Comparison on Remeshing and Mesh Enrichment Based Forming Simulations

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1. INTRODUCTION

To investigate the effects achieved by the mesh enrichment based automated forming simulations and identify the potential needs for future improvements, three different forming simulations have been performed based on the mesh enrichment procedure and DEFORM's remeshing procedure respectively, and the simulation results are compared w.r.t. the selected criteria in this document.

2. SELECTED CRITERIA FOR SIMULATION COMPARISON

According to the recent communications between GE and SCOREC, the following criteria have been chosen to evaluate the simulations performed based on the mesh enrichment procedure and DEFORM's remeshing procedure:

A) Total numbers of mesh enrichment steps and remeshing steps needed.

B) Accumulated simulation time and the percent time spent on remeshing/mesh enrichment process.

C) Element quality before and after remeshing/mesh enrichment steps. In this study the element quality of the workpiece mesh is evaluated through the worst element shape (measured by the mean ratio in the form of $15552V^2 \Big/ \left(\sum_{i=1}^{6} l_i^2\right)^3$, where V is the volume and l_i is the length of the i-th bounding edge of the tetrahedral element) and the largest dihedral angle. Both the two values are calculated before and after remeshing/mesh enrichment steps to show the effects achieved based on the simulation monitoring and element shape improvement developed in the project.

D) Solution transfer efficiency and accuracy. The CPU time spent on solution transfer is considered for the efficiency comparison between the local solution transfer applied in the mesh enrichment procedure and the global solution transfer used in the remeshing procedure. To evaluate the behaviors of the two solution transfer processes, the accumulated L_2 strain norm vs. Stroke and the relative changes of L_2 strain norm before and after remeshing/mesh enrichment steps are investigated.

E) The minimum boundary edge lengths of the workpiece mesh before and after remeshing/mesh enrichment steps are investigated to observe its effects on the allowed time step size.

F) The number of nodes and elements used in the evolving workpiece mesh.

G) Distributions of selected history-dependent field variables and the mesh density of the final workpiece, and the peak values of selected field variables.

H) The load stroke curves achieved.

3. EXAMPLE SIMUATIONS

Three industrial problems, (1) a steering link problem (from SFTC), (2) a gear carrier problem and (3) an extrusion problem with elasto-plastic material (from GE), are investigated to demonstrate the capabilities developed in the project. All the three problems are first solved based on DEFORM's remeshing procedure and the SCOREC-GE's mesh enrichment procedure respectively, and then the results are compared w.r.t the selected criteria.

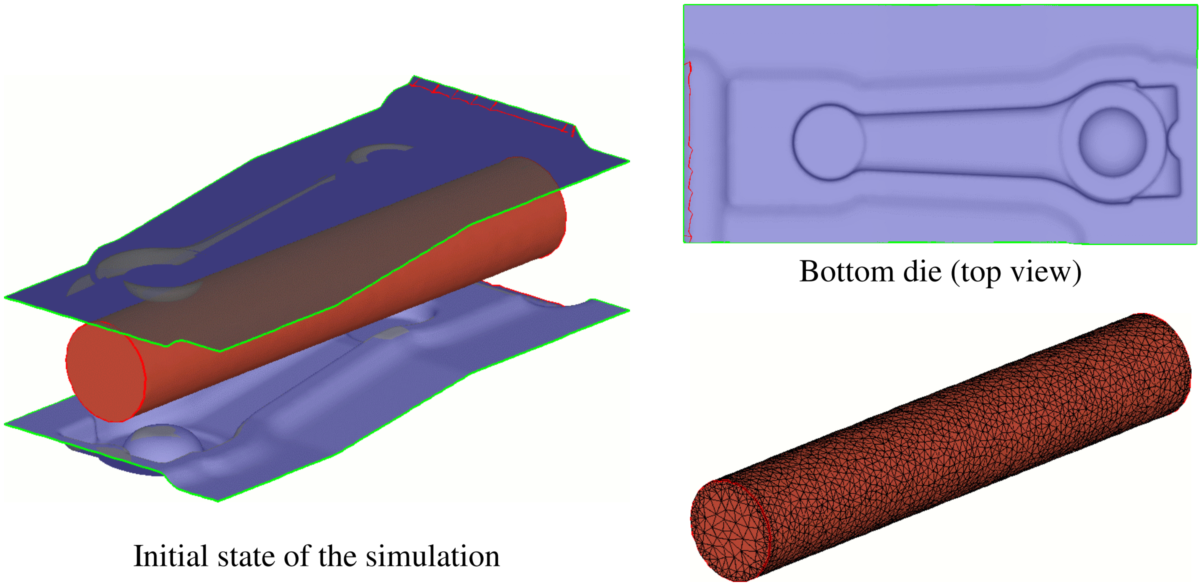
3.1 Steering Link Problem

The steering link problem shown in Figure 1 is considered. The plastic behavior of the material is specified with a material flow stress function. A total relative stroke of 41.7mm (starting from Z-Stroke=258.3mm and ending at Z-stroke=270.0mm) is defined with an initial stroke of 0.15mm per step. The allowed maximum geometric interference is 0.60mm. The initial workpiece mesh consists of 6,765 mesh vertices and 28,885 mesh regions.

The problem is solved without intervention respectively by 1) DEFORM's remeshing procedure and 2) the mesh enrichment procedure. The first remeshing step is needed at the relative stroke of 12.15mm (namely Z-stroke=270.45mm) and total 35 DEFORM's remeshing steps are required. The first mesh enrichment step is triggered at the relative stroke of 12.06mm (namely Z-stroke=270.36mm) and total 21 mesh enrichment steps are required.

The remeshing-based simulation is completed in 99,537 seconds (in CPU time on *monopoly* of SCOREC, RPI under SunOS 5.8). The CPU time spent on remeshing process (including solution transfer) is 13,733 seconds, roughly corresponding to 13.80% of the overall simulation run time. The final workpiece mesh resulted from the remeshing procedure consists of 13,983 mesh vertices and 61,787 mesh regions. Based on the mesh enrichment procedure, the simulation is completed in 89,905 seconds (in CPU time on *monopoly* of SCOREC, RPI under SunOS 5.8), about 90.3% of the total run time used by the remeshing-based simulation. The final workpiece mesh resulted from the mesh enrichment procedure consists of 15,789 mesh vertices and 66,795 mesh regions. The CPU time spent on mesh enrichment process (including solution transfer) is 9,031 seconds, roughly corresponding to 10.04% of the overall simulation run time.

The CPU usage in the first mesh enrichment step is depicted in Table 1 and Figure 2. It can be seen that Tasks 4 and 5, namely error estimation, mesh size specification and application of local mesh modifications, take the majority (about *73.02%*) of the total enrichment time (they provide a potential space to further improve the efficiency of the mesh enrichment process). Throughout the entire simulation, it takes an average of 60 seconds to enrich every 6,000 elements during a single mesh enrichment step (here the number of elements considered is defined as the average of the numbers of elements in the workpiece mesh before and after a mesh enrichment step).



Bottom die (top view)

Initial state of the simulation

Initial workpiece mesh

Figure 1 Setup of the steering link problem.

Table 1 Distribution of CPU usage in the first mesh enrichment step.

