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A FINITE ELEMENT EVALUATION OF RESIDUAL STRESS IN A THREAD FORM GENERATED BY A COLD-ROLLING PROCESS

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A Finite Element Evaluation of Residual Stress In a Thread Form Generated by a Cold-Rolling Process

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ABSTRACT

This paper presents a finite element evaluation of residual stress in a thread form generated by a cold rolling process. Included in this evaluation are a mesh development study, methodology sensitivity studies, and the effects of applied loads on the stress in a rolled thread root. A finite element analysis of the thread forming process using implicit modelling methodology, incremental large deformation, elastic-plastic material properties, and adaptive meshing techniques was performed. Results of the study indicate the axial component of the residual stress in the thread root of the fastener is highly compressive. Results also indicate that a rolled threaded fastener loaded to an average tensile stress equal to yield through the cross-section will retain compressive stresses in the thread root. This compressive stress state will be advantageous when evaluating fasteners for fatigue and environmental concerns.

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. Empirical testing efforts [1] to understand the fundamentals principles acting to generate the final stress state in a thread root fabricated by a rolling process are unable to quantitatively correlate changes in process parameters with changes in stress states.

Hence, potential design benefits that might be realized from a basic understanding of the residual stresses generated by a cold rolled thread forming process have, for the most part, not yet been established. This lack of predictive capability prompted efforts to develop an analytical program to determine thread root stresses due to the rolling process through the use of computer modelling. This paper is a continuation of the work of Reference 2 and reports the stress states in a thread root developed during and after cold rolling under simulated applied loadings.

DISCUSSION

This work supports an effort to gain more assurance of improved fastener fatigue resistance through the use of rolled fasteners. During the cold-forming thread rolling process, threads are formed on a round workpiece as it passes between rotating dies. This process generates a thread form without metal loss and with a higher yield strength due to the cold-working process. Testing has indicated that this process improves fatigue life,[1,3,4], which is attributed to the creation of compressive residual stresses on the thread root surface. In an effort to verify this empirical result, an analytical evaluation is desired to obtain a fundamental analytical understanding of the thread rolling process to support design applications.

To obtain a better fundamental understanding of the principles behind the apparent increased performance brought about by thread rolling finite element analysis is being performed. Reference 2 examined the residual stress state of a modified, oversized ACME thread root as part of a software

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qualification program supporting this analytical methodology. These analytical methodologies are extended to the evaluations of a thread form and include:

- Establishment of an adequate mesh for use in a 2-D plane strain finite element model representation of the thread form.
- Application of simulated end loading subsequent to residual stress state determination.
- Sensitivity studies to verify accuracy of the results.

The studies performed in this report primarily focus on the X-direction stress, or axial stress with respect to a loaded stud. Note the graphical output refers to the X-direction stress as the first component of stress (S_{11}). This stress state is of critical concern when addressing fatigue effects on studs.

Finite Element Model

For this evaluation the MARC software analysis package [5] with Lagrangian update capabilities, large strain formulation, plasticity/work hardening, adaptive meshing [6], and contact/friction options was used. In addition, an implicit, static, rate and time-independent analysis using rigid body motion as a means of providing loading to simulate a metal forming process was assumed.

The finite element modelling incorporated 2-D, four-noded, first-order (linear) isoparametric plane strain elements (MARC Element 11). This element provides for the finite strain plasticity and updated Lagrangian procedures necessary to address a highly non-linear contact problem.

Although the thread rolling process is a 3-D process, this initial investigation assumes a 2-D plane strain model is acceptable based on the localized stress effect created by the rolling process with respect to the overall thread and stud dimensions.

Material Properties

This study addresses commercially available ASTM Alloy 625 material. The elastic-plastic material properties used in the finite element analysis are shown in Table 1 and are the results of prior tensile testing [2].

Mesh and Model Development

Figure 1 provides the dimensions of the thread form used in this evaluation. These dimensions formed the basis for both the rigid body die model and the desired final deformed thread configuration.

The initial modelling effort consisted of a five thread 2-D plane strain model employing a standard rectangular mesh (Figure 2), with symmetry boundary conditions invoked on the three sides not subject to die indentation.

