Using Energy History Data to Obtain Load vs. Deflection Curves from Quasi-Static Abaqus/Explicit Analyses

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Abstract: The modeling of quasi-static forming processes and loading conditions with Abaqus/Explicit can present challenges related to the generation of system level force vs. deflection curves and the investigation of general stability behavior. This paper describes a procedure whereby energy history data can be used to generate estimates of quasi-static force vs. deflection curves. The procedure utilizes the principle of virtual work to establish an estimate for the quasi-static equilibrium curve and is accurate when the dynamic inertial forces of the simulation remain small compared to the internal deformation induced forces. The force vs. deflection curves generated by this procedure can also be used to characterize general structural stability characteristics. The procedure is valid for loading conditions that are proportional and monotonic, and is applicable to general structures when simulating quasi-static conditions.
Keywords: Coronary Stent, Explicit Dynamics, Forming, Load Curve, Quasi-Static, Stability.

1. Introduction

The extremely robust contact algorithms available in /Explicit provide a clear advantage over /Standard for many simulations associated with quasi-static processes in manufacturing as well as when evaluating proposed designs for in-service performance. However, using a purely explicit dynamics solver can introduce additional complexity in obtaining quasi-static solutions. The analyst must take care when implementing mass scaling and defining loading rates to remove or limit the influence of inertial and damping forces on a system's quasi-static response. In terms of generating analysis results, it is often required to describe the system in terms of a response curve that relates a general loading condition to a simplified measure of deformation. The creation of a simple system level quasi-static load vs. deflection curve may at first appear to be straight forward, but the process is often complicated by the presence of complex geometries, distributed boundary restraints and loads, contact and the presence of inertial and damping forces. An energy based post-processing procedure is presented whereby energy history data is used to generate an estimate of a system's characteristic quasi-static load vs. deflection response. The procedure is illustrated via a simulation of the deployment of a coronary stent into a mock artery. The objective of the simulation is to generate a curve of the applied radial force vs. the stent radial expansion. The stent deployment example is also used to illustrate the influence of excessive mass scaling and/or using an overly compressed time scale on simulating quasi-static processes. A second type of simulation is performed in which the stent/artery system in the deployed configuration has a vacuum pressure applied to the inside of the mock artery as a means to evaluate the system strength. The energy based post-processing procedure is used to generate a pressure vs. contained volume stability curve for the system.

2. Formulation

The energy based procedure for generating a quasi-static load-deflection curve assumes that the system excitation is monotonic and the resulting loads are proportional and can be described in term of a single load parameter. It is also assumed that the deformation state of the system can be characterized by a single response variable. The procedure is valid for quasi-static behavior in which the inertial and alpha-beta type damping forces are small compared to internal forces and external forces due to boundary/contact restraints and applied loads. The internal forces are those associated with elastic strains, hourglass controls, plastic strains, viscoelasticity and possibly friction. As a system's response becomes less quasi-static the dynamic nature of the response becomes evident by the presence of oscillations in the generated load-deflection curve. Therefore, the procedure described herein is also a good tool for evaluating the appropriateness of mass scaling and time compression techniques.

The energy based procedure for generating a quasi-static load-deflection curve is based upon the Virtual Work Principle. The work due to external forces (E) can be represented by the product of the load parameter "P" and the systems characteristic deformation variable (U).

(1) $$E = +P * U$$

The positive sign indicates positive work in that the forces generally act along the line of action of the displacements. The potential energy of the system would decrease as a result of this positive work. The total internal work done on the system (– I), corresponds to the sum of internal forces times the system's relative deformation. The negative sign associated with the internal work indicates the internal forces generally oppose the displacements. That is, the internal forces resist the deformations thereby increasing the potential energy of the system. The total work (W) associated with the system is equal to the sum of the external and internal work.

(2) $$W = E - I = (P * U) - I$$

A necessary condition for static equilibrium is that all forces during a small infinitesimal virtual displacement from the equilibrium position do zero net work. This requirement can be expressed mathematically as:

(3) $$\delta W = \delta E - \delta I = 0 = (P - \partial I/\partial U) * \delta U$$

From Equation 3 it follows that if the internal work (I) can be expressed as a function of the characteristic deformation variable (U), then the external forces as represented by the characteristic load parameter can be expressed as a derivative of the internal energy.