Task	**Task Description**	**CPU Time for this task (seconds)**
1	Setup the workpiece mesh and solution fields from keyword file	19.52 (*7.33%*)
2	Workpiece model topology update	9.14 (*3.43%*)
3	Setup the die surfaces from keyword file	11.35 (*4.26%*)
4	Error estimation and mesh size specification via an *h*-adaptive process	75.53 (*28.35%*)
5	Post-processing on mesh size and application of local mesh modifications	119.25 (*44.67%*)
6	Local solution transfer during local mesh modifications	17.84 (*6.70%*)
7	Keyword assembly based on updated workpiece mesh and solution fields	10.0 (*3.75%*)
8	Other	3.78 (*1.42%*)
Total		266.41

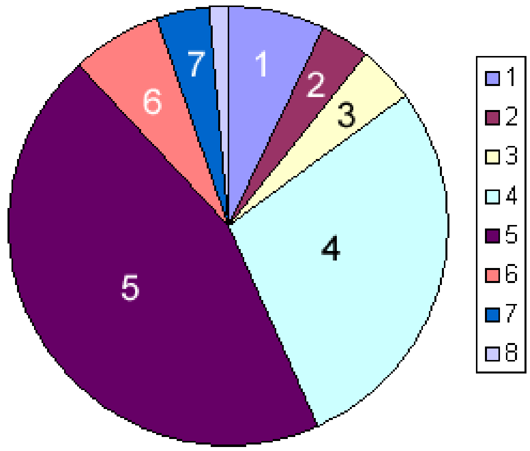


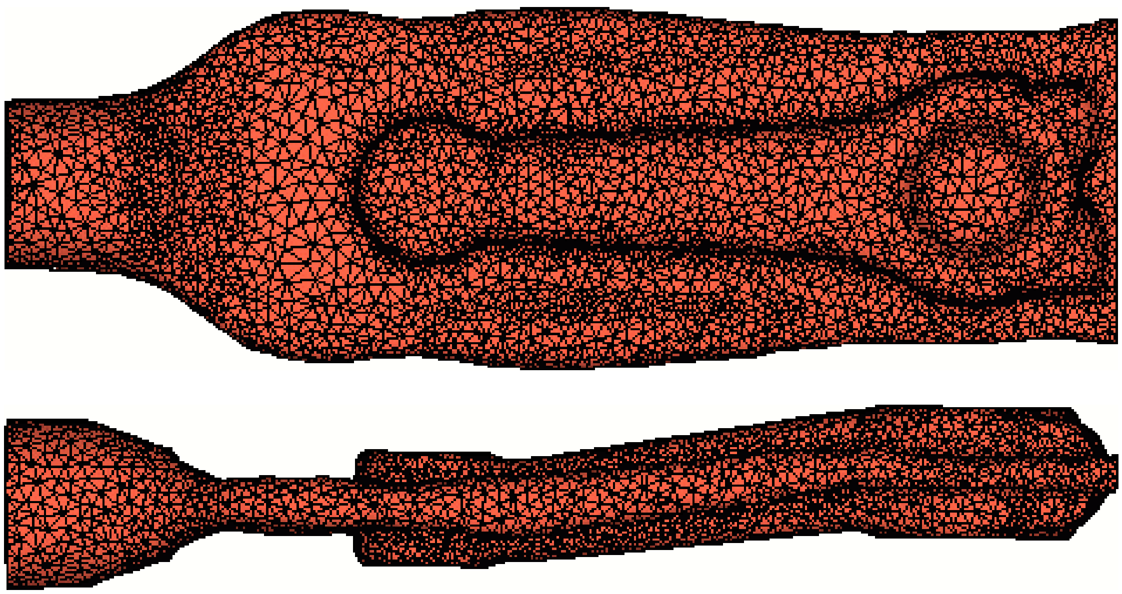
Figure 2 Distribution percentage of CPU usage in the first enrichment step.

The overall simulation comparison is summarized in Table 2. One can see that the higher peak values in temperature, effective strain and effective stress are achieved in the mesh enrichment-based simulation. The final workpiece meshes achieved in the two simulations are shown in Figure 3. From the figure, it can be seen that using the adapted workpiece mesh, the mesh enrichment based simulation well captures all important die features. The accumulated simulation time and the number of nodes in the workpiece mesh vs. the Z-stroke are shown in Figures 4 and 5. The results show that the mesh enrichment based simulation is performed more efficiently than the remeshing-based simulation, especially during the late simulation stage where die-fill becomes of a major interest.

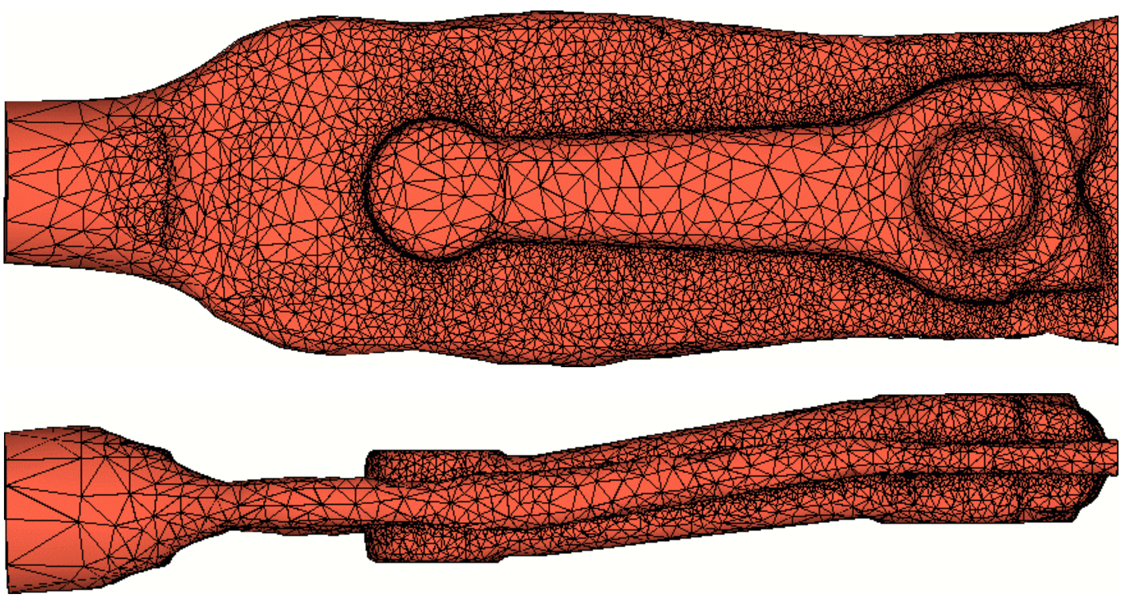
Table 2 Comparison summary of steering link simulations.

Mesh updating method	Remeshing	Mesh enrichment
Number of remeshing/mesh enrichment steps	35	21
Overall CPU run time (in seconds)	99,537	89,905
CPU time for remeshing/mesh enrichment steps (including solution transfer, in seconds)	13,733	9,031
CPU time for solution transfer (in seconds)	2,539	271.28
Number of mesh vertices/regions in the final workpiece mesh	13,893 / 61,787	15,789 / 66,795
Min/Max mesh edge length in the final workpiece mesh	0.9239 / 7.8963	0.5601 / 26.7989
Min/Max temperature in the final workpiece (°F)	904.359 / 1,290.91	979.858 / 1,324.78
Min/Max effective strain in the final workpiece	0.02577 / 1.60293	0.00364 / 4.08916
Min/Max effective stress in the final workpiece	2.57548 / 225.975	1.58849 / 235.682

It should be noted that DEFORM's remeshing procedure is applied to the last mesh and solution data step stored ***after*** the element distortion and/or discretization errors become unacceptably large, while the mesh enrichment procedure is applied to the last mesh and solution data step stored ***before*** the element distortion and/or discretization errors become unacceptably large. This makes it possible for the remeshing-based simulation to proceed and finish even if the remeshing procedure consecutively fails to yield an acceptable workpiece mesh.



After 35 remeshing steps
(13,983 mesh vertices and 61,787 mesh regions)



After 21 mesh enrichment steps
(15,789 mesh vertices and 66,795 mesh regions)

Figure 3 The final workpiece meshes achieved in steering link simulations.