The model loading consisted of a total indentation of 0.040" over 100 load increments with subsequent unloading over the same number of increments. This mesh configuration resulted in ill-conditioned elements causing convergence problems and lead to premature termination of the runs. An ill-conditioned element is one that distorts to such a degree that it turns itself inside out, provides an unacceptable aspect ratio, or generates a skew angle approaching or greater than 180 degrees [6]. Any of these conditions force the code to abort the solution and flag the user. Observations from this study included:

- The smaller the mesh, the more difficult convergence became due to the relatively large displacement to element size ratio. A series of models were run varying the number of iterations, the number of elements and element density, and the convergence tolerances without any success in approaching the desired deformation. The best results obtained were 50% completion of the desired deformation.
- A study using coarser elements resulted in program termination due to ill-conditioning elements. Again, a trade-off between number of elements and element size was assessed. With fewer elements, there were some cases that ran to completion, but the stresses reported across the element differed by such a large amount that the results were questionable. The results indicate that an acceptable aspect ratio for a rectangular element would undergo a transformation to a final element configuration whose shape is too deformed to prevent ill-conditioning of the elements prior to completion of the loading.

With an automatic mesh reconfiguration program unavailable, another avenue of mesh generation was applied. This alternate method entailed the use of material flow lines as the basis for mesh generation. When a material undergoes large plastic deformation the stress state in the surrounding region takes on a stress pattern that will reflect the deformed condition. This final stress field flow pattern was used to develop a workable mesh configuration.

An adequate mesh was developed by considering the flow field in the direction normal to the indentation. In this approach a finite element mesh is generated, so elements in the direction of the deformation initially have high aspect ratios (4:1 as modelled mesh). However, upon completion of the loading the final deformed element shapes will ideally approach a one-to-one element aspect ratio (0.5:1 final mesh aspect ratio). This modified mesh resulted in the model running to completion. The modified mesh concept is demonstrated in Figure 3 for the entire plane strain model, and Figures 4a through 4f for a single thread form development. Figures 4a through 4f also demonstrate the adaptive meshing option.

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Indentation Results

The y displacement (δ_y) results in this evaluation only reached a crest-to-root distance of 0.0552". Attempts to further deform the model to reach the desired crest-to-root distance (0.0718") resulted in ill-conditioned elements and/or convergence problems. To progress further would require either extensive mesh modifications or automatic remeshing capabilities. Although the finite element (FE) model final crest-to-root distance is less than desired, the trends observed and conclusions drawn are judged to be appropriate for thread rolling process evaluations.

Figure 5 reflects the symmetry of the model results; and, therefore, throughout this report only one location (center thread root surface node, node 72 see Figure 4f) was selected to assess the relative effects of each variation on the particular parameter. Figures 6 and 7 illustrate the first component of stress (S_{11}); that is axial stress, with respect to a thread orientation for the final loaded increment (inc. 99) and the fully unloaded increment (inc. 196), respectively. Comparison of the S_{11} values show a significant increase in compressive stress. For the fully loaded condition (Figure 6), the compressive stress is actually beginning to decrease in the thread root region due to the flow of the material up into the flank portions of the thread. As the material flows up into the die and forms the crest, compressive stress in the flank region begins to increase. This increase in flank compressive stress and decrease in root stress is a result of the material flowing to reach an equilibrium state under the uniformly applied loading.

Figure 7, representing the fully unloaded condition, shows an increase in the compressive stress in the thread root subsequent to unloading. This increase in compressive stress reflects the amount of springback that occurs upon unloading. This springback is also partially responsible for the creation of the tensile stress along the upper top surface of the thread flank.

One can also observe that the depth of the compressive stress state during loading is relatively deep, as opposed to the close proximity to the surface of the high compressive region subsequent to the unloading. Although the reported stress is significantly greater than yield, this is attributed to a shift in the yield stress curve associated with the hydrostatic stress state that results from the high plastic deformation.

It is judged that although an increase in the depth of penetration would relax the compressive stress in the root existing during loading, the final unloaded residual stress state will be highly compressive. This judgement is supported by the results of the sensitivity studies.

