

KAPL-P-000196

(K97133)

CONF-980708--

A MESH DENSITY STUDY FOR APPLICATION TO LARGE DEFORMATION ROLLING
PROCESSEVALUATION

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December 1997

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A Mesh Density Study for Application to Large Deformation Rolling Process Evaluations

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Abstract

When addressing large deformation through an elastic-plastic analysis the mesh density is paramount in determining the accuracy of the solution. However, given the nonlinear nature of the problem, a highly-refined mesh will generally require a prohibitive amount of computer resources. This paper addresses finite element mesh optimization studies considering accuracy of results and computer resource needs as applied to large deformation rolling processes. In particular, the simulation of the thread rolling manufacturing process is considered using the MARC software package[1] and a Cray C90 supercomputer. Both mesh density and adaptive meshing on final results for both indentation of a rigid body to a specified depth and contact rolling along a predetermined length are evaluated.

Background

Many applications in the industrial world rely on threaded fasteners as a means for joining components. Depending on the application, fatigue behavior and/or the component's environment can dictate equipment life expectancy. Cold rolling manufacturing processes have been developed as a means of introducing beneficial residual stresses into thread roots, thereby increasing resistance to fatigue and environmental effects. However, the benefits are predominately determined by empirical means with very little numerical assessment of the residual stress magnitudes. Hence, potential design benefits that might be realized from a basic understanding of the residual stresses generated due to the cold rolled thread forming process have, for the most part, not yet been established. To gain further understanding of the stress states in a thread root developed during and after cold rolling, finite element studies were performed to predict the thread root residual stresses. In particular, the sensitivity of the results to the finite element mesh was investigated and presented herein.

Discussion

The accuracy of a finite element analysis is very much dependent on the type of element and degree of mesh density selected to perform the analysis. When establishing the finite element mesh, consideration must be given to the component geometry, the applied loading, and the computer resources.

The need for contact algorithms dictates the use of linear elements for model construction, thereby increasing the total number of elements required for an accurate solution. For these sensitivity studies a linear displacement/ constant strain 4 noded quad (MARC element library # 11) plane strain element was used[1]. This element provided both a linear variation of displacement within the element and a constant strain (stress) across the element. Use of this element provides for continuity of displacements across element boundaries, but continuity of strain is not guaranteed.

An appropriate mesh density (also referred to as degree of mesh refinement) can be established using either a global or local criteria and also in a symmetric or unsymmetrical approach. A global mesh configuration provides for mesh refinements to be applied uniformly throughout the entire model. This type of mesh refinement is applicable regardless of the type of loading or exist-

ence of geometric discontinuities. Global mesh refinement is relatively easy to implement, however, it can generate a large number of elements that might tax available computer resources.

Local mesh configuration refinements account for loading locations and discontinuities, either geometric or resulting final deformed shapes. Mesh refinement can result in a labor intensive iterative process to obtain an optimized mesh. A modification to this technique permits the user to provide mesh refinement about a specific node or provide a bias for the element distribution. Although this approach will decrease computer run time, the amount of time spent to apply this technique to a simple sensitivity study may be prohibitive. (See Figure 1)