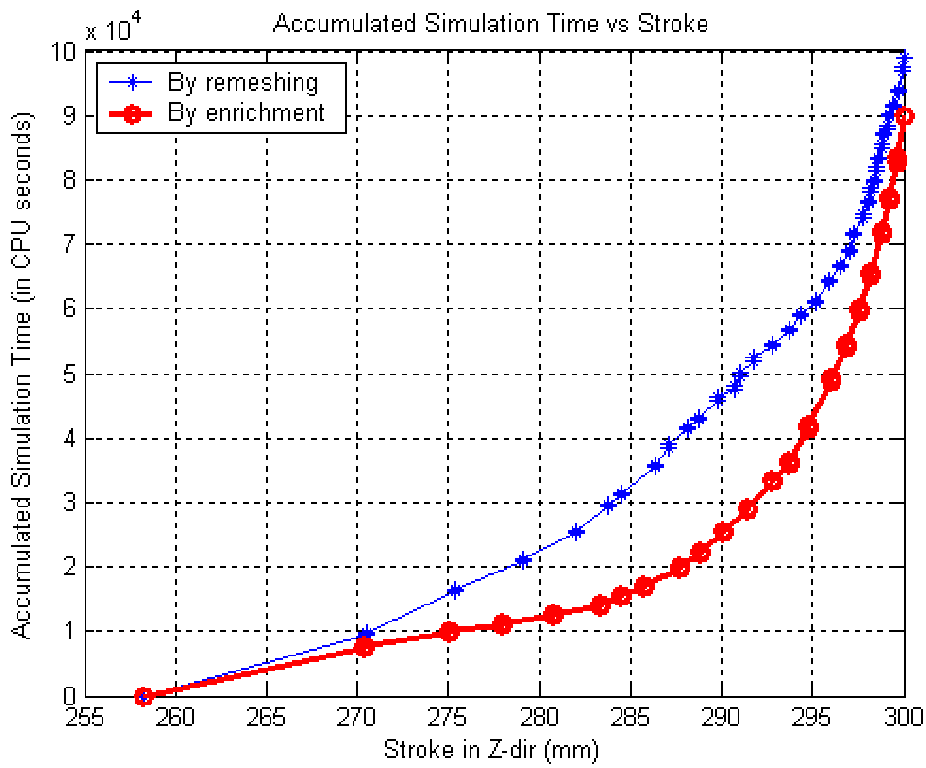


Figure 4 Accumulated run time of steering link simulations.

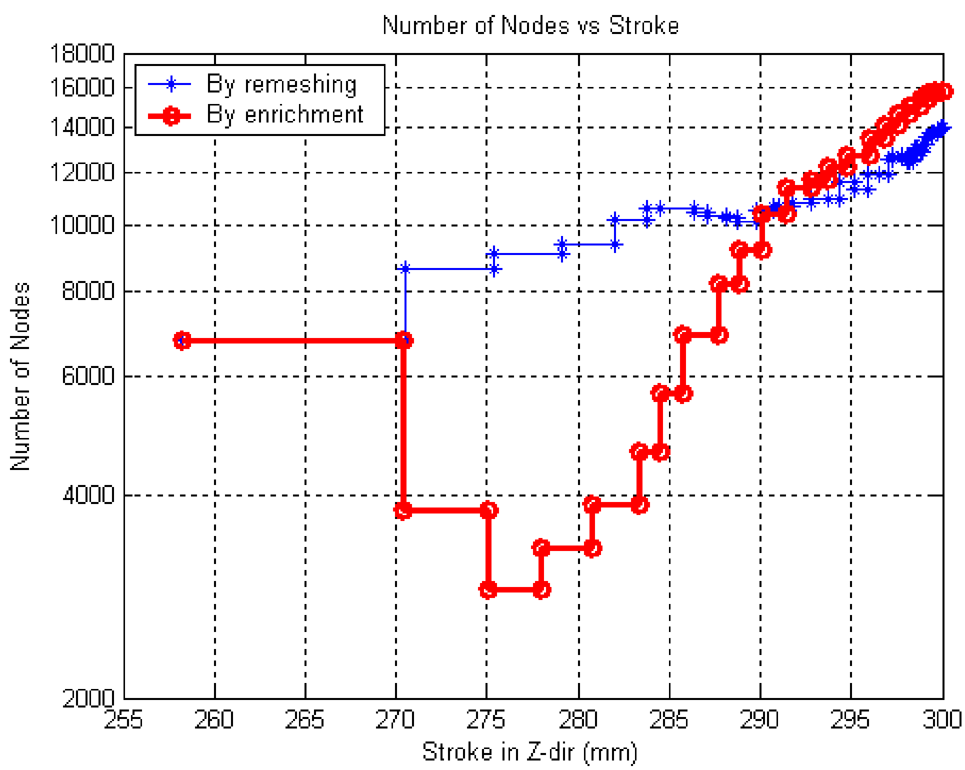


Figure 5 Numbers of nodes used in steering link simulations.

Control of element quality

Figures 6 and 7 show the element quality measured based on the minimum mean ratio and the maximum dihedral angles of the workpiece mesh before and after the remeshing/mesh enrichment steps respectively. It can be seen that throughout the mesh enrichment-based simulation, the element quality of the workpiece mesh is more effectively controlled through the element distortion monitoring and shape improvement.

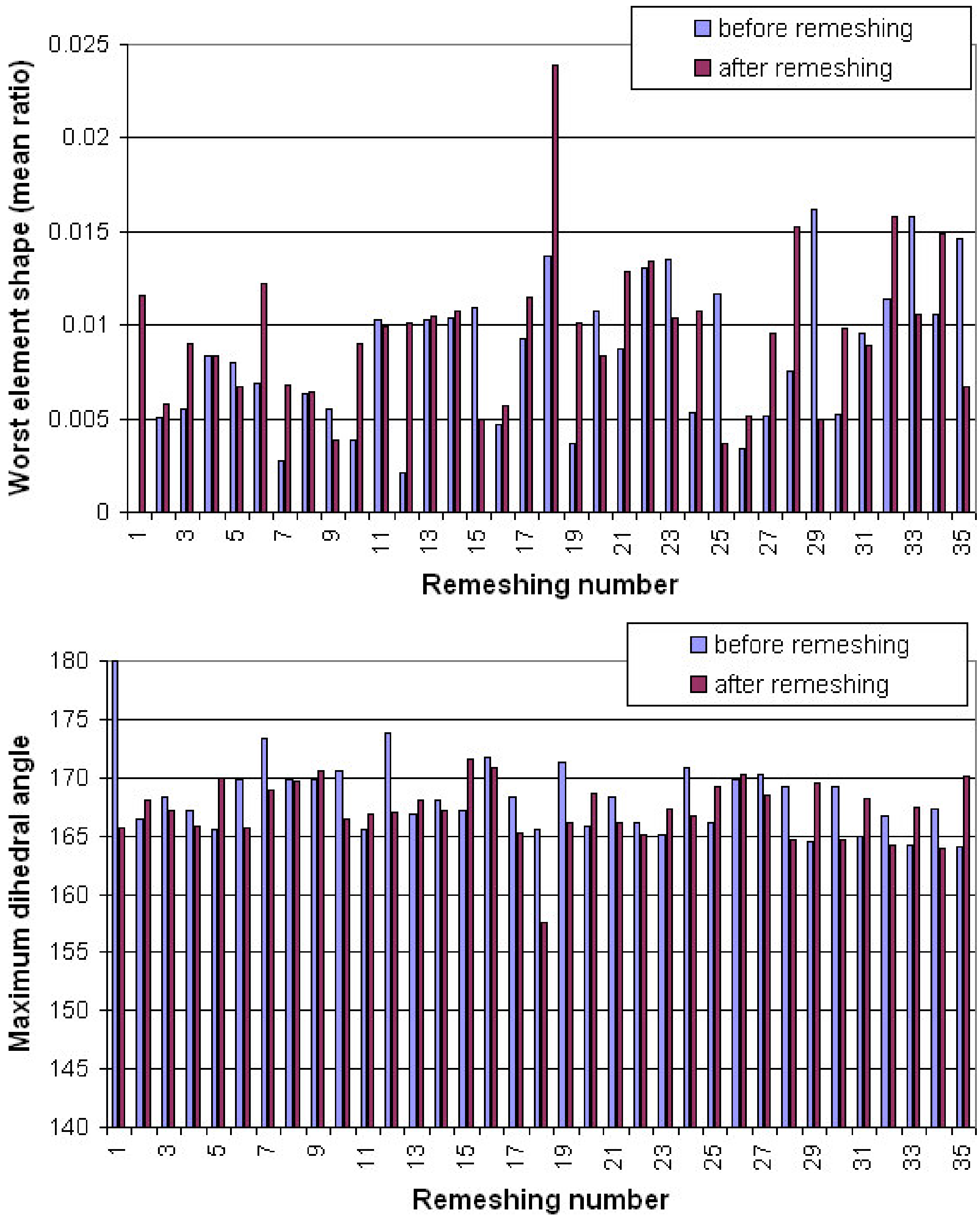
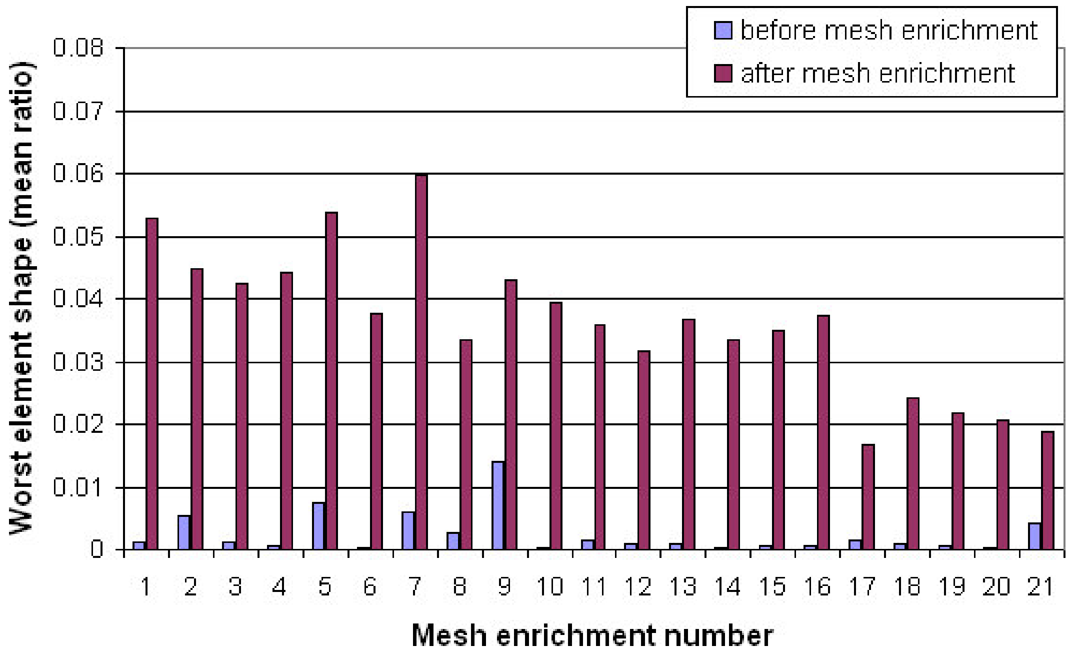


