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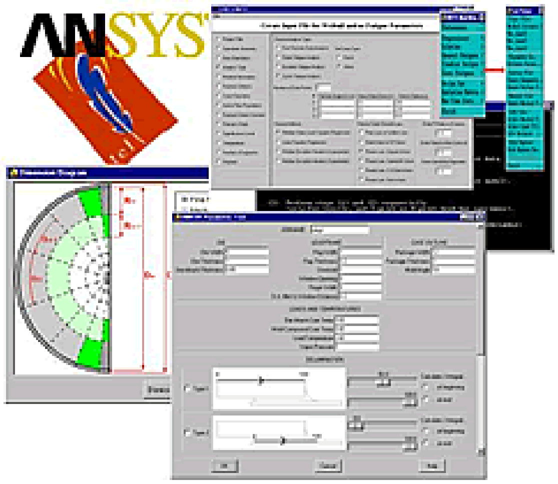

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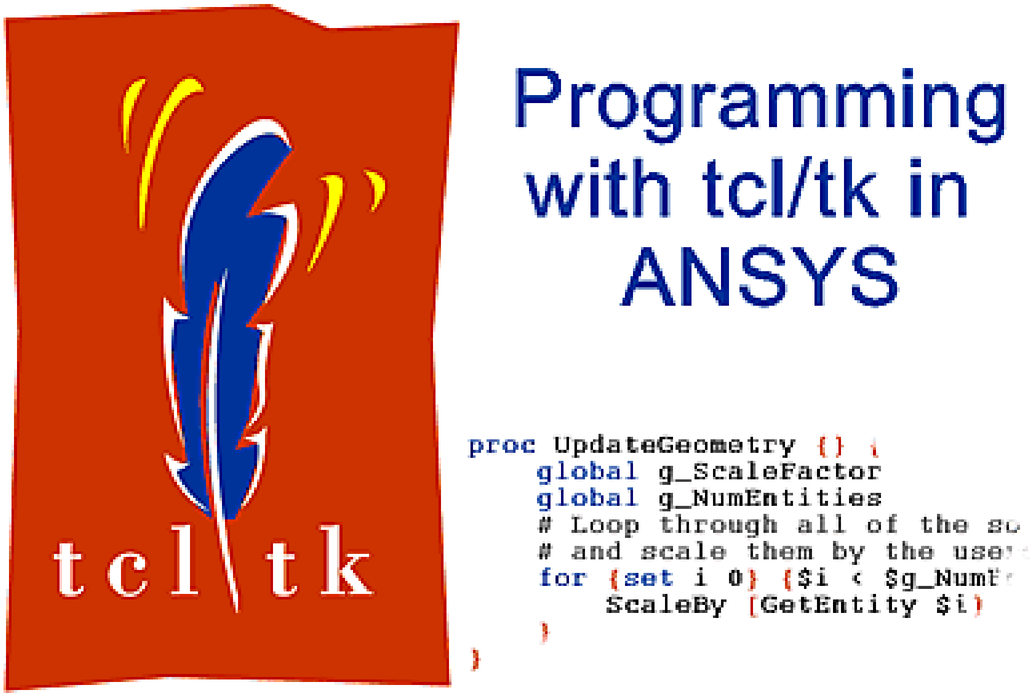
Programming with Tcl/Tk in ANSYS

by Matt Sutton



```
proc UpdateGeometry {} {
    global g_ScaleFactor
    global g_NumEntities
    # Loop through all of the so
    # and scale them by the use
    for {set i 0} {$i < $g_NumE
        ScaleBy [GetEntity $i]
    }
}
```

Introduction

In this article we will explore programming with tcl/tk (pronounced tickle tee-kay) in ANSYS. Tcl, an acronym that stands for Tool Command Language, is an embedded programming language that was developed by John Ousterhout in the late 1980 s while he was a professor at Berkeley. Initially, tcl grew out of a need for a simple, embeddable command language that Dr. Ousterhout and his colleagues could reuse within different integrated circuit design tools that they were developing at the time [1]. In a recent article, Dr. Ousterhout outlined the requirements he had in mind when he created tcl.

> The notion of embeddability is one of the most unique aspects of Tcl, and it led me to the following three overall goals for the language:
>
> - The language must be extensible: it must be very easy for each application

to add its own features to the basic features of the language, and the application-specific features should appear natural, as if they had been designed into the language from the start.

- The language must be very simple and generic, so that it can work easily with many different applications and so that it doesn't restrict the features that applications can provide.
- Since most of the interesting functionality will come from the application, the primary purpose of the language is to integrate or glue together the extensions. Thus the language must have good facilities for integration. [1]

Shortly after developing tcl, Dr. Ousterhout s interests shifted from integrated circuit design tools to graphical user interfaces (GUIs). At this time, again in the late 1980 s, GUIs were still very much in their infancy. Furthermore, the manpower needed at that time to develop a usable GUI was rather substantial. Driven by a fear that his research team would be under staffed to tackle complex GUI development projects, Dr. Ousterhout realized that substantial interactive systems could be built out of smaller reusable components, which were then programmatically glued together. It was clear to Dr. Ousterhout that the tcl language would be ideal as the programmatic glue for such interactive systems, if only there existed a set of GUI components from which to build a system. Consequently, he begin developing tk in order to fulfill the need for a toolkit of reusable GUI components.

Tcl/tk began to gain popularity throughout the software development community primarily via word-of-mouth. Today it is widely used throughout a plethora of industries largely because the source code for the tcl interpreter is freely available for download from the internet [2].

Furthermore, the 5.7 release of ANSYS marked a substantial advancement of tcl within ANSYS. Within the 5.7 release, a fully functional tcl interpreter was exposed via the ~eui external command. Each subsequent release of ANSYS has continued to add functionality based on tcl/tk, culminating in the ANSYS 6.1 release in which the new GUI is completely implemented with tcl/tk.

The remainder of this article focuses on programming with tcl/tk in ANSYS. We will first briefly look at the tcl language and the tk toolkit in a generic sense. Then we will explore ways in which programs written in tcl can be written to interface directly with ANSYS. Finally, we will wrap up some loose ends and discuss a few of the more advanced aspects of tcl that help mitigate complexity in large projects.