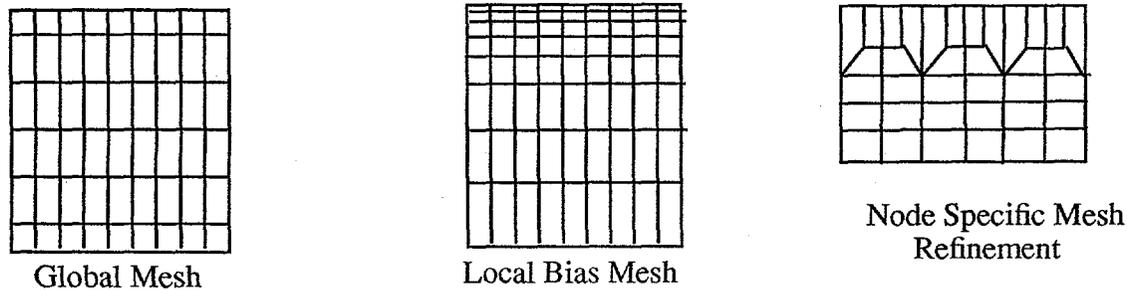


Figure 1

For any of the mesh refinement approaches selected, the sensitivity study procedure would generate an initial coarse mesh and perform a benchmark analysis. Using this mesh as a datum, refine the mesh and rerun the analysis. Each time the mesh is refined and the analysis performed a comparison of the results (stress, strain, displacement, etc.) at selected points in the model, coupled with a comparison of computer resources utilized (run time and memory), will formulate the basis for selection of an optimized mesh.

In addition to the user controlled mesh refinement options, MARC has an adaptive meshing option (automatic mesh refinement). This option allows the user to select a specific criteria/limit, which upon exceeding, the element subdivides into additional equal elements within the initial element boundary. Different levels of adaptation are available depending on the degree of accuracy required. (Figure 2)

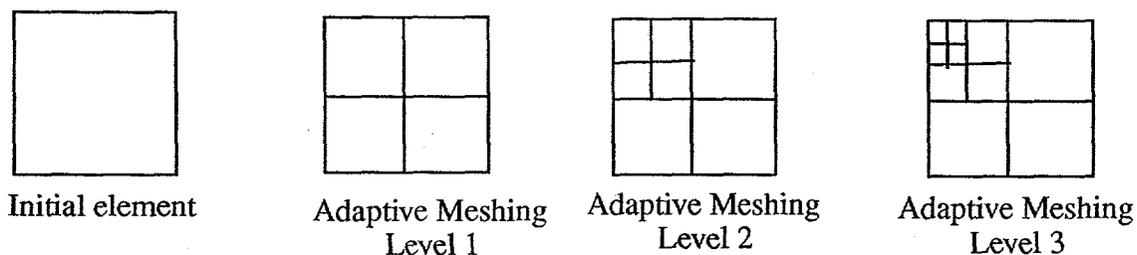


Figure 2

Both the global mesh refinement and the adaptive mesh option were evaluated to determine an optimum mesh for undertaking a thread form rolling analysis. The basis for this decision was threefold. First, the simplistic nature of the loading geometry and the expected deformed geometry did not appear to require exotic modelling efforts to localize either element configuration or stresses. Second, adaptive meshing techniques can be used as a check against the results of the

user driven mesh doubling techniques. Third, the mesh selected in this study must be readily expandable to a third dimension to allow for actual process simulation modelling.

Studies Performed

Mesh sensitivity studies were performed for two cases: (1) rigid body indentation of a die into the base material to simulate an actual thread form and (2) plate deformation due to rolling.

Indentation Study

A single thread model was constructed to test the effect of mesh density on the residual stresses generated by the indentation facet of the thread rolling process. This model utilized plane strain elements and consisted of a one inch thick flat plate supported along the bottom surface with a rigid body indenter representing a single thread form. The rigid body thread form was indented approximately 40 mils into the plate without friction and then removed. No consideration was given to rate of deformation, incremental loading, convergence testing, or rolling. It was assumed that any conclusions regarding mesh accuracy would be the same whether a single thread or multiple threads were used.

To determine the optimized mesh with respect to computer run time and indentation solution accuracy, a common set of node points was selected for investigation. The stress at these node points are directly influenced by loading and mesh refinement. The selected nodes were the surface node (node 8) directly under the thread form and the adjacent node (as shown in the coarse mesh of Figure 3) through the depth of the plate (node 65). As the mesh is refined the number of nodes between Nodes 8 and 65 increases. By monitoring these two locations the effects of the mesh refinement on both the stress at the surface and at a depth slightly below the surface can be assessed.