(4) $$P = \partial I / \partial U$$

Abaqus x-y data post-processing operations are used to sum the internal energy history data from desired portions of the model. The total internal energy is generated as the sum of strain energy, hourglass artificial energy, plastic dissipation energy, viscoelastic energy and frictional dissipation (if desired). Using the Abaqus default of the entire model internal energy may not be appropriate, for example, when modeling complex forming tools as deformable structures. The system internal energy is then expressed as a function of the system's characteristic deformation variable by using the Abaqus x-y curve operations, and upon differentiation the load-deflection curve is generated.

3. Stent Deployment Example

The Abaqus/Explicit example model of a coronary stent being expanded into a mock artery is shown in Figure 1. The stent is manufactured using a Cobalt-Chromium alloy material modeled with Mises plasticity and the mock artery utilizes a simple neo-hookean hyper-elastic material model. The inside surface of the artery is the master surface for penalty based contact with the nodes located on the outside surface of the stent. The stent is expanded into the artery via an idealized deployment balloon that is referred to herein as the expansion tool. The expansion tool consists of a single row of membrane elements that encompass a 360 degree cylinder with 180 individual facets. The expansion tool material properties were selected so as to not influence the system's critical time increment size while ensuring appropriate default contact penalty stiffness between the expansion tool master surface and the slave nodes on the inside surface of the stent.

The nodes of the expansion tool had boundary condition restraints imposed on the axial and circumferential degrees of freedom. Radial motions were applied to the expansion tool so as to impart an expansion to the stent. The effective stent expansion force could not be generated from the expansion tool boundary reaction forces due to the significant inertia and elastic stiffness associated with the expansion tool representation. Also, requested history output for the total integrated contact force between the expansion tool and stent could not be used since the contact was over a complete 360 degree closed surface. The expansion tool motion was defined in terms of a radial velocity history by using the smooth step option applied to a boundary condition amplitude curve. The velocity history and resulting radial displacement of the expansion tool are presented in Figure 2. It should be noted that the unit system used in the stent deployment example and the following stability example correspond to units of Lb_f-inch-sec. The overall duration of the simulation was approximately 6-7 times the period of the estimated radial mode frequency of the expanded stent. Figure 3 contains displaced shape plots corresponding to completion of the expansion process.

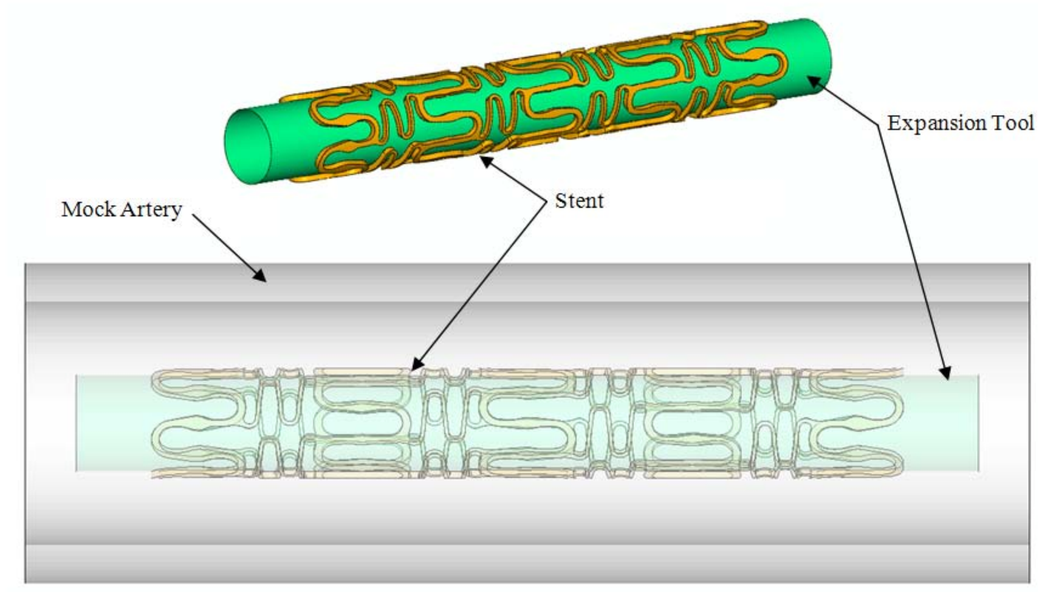

Figure 1. Coronary stent and mock artery model.

