/P_kElasticNeg)
      gammaKLimEnv = MAX(0.0, (1.0-P_kmin))
C
      P_k1 = MIN(TgammaK, gammaKLimit)
      TgammaK = MIN(P_k1, gammaKLimEnv)
      TgammaD = MIN(TgammaD, gammaDLimit)
      TgammaF = MIN(TgammaF, gammaFLimit)
    ELSE IF (strain .LT. uultAbs .AND. strain .GT.-uultAbs) THEN
      CALL posEnvlpStress(TmaxStrainDmnd, envlpPosDamgdStress,
     +     envlpPosStrain, EXTSTRESS)
      P_kminP = EXTSTRESS/TmaxStrainDmnd
      CALL negEnvlpStress(TminStrainDmnd, envlpNegDamgdStress,
     +     envlpNegStrain, EXTSTRESS)
      P_kminN = EXTSTRESS/TminStrainDmnd
      P_kmin = MAX(P_kminP/P_kElasticPos, P_kminN/P_kElasticNeg)
      gammaKLimEnv = MAX(0.0, (1.0-P_kmin))
C
      TgammaK = MIN(gammaKLimit, gammaKLimEnv)
      TgammaD = MIN(TgammaD, gammaDLimit)
      TgammaF = MIN(TgammaF, gammaFLimit)
C
    END IF
C
C
    RETURN
    END
C
C
C    ****************************************
C          PINCHING4: commitState
C    ****************************************
    SUBROUTINE commitState(I_Tstate,dstrain,TstrainRate,
     +          P_lowI_TstateStrain,P_lowI_TstateStress,
     +          hghI_TstateStrain,hghI_TstateStress,
     +          TminStrainDmnd,TmaxStrainDmnd,
     +          Tenergy,Tstress,Tstrain,
     +          TgammaK,TgammaD,TgammaF,
     +          P_kElasticPos,P_kElasticNeg,
     +          gammaKUsed,gammaFUsed,
     +          envlpPosStress,envlpNegStress,TnCycle,
     +          I_Cstate,CstrainRate,
     +          P_lowI_CstateStrain,P_lowI_CstateStress,
     +          hghI_CstateStrain,hghI_CstateStress,
     +          CminStrainDmnd,CmaxStrainDmnd,
     +          Cenergy,Cstress,Cstrain,
```

```
     +            CgammaK,CgammaD,CgammaF,
     +            P_kElasticPosDamgd,P_kElasticNegDamgd,
     +            uMaxDamgd,uMinDamgd,
     +            envlpPosDamgdStress,envlpNegDamgdStress,CnCycle)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION PROPS(41),
     +        envlpPosStrain(6), envlpPosStress(6),
     +        envlpNegStrain(6), envlpNegStress(6),
     +        envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +        state3Strain(4), state3Stress(4),
     +        state4Strain(4), state4Stress(4)
C
C
      INTEGER I_Cstate, I_Tstate
      REAL dstrain
      REAL Cstrain, Cstress, CstrainRate
      REAL Tstrain, Tstress, TstrainRate
      REAL P_lowI_TstateStrain, P_lowI_TstateStress
      REAL hghI_TstateStrain, hghI_TstateStress
      REAL P_lowI_CstateStrain,P_lowI_CstateStress
      REAL hghI_CstateStrain,hghI_CstateStress
      REAL TminStrainDmnd,TmaxStrainDmnd
      REAL CminStrainDmnd,CmaxStrainDmnd
      REAL Cenergy, Tenergy
      REAL CnCycle, TnCycle
      REAL TgammaK,TgammaD,TgammaF
      REAL CgammaK,CgammaD,CgammaF
      REAL gammaKUsed,gammaFUsed
      REAL P_kElasticPos,P_kElasticNeg