Simulated Applied Stud Loading

In addition to understanding the residual stress state created by the thread rolling process, the goal of this study is to develop a process by which fatigue benefits derived from the rolling process can be quantitatively understood. One means of accomplishing this is to generate a 3-D rolled thread model, and gradually apply end loads while tracking the stress state at the thread root. Determination of the thread stress to load ratio can eventually be used to correlate with stud fatigue test results.

The first step toward that goal uses the results from the 2-D plane strain model and applies an incremental displacement driven loading. Two different loading conditions were examined. First, the final thread form geometry, with the residual stress state from an incrementally loaded/unloaded condition, was restrained at one end while the other end was incrementally displacement loaded. The criteria by which loading was considered complete was based on the average cross-section of the model reaching von Mises yield stress.

Figures 6 through 8 track the stress state of the center thread root throughout the entire loading/unloading and applied end loading to a yielded cross-section process. For all three cases the same legend is displayed to allow for easier tracing of the stress field changes.

Nodal values are extrapolated from Gauss point stresses and are used for the graphical display. Results indicate an additional benefit could be realized from further mesh refinement to more accurately calculate the residual stress states. These results demonstrate the formation of a compressive residual stress state in the rolled thread root that will remain slightly compressive, even when the model is axially loaded to yield through the cross-section. It is these results that provide promise for development of design correlations for fatigue in rolled threads.

The second case examined simulated a non-rolled (cut) thread with the rolled thread geometry without the residual stress state, and applied a similar incremental displacement end loading. Figure 9 reflects the tensile nature of the non-rolled thread root under an end loading.

Comparison of these two cases emphasizes the distinct difference between the thread roots that have a compressive thread root stress state (rolled threads) and those that do not (cut threads).

Model Sensitivity Studies

Performance of this evaluation required assumptions to be made in an effort to obtain model convergence and reduce computer usage (CPU and memory requirements). Sensitivity studies were performed to assess the impact of these assumptions on the results and conclusions. These sensitivity studies varied the mesh density, the incremental loading/unloading,

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the coefficient of friction, and two convergence tolerances. In addition, a study assessing the reliability of the final element configuration was performed.

Mesh Density Study

Difficulties in developing a full thread form were due to the lack of an adequately refined mesh. To confirm the adequacy of the results presented, a mesh coarsening approach was taken. Similar to a mesh refinement, should a change in mesh result in less than a 10% change (arbitrarily selected) in reported stress values then the initial mesh can be considered to be adequate to predict stress results. However, should the comparison reflect a change greater than 10%, then an additional mesh refinement should be applied to ensure accuracy of results.

Figures 10a and 10b plot S_{11} stress with respect to increments over the course of loading and unloading of the workpiece. As indicated by Figure 10a, the coarser mesh model provides a residual stress approximately 40% less than the refined mesh model. From this result, it could be concluded that further mesh refinements would be required prior to acceptance of a quantitative representation of the thread root residual stress. However, the trend toward higher compressive residual stress with a finer mesh is assumed given these results. Although the finer provided greater compressive stress, the runtime was three to four times greater than that of the coarse mesh. Given the conservative nature of the coarse mesh results, the subsequent sensitivity studies were performed with the coarse model primarily to conserve computer resources. The trends observed will not be affected by the use of the coarse mesh.

The highly irregular patterns observed in Figure 10a are attributed to both the coarseness of the mesh when experiencing large plastic deformations, and the relaxed tolerances needed to ensure convergence. Node 72 is a surface node associated with elements that are highly distorted. As these elements are deformed with additional loading, the absolute displacement convergence tolerances used are compared to the incremental calculated values. In some cases the allowable may be just met, while in other increments it might be just missed. For the latter case additional iterations are required, thereby changing the difference between the allowable and reported values. It is this variability of the results caused by the selected convergence tolerance that contributes to the swing in results observed between increments. A confirmation of this observed condition is seen in Figure 10b, a plot of the S_{11} stress for the adjacent node (1201) below Node 72 in the coarse model. For the refined model it is the third node below the surface, but in the same geometric location as Node 1201 in the coarse model. Notice that for this case there is less variability in the nodal results and approximately the same final residual stress state. This indicates the mesh below the highly distorted surface elements provides reasonably stable results.