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The Tcl/Tk Programming Language

Tcl is an interpreted command language, and as such, requires an external piece of software known as the interpreter, which executes a tcl program stored in a text file. Outside of ANSYS, two interpreters are widely used: tclsh and wish. Tclsh simply implements the core tcl language, whereas wish extends the tclsh interpreter by natively exposing the tk toolkit. Therefore, GUI applications written outside of ANSYS should be executed using the wish interpreter. Since wish is a superset of tclsh, it can be used exclusively if desired. Inside of ANSYS, the equivalent of a wish interpreter is provided by the ~eui external command. Since this article focuses on tcl/tk within ANSYS, we will execute all of the example programs from within ANSYS via the ~eui command. However, I have often found that I am more productive initially if I begin developing a new application outside of ANSYS using an off the shelf tcl interpreter [2]. Only after the application is functioning correctly do I typically move into ANSYS.

Let s begin with the prototypical example application used to introduce all modern programming languages; the Hello World app. Please follow the steps below to create this application.

1. Launch ANSYS and note the working directory.
2. Launch you favorite text editor and type in the listing shown in Figure 1. Tcl is case sensitive and somewhat non-freeform. Therefore it is imperative that you type the program in exactly as it is listed in Figure 1.
3. Save this file in the current ANSYS working directory with the name hello1.tcl
4. Execute this script in ANSYS using the ANSYS command listed at the bottom of Figure 2.

```
proc HelloWorld1 {} {
    puts  Hello World!
}

HelloWorld1
```

Figure 1. First "Hello World" application.

```
~eui,  source [file join [pwd] hello1.tcl]
```

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Figure 2. Command to execute a tcl script within ANSYS that is located in the current working directory.

Follow these steps and you should see the string Hello World! printed in the ANSYS output window.

As you can see, tcl has a syntax that is very similar to the C programming language. It is a structured, procedural language that has a rich set of control structures. The first line in our example program declares a procedure named HelloWorld1 . Procedures in tcl are analogous to functions in C or subroutines in FORTRAN. The second line calls a built-in tcl procedure named puts which prints a string to the standard output. The third line contains the closing brace for the procedure, and the final line simply calls the procedure named HelloWorld1. You will notice that there is no main function. In fact, execution in tcl begins with the first executable statement, which in this case is the last line. Consequently, this program could have simply been written using a single line: `puts  Hello World!`

The fundamental data type in tcl is the string. Consequently, all variables used in a tcl program are represented within the tcl interpreter as strings. This provides a great deal of flexibility at a small cost in performance. Remember, however, tcl is not intended to be a computational workhorse, but rather a glue language, so the performance hit for typical glue code should be negligible. The second most common data type in tcl is the list. Internally, a list is stored within tcl as a special kind of string. A list allows you to effortlessly manipulate a collection of data. Before we move to the next example there is one last concept regarding variables that needs to be mentioned, that is the concept of scope. Variables within tcl can live within one of two scopes: the local or global scope. (Tcl namespaces add an additional scope, however, namespaces will not be discussed in this article.) The following example demonstrates the concept of local and global variables as well as lists and function arguments.

```
proc Hello2 {People} {
    global Salutation
    foreach Person $People {
        puts  Hello $Person
    }
    set NumberOfPeople [llength $People]
    if { $NumberOfPeople > 1 } {
        puts  I said hello to $NumberOfPeople people.
    } else {
        puts  I said hello to one person.
    }
    puts $Salutation
}
set Salutation  Good-bye!
Hello2 [list Fred Jane Bob]
```

Figure 3. Second "Hello" application.

To execute the code in Figure 3, follow the same steps mentioned above. However, save the code in Figure 3 with the name hello2.tcl. Substitute the file name hello2.tcl for hello1.tcl in the command given in Figure 2. You should see the following output in the ANSYS output window:

```
Hello Fred
Hello Jane
Hello Bob
I said hello to 3 people.
Good-bye!
```

Figure 4. Output from hello2.tcl.

The example program in Figure 3 is somewhat more substantial, but it succinctly demonstrates many of the features of tcl. Most of the programmatic constructs should be familiar except perhaps the foreach construct. The foreach construct is used to iterate over the contents of a tcl list. The list is passed into the function Hello2 via the People variable. The global variable, Salutation is set to Good-bye! outside of the procedure Hello2 on the second to last line.

In the next example, we will use the tk toolkit to create a simple GUI. The GUI will consist of a single button that, when pressed, will invoke the Hello2 procedure shown in Figure 3. Figure 4 shows the code.

```
destroy .tplvl
set t [toplevel .tplvl]
set b1 [button .tplvl.b1  command  Hello2 Jim  \
     text  Say Hello  ]

pack $b1
proc Hello2 {People} {
    global Salutation
    foreach Person $People {
        puts  Hello $Person
    }
    set NumberOfPeople [llength $People]
    if { $NumberOfPeople > 1 } {
        puts  I said hello to $NumberOfPeople people.
    } else {
        puts  I said hello to one person.
    }
    puts $Salutation
}
set Salutation  Good-bye!
```

Figure 5. Second "Hello" application.

Again, to execute this code, follow the procedure outlined above. However, save this file as hello3.tcl and change the ~eui command listed in Figure 2 accordingly. You should see the following window on your screen.

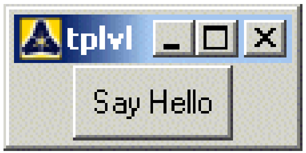

Figure 6. Tk window for the example in Figure 5.

Let s analyze the first five lines in Figure 5 since they are different from the code in Figure 4. The first two lines are necessary when programming in tcl/tk within ANSYS. The first line destroys any previous instance of the window shown in Figure 6. If no instance of this window exists, then the first line simply returns. The second line actually creates a new toplevel window into which we can add additional tk widgets to form the GUI for our application. We are implicitly storing the returned value from the toplevel call into the variable t.

The tk toolkit uses an implicit hierarchical syntax to impose parent-child relationships between widgets. The root window of any tk application is referenced in the code as the . window. All other windows are children on the root window . . So, in Figure 5 on line two, we are creating a new toplevel window named tplvl whose parent is the root window . . This relationship is encoded in the name of the window, which is .tplvl . The encoding is analogous to the file structure used on most modern operating systems, especially UNIX. The separator for encoding the parent child relationship is the . .

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On the third and fourth lines we are creating a button that will be a child of the new toplevel window we just created. This is accomplished by encoding the parent child relationship into the name of the button. The name of the button is given as the first argument to the button command, which is .tplvl.b1 . So, following the naming convention used by tk, we see that the button, b1, is a child of the toplevel window, tplvl, who is a child of the root window . This parent-child relationship insures that when the window shown in Figure 6. is created by the tk toolkit, the button will appear inside the toplevel window.