      REAL P_kElasticPosDamgd,P_kElasticNegDamgd
      REAL uMaxDamgd,uMinDamgd
C
      I_Cstate = I_Tstate
C
      IF (dstrain .GT. 1.0E-12 .OR. dstrain<-(1.0E-12)) THEN
         CstrainRate = dstrain
      ELSE
         CstrainRate = TstrainRate
      END IF
C
      P_lowI_CstateStrain = P_lowI_TstateStrain
      P_lowI_CstateStress = P_lowI_TstateStress
      hghI_CstateStrain = hghI_TstateStrain
      hghI_CstateStress = hghI_TstateStress
```

```
      CminStrainDmnd = TminStrainDmnd
      CmaxStrainDmnd = TmaxStrainDmnd
      Cenergy = Tenergy
C
      Cstress = Tstress
      Cstrain = Tstrain
C
      CgammaK = TgammaK
      CgammaD = TgammaD
      CgammaF = TgammaF
C
      P_kElasticPosDamgd = P_kElasticPos*(1 - gammaKUsed)
      P_kElasticNegDamgd = P_kElasticNeg*(1 - gammaKUsed)
C
      uMaxDamgd = TmaxStrainDmnd*(1 + CgammaD)
      uMinDamgd = TminStrainDmnd*(1 + CgammaD)
C
      envlpPosDamgdStress = envlpPosStress*(1-gammaFUsed)
      envlpNegDamgdStress = envlpNegStress*(1-gammaFUsed)
C
      CnCycle = TnCycle
C
C
      RETURN
      END
C
C
C
C
C     ****************************************
C        PINCHING4 INTERFACE:SPIN2UEL
C     ****************************************
      SUBROUTINE SPIN2UEL(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy, strain, dstrain,
     +SPR_DISP, SPR_F, SPR_K, SVARS, I_SPR_NUM, kblock)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
```

```
     +          state4Strain(4), state4Stress(4),
     +          SVARS(kblock,200)
C
      REAL strain, dstrain
      REAL Cstrain, Cstress, CstrainRate
      REAL P_lowI_CstateStrain, P_lowI_CstateStress
      REAL hghI_CstateStrain, hghI_CstateStress
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL Cenergy
      REAL CgammaK, CgammaD, CgammaF
      REAL Ttangent
      REAL gammaKUsed, gammaFUsed
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
      REAL uMaxDamgd,uMinDamgd
      REAL P_kunload
      REAL CnCycle
      REAL elasticStrainEnergy
      REAL SPR_DISP, SPR_K, SPR_F
C
      INTEGER I_Cstate
C
      INTEGER I_SPR_NUM
C
C
      IF (I_SPR_NUM .EQ. 1) THEN
         SVARS(kblock,1) = envlpPosDamgdStress(1)
         SVARS(kblock,2) = envlpPosDamgdStress(2)
         SVARS(kblock,3) = envlpPosDamgdStress(3)
         SVARS(kblock,4) = envlpPosDamgdStress(4)
         SVARS(kblock,5) = envlpPosDamgdStress(5)
         SVARS(kblock,6) = envlpPosDamgdStress(6)
         SVARS(kblock,7) = envlpNegDamgdStress(1)
         SVARS(kblock,8) = envlpNegDamgdStress(2)
         SVARS(kblock,9) = envlpNegDamgdStress(3)
         SVARS(kblock,10) = envlpNegDamgdStress(4)
         SVARS(kblock,11) = envlpNegDamgdStress(5)
         SVARS(kblock,12) = envlpNegDamgdStress(6)
         SVARS(kblock,13) = state3Strain(1)
         SVARS(kblock,14) = state3Strain(2)