The coarse mesh shown in Figure 3 modelled only two elements in contact under the roller and represented the base case mesh. For this case the basic element size was taken as 0.500" x 0.250". All the other cases were generated from this case. Figure 4 represents a first generation doubling mesh refinement used in this study.

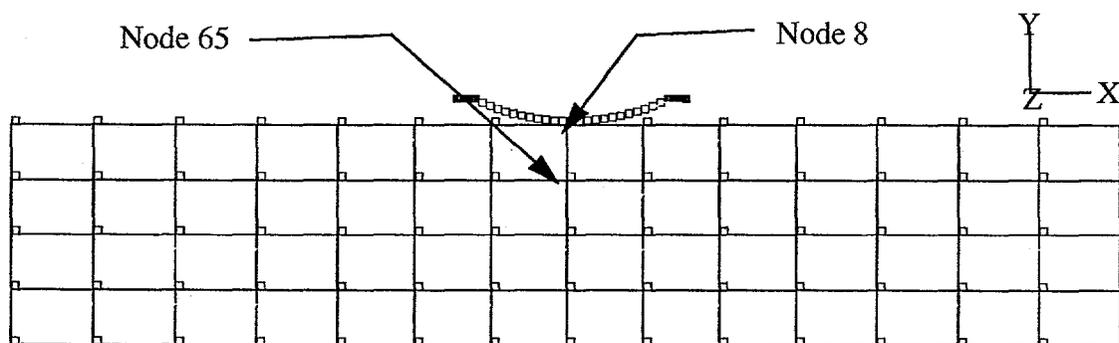


Figure 3 - Basic Mesh - Datum Model - Indentation

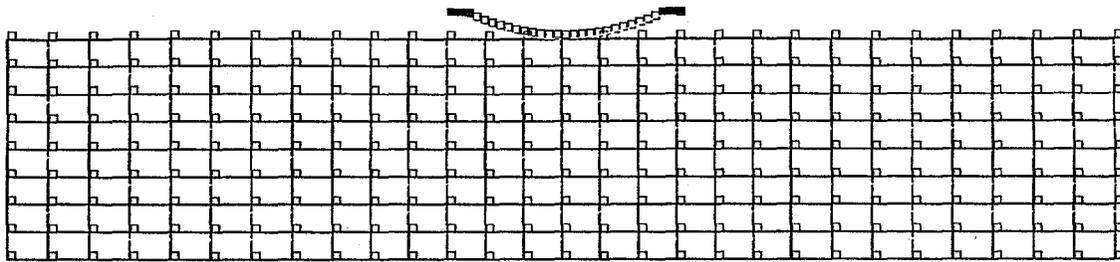


Figure 4 - First Generation Mesh - Indentation Study

A second series of models was created using the datum mesh and the adaptive mesh option with applied adaptive meshing of levels 1, 2, and 3 (Figure 2), each in a separate case. An additional case was evaluated using the second generation mesh from the first series and the adaptive meshing option to a level 2. This provided an additional data point based on an extremely refined mesh. The adaptive mesh capability automatically increases the number of nodes and elements to enhance solution accuracy. During this process an element is divided into smaller elements while writing constraint equations for newly generated common nodes thereby ensuring compatibility. For this study, the user defined adaptive criteria/limit is based on a von Mises stress value. Figure 5 provides an example of the adaptive mesh.