When you press the button, Say Hello , the tk toolkit will translate that event into a call to the procedure Hello2. This link between pressing a button and executing some tcl code is created via the command argument to the button function. As you can see on the third line in Figure 5, the command argument is followed by a string. This string contains the name of a procedure, Hello2, followed by arguments to that procedure. This creates the implicit link between the user s action of pressing the button and a command that is executed.

The fifth line in figure 5 contains the command pack $b1. As mentioned above, this command is responsible for placing the button onto the toplevel window. The pack command in tk works much like packing a box with smaller rectangular items. Once all the items are packed, and just prior to displaying the window, the tk toolkit shrinks the outer box, in this case the toplevel window, around the smaller boxes so that all of the slack space is taken up. The packing mechanism is a powerful tool for placing widgets on a window because it allows the tk framework to reposition widgets on the screen as a window is resized.

The tk toolkit provides two additional mechanisms for placing widgets on the screen. They are the grid command and the place command. The grid command is similar in power to the pack command. It differs slightly in methodology in that it allows you to place widgets into cells within a virtual grid that overlays a window. A powerful feature of the tk toolkit is that both the pack and grid commands can be use in conjunction within the same window. Furthermore, by exploiting the hierarchical nature of tk, along with certain grouping widgets like the frame widget, extremely complex user interfaces can be constructed. Though a detailed discussion of such techniques is beyond the scope of this article, additional information on these commands can be found in references 3, 4 and 5.

The tk toolkit has a substantial assortment of standard widgets. In addition, several free add-on packages such as Bwidgets, Iwidgets, incr tcl, etc& exist which provide higher level GUI widgets. A list of the standard widgets is shown in Table 1.

Widget	Description
button	Creates a standard pushbutton
canvas	Creates a canvas on which graphic primitives can be drawn
checkbutton	Creates a standard check button
entry	Creates a single line text entry box
frame	Creates a virtual frame useful for grouping widgets
label	Creates a static text label
listbox	Creates a standard list box
menu	Creates either a popup menu or a standard application menu
menubutton	Creates a menu item with an associated on/off state
message	Creates a small message window
radiobutton	Creates a standard exclusive radio button
scale	Creates a sliding scale control
scrollbar	Creates a standard scroll bar
text	Creates a multi-line text widget with extensive formatting capabilities
toplevel	Creates a new toplevel window into which widgets can be placed

Table 1. Standard tk widgets.

Programming Tcl/tk in ANSYS Just think APDL

Now that we have introduced tcl/tk in a generic sense, we next move to writing a small tcl/tk application that interacts directly with ANSYS. This application will simply create a node at a given location in the x-y plane. As you will see, interacting with ANSYS through tcl is extremely straightforward. In a nutshell, you simply construct APDL commands as strings within tcl and then send them to ANSYS. Consider the code shown in Figure 7.

```
destroy .tplvl
set t [toplevel .tplvl]
wm title $t  Create Node
set xLab [label $t.lx  text  X: ]
set yLab [label $t.ly  text  Y: ]
set xEntry [entry $t.ex  textvariable x]
set yEntry [entry $t.ey  textvariable y]
set b1 [button $t.b1  command  CreateNode  \
          text  Create Node  ]
grid $xLab  row 0  column 0
grid $xEntry  row 0  column 1
```

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```
grid $yLab  row 1  column 0
grid $yEntry  row 1  column 1
grid $b1  row 2  column 0  columnspan 2