         SVARS(kblock,15) = state3Strain(3)
         SVARS(kblock,16) = state3Strain(4)
         SVARS(kblock,17) = state3Stress(1)
         SVARS(kblock,18) = state3Stress(2)
         SVARS(kblock,19) = state3Stress(3)
         SVARS(kblock,20) = state3Stress(4)
         SVARS(kblock,21) = state4Strain(1)
         SVARS(kblock,22) = state4Strain(2)
         SVARS(kblock,23) = state4Strain(3)
         SVARS(kblock,24) = state4Strain(4)
```

```
    SVARS(kblock,25) = state4Stress(1)
    SVARS(kblock,26) = state4Stress(2)
    SVARS(kblock,27) = state4Stress(3)
    SVARS(kblock,28) = state4Stress(4)
    SVARS(kblock,29) = DBLE(I_Cstate)
    SVARS(kblock,30) = Cstrain
    SVARS(kblock,31) = Cstress
    SVARS(kblock,32) = CstrainRate
    SVARS(kblock,33) = P_lowI_CstateStrain
    SVARS(kblock,34) = P_lowI_CstateStress
    SVARS(kblock,35) = hghI_CstateStrain
    SVARS(kblock,36) = hghI_CstateStress
    SVARS(kblock,37) = CminStrainDmnd
    SVARS(kblock,38) = CmaxStrainDmnd
    SVARS(kblock,39) = Cenergy
    SVARS(kblock,40) = CgammaK
    SVARS(kblock,41) = CgammaD
    SVARS(kblock,42) = CgammaF
    SVARS(kblock,43) = gammaKUsed
    SVARS(kblock,44) = gammaFUsed
    SVARS(kblock,45) = Ttangent
    SVARS(kblock,46) = P_kElasticPosDamgd
    SVARS(kblock,47) = P_kElasticNegDamgd
    SVARS(kblock,48) = uMaxDamgd
    SVARS(kblock,49) = uMinDamgd
    SVARS(kblock,50) = P_kunload
    SVARS(kblock,51) = CnCycle
    SVARS(kblock,52) = elasticStrainEnergy
    SVARS(kblock,53) = strain
    SVARS(kblock,54) = dstrain
    SVARS(kblock,55) = SPR_DISP
    SVARS(kblock,56) = SPR_F
    SVARS(kblock,57) = SPR_K
ELSE IF (I_SPR_NUM .EQ. 2) THEN
    SVARS(kblock,58) = envlpPosDamgdStress(1)
    SVARS(kblock,59) = envlpPosDamgdStress(2)
    SVARS(kblock,60) = envlpPosDamgdStress(3)
    SVARS(kblock,61) = envlpPosDamgdStress(4)
    SVARS(kblock,62) = envlpPosDamgdStress(5)
    SVARS(kblock,63) = envlpPosDamgdStress(6)
    SVARS(kblock,64) = envlpNegDamgdStress(1)
    SVARS(kblock,65) = envlpNegDamgdStress(2)
    SVARS(kblock,66) = envlpNegDamgdStress(3)
    SVARS(kblock,67) = envlpNegDamgdStress(4)
    SVARS(kblock,68) = envlpNegDamgdStress(5)
    SVARS(kblock,69) = envlpNegDamgdStress(6)
    SVARS(kblock,70) = state3Strain(1)
    SVARS(kblock,71) = state3Strain(2)
    SVARS(kblock,72) = state3Strain(3)
```

```
      SVARS(kblock,73) = state3Strain(4)
      SVARS(kblock,74) = state3Stress(1)
      SVARS(kblock,75) = state3Stress(2)
      SVARS(kblock,76) = state3Stress(3)
      SVARS(kblock,77) = state3Stress(4)
      SVARS(kblock,78) = state4Strain(1)
      SVARS(kblock,79) = state4Strain(2)
      SVARS(kblock,80) = state4Strain(3)
      SVARS(kblock,81) = state4Strain(4)
      SVARS(kblock,82) = state4Stress(1)
      SVARS(kblock,83) = state4Stress(2)
      SVARS(kblock,84) = state4Stress(3)