Figure 6 Element quality control in remeshing based simulation of steering link.

Furthermore from the triggering of remeshing/mesh enrichment steps that can be seen from Figures 6 and 7, one can observe that the geometric interference between the workpiece and dies are more effectively controlled based on the mesh enrichment procedure, especially during the late stage of the simulation (corresponding to Z-stroke from 295.0 to 300.0mm, refers to Figures 4 & 5). The two simulations take 18 remeshing steps and 7 mesh enrichment steps respectively during the stage from Z-stroke=295.0mm to Z-stroke=300.0mm.



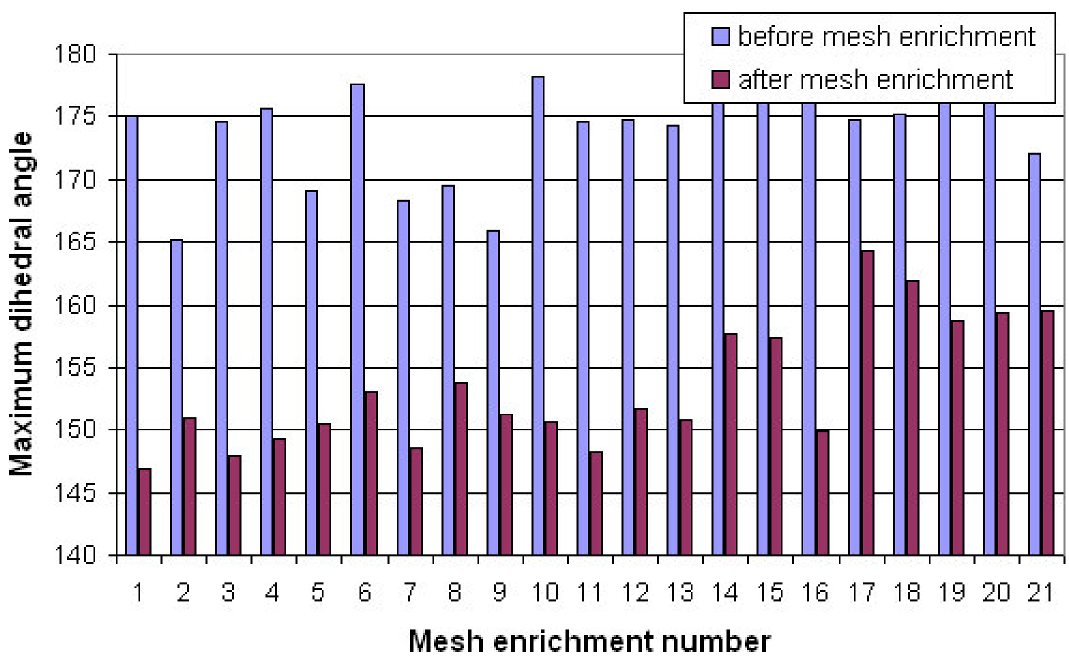


Figure 7 Element quality control in mesh enrichments based simulation of steering link.

Consideration of solution transfer

For this plastic deformation problem, the field variables, including the nodal velocity, the nodal temperature, the elemental effective strain and the elemental damage factor, need to be transferred during the remeshing/mesh enrichment steps. To investigate the accuracy on transferring the history-dependent solution information, the relative percentage changes of L_2 strain norm during the remeshing/mesh enrichment steps, defined by $\frac{\|\varepsilon\|_{L_2}^{before} - \|\varepsilon\|_{L_2}^{after}}{\|\varepsilon\|_{L_2}^{before}} \times 100\%$, where $\|\varepsilon\|_{L_2}^{before}$ and $\|\varepsilon\|_{L_2}^{after}$ are the L_2 strain norm of the workpiece before and after remeshing/mesh enrichment steps respectively, are given in Figure 8. It can be seen that based on the local solution transfer technique developed and adopted in the mesh enrichment procedure, the relative change of L_2 strain norm is much smaller than that based on DEFORM's global transfer technique.

It has also been observed that DEFORM's global solution transfer procedure tends to diffuse the peak values of the deformation-dependent field variables, especially during the early simulation stage. As a result the remeshing-based simulation results in a smaller accumulated L_2 strain norm than the enrichment-based simulation as shown in Figure 9. At the completion of the remeshing-based simulation, the L_2 strain norm of the workpiece is 406.94, which is about 86.3% of the final L_2 strain norm (471.53) achieved in the mesh enrichment based simulation. To further investigate the impact of DEFORM's global solution transfer on L_2 strain norm, another DEFORM's remeshing based simulation (we call it the reference remeshing-based simulation) is performed with a finer workpiece mesh. The simulation takes 24 remeshing steps and total CPU time of 168,830 seconds. The resulted final workpiece mesh consists of 22,631 mesh vertices and 104,508 mesh regions. The L_2 strain norm of the final workpiece is 415.70 (that is greater than 406.94).

The CPU time spent on DEFORM's global solution transfer process applied in 35 remeshing steps is 2,539 seconds, which corresponds to 18.48% of the total remeshing time (13,733 seconds). The CPU time spent on the local solution transfer process applied in 21 mesh enrichment steps is 271.28 seconds, which corresponds to 3.00% of the total mesh enrichment time (9,031 second). It can be seen the local solution transfer process developed is more efficient than DEFORM's global solution transfer process.