proc CreateNode {} {
    global x y
    set NextNode [ans_getvalue  NODE,0,NUM,MAXD ]
    ans_sendcommand  /prep7
    ans_sendcommand  n,$NextNode,$x,$y
}
```

Figure 7. Application to create a node in ANSYS.

To execute the code shown in Figure 7, enter the text into a text file named createnode.tcl and save this file in the current ANSYS working directory. Next issue the command shown in Figure 2 substituting createnode.tcl for hello1.tcl. When this code is executed a window resembling the one shown in Figure 8 should appear.

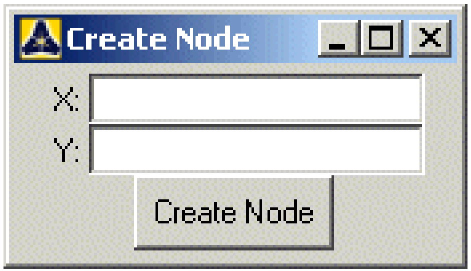

Figure 8. Create node dialog.

The interesting code in this example is contained within the CreateNode procedure. All of the code above the CreateNode procedure is responsible for creating and displaying the various widgets within the dialog box. Please refer to the previous section to gain an overview of what this code does. [3,4,5]

The CreateNode procedure is called whenever the button Create Node is pressed. The first line within this procedure declares two variables, x and y, as global variables. These variables are attached to the two entry boxes adjacent to the X: and Y: labels. Whenever a user enters a number into one of the text boxes, the tk toolkit updates the corresponding variable to contain the value entered by the user. By declaring these variables as global variables in the procedure CreateNode, we gain access to the values that the user typed into the two entry boxes.

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The next line in the CreateNode procedure creates a local variable named NextNode. This variable stores the result from a call to a procedure named ans_getvalue. The ans_getvalue procedure is the first of the two primary procedures used to communicate with ANSYS via tcl. This procedure mimics the *GET APDL command. In fact, the single argument to the ans_getvalue procedure is a string containing fields 3 through 8 of the *GET command in comma delimited format. Therefore, any parameter from an ANSYS database that is accessible via the *GET APDL command can also be accessed and stored in a tcl variable via the ans_getvalue procedure. So, by interpreting the argument as a *GET command, we see that we are simply asking ANSYS to return the next higher node number not yet defined in the database. We will then use this number to create a unique node at a given position.

The next two lines in the CreateNode procedure are calls to a function named ans_sendcommand. This is the second of the two primary procedures used to communicate with ANSYS. As mentioned above, the first procedure, ans_getvalue, is used to extract data from the ANSYS database. The ans_sendcommand procedure, however, is the compliment of the ans_getvalue procedure. This procedure is used to send specific APDL commands to ANSYS. The single argument to this function is a string comprising a valid APDL command. As you can see, the first call to ans_sendcommand sends the /prep7 command to ANSYS to force ANSYS to enter the preprocessor. The second call to the ans_sendcommand is more interesting. This call constructs, via variable substitution, an ANSYS command to create a node. As you can see, we build up the command by substituting the value of the NextNode variable into the second field of the ANSYS N command, and then the value of the x and y variables into the subsequent fields of the N command.

So, as an example, lets say there are no nodes currently defined in the database. The user types 0.5 into the X: entry and 1.5 into the Y: entry and then presses the Create Node button. This causes the CreateNode procedure to be called. When the call to ans_getvalue is executed, a return value of 1 is stored in the NextNode variable since no nodes are currently defined in the database. The tk toolkit has already stored 0.5 in the x variable and 1.5 in y variable. Since we declared these variables as global, we have access to their values within the CreateNode procedure. So, when the second call to ans_sendcommand is executed, the tcl interpreter substitutes the values for these three variables into the procedure argument before passing control to the ans_sendcommand. This variable substitution results in a string equal to n,1,0.5,1.5 . The ans_sendcommand then takes this string and feeds it to the ANSYS APDL command interpreter. Finally, the command interpreter executes this command just as if you had typed it into the command window. The result then is a new node at the location specified by the user.

Conclusion