Incremental Loading Study

The finite element mesh modelling was initially performed in a single loading/unloading method to facilitate mesh development. This precluded the occurrence of ill-conditioned elements after a series of loading/unloadings had occurred. In an actual rolling process the indentation/rolling occurs over a number of loading/unloading increments. This study assesses the effects of increasing the increments over which the total thread form is generated. The initial base case performed the 40 mil indentation in a single loading. This study compares those results with a 40 mil total indentation obtained in two (20 mils/set), four (10 mils/set) and five sets (8 mils/set) of loading/unloading intervals.

The results of this study (Figure 11) show approximately the same trends for each series. Each subsequent loading pattern shows an increasing compressive residual stress value until the final loading increments. A slight decrease in compressive residual stress in the thread root is observed over the last loading increment. This change in compressive residual stress is attributed to the tendency for the coarser mesh to generate ill-conditioned elements. The ill-conditioning of the elements results in a large stress differential across the Gauss points making up the element, thereby skewing the reported surface results. It should be noted that with the exception of the single load step case, the multiple load cases appear to have approximately the same residual stress value. Further investigation indicates that the single load step case tends toward an ill-conditioned element; therefore, under predicting the final result. Results indicate that as the number of incremental loading/unloading increases, the greater the compressive residual stress value in the thread root.

Frictional Effects Study

Although Reference 2 results indicated minimal effects of coefficient of friction assumptions on the residual stress state, it was observed that the rigid body sliding along the elements making up the surface was one of the governing factors in generating ill-conditioned elements Although the impact on residual stress was small, delaying the onset of ill-conditioning, thereby maintaining better element configuration, would allow for a better prediction of residual stresses. Examination of the model results indicated that the incorporation of friction allowed for more uniform deformation in the surface elements, thereby maintaining a better aspect ratio. Figure 12 shows less fluctuation due to element distortion over the final few increments. This smaller fluctuation results in slightly deeper penetration and a higher compressive residual stress state. Again these results support the conservative nature of the results used in the simulated end loading study.

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Convergence Tolerance Study

The relatively small element size coupled with the relatively large displacements created various convergence problems in the initial attempt to obtain a solution. Attempts involving both mesh changes/refinements and tolerance alterations were made to obtain a solution. Due to the difficulty in obtaining solutions, once a solution had been obtained it was necessary to perform a sensitivity on the corresponding tolerance value. The inability to obtain a converged solution with a tighter tolerance restricts the accuracy of this sensitivity study. Rather than tightening the tolerance (as required in a true tolerance study) a relaxation of the tolerance was examined similar to that in the mesh density. For the tolerance used (0.001) two additional cases were examined. One case relaxed the tolerance by five times the initial value (0.005), while the second case made an order of magnitude change (0.01). The results of this study are shown in Figure 13.

The results of Figure 13 indicate that convergence tolerance selection makes a difference in stress results only in the final loading step. The final step demonstrates that the more relaxed tolerances provide a greater compressive residual stress, than the tighter tolerance used in the base case. At first glance it would appear that the tightening of the tolerance should result in a greater compressive residual stress state. However, the tightening of the tolerance in the final steps of the coarse mesh initiates the process by which the elements begin to become ill-conditioned, and the solution begins to break down. This was concluded based on the large differential in stress values across a single element. The results of this study are not as conclusive as the other studies presented herein. However, the fact that there was no change in the results for the lower two tolerances and no trend toward ill-conditioned elements lends support for the reasonableness of the solution used to address the residual stress levels in a rolled thread root.

Iterative Solver Tolerance Study

Large deformation and the need for updating of the geometry with each iteration promoted the use of an iterative solver. A full Newton Raphson method was used for all the cases, with iterative solver tolerances modified where required. Maintaining the base case displacement convergence tolerance, the model was capable of running a study on the conjugate gradient solver tolerance by varying the base case value of 0.001 by an order of magnitude in either direction. For this study, the tighter the assumed tolerance the better behaved the model; and, hence, the greater the compressive residual stress value in the thread root. These results also support the slightly conservative nature of the quantitative stress values reported for the end loading results. The results of this study are found in Figure 14.