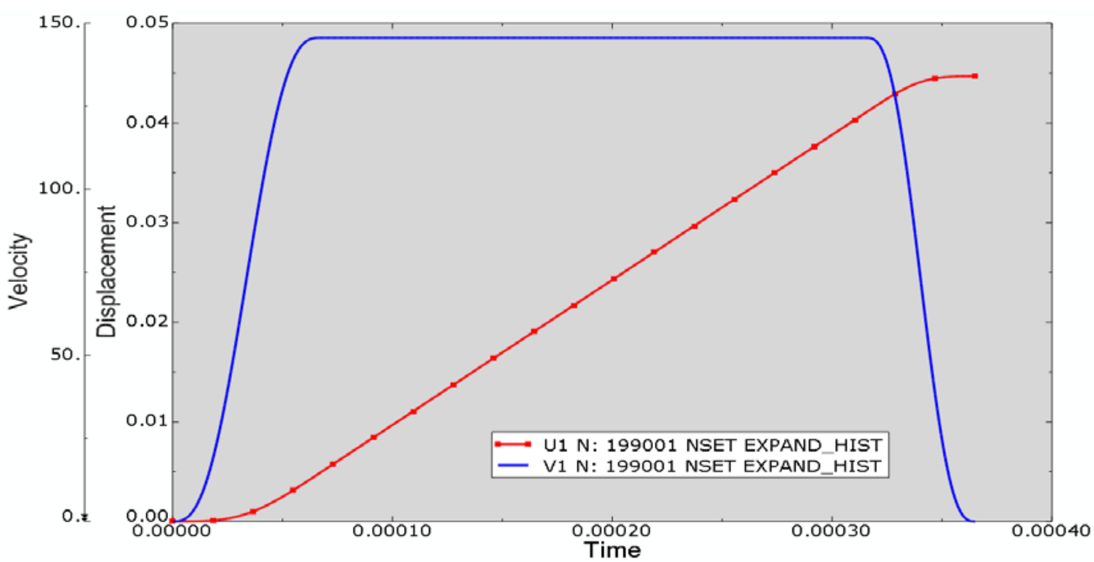

Figure 2. Expansion tool velocity and displacement history curves

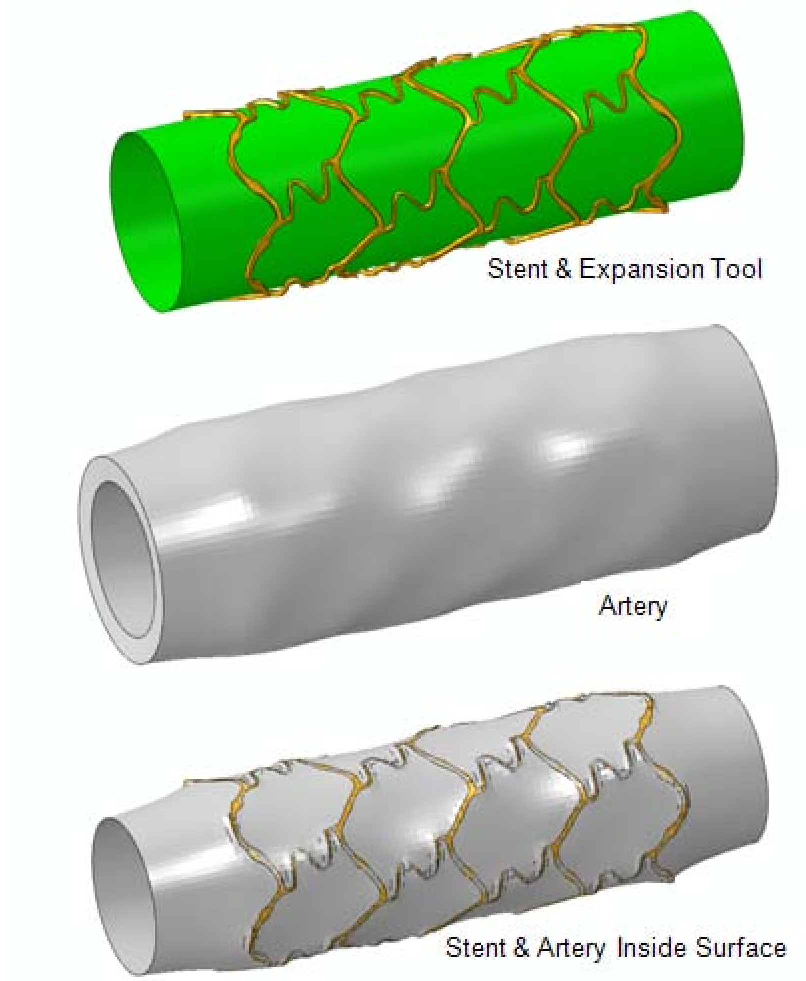

Figure 3: Displacement plots at the end of the expansion step.

Figure 4 shows the combined internal energy associated with the stent and mock artery obtained from the history data and plotted as a function of time. Figure 4 also shows the radial displacement of the expansion tool as a function of time, which will be used to represent the characteristic deformation variable of the system. The combine curve feature of the