      SVARS(kblock,85) = state4Stress(4)
      SVARS(kblock,86) = DBLE(I_Cstate)
      SVARS(kblock,87) = Cstrain
      SVARS(kblock,88) = Cstress
      SVARS(kblock,89) = CstrainRate
      SVARS(kblock,90) = P_lowI_CstateStrain
      SVARS(kblock,91) = P_lowI_CstateStress
      SVARS(kblock,92) = hghI_CstateStrain
      SVARS(kblock,93) = hghI_CstateStress
      SVARS(kblock,94) = CminStrainDmnd
      SVARS(kblock,95) = CmaxStrainDmnd
      SVARS(kblock,96) = Cenergy
      SVARS(kblock,97) = CgammaK
      SVARS(kblock,98) = CgammaD
      SVARS(kblock,99) = CgammaF
      SVARS(kblock,100) = gammaKUsed
      SVARS(kblock,101) = gammaFUsed
      SVARS(kblock,102) = Ttangent
      SVARS(kblock,103) = P_kElasticPosDamgd
      SVARS(kblock,104) = P_kElasticNegDamgd
      SVARS(kblock,105) = uMaxDamgd
      SVARS(kblock,106) = uMinDamgd
      SVARS(kblock,107) = P_kunload
      SVARS(kblock,108) = CnCycle
      SVARS(kblock,109) = elasticStrainEnergy
      SVARS(kblock,110) = strain
      SVARS(kblock,111) = dstrain
      SVARS(kblock,112) = SPR_DISP
      SVARS(kblock,113) = SPR_F
      SVARS(kblock,114) = SPR_K
    END IF
C
C
    RETURN
    END
C
C
```

```
C     ****************************************
C        PINCHING4 INTERFACE:SUEL2PIN
C     ****************************************
      SUBROUTINE SUEL2PIN(envlpPosDamgdStress, envlpNegDamgdStress,
     +state3Strain, state3Stress, state4Strain, state4Stress,
     +I_Cstate, Cstrain, Cstress, CstrainRate, P_lowI_CstateStrain,
     +P_lowI_CstateStress, hghI_CstateStrain, hghI_CstateStress,
     +CminStrainDmnd, CmaxStrainDmnd, Cenergy, CgammaK,
     +CgammaD, CgammaF, Ttangent, gammaKUsed, gammaFUsed,
     +P_kElasticPosDamgd, P_kElasticNegDamgd, uMaxDamgd,uMinDamgd,
     +P_kunload, CnCycle, elasticStrainEnergy,
     +SPR_F, SPR_K, SVARS, I_SPR_NUM, kblock)
C
C
      include 'vaba_param.inc'
C
      PARAMETER (TOL = 1.E-32)
C
      DIMENSION envlpPosDamgdStress(6), envlpNegDamgdStress(6),
     +          state3Strain(4), state3Stress(4),
     +          state4Strain(4), state4Stress(4), SVARS(kblock,200)
C
      REAL strain, dstrain
      REAL Cstrain, Cstress, CstrainRate
      REAL P_lowI_CstateStrain, P_lowI_CstateStress
      REAL hghI_CstateStrain, hghI_CstateStress
      REAL CminStrainDmnd, CmaxStrainDmnd
      REAL Cenergy
      REAL CgammaK, CgammaD, CgammaF
      REAL Ttangent
      REAL gammaKUsed, gammaFUsed
      REAL P_kElasticPosDamgd, P_kElasticNegDamgd
      REAL uMaxDamgd,uMinDamgd
      REAL P_kunload
      REAL CnCycle
      REAL elasticStrainEnergy
      REAL SPR_DISP, SPR_K, SPR_F
C
      INTEGER I_Cstate
C
      INTEGER I_SPR_NUM
C
      IF (I_SPR_NUM .EQ. 1) THEN
         envlpPosDamgdStress(1) = SVARS(kblock,1)
         envlpPosDamgdStress(2) = SVARS(kblock,2)
         envlpPosDamgdStress(3) = SVARS(kblock,3)