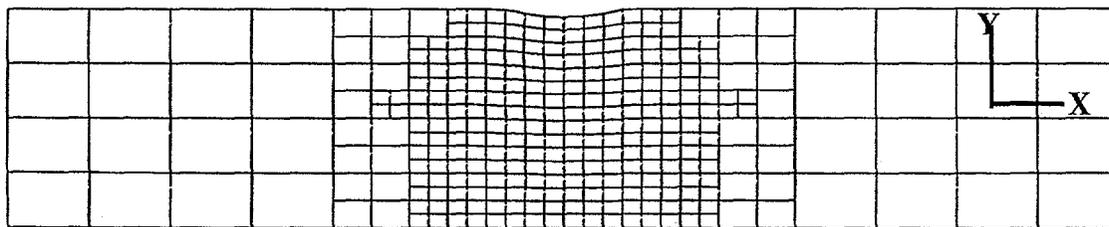


Figure 5 - Adaptive Mesh Option - Level 2 - Indentation Study

Rolling Study

Mesh density in the rolling direction was assessed using a plane strain finite element model of a one inch thick plate five inches long. A rigid body roller without the thread form was modelled to simulate plate rolling. A single pass of 0.050 inch thickness reduction was modelled with the plate bottom surface fixed in the through thickness direction and a single node on the bottom surface restrained in the rolling direction to maintain model stability.

Mesh refinement followed the doubling pattern applied for the indentation portion of this study. A basic mesh was selected (Figure 6) and then refined by creating first a 2^2 and then a 2^4 number of elements. The adaptive mesh option for the rolling sensitivity study was not examined.

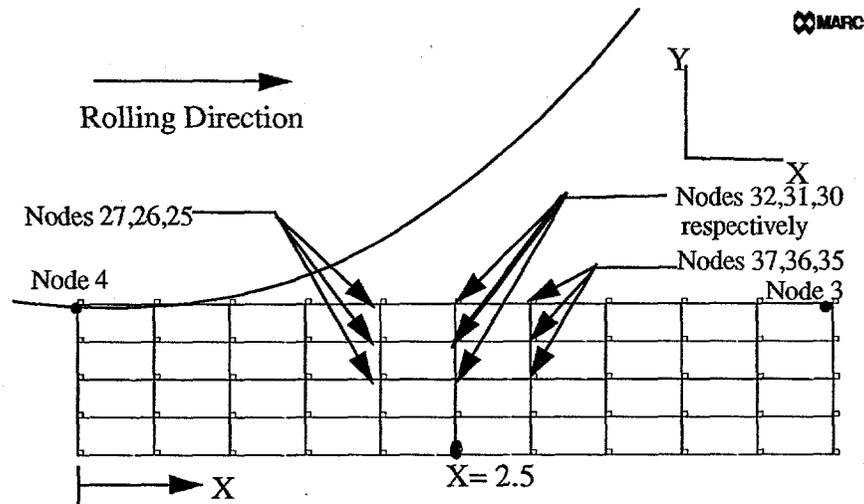


Figure 6 - Basic Mesh - Datum Model - Rolling Study

Nodal points chosen to assess mesh optimization are based on residual stress levels at these locations and overall plate dimensional changes after the rolling. Changes in displacement are assessed on the rolled surface end points, nodes 4 and 3, starting and ending of rolling respectively, and at node 32 representing the maximum displacement at a point sufficiently removed from any end effects.

Indentation Study Results

Table 1 identifies the cases used to optimize the mesh for the indentation portion of this effort. The table groups information with respect to either mesh doubling or adaptive mesh refinement methods. Included are the number of elements, degrees of freedom (DOF), and C90 computer run time (CPU) associated with each run.

Table 1 Indentation Study Cases

File Name	Total Number Elements	Total Number Degrees of Freedom	Run Time (CPU)	File Name	Total Number Elements	Total Number Degrees of Freedom	Run Time (CPU)
Basecase	56	150	155.7	AdaptAL1	120	262	287.2
Basecase2X	224	522	340.7	AdaptAL2	408	734	464.8
Basecase4X	896	1938	1495.0	AdaptAL3	1528	2482	1923.9
Basecase8X	3584	7458	6390.0	Adapt4XAL2	5240	8654	11294.3

Table 1 results are graphically presented in Figure 7 and are correlated with respect to DOF. Based on these results the following observations can be made:

- 1) Curves 1 and 2 represent stress results in the transverse direction (S_x) to the indentation for nodes 8 and 65, respectively. Results for each point follow the same trends (exclusive of magnitude) with each successive mesh refinement. The results also show very little change in stress magnitudes beyond a 2000 DOF model configuration with each successive mesh refinement. This indicates that the elemental response for the transverse direction can be accurately represented for the entire model by using the mesh represented by approxi-

mately 16 elements through the thickness (i.e. 0.0625" per element for Basecase4X).