Non-Positive Definite Study

Establishment of a mesh which demonstrated convergence was facilitated by an option that forced convergence once the predetermined number of iterations had been reached to allow the analysis to continue. This option is associated with a non-positive definite flag. This approach is only valid if the elements do not become so ill-conditioned that they turn inside-out. To confirm that there were no inappropriately formed elements, a run was made with the non-positive definite flag turned off. Figure 15 demonstrates no difference between the two runs, thereby indicating the elements deforming over the duration of the run are not sufficiently ill-conditioned to invoke this option. This further supports the adequacy of the results presented.

Uncertainties

Based on the limited geometric representation of a rolled thread using 2-D plane strain modelling assumptions; additional confirmatory and theoretical work must be completed, including expansion of the results into 3-D, before final determination of the quantitative thread root residual stress state generated by cold-rolling. The extension of the 2-D work into 3-D addresses the following uncertainties:

- Differences created between indentation only and rolling/indentation modelling along with the influence of roll draft on the final stress state.
- Determination of the effects of increased thread form depth and thread configuration on final stress states.
- Determination of the contribution to and/or relaxation of residual stress that occurs as a result of a 3-D representation of the cold-forming process.
- The effects of geometric differences in thread configurations (helical versus cylindrical thread forms) and processes (through-feed versus in-feed processing).
- Residual stress state impact of evaluations made regarding the effects, if any, of load transfer through thread flank-to-flank contact.

The use of a metal forming software package (e.g., MARC/Autoforge) will eliminate the element ill-conditioning that comes with die penetration. It will also permit automatic mesh reconfiguration to provide improved solution accuracy.

None of these items are judged to significantly alter the nature of the residual stress state.

Summary

The results of this study provide an initial understanding of favorable fatigue test results demonstrated to date for rolled threads [1 and 4]. It also identifies the potential for increased fatigue resistance for design applications that incorporate rolled threads. Although additional analytical and pos-

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sibly experimental qualification need to be addressed, there is a high degree of confidence that the end goal of developing design considerations will be attainable.

References:

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[2] Martin, JA "Fundamental Finite Element Evaluation of a Three Dimensional Rolled Thread Form: Modelling and Experimental Results" - PVP-373 pg 457-467 presented at ASME Pressure Vessel and Piping Conference at San Diego July 26-30 1998

[3] Lin CS, Lourilliard JJ, and Hood AC, "Stress Corrosion Cracking of High Strength Bolting", SPS Technologies, Inc. ASTM STP 425, 1967, pgs 84 to 98

[4] Roach TS, Aerospace High Performance Fasteners Resist Stress Corrosion Cracking, SPS Technologies, Inc., *Material Performance*, Vol 23, No. 9 September 1984, pg 42

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

[6] Martin, JA "A Mesh Density Study for Application to Large Deformation Rolling Process Evaluations" - PVP-373 pg 177-184 presented at ASME Pressure Vessel and Piping Conference at San Diego July 26-30 1998

Table 1: Material Properties at Room Temperature

Tensile Properties	ASTM Alloy 625
Ultimate Tensile Strength (ksi)	137.9
0.2% Yield Strength (ksi)	86.7
Elongation (%)	41.7
Reduction in Area (%)	52.0
Elastic Modulus, E (10e3Ksi)	29.8