         envlpPosDamgdStress(4) = SVARS(kblock,4)
         envlpPosDamgdStress(5) = SVARS(kblock,5)
         envlpPosDamgdStress(6) = SVARS(kblock,6)
```

```
    envlpNegDamgdStress(1) = SVARS(kblock,7)
    envlpNegDamgdStress(2) = SVARS(kblock,8)
    envlpNegDamgdStress(3) = SVARS(kblock,9)
    envlpNegDamgdStress(4) = SVARS(kblock,10)
    envlpNegDamgdStress(5) = SVARS(kblock,11)
    envlpNegDamgdStress(6) = SVARS(kblock,12)
    state3Strain(1) = SVARS(kblock,13)
    state3Strain(2) = SVARS(kblock,14)
    state3Strain(3) = SVARS(kblock,15)
    state3Strain(4) = SVARS(kblock,16)
    state3Stress(1) = SVARS(kblock,17)
    state3Stress(2) = SVARS(kblock,18)
    state3Stress(3) = SVARS(kblock,19)
    state3Stress(4) = SVARS(kblock,20)
    state4Strain(1) = SVARS(kblock,21)
    state4Strain(2) = SVARS(kblock,22)
    state4Strain(3) = SVARS(kblock,23)
    state4Strain(4) = SVARS(kblock,24)
    state4Stress(1) = SVARS(kblock,25)
    state4Stress(2) = SVARS(kblock,26)
    state4Stress(3) = SVARS(kblock,27)
    state4Stress(4) = SVARS(kblock,28)
    I_Cstate = INT(SVARS(kblock,29))
    Cstrain = SVARS(kblock,30)
    Cstress = SVARS(kblock,31)
    CstrainRate = SVARS(kblock,32)
    P_lowI_CstateStrain = SVARS(kblock,33)
    P_lowI_CstateStress = SVARS(kblock,34)
    hghI_CstateStrain = SVARS(kblock,35)
    hghI_CstateStress = SVARS(kblock,36)
    CminStrainDmnd = SVARS(kblock,37)
    CmaxStrainDmnd = SVARS(kblock,38)
    Cenergy = SVARS(kblock,39)
    CgammaK = SVARS(kblock,40)
    CgammaD = SVARS(kblock,41)
    CgammaF = SVARS(kblock,42)
    gammaKUsed = SVARS(kblock,43)
    gammaFUsed = SVARS(kblock,44)
    Ttangent = SVARS(kblock,45)
    P_kElasticPosDamgd = SVARS(kblock,46)
    P_kElasticNegDamgd = SVARS(kblock,47)
    uMaxDamgd = SVARS(kblock,48)
    uMinDamgd = SVARS(kblock,49)
    P_kunload = SVARS(kblock,50)
    CnCycle = SVARS(kblock,51)
    elasticStrainEnergy = SVARS(kblock,52)
    SPR_F = SVARS(kblock,56)
    SPR_K = SVARS(kblock,57)
ELSE IF (I_SPR_NUM .EQ. 2) THEN
```

```
envlpPosDamgdStress(1) = SVARS(kblock,58)
envlpPosDamgdStress(2) = SVARS(kblock,59)
envlpPosDamgdStress(3) = SVARS(kblock,60)
envlpPosDamgdStress(4) = SVARS(kblock,61)
envlpPosDamgdStress(5) = SVARS(kblock,62)
envlpPosDamgdStress(6) = SVARS(kblock,63)
envlpNegDamgdStress(1) = SVARS(kblock,64)
envlpNegDamgdStress(2) = SVARS(kblock,65)
envlpNegDamgdStress(3) = SVARS(kblock,66)
envlpNegDamgdStress(4) = SVARS(kblock,67)
envlpNegDamgdStress(5) = SVARS(kblock,68)
envlpNegDamgdStress(6) = SVARS(kblock,69)
state3Strain(1) = SVARS(kblock,70)
state3Strain(2) = SVARS(kblock,71)
state3Strain(3) = SVARS(kblock,72)
state3Strain(4) = SVARS(kblock,73)
state3Stress(1) = SVARS(kblock,74)
state3Stress(2) = SVARS(kblock,75)
state3Stress(3) = SVARS(kblock,76)
state3Stress(4) = SVARS(kblock,77)