We ve covered quite a bit of information in this article culminating in a description of how the tcl programming language interfaces with ANSYS. However, the key idea when programming in tcl for ANSYS was shown to be quite simple; that is Just think APDL . By using a combination of the ans_getvalue and ans_sendcommand procedures along with the tk toolkit, complex, highly interactive, and visually pleasing applications can be created within ANSYS that customize its functionality for a given process. Though we have covered a substantial amount of territory in this article, we ve really only highlighted a few aspects of programming in tcl. Hopefully, this introduction has successfully whetted you re appetite for programming in tcl within ANSYS. If so, I suggest that you peruse through the references sited at the end of this article to become more grounded in tcl/tk programming.

References

[1] www.tcl.tk/doc/tclHistory.html

[2] www.activestate.com/Solutions/Programmer/Tcl.plex

[3] Raines, P. & J. Tranter, *Tcl/Tk in a Nutshell*, O Reilly, 1999

[4] Harrison, M. & M. McLennan, *Effective Tcl/Tk Programming,* Addison-Wesley, 1998.

[5] Foster-Johnson, E., *Graphical Applications with Tcl/Tk*, M&T Books, 2/ed, 1997.

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Restarting an ANSYS Run

by Ted Harris

You ve just run your deflection analysis and checked the results, only to realize that you forgot a load step. Or you just ran a contact analysis but found that your contact stiffness was too low. Another possibility is that you ran your nonlinear analysis and it converged for part of the load but not all of the load. Do you have to rerun the whole thing to fix it? The answer is, No, because you can perform a restart analysis to pick up where you left off.

ANSYS always allows you to restart from the last converged substep of the last load step, or in other words from the last set of good results in your model. Additionally, with some foresight you can have ANSYS create restart files at certain intervals in your analysis. Restarts can be performed for any of the time points for which these restart files have been written.

The original type of restart in ANSYS is called a single-frame restart. This allows us to restart from the last converged solution. The single-frame restart requires a .db file saved in the same state as when the solution was initiated, the .emat file, if created, the .tri file if the frontal solver is being used, and the .esav or .osav files. Note that if your solution does not converge, ANSYS will automatically save the .db file for you.

The newer type of restart, the multi-frame restart, made its debut in ANSYS 5.6. This allows us to specify multiple restart points, if desired. To modify the behavior from the default, which is to allow a restart from the last converged substep, we utilize the RESCONTROL command. RECONTROL is available in the GUI through the solution controls dialog box (**Main Menu > Solution > Analysis Type > Sol n Controls**). The right side of the Sol n Options tab contains the input fields for the RESCONTROL command.

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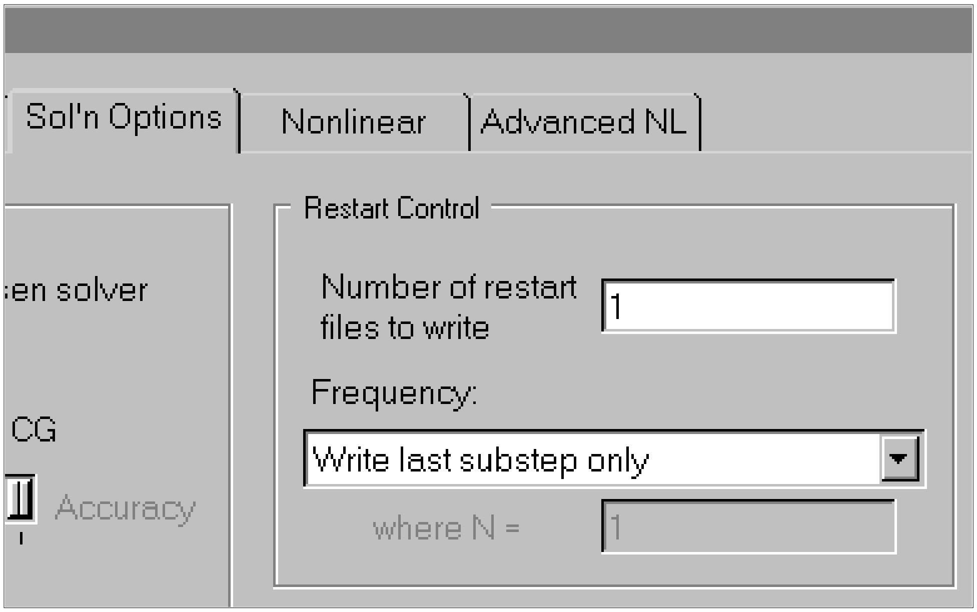

Number of restart files to write: 1

Frequency: Write last substep only

where N = 1

We have the option to specify a total number of restart files to write, as well as a frequency at which they will be written, such as every third substep. Note that by default, only a single set of restart files will be written, for the last converged substep of the last load step.

The files used in a multi-frame restart are the jobname.rdb file, which is a version of the .db file that has been automatically saved in the state the database was in at the start of the solution, the jobname.ldhi file, which contains the load history, and the jobname.rnnn file(s), which contain element saved data and solution settings for each restart point. These last files will have names of jobname.r001 for the first restart point, jobname.r002 for the second restart point, etc.

In order to perform a restart, we must have left the solution module since the last solution was completed. Otherwise, ANSYS thinks we want to continue with a subsequent load step. An exception is an unconverged solution, from which a restart can be initiated while still in the solution module.

In most cases we will be doing a multi-frame restart, even if from the last converged substep, because this is the default behavior in ANSYS.

To restart an analysis, we click on **Main Menu** > **Analysis Type** > **Restart**. The following image shows a typical result of performing that operation:

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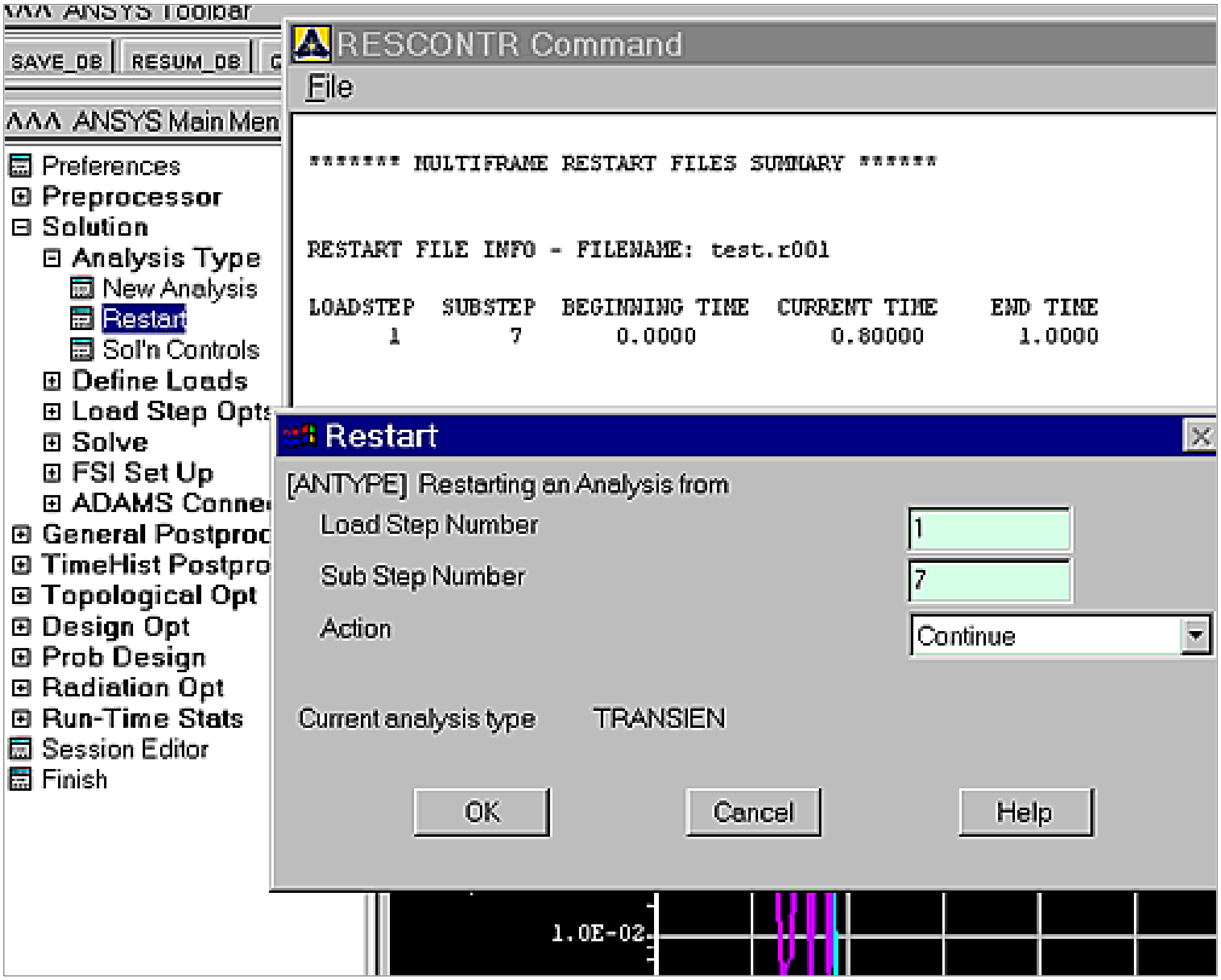