- 2) Curve 3 represents the stress (S_y) for node 65 in the through thickness direction and coincident with the indentation loading. The results indicate that the change in stress magnitude does not appear to level out until the model reaches about 7500 DOF. However, this degree of refinement also increases the required CPU threefold from the previous case (Curve 4). Hence, to accurately predict stresses in the through thickness direction, a mesh refinement of approximately 32 elements through the thickness is needed. Any relaxation of this mesh would need to have the stress levels assessed for accuracy.

If more complex loading models are being considered the need for accuracy of the (S_y) stress must be balanced against the available CPU. In the case of a rolling qualification program, the more critical stress components are those that will potentially contribute to crack propagation, i.e. the stress profiles that lie in the transverse and parallel directions to the rolling process. Thus for actual manufacturing process evaluations some relaxation of the mesh requirements in the through thickness direction when considering S_y stress may be tolerated.

S_y stress results, at only node 65 are considered for evaluation of mesh adequacy. When addressing contact elements, size dictates the contact tolerance, which in turn determines which elements and when they come in contact with the rigid body. As a mesh became more refined, without proper adjustment to tolerances, surface nodes may stick to the rigid body upon loading/unloading thereby creating fictitious stress results. Thus the parameters and tolerances associated with contact problems would need to be adjusted with each new mesh. For comparison consistency, this mesh study was conducted divorced from convergence reliance, therefore, the results from Node 8 have been omitted from the mesh refinement selection process.

- 3) Curve 4 represents the relationship between degrees-of-freedom and required CPU. The curve depicts an exponential relationship between degrees-of-freedom and applied computer time, which is considered fairly standard for a nonparallel computational scheme. Mesh selection should not be dictated solely by the results of Curve 4. However, it could be used for a secondary criteria should there be little difference between stress results of subsequent mesh refinements.

- 4) Curve 5 identifies a 2000 DOF model as the optimal cross-section mesh.

During the course of this study, examination of the results revealed that the increment at which adaptation occurred was critical to obtaining the correct solution. Results from case "AdaptAL3" (not shown in Figure 7) did not follow the trends observed by the other mesh refinement models. For three of the four cases that utilize the adaptive option, adaptation was completed prior to the last loading increment. However, for AdaptAL3 the last loading increment was also the one that experienced adaptive meshing. During the adaptive process the overall compliance of the model is changed when the mesh undergoes refinement (i.e., an increase in DOF). This increase in DOF influences the stress calculations for each subsequent increment. Comparing the final mesh state from the other mesh cases to that of model AdaptAL3 indicated that the AdaptAL3 model had not reached a fully adapted mesh state. Thus the irregular stress results observed were created by a difference in model compliance rather than any software or modelling problems.

A lesson learned from this portion of the mesh sensitivity studies was that the use of adaptive meshing must be considered carefully when evaluating not only mesh adequacy, but also accuracy of the results. An incomplete adaptive process could generate results significantly different from reality.

Rolling Study Results

Results for the rolling study case are reported in Table 2. The maximum percent change in stress from the previous coarser mesh is the basis for optimization. Stress results are examined for stresses parallel to the rolling direction (S_x) at Nodes 26, 31, and 36 (Figure 6). Selection of these nodes eliminates any end effects that might influence the results. In addition, the surface nodes associated with contact are affected by changes to convergence tolerances necessitated by increased mesh refinement. To eliminate this variable, i.e., contact tolerance/convergence criteria, from the mesh sensitivity studies, surface nodes have been omitted from stress comparisons. In addition, the nodes representing the surface end points and the maximum through thickness displacements have been examined in Table 3 to assess mesh refinement influence due to a rolling type loading.