Abaqus/Viewer x-y create curve utility is used to express the internal energy as a function of the expansion tool radial displacement, as shown in Figure 5. The energy-displacement curve is differentiated to obtain the force vs. deflection curve shown in Figure 6. Notice that two curves are shown in Figure 6, the second of which accounts for the impact of friction by including the frictional dissipation energy as a contributor to the total internal energy.

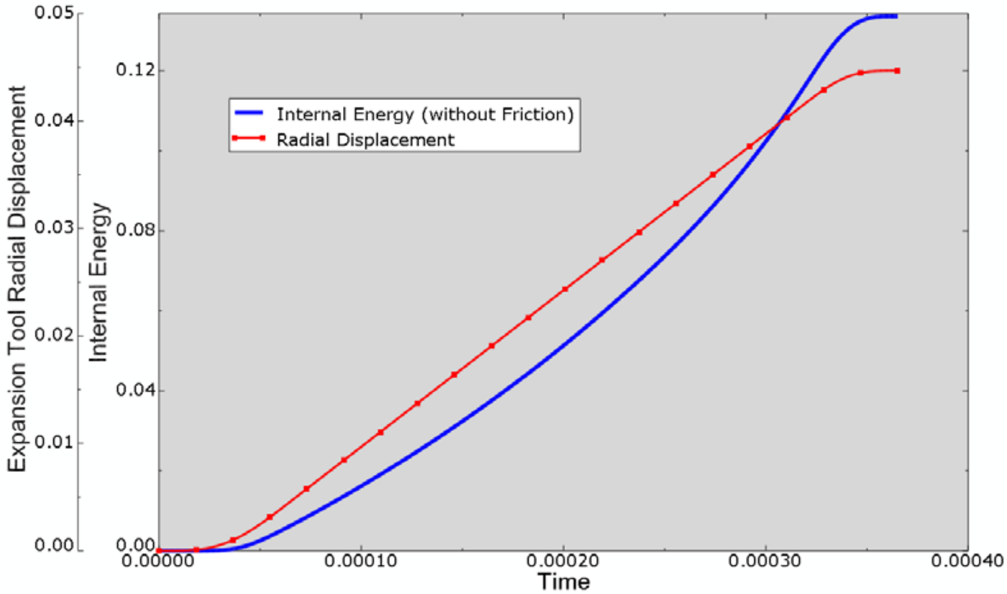

Figure 4. Internal energy and expansion tool radial displacement history curves.