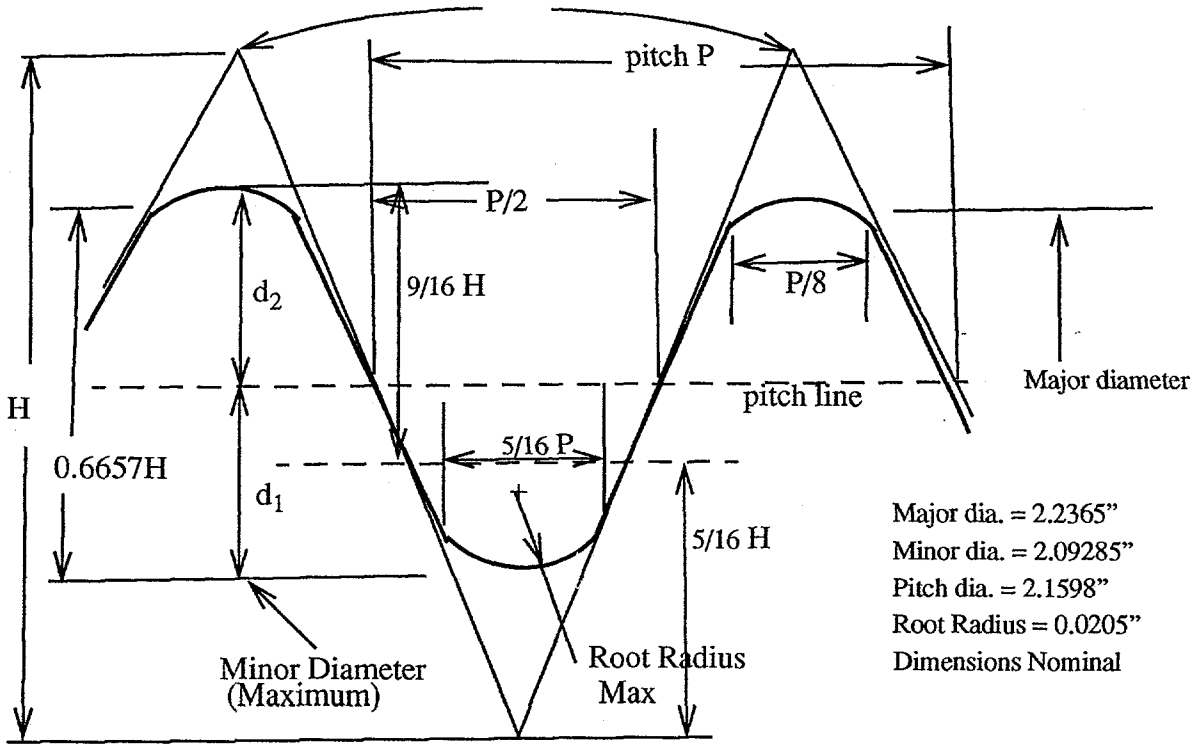

Figure 1 Geometric Configuration of Thread Form

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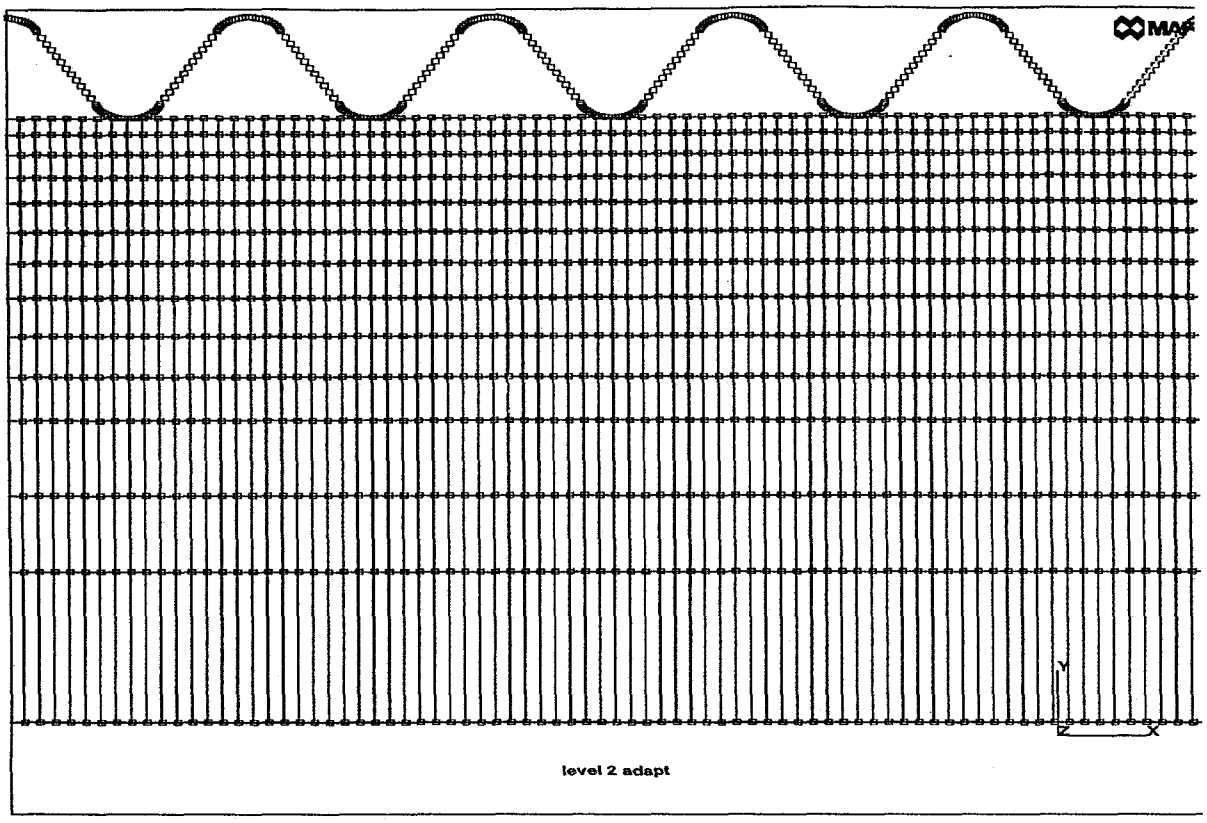