```
******* MULTIFRAME RESTART FILES SUMMARY ******


RESTART FILE INFO - FILENAME: test.r001

LOADSTEP  SUBSTEP  BEGINNING TIME  CURRENT TIME    END TIME
    1        7        0.0000          0.80000       1.0000
```

Restart

[ANTYPE] Restarting an Analysis from

Load Step Number: 1

Sub Step Number: 7

Action: Continue

Current analysis type: TRANSIEN

The white listing window shows us the available restart points for our analysis. In the case shown, we have a single restart point at load step 1, sub step 7. This corresponds to time 0.8 of our solution. We input the load step and sub step numbers for the desired restart point into the grey window, as shown. The action continue means that our analysis will attempt to progress with the solution. The other available actions are, end load step, and create results file. Typically we want our analysis to continue.

The procedure to do a restart analysis is as follows:

1. If you are still in ANSYS, leave the solution module and return to it by entering FINISH and then /SOLU or click on **Main Menu** > **Finish or Main Menu** > **General Postproc** and then return to **Main Menu** > **Solution**.
2. Specify a restart analysis by issuing ANTYPE,,REST (**Main Menu** > **Solution** > **Restart**).
3. Make the changes necessary to the loads, boundary conditions, solution options, etc. for the restart. For example, you can increase the number of substeps to enhance the convergence process, or change the loads to model a different loading condition.

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4. In case you used the Frontal solver (not the default), specify whether the triangularized matrix, jobname.tri, will be reused. See the documentation on the KUSE command for more information.
5. Initiate the restart solution by issuing the SOLVE command. (**Main Menu > Solution > Solve > Current LS**).

At this point, the solution will continue. Any results sets on the results file for load step/sub step/time points after the specified restart point will be deleted. If the restart solution is successful, new results sets will be added to the results file at the appropriate load step/sub step/time point indices.

By default ANSYS will utilize the multi-frame restart files, which again will allow us to at least perform a restart from the last converged substep of the last load step. We can use RESCONTROL prior to the initiation of our first solution to specify more restart points. The drawback in specifying lots of restart points is that our restart files will take up more and more room on our hard disk.

Note that for surface to surface contact elements, we must set KEYOPT(10) to 1 or 2 in order for the contact stiffness, FKN, to be changed between load steps or in a restart. This step is no longer necessary in ANSYS 7.0, however.

An additional capability of the multi-frame restart is to add results sets to the results file. This can be done for load step/sub step/time points for which restart files have been written but for which no results were initially written to the results file.

Restarts are useful in allowing us to explore a different load history than we originally planned as well as in recovering from an unconverged solution. We can hopefully make changes to our model to get a converged solution without having to run the entire solution again.

More information can be found in the on-line Help System, in the *Basic Analysis Procedures Guide*, Section 3.16, entitled *Restarting an Analysis*.

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Testing Elastomers for ANSYS

by Kurt Miller of Axel Products, Inc.

Introduction

The objective of the testing described herein is to define and to satisfy the input requirements of mathematical material models for elastomers that exist in ANSYS.

The testing of elastomers for the purpose of defining material models is often misunderstood. The appropriate experiments are not yet clearly defined by national or international standards organizations. This difficulty derives from the complex mathematical models that are required to define the nonlinear and the nearly incompressible attributes of elastomers.

Most of these models are referred to as hyperelastic material models and they include Mooney-Rivlin and Ogden models. However, most models share common test data input requirements. In general, stress and strain data sets developed by stretching the elastomer in several modes of deformation are required and fitted to sufficiently define the variables in the material models. A typical set of 3 stress strain curves appropriate for input into fitting routines is shown is shown in Figure 1.