state4Strain(1) = SVARS(kblock,78)
state4Strain(2) = SVARS(kblock,79)
state4Strain(3) = SVARS(kblock,80)
state4Strain(4) = SVARS(kblock,81)
state4Stress(1) = SVARS(kblock,82)
state4Stress(2) = SVARS(kblock,83)
state4Stress(3) = SVARS(kblock,84)
state4Stress(4) = SVARS(kblock,85)
I_Cstate = INT(SVARS(kblock,86))
Cstrain = SVARS(kblock,87)
Cstress = SVARS(kblock,88)
CstrainRate = SVARS(kblock,89)
P_lowI_CstateStrain = SVARS(kblock,90)
P_lowI_CstateStress = SVARS(kblock,91)
hghI_CstateStrain = SVARS(kblock,92)
hghI_CstateStress = SVARS(kblock,93)
CminStrainDmnd = SVARS(kblock,94)
CmaxStrainDmnd = SVARS(kblock,95)
Cenergy = SVARS(kblock,96)
CgammaK = SVARS(kblock,97)
CgammaD = SVARS(kblock,98)
CgammaF = SVARS(kblock,99)
gammaKUsed = SVARS(kblock,100)
gammaFUsed = SVARS(kblock,101)
Ttangent = SVARS(kblock,102)
P_kElasticPosDamgd = SVARS(kblock,103)
P_kElasticNegDamgd = SVARS(kblock,104)
uMaxDamgd = SVARS(kblock,105)
uMinDamgd = SVARS(kblock,106)
```

```
      P_kunload = SVARS(kblock,107)
      CnCycle = SVARS(kblock,108)
      elasticStrainEnergy = SVARS(kblock,109)
      SPR_F = SVARS(kblock,113)
      SPR_K = SVARS(kblock,114)
    END IF
C
C
    RETURN
    END
C
C
    SUBROUTINE
SGEOM(U,COORDS,SPR_LEN,SPR_DISP,SPR_DISP_WD,SPR_COS_X,
   +SPR_COS_Y, SPR_DISP_X,SPR_DISP_Y,PROPS,SVARS,kblock)
C
C
    include 'vaba_param.inc'
C
    PARAMETER (TOL = 1.E-16)
C
    DIMENSION U(kblock,6), COORDS(kblock,3,2), PROPS(41),
   +SVARS(kblock, 200)
C
C
    REAL SPR_COORD_X, SPR_COORD_Y
    REAL SPR_DISP_X, SPR_DISP_Y, SPR_DISP_Z
    REAL SPR_LEN_X, SPR_LEN_Y
    REAL SPR_LEN0, SPR_LEN
    REAL SPR_COS_X, SPR_COS_Y
C
    REAL SPR_DISP, SPR_DISP_WD
C
    INTEGER ISPR_DIR_1, ISPR_DIR_2, ISPR_DIR_0
C
C
    ISPR_DIR_1 = INT(PROPS(40))
    ISPR_DIR_2 = INT(PROPS(41))
    IF (ISPR_DIR_1 .EQ. 1 .AND. ISPR_DIR_2 .EQ. 2) THEN
      ISPR_DIR_0 = 3
    ELSE IF (ISPR_DIR_1 .EQ. 1 .AND. ISPR_DIR_2 .EQ. 3) THEN
      ISPR_DIR_0 = 2
    ELSE IF (ISPR_DIR_2 .EQ. 2 .AND. ISPR_DIR_2_ .EQ. 3) THEN
      ISPR_DIR_0 = 1
    END IF
C
    SPR_COORD_X = COORDS(kblock,2,ISPR_DIR_1) -
   +COORDS(kblock,1,ISPR_DIR_1)
    SPR_COORD_Y = COORDS(kblock,2,ISPR_DIR_2) -
```

```
     +COORDS(kblock,1,ISPR_DIR_2)
C
      SPR_LEN0 =
SQRT(SPR_COORD_X*SPR_COORD_X+SPR_COORD_Y*SPR_COORD_Y)
C
      SPR_DISP_X = U(kblock,ISPR_DIR_1+3) - U(kblock,ISPR_DIR_1)
      SPR_DISP_Y = U(kblock,ISPR_DIR_2+3) - U(kblock,ISPR_DIR_2)
C
C     Adjust spring deformation and orientation for 'zero'' deformation case
      IF (ABS(SPR_DISP_X) .LE. TOL .OR. ABS(SPR_DISP_Y) .LE. TOL) THEN
         SPR_DISP_X = SPR_DISP_X + TOL * 1.D0/SQRT(2.0)
         SPR_DISP_Y = SPR_DISP_Y + TOL * 1.D0/SQRT(2.0)
      END IF
C
      SPR_LEN_X = SPR_COORD_X + SPR_DISP_X
      SPR_LEN_Y = SPR_COORD_Y + SPR_DISP_Y
C
C     * Radial spring length should not be zero!