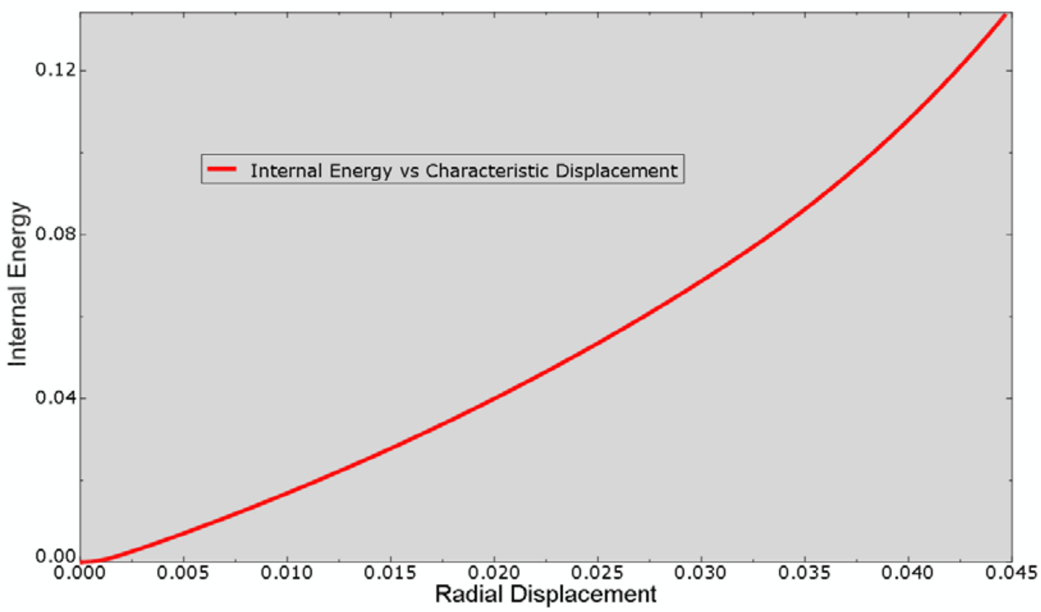

Figure 5. Internal energy vs. expansion tool radial displacement.

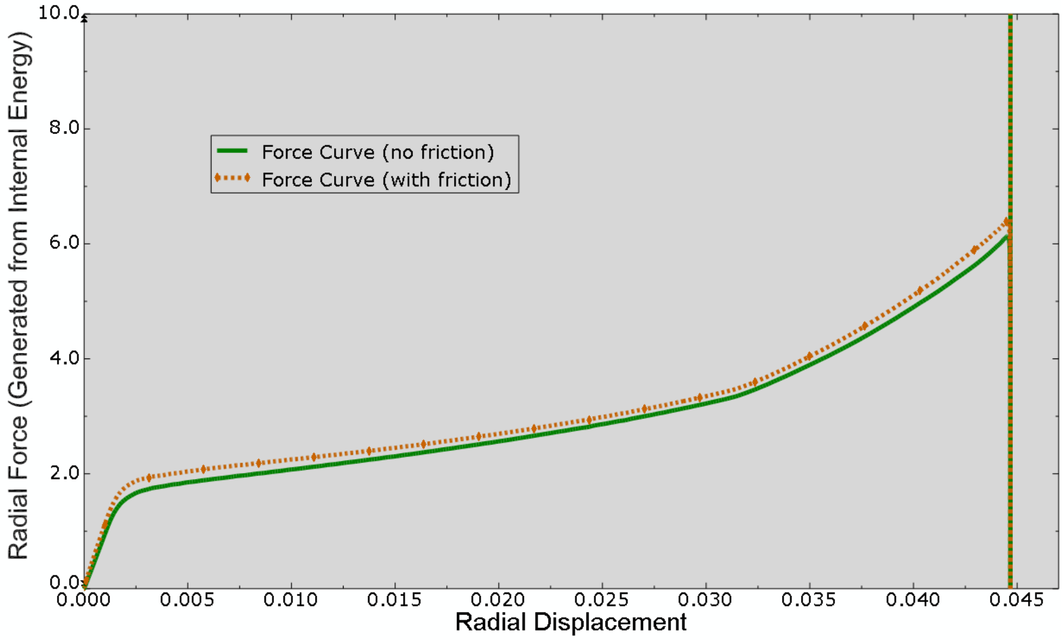

Figure 6. Generated load vs. deflection curves.

In Figure 6, it can be noticed that the curves become essentially vertical with exaggerated force values as the stent approaches the final configuration. This is due to numerical round-off precision errors that occur during the differentiation of the x-y data. For this example, the radial velocity smooth step loading function (see Figure 2) produces several solution points at the end of the simulation that have nearly identical displacements. The small changes in displacement are not accurately resolved within the significant digits available for storing the x-y data. This numerical problem does not occur at the beginning of the simulation where the displacement begins at zero. An alternate approach to obtain the force vs. deflection curve that avoids this numerical issue uses an expansion tool radial velocity profile that does not return to zero but remains at the constant level until the original targeted displacement value is exceeded. The result of this approach as compared to using the original smooth step velocity profile, where the velocity returns to zero, is illustrated in Figure 7.