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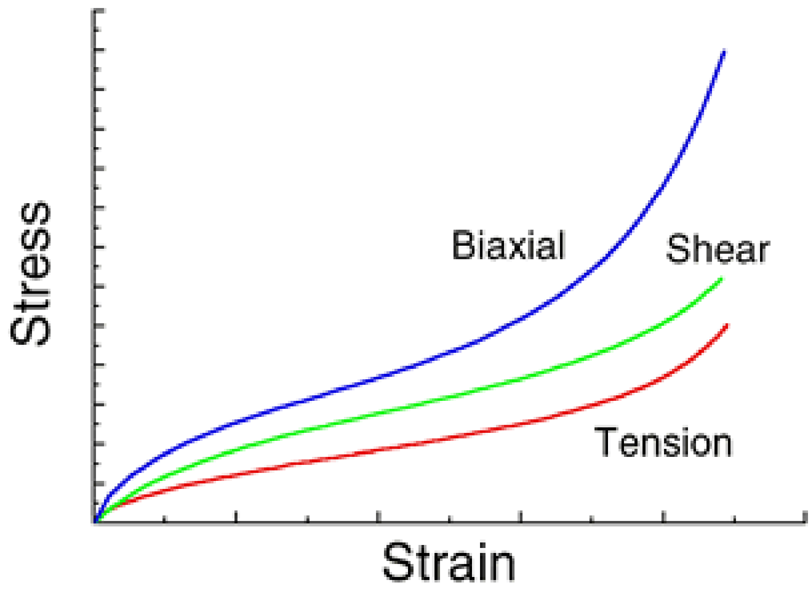

Figure 1. A Typical Final Data Set for Input into the ANSYS Curve Fitter.

Testing in Multiple Strain States

The modes of deformation each put the material into a particular state of strain. One objective of testing is to achieve pure states of strain such that the stress strain curve represents the elastomer behavior only in the desired state. The purpose of fitting multiple states of strain rather than just tension is that hyperelastic material models may easily create non-physical results in strain states not represented in the experimental data.

For incompressible elastomers, the basic strain states are simple tension, pure shear and equal biaxial extension. For slightly compressible situations or situations where an elastomer is highly constrained, a volumetric compression test may be needed to determine the bulk behavior.

Simple Tension Strain State

The most significant requirement for simple tension is that in order to achieve a state of pure tensile strain, the specimen must be much longer in the direction of stretching than in the width and thickness dimensions. The objective is to create an experiment where there is no lateral constraint to specimen thinning. A non-contacting strain measuring device such as a video extensometer or laser extensometer is required to measure strain where the pure strain condition exists.

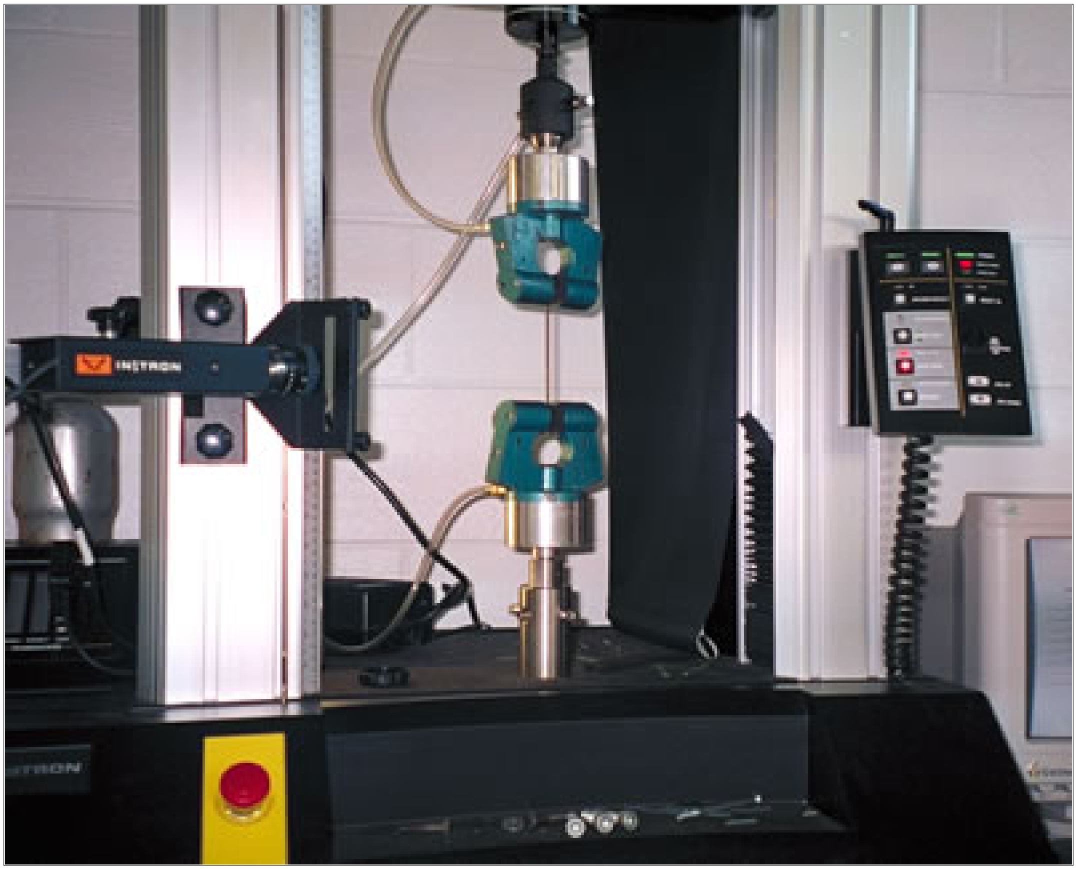

Figure 2. A Tension Experiment using a Video Extensometer.

Pure Shear Strain State

The pure shear experiment used for analysis is not what most of us would expect. The experiment appears at first glance to be nothing more than a very wide tensile test. However, because the material is nearly incompressible, a state of pure shear exists in the specimen at a 45-degree angle to the stretching direction. The most significant aspect of the specimen is that it is much shorter in the direction of stretching than the width. The objective is to create an experiment where the specimen is perfectly constrained in the lateral direction such that all specimen thinning occurs in the thickness direction.

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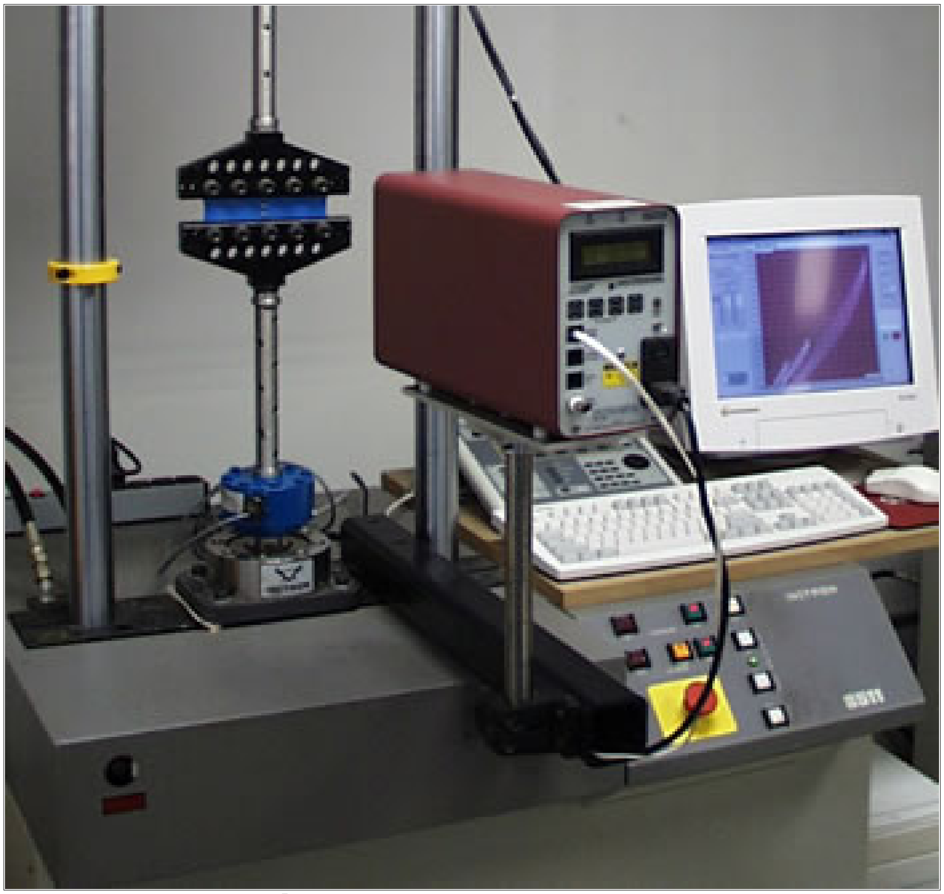

Figure 3. A Pure Shear Experiment using a Laser Extensometer.

Equal Biaxial Strain State

For incompressible or nearly incompressible materials, equal biaxial extension of a specimen creates a state of strain equivalent to pure compression. Although the actual experiment is more complex than the simple compression experiment, a pure state of strain can be achieved which will result in a more accurate material model. The equal biaxial strain state may be achieved by radial stretching a circular disc.

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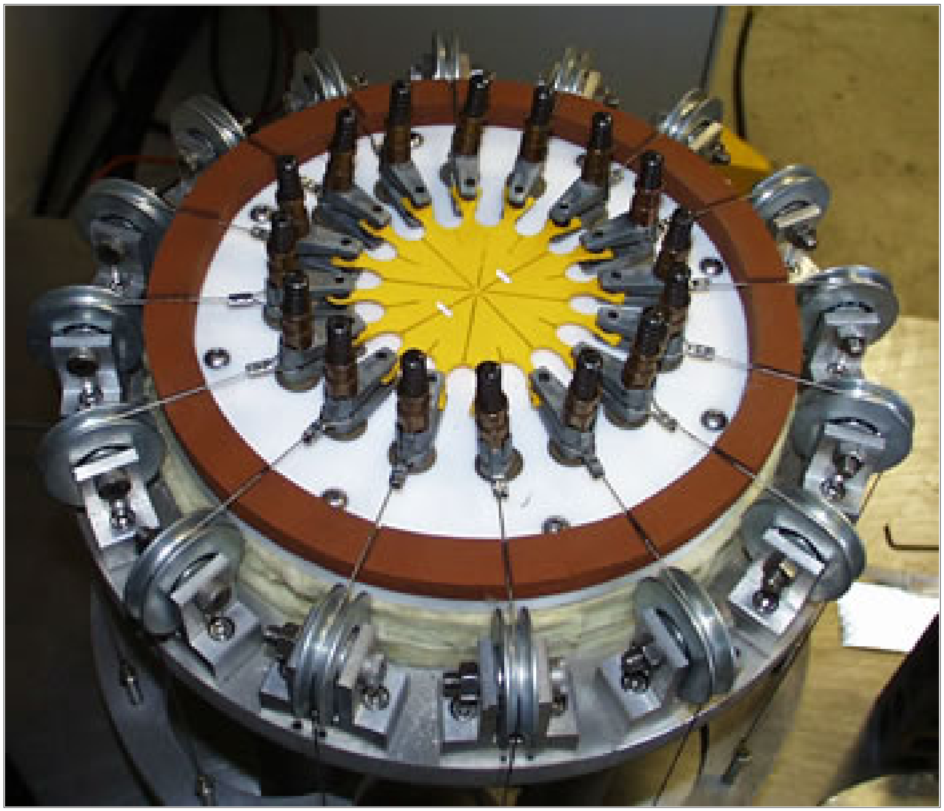

Figure 4. A Biaxial Extension Experiment.

Volumetric Compression

Volumetric compression is an experiment where the compressibility of the material is examined. In this experiment, a cylindrical specimen is constrained in a fixture and compressed. The actual displacement during compression is very small and great care must be taken to measure only the specimen compliance and not the stiffness of the instrument itself. The initial slope of the resulting stress-strain function is the bulk modulus. This value is typically 2-3 orders of magnitude greater than the shear modulus for elastomers.

Using Slow Cyclic Loadings to Create Stress Strain Curves

The structural properties of elastomers change significantly during the first several times that the material experiences straining. This behavior is commonly referred to as the Mullin s effect. If an elastomer is loaded to a particular strain level followed by complete unloading to zero stress several times, the change in structural properties from cycle to cycle as measured by the stress strain function will diminish. When the stress strain function no longer changes significantly, the material may be considered to be stable for strain levels below that particular strain maximum.