Table 2 Rolling Study Cases

File Name	Total Number Elements	Total Number Degrees of Freedom	Run Time (CPU)	% Change in S_x from previous mesh
CaseC	40	110	54.7	----
CaseC2X	160	378	228.6	32.1
CaseC4X	640	1394	1070.0	3.8 - 7.3

Table 2 results indicate that a mesh of 16 elements through the thickness provides sufficient refinement to have a high degree of confidence in the results. This conclusion is based on the relatively small change in the stress values when refining the mesh between cases CaseC2X and CaseC4X. This level of mesh refinement coincides with the conclusions drawn by the indentation study.

Also in support of this mesh density is the change in maximum displacement, as reported for node 32, of approximately 1.0% from the previous case when comparing cases CaseC2X and CaseC4X (Table 3). This indicates that compliance of the model is sufficiently defined to eliminate the need for further mesh refinement. An additional observation concerns the increasing displacement reported for the surface end nodes. Each mesh refinement creates a more flexible surface element thereby permitting greater surface deformation during the rolling process. This is also reflected in the surface stresses in the rolling direction. Based on this information, proper interpretation of surface rolling directional stress results is required from any qualification test modelling effort. If surface stress results are to be evaluated, gauss point stresses should be utilized.

For this rolling study a length to depth aspect ratio of 2:1 was maintained through out the refinement process. Although other ratios could have been used, this aspect ratio was demonstrated to adequately represent the stress state without generating too many elements.

Table 3 2D Rolling Study Displacement Results (inches)

Location		CaseC	CaseC2X	CaseC4X
Node 3	δx	0.259	0.296	0.330
	δy	-0.044	-0.047	-0.047
Node 4	δx	0.007	0.031	0.064
	δy	-0.037	-0.038	-0.047
Maximum δy (Node 32)		-0.0445	-0.0468	-0.0473
Change in δy from previous mesh		N/A	5.1%	1.0%

Additional insight into mesh adequacy can be obtained from the degree of element distortion and the stress gradient that exists across an element. Element distortion is related to aspect ratio, element taper, and skew angularity. The results of the study indicated that the coarser the mesh the greater the amount of element distortion that occurs. This is a direct result of the larger element experiencing more deformation at one end. Hence the distortion will be greater across the element. In contrast, the smaller the elements, the more flexible the component, thereby permitting a better representation of the deformed shape and less elemental distortion.

A large stress gradient occurring across an element indicates a significant difference in gauss points stresses within the element, resulting in reduced accuracy of stress results. This large elemental gradient is typically reduced or eliminated by providing a mesh refinement in the area in question. The elemental stress gradient is generally linked to the change in stress comparisons that is often used when comparing the results between mesh densities. Hence, a small difference between stress results from subsequent mesh refinements will also eliminate large elemental stress gradients. In general, as mesh refinement was introduced, the maximum stress gradient across an element reduced from an initial condition gradient of 214% to one of less than 10%.

Conclusions

A mesh density sensitivity study was performed to establish a reasonable mesh for use in a finite element model simulation of the thread rolling process. Results of the indentation study concluded a mesh that maintained a through thickness density of 16 elements (element thickness = 0.0625") provided an optimum balance between stress accuracy and computer resources. An optimum mesh from the rolling study was considered established when a length to depth aspect ratio of 2:1 was maintained based on a reasonable through thickness mesh selection.

References:

[1] MARC Software Version 6.2, MARC Analysis Research Corp. Palo Alto, Ca

Acknowledgment

The author would like to thank Drs. GT Embley and SJ Pavone for their input in preparing this manuscript. The author would also like to thank J. Dierberger of MARC Analysis Research Corporation for support in the use of the MARC software.