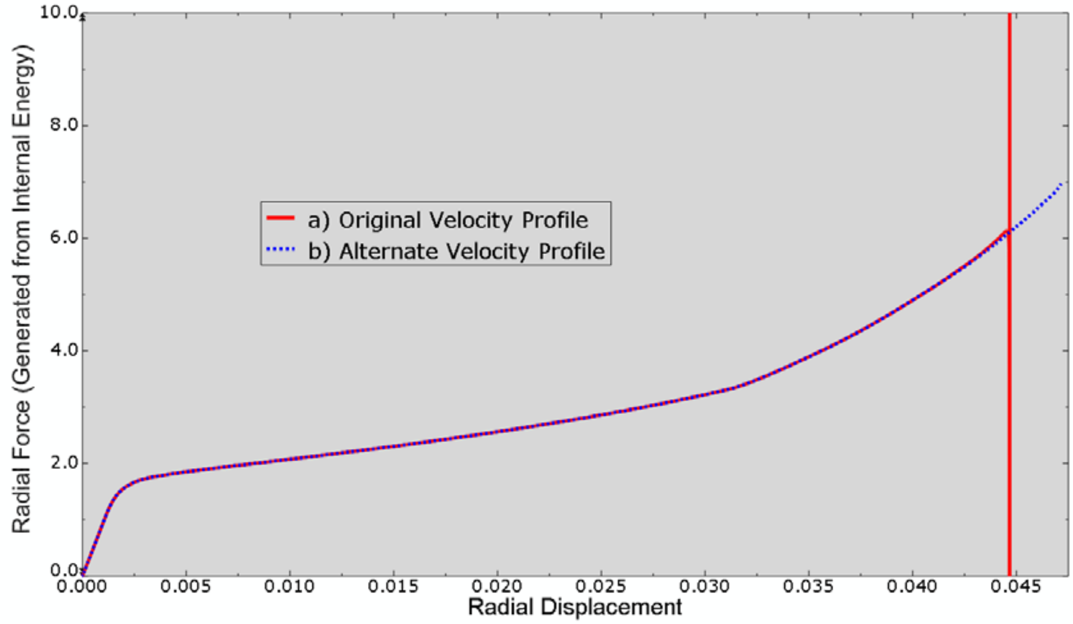

Figure 7. Expansion curve extended via an alternate velocity profile.

To illustrate how the load curve generation procedure can be used to evaluate the quasi-static behavior of a given simulation, the original stent expansion analysis was rerun with two numerical techniques that are often used to improve the efficiency of /Explicit solutions; global mass scaling and time compression. In the first supplemental analysis, mass scaling was used to increase the critical time increment size for the elements by a factor of 10 (mass increased by 100). The second analysis kept the original element mass and time increments but increased the speed of the expansion by a factor of 10. Figure 8 provides the generated radial force vs. deflection curves for the three cases. The original analysis clearly behaves in a manner one would expect for a quasi-static solution of the stent being expanded in to a mock artery. The initial slope is characteristic of a high radial stiffness that drops off dramatically as material yielding occurs at key locations within the stent. The later change in slope that occurs at a displacement of about 0.032" corresponds to the stent establishing contact with the mock artery. However, both the mass scaling and time compression analyses have significant dynamic influences as suggested by the oscillatory nature of the response curves. It should also be pointed out that the inertial and/or damping force effects due to mass scaling and/or time compression can greatly change the solution, which may not always be apparent from viewing a plot of the displaced shape. Figure 9 shows the displaced shape of the stent (tube not shown) for the mass scaled supplemental analysis, which looks very similar to the shape of the original analysis that was shown in Figure 3. However, where the original analysis had a maximum plastic strain of 0.195, the mass scaled analysis had a maximum plastic strain of 0.270.