Mesh size and time step size control

The minimum boundary edge length changes in the simulations are shown in Figure 10. The curves that based on the mesh size control guided by solution error indication and geometric approximation treatment, the minimum boundary edge length in the enriched workpiece mesh drops from around 1.0mm in the initial workpiece mesh to 0.7~0.9mm during the early simulation stage (before Z-stroke=285.0mm) and then to 0.5~0.8mm (after Z-stroke=285.0mm). To avoid too small time step size or excessive substeps, the minimum boundary edge length is successfully kept above 0.50mm throughout the enrichment-based simulation with the satisfaction of the mesh discretization and geometric approximation needs. In the remeshing-based simulation, the minimum boundary edge length in the updated workpiece mesh is maintained between 0.85 and 0.95 during the late simulation stage (from Z-stroke= 295.0mm to Z-stroke=300.0mm). It has been observed that during this stage DEFORM's remeshing procedure frequently fails to satisfy the prescribed geometric interference limitation though DEFORM's surface curvature control is enabled. As a result, a number (18) of remeshing steps are needed while only 7 mesh enrichment steps are taken during the same stage in the enrichment-based simulation.

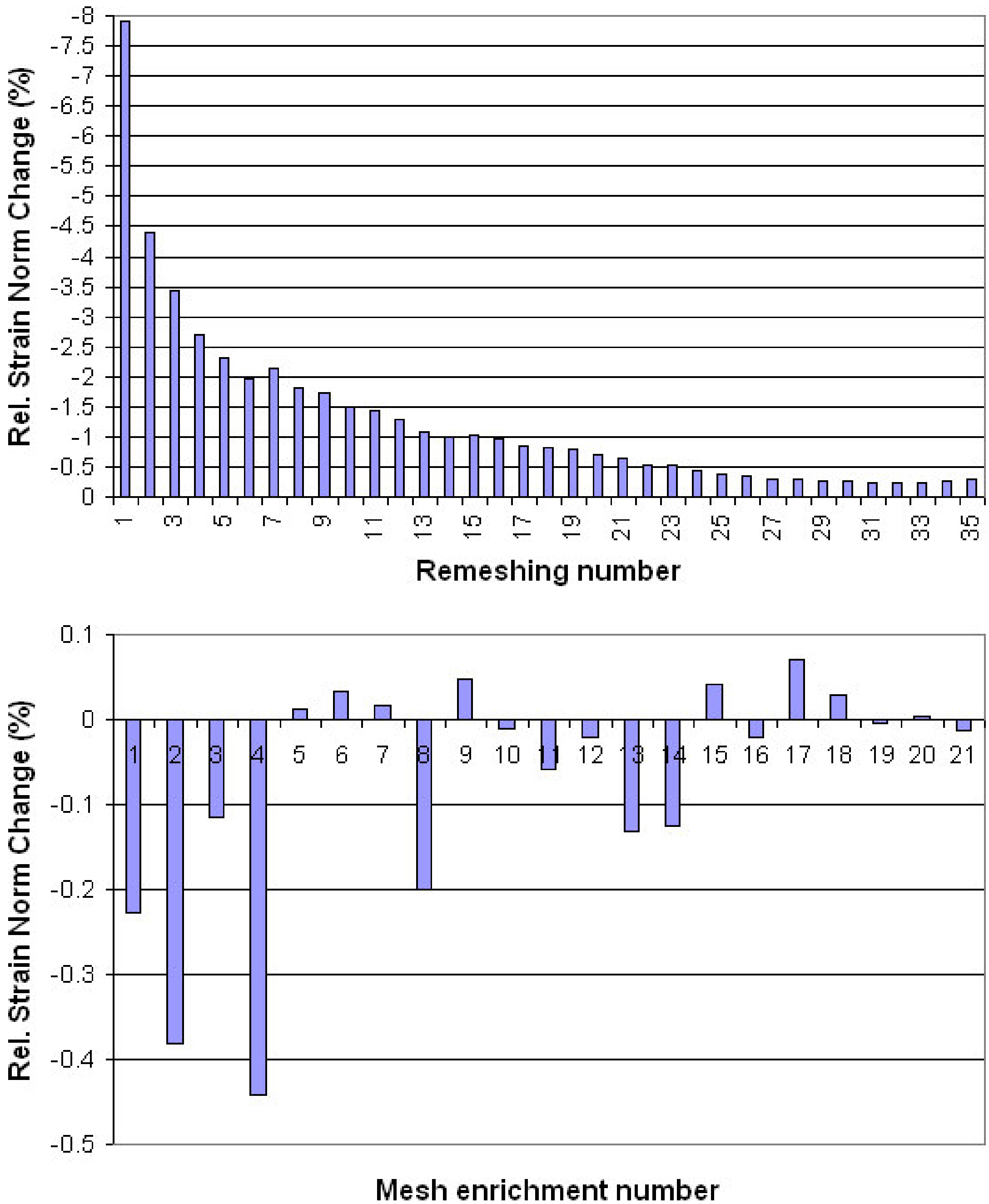


Figure 8 Relative percentage L_2 strain norm changes during remeshing/enrichment steps in steering link simulations.

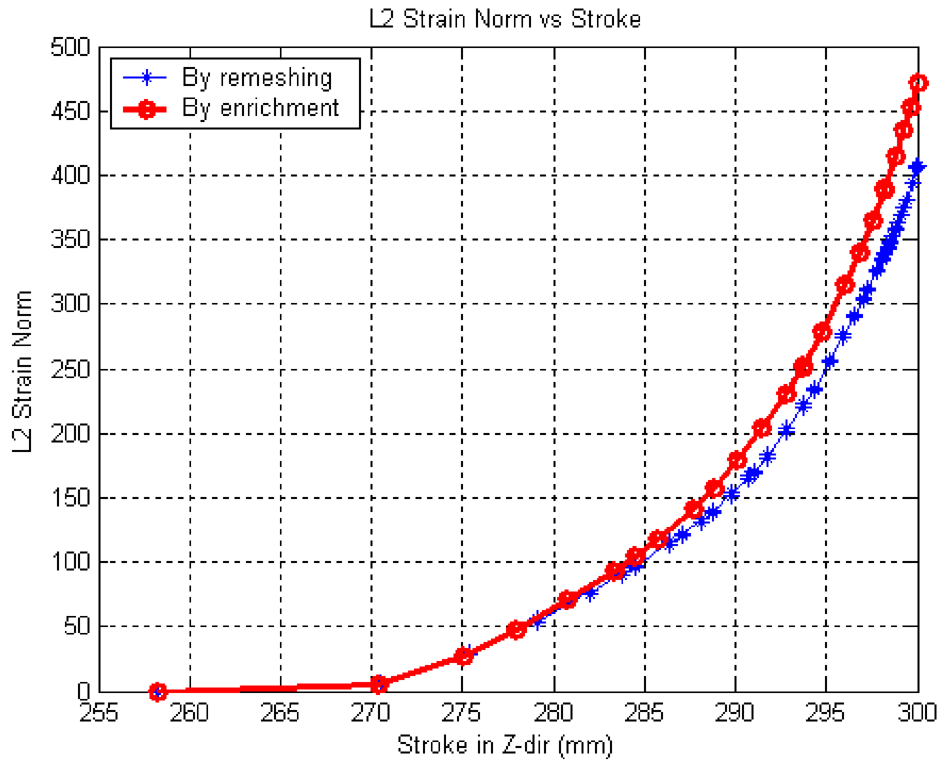


Figure 9 Accumulated L_2 strain norm in steering link simulations.

The result of the boundary edge length and nodal velocity of the workpiece mesh based time step size adjustment is shown in Figure 11. It can be seen from Figures 4 and 11 that:

A) using relatively larger time step sizes during the early simulation stage (corresponding to Z-stroke from 258.3 to 292.0) helps to reduce the solution time when the deformation is small;

B) using relatively smaller time step sizes during the late simulation stage helps to prevent fast element distortion and reduce mesh enrichment steps needed (As explained earlier in this section, another reason for more remeshing steps is that DEFORM's remeshing procedure fails to yield a workpiece mesh as good as the mesh enrichment procedure during the late simulation stage in the view of the geometric interference requirement).