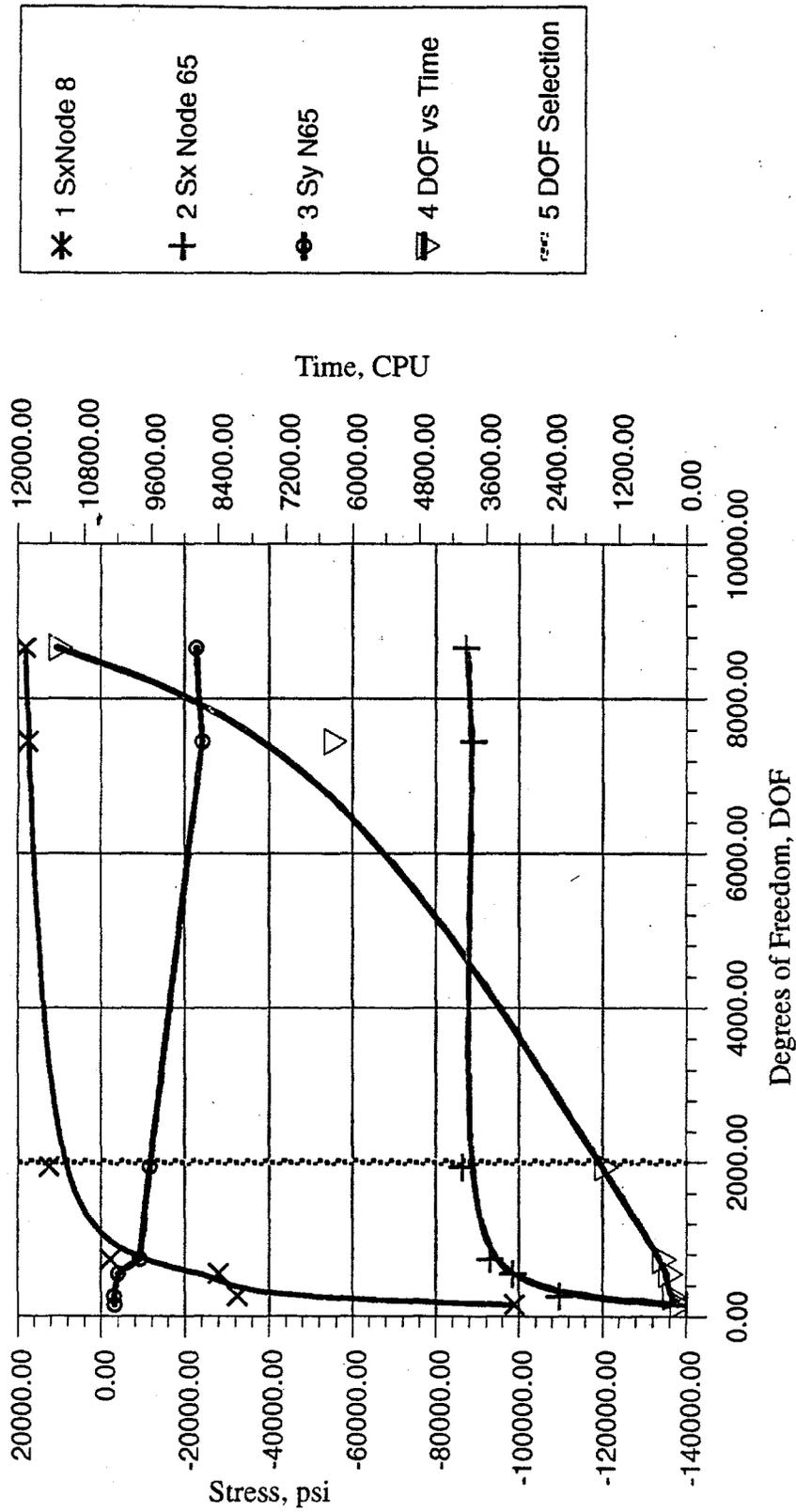


Figure 7 - Indentation Study Results