Figure 2: Initial Rectangular Finite Element Mesh

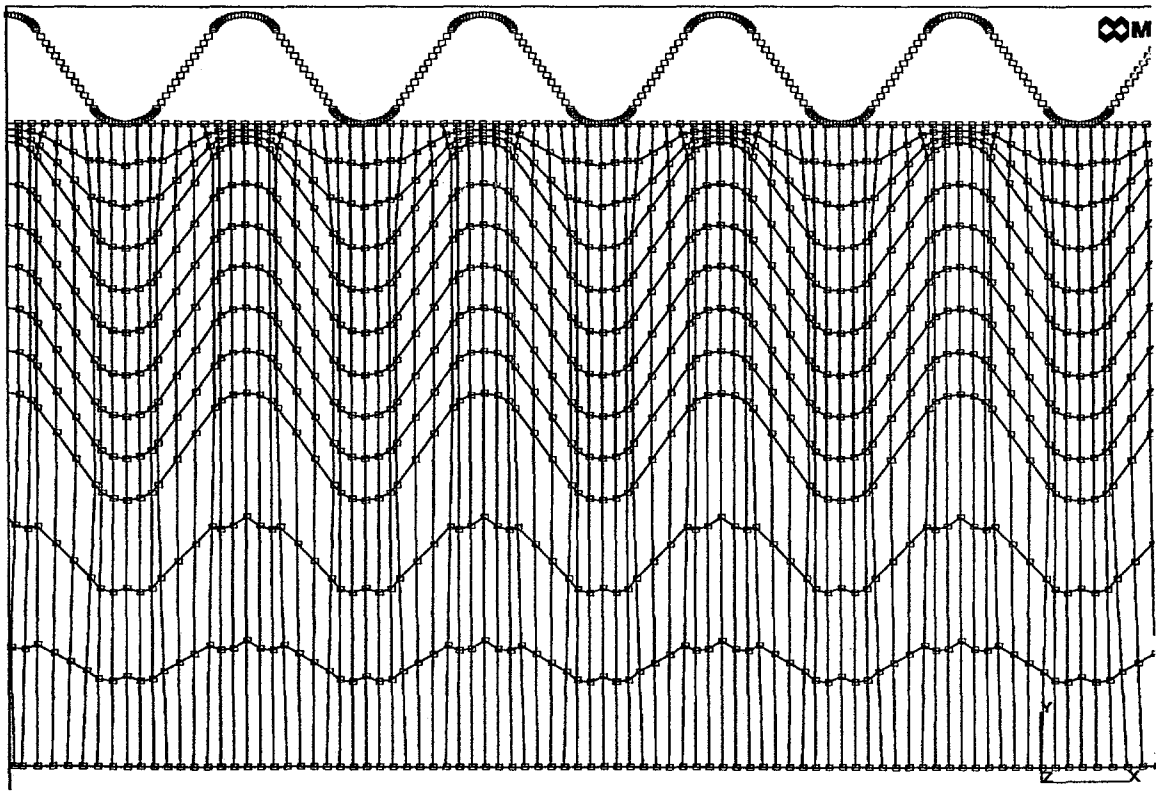

Figure 3: Modified Finite Element Mesh Based On Expected Deformed Shape

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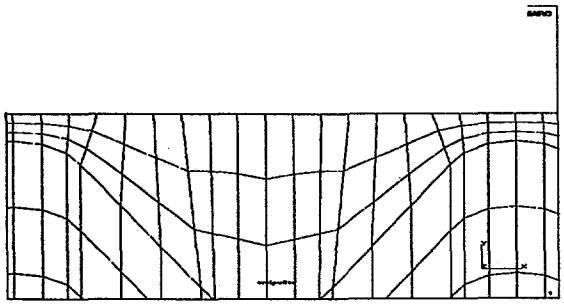

Figure 4a: Increment 0

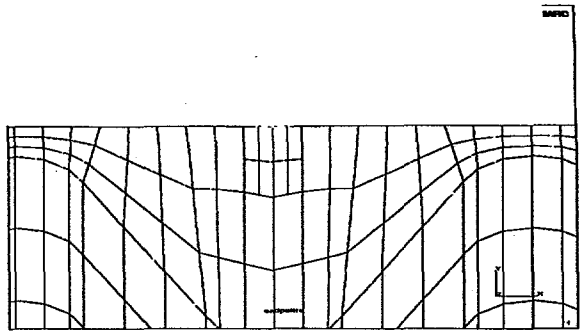