The interior mesh density and strain distribution of the final workpiece achieved in the two simulations are compared in Figure 12.

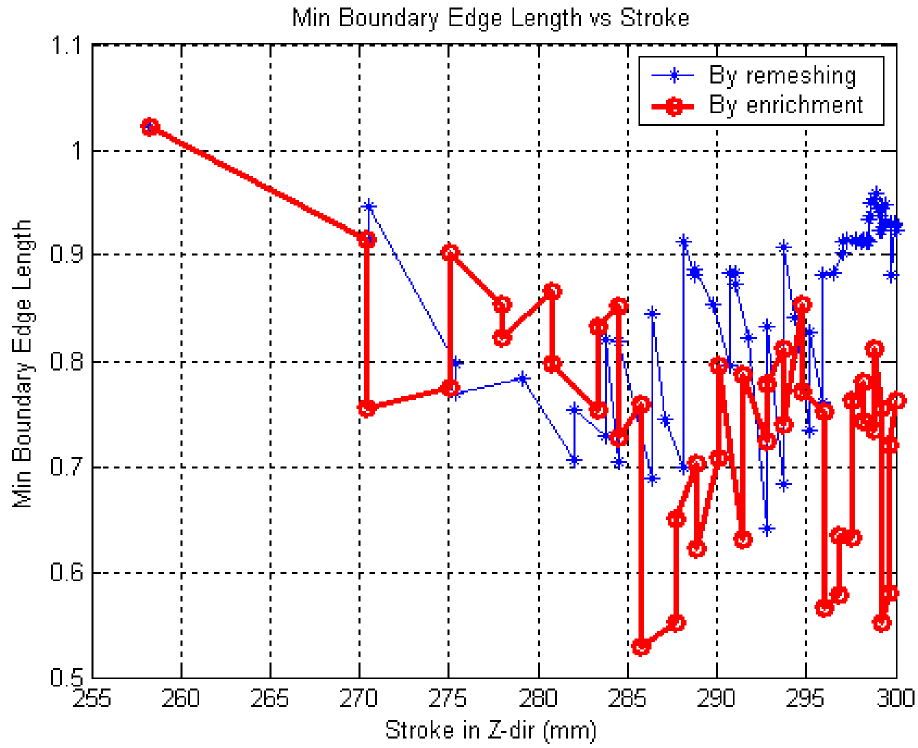


Figure 10 Minimum boundary edge length changes in steering link simulations.

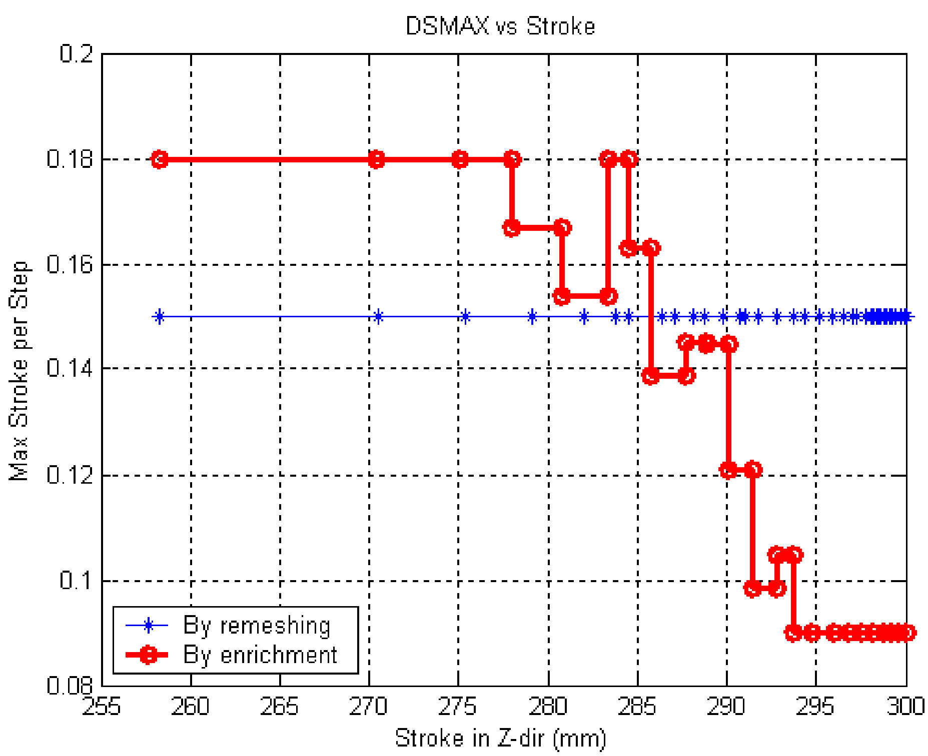
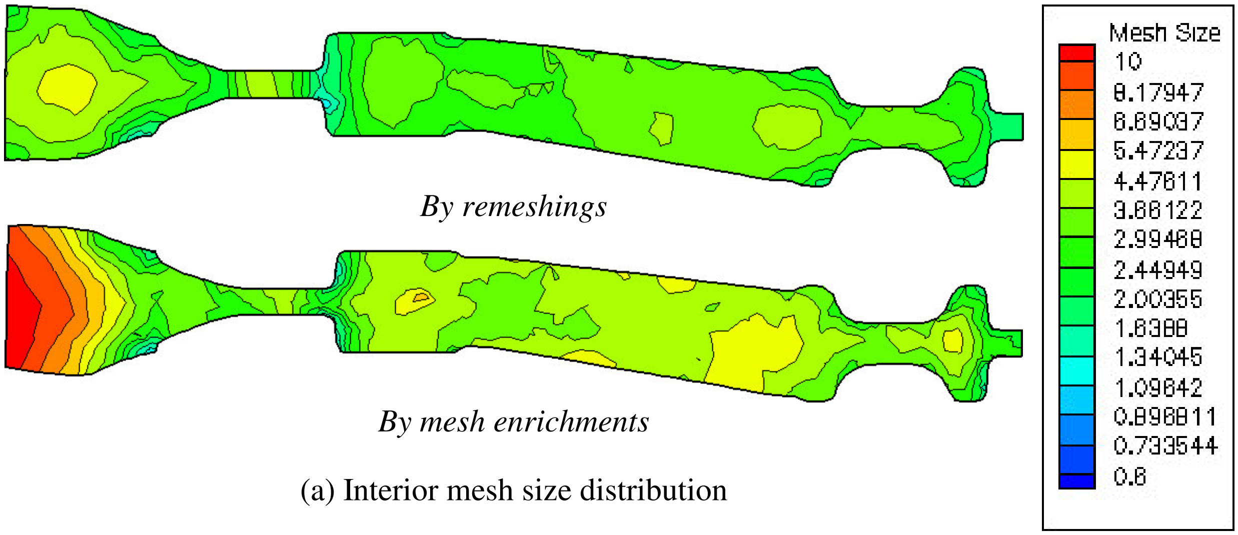
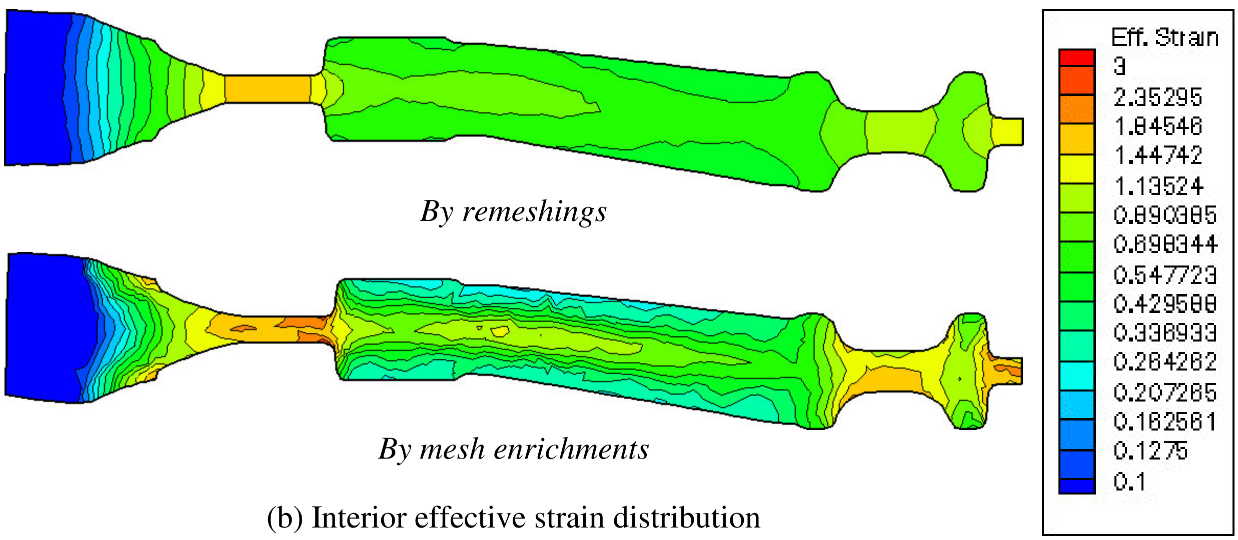