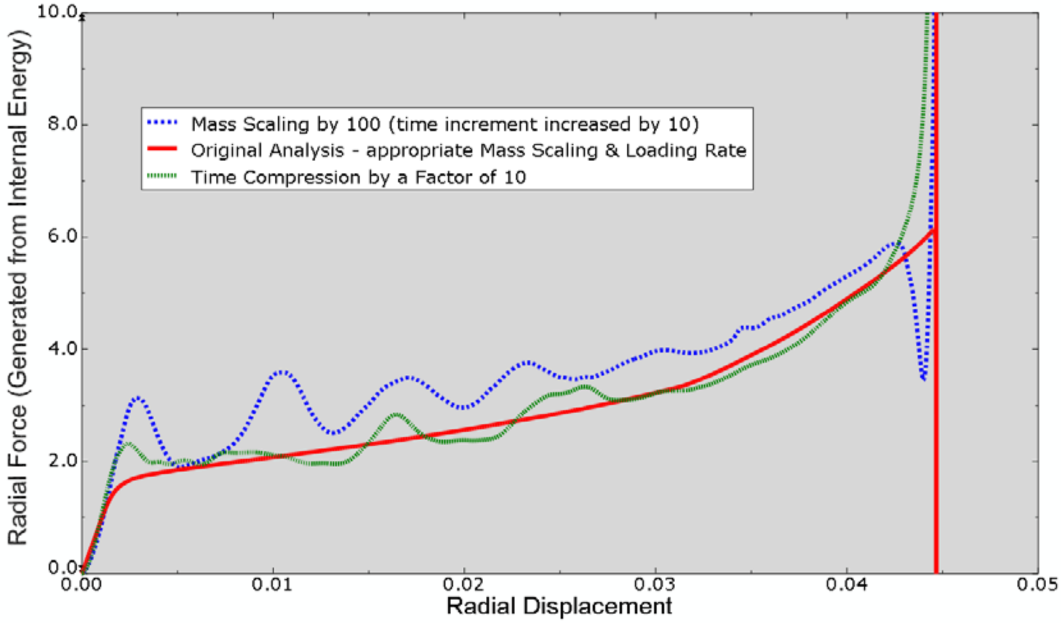

Figure 8. Effects of mass scaling and time compression.

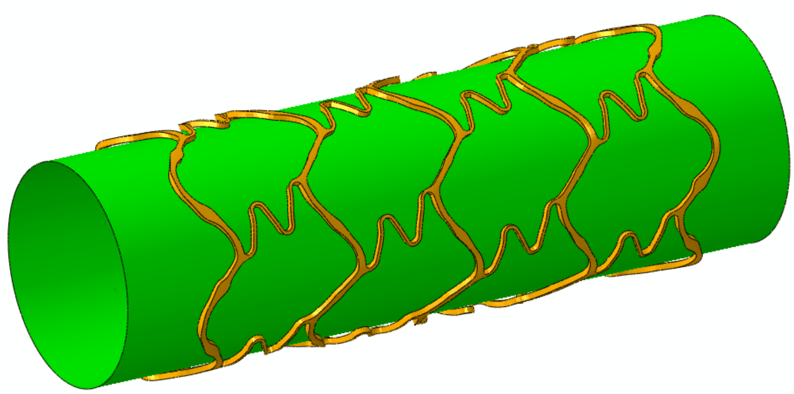

Figure 9. Displaced shape for the mass scaled analysis.

4. Stability Curve Example

A buckling limit load analysis was performed on the expanded stent and mock artery system with the objective of obtaining a qualitative measure of the system's overall radial strength. A vacuum pressure was applied to the inside surface of the mock artery, providing a simple means by which a uniform radial compressive load could be imposed onto the system. A slight geometric imperfection was imparted to the expanded stent by including a combination of N = 2, 3, and 4 circumferential waves in the original geometry of the expansion tool. Hydrostatic fluid elements were used to line the inside of the artery and close off the artery ends. The vacuum pressure was applied by ramping on a negative pressure to the PCAV variable (dof 8) of the contained volume reference node. The volume contained by the hydrostatic fluid elements was requested as history output (CVOL). In this example, the loading function was a vacuum pressure that increased linearly from 0 to 30 psi over the duration of the limit load analysis step. The continually increasing load made the determination of any system instability by inspection of the PCAV vs. CVOL curve difficult at best. However, by expressing the internal system energy as a function of the contained volume output variable (CVOL), and differentiating with respect to the contained volume, it was possible to generate a system pressure vs. volume stability curve. Figure 10 shows the stability curve that was generated for the stent/artery system, as well as the PCAV vs. CVOL curve derived from the history output data. The stability point is at about a vacuum pressure of 21.5 psi, which is not discernable from an inspection of the PCAV vs. CVOL curve. Figure 11 shows the post-bucking configuration of the stent and mock artery system at the end of the limit load analysis step.