Figure 4b: Increment 2

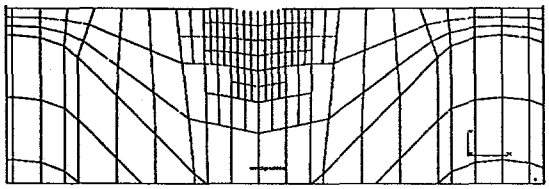

Figure 4c: Increment 4

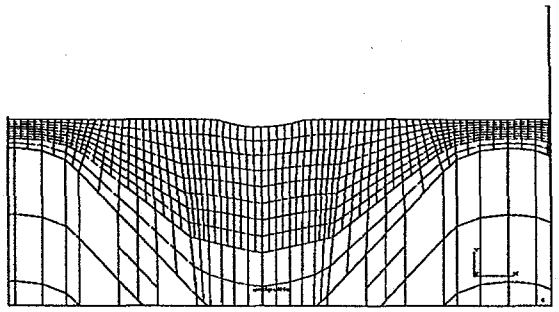

Figure 4d: Increment 11

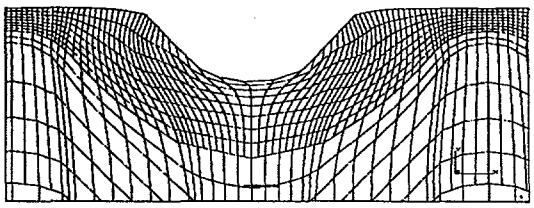

Figure 4e: Increment 75

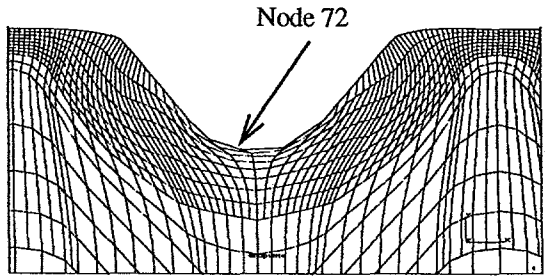

Figure 4f: Increment 196