Figure 11 Time step size adopted in steering link simulations.



(a) Interior mesh size distribution

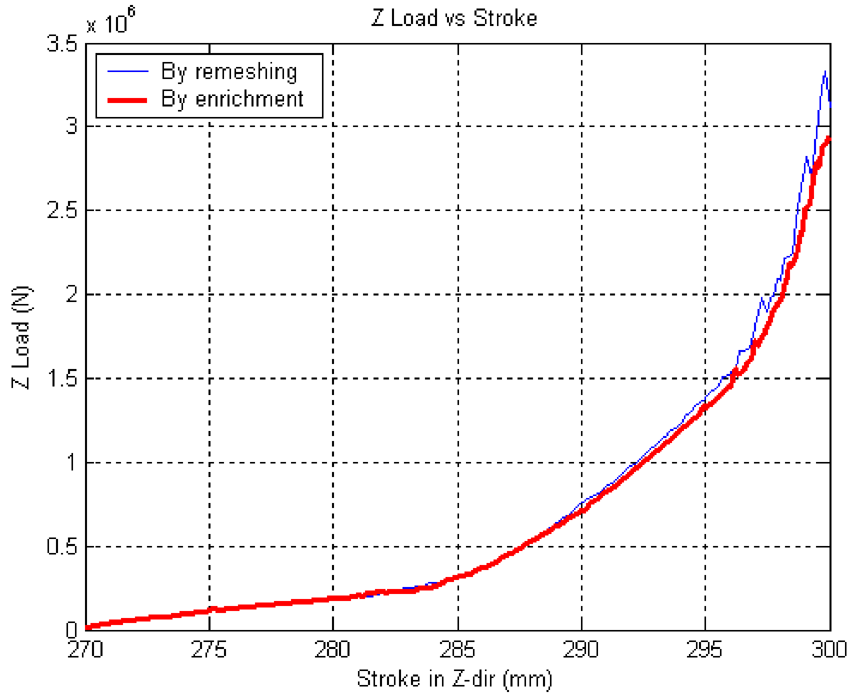


(b) Interior effective strain distribution

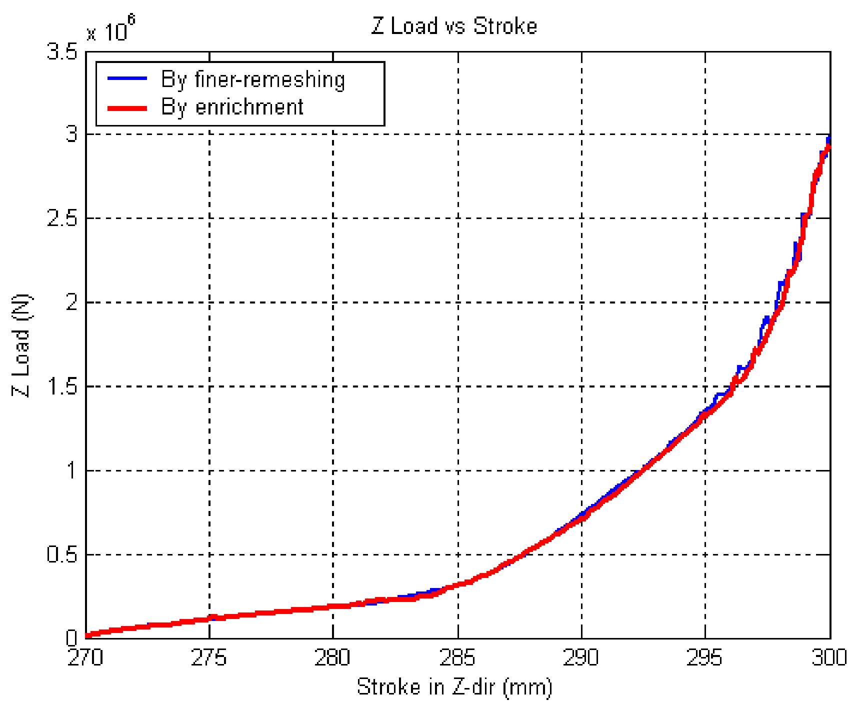
Figure 12 The final interior mesh size and effective strain profiles achieved in steering link simulations.

Load stroke curves

The load stroke curves achieved in the two simulations are compared in Figure 13.a. One can see that the mesh enrichment based simulation results in a smoother load stroke curve and a lower estimated load during the late simulation stage (the load is 0.29464E+07 N at Z-stroke=300.0mm) than the remeshing-based simulation (the load is 0.31140E+07 N at Z-stroke=300.0mm). In the reference remeshing based simulation (a remeshing based simulation performed with a finer mesh as described in *consideration of solution transfer*), the estimated load at Z-stroke=300.0mm is 0.29934E+07 N (which is close to the amount in the mesh enrichment based simulation). The load stroke curves for the enrichment-based simulation and the reference remeshing-based simulation are compared in Figure 13.b. The two curves looks similar but the one for the mesh enrichment based simulation is still smoother.



(a) Mesh enrichment based simulation yields a smoother load stroke curve than the remeshing-based simulation.



(b) The load stroke curve resulted from the mesh enrichment-based simulation is close to the one resulted from the reference remeshing-based simulation

Figure 13 The load stroke curves achieved in steering link simulations.

3.2 Gear Carrier Problem

The setup of the gear carrier problem is shown in Figure 14. A total relative stroke of 7.82mm (starting from Z-stroke =260.5mm and ending at Z-stroke=268.37mm) is to be applied with an initial stroke of 0.04mm per step. The allowed geometric interference is 0.25mm. The initial workpiece mesh consists of 7,885 mesh vertices and 33,743 mesh regions.