If the elastomer is then taken to a new higher strain maximum, the structural properties will again change significantly. One example of this behavior is shown in Figure 5 where an elastomers is strained to 20% strain for 10 repetitions followed by straining to 50% for 10 repetitions and followed by straining to 100% for 10 repetitions.

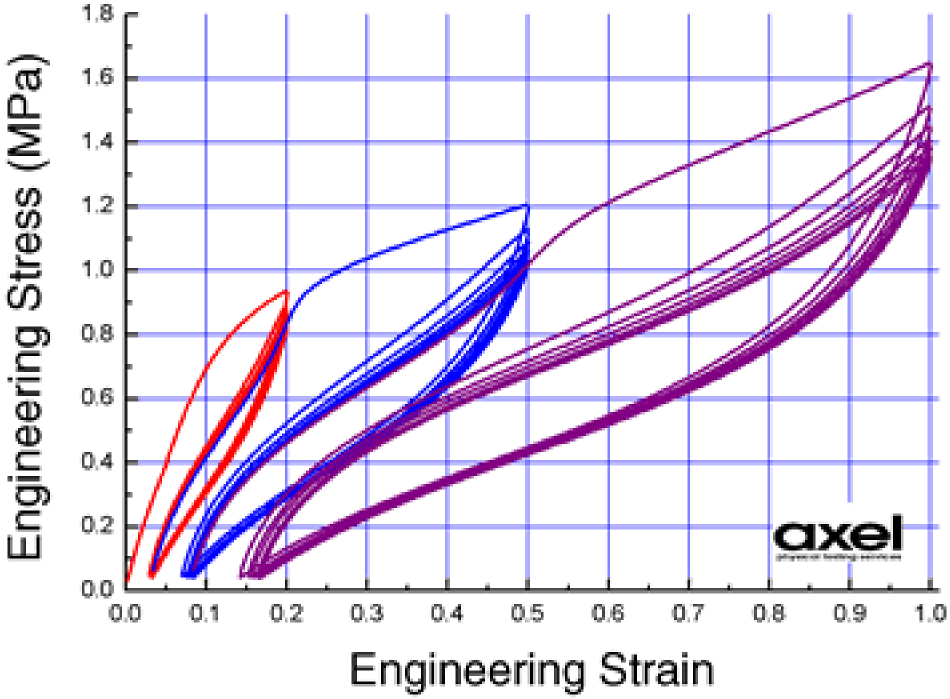

Figure 5. Multiple Strain Cycles of an Elastomer at 3 Maximum Strain Levels.

Observations

Several observations can be made regarding this behavior that is true to a varying degree for all elastomers.

1. The stress strain function for the 1st time an elastomer is strained is never again repeated. It is a unique event.

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2. The stress strain function does stabilize after between 3 and 20 repetitions for most elastomers.
3. The stress strain function will again change significantly if the material experiences strains greater than the previous stabilized level. In general, the stress strain function is sensitive to the maximum strain ever experienced.
4. The stress strain function of the material while increasing strain is different than the stress strain function of the material while decreasing strain.
5. After the initial straining, the material does not return to zero strain at zero stress. There is some degree of permanent deformation.

Limitations of Hyperelastic Material Models

Most material models in commercially available finite element analysis codes allow the analyst to describe only a subset of the structural properties of elastomers. This discussion revolves around hyperelastic material models such as the Mooney-Rivlin and Ogden formulations and relates to those issues which effect testing.

1. The stress strain functions in the model are stable. They do not change with repetitive loading. The material model does not differentiate between a 1st time strain and a 100th time straining of the part under analysis.
2. There is no provision to alter the stress strain description in the material model based on the maximum strains experienced.
3. The stress strain function is fully reversible so that increasing strains and decreasing strains use the same stress strain function. Loading and unloading the part under analysis is the same.
4. The models treat the material as perfectly elastic meaning that there is no provision for permanent strain deformation. Zero stress is always zero strain.

The Need for Judgment

Because the models use a simple reversible stress strain input, one must input a stress strain function that is relevant to the to loading situation expected in the application. Naturally, this may be difficult because the very purpose of the analysis is to learn about the stress strain condition in the part. However, there are a few guidelines that may be considered.

1. If the focus of the analysis is to examine the first time straining of an elastomeric part, then use the first time stress strain curves from material tests. This might be the case when examining the stresses experienced when installing a part for the first time.
2. If the focus of the analysis is to understand the typical structural condition of a part in service, use stress strain curves derived by cycling a material until it is stable and extracting the stabilized increasing strain curve.
3. If the focus of the analysis is to understand the unloading performance of a part in service by examining the minimum stress conditions, extract a stabilized decreasing strain curve.
4. Perform experiments at strain levels that are reasonable for the application. Large strains that greatly exceed those that the part will experience will alter the material properties such that they are unrealistic for the application of interest.
5. Stabilize the material at 2 or more different levels to cover a broader range of performance and to measure just how sensitive the structural properties are to maximum strain levels.

Conclusion

Physical testing of elastomers for the purpose of fitting material models in finite element analysis requires experiments in multiple states of strain under carefully considered loading conditions. The material models themselves have limitations and these limitations must also be considered.

More technical downloads on the testing of plastics and elastomers may be found at: www.axelproducts.com/pages/Downloads.html.

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