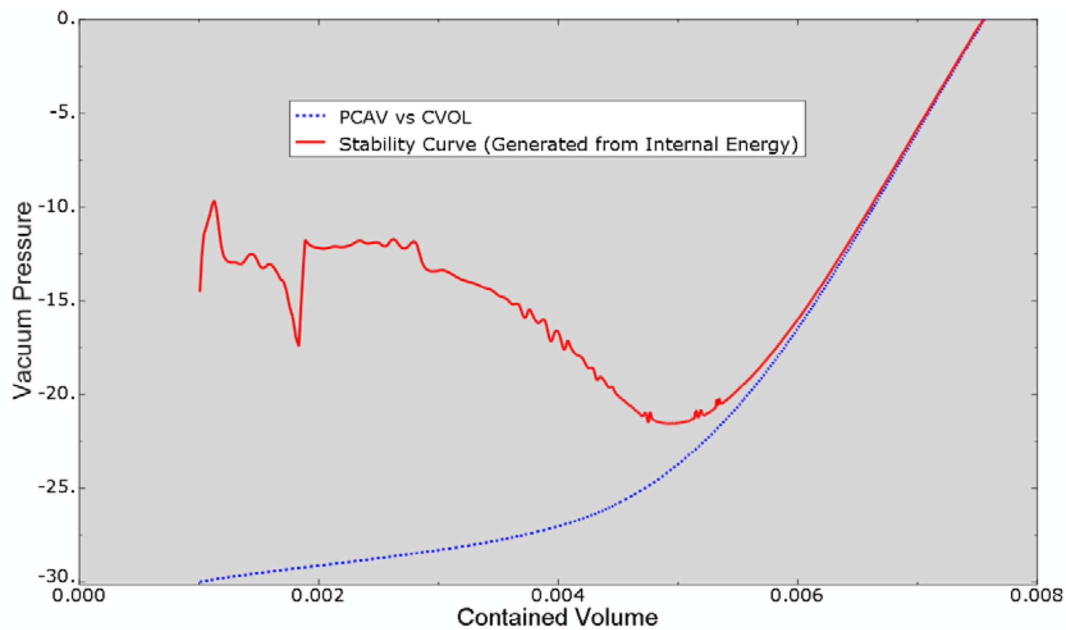

Figure 10. Generation of a stability curves for radial strength evaluation.

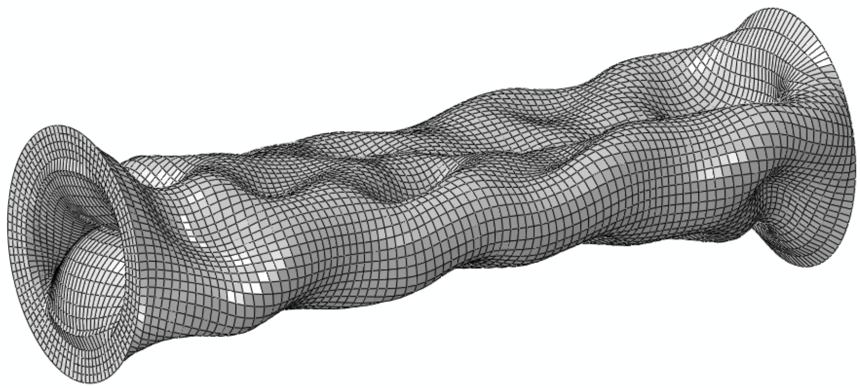

Figure 11. Post-buckling configuration.

5. Summary

It has been shown that the Virtual Work Principle can be used to generate system level load vs. deflection curves by post-processing energy history data. The technique was illustrated on an example problem of a coronary stent being expanded into a mock artery. The load-deflection curves generated with this technique can also be used to evaluate the influences of mass scaling and/or time compression on performing quasi-static analyses with Abaqus/Explicit. The ability of the load-deflection curve generation technique to aid in the investigation of stability behavior was also illustrated.