      SPR_LEN = SQRT(SPR_LEN_X*SPR_LEN_X+SPR_LEN_Y*SPR_LEN_Y)
C
      SPR_DISP = SPR_LEN - SPR_LEN0
C
      SPR_COS_X = SPR_LEN_X/SPR_LEN
      SPR_COS_Y = SPR_LEN_Y/SPR_LEN
C
C     Record spring orientation
C     * Discard if unrealistically huge, zero or one
      IF (ABS(SPR_COS_X * SPR_COS_Y) .LT. ONE) THEN
         IF (ABS(SPR_COS_X * SPR_COS_Y) .GT. ZERO) THEN
            SVARS(kblock,124) = SPR_COS_X
            SVARS(kblock,125) = SPR_COS_Y
         END IF
      END IF
C
C     * Compute connection withdrawl deformation
      SPR_DISP_Z = U(kblock,ISPR_DIR_0+3) - U(kblock,ISPR_DIR_0)
      SPR_DISP_WD = SPR_DISP_Z
C
C
      RETURN
      END
C
C
      SUBROUTINE SNFORCE(PROPS, SPR_F, SPR_COS_X, SPR_COS_Y, SRESID,
     +SPR_SGN, SPR_F_WD)
C
C
      include 'vaba_param.inc'
C
```

```
      PARAMETER (TOL = 1.E-16)
C
C
      DIMENSION SRESID(6), PROPS(41)
C
      REAL SPR_F
      REAL SPR_F_X, SPR_F_Y
      REAL SPR_COS_X, SPR_COS_Y
      REAL SPR_F_WD
      REAL SPR_SGN
      INTEGER ISPR_DIR_1, ISPR_DIR_2, ISPR_DIR_0
C
C
C     Retrieve spring directional parameters
      ISPR_DIR_1 = INT(PROPS(40))
      ISPR_DIR_2 = INT(PROPS(41))
      IF (ISPR_DIR_1 .EQ. 1 .AND. ISPR_DIR_2 .EQ. 2) THEN
         ISPR_DIR_0 = 3
      ELSE IF (ISPR_DIR_1 .EQ. 1 .AND. ISPR_DIR_2 .EQ. 3) THEN
         ISPR_DIR_0 = 2
      ELSE IF (ISPR_DIR_2 .EQ. 2 .AND. ISPR_DIR_2_ .EQ. 3) THEN
         ISPR_DIR_0 = 1
      END IF
C
C     Radial spring force components
      SPR_F_X = SPR_F * SPR_COS_X * SPR_SGN
      SPR_F_Y = SPR_F * SPR_COS_Y * SPR_SGN
C
C     Update radial spring nodal force vector
      SRESID(ISPR_DIR_1) = -SPR_F_X
      SRESID(ISPR_DIR_2) = -SPR_F_Y
      SRESID(ISPR_DIR_1+3) = SPR_F_X
      SRESID(ISPR_DIR_2+3) = SPR_F_Y
C
C     Withdrawl spring force component
      SRESID(ISPR_DIR_0) = -SPR_F_WD
      SRESID(ISPR_DIR_0+3) = SPR_F_WD
C
C
      RETURN
      END
```