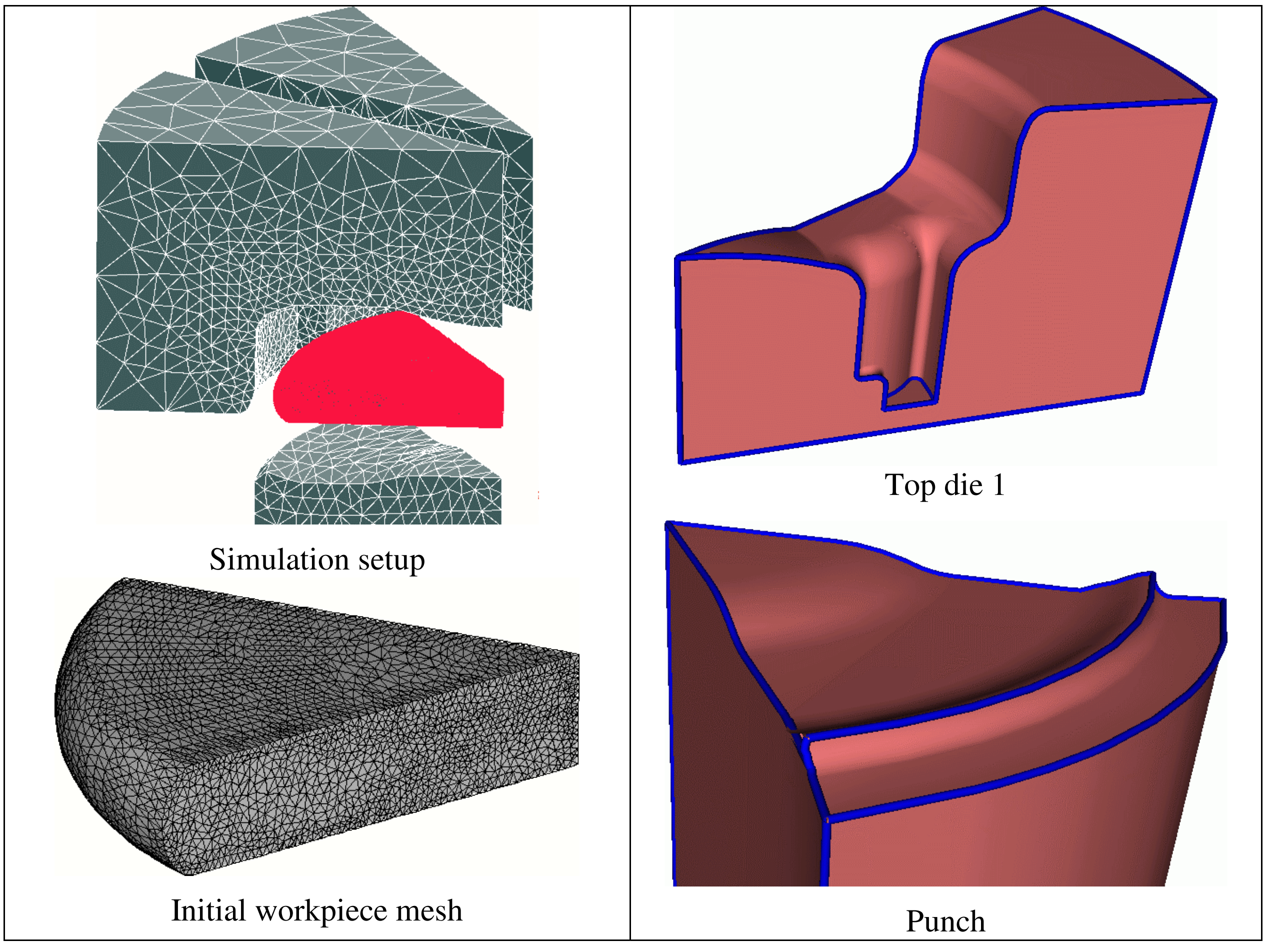
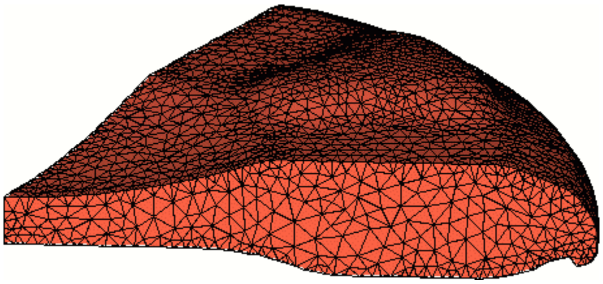


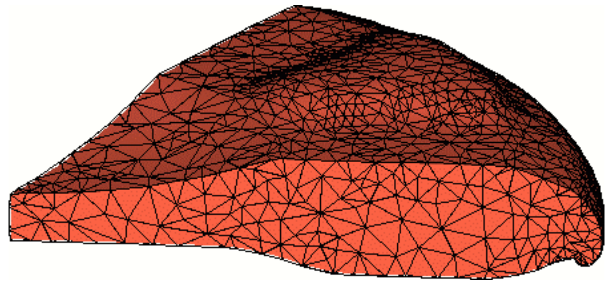
Figure 14 Setup of the gear carrier problem based on the one-sixth model.

To focus on the effects to be resulted from the remeshing and mesh enrichment procedure, we first run the simulation to Z-stroke=266.164mm without any remeshing/mesh enrichment steps, and then solve the problem respectively by 1) DEFORM's remeshing procedure and 2) the mesh enrichment procedure. The first mesh enrichment step is triggered by the developed simulation monitoring procedure at Z-Stroke =266.2106mm. The simulation is completed after a total of 14 mesh enrichment steps with 7,529 mesh vertices and 34,117 mesh regions in the final mesh. The first DEFORM remeshing step is triggered at Z-Stroke =266.3090mm (roughly corresponding to the second mesh enrichment step). It takes total 18 remeshing steps with 8,725 mesh vertices and 36,717 mesh regions in the final mesh. The updated workpiece meshes after the first remeshing/mesh enrichment step and the final workpiece meshes are shown in Figure 15. The numbers of the nodes of the evolving workpiece mesh throughout the two simulations are compared in Figure 16.

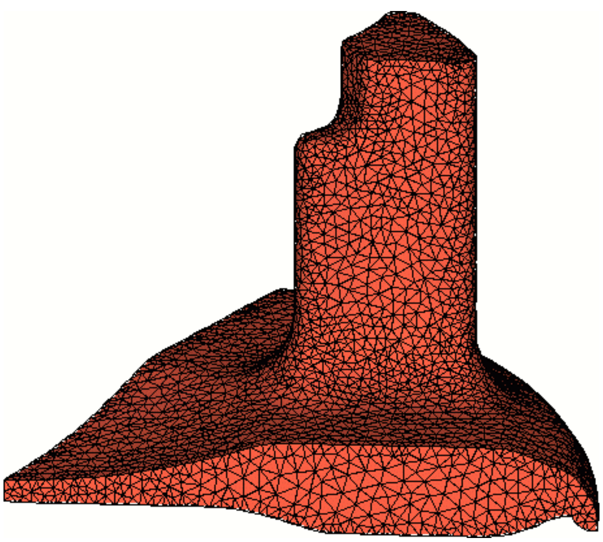
CPU times of total 59,972 seconds and 59,499 seconds (on *monopoly* of SCOREC, RPI under SunOS 5.8) are taken for the remeshing-based simulation and the enrichment-based simulation to complete respectively. The accumulated simulation time vs. Z-stroke is compared in Figure 17 and the simulation comparison is summarized in Table 3.



After the first remeshing step
(6,651 mesh vertices and 28,624 mesh regions)

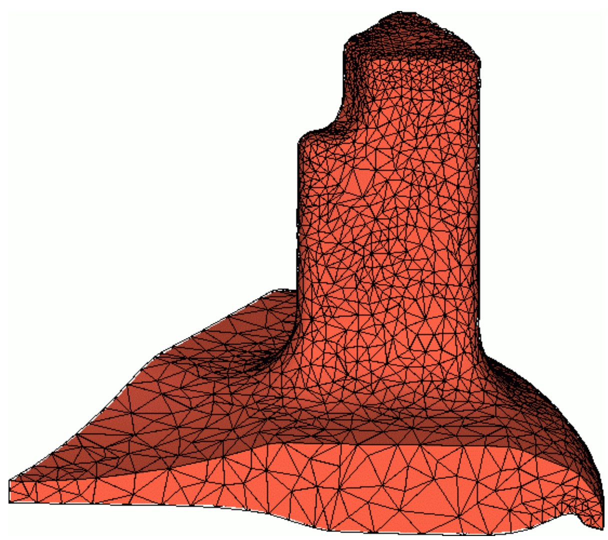


After the first mesh enrichment step
(3,536 mesh vertices and 18,428 mesh regions)



Final (after 18 remeshing steps,
8,725 mesh vertices and 36,717 mesh regions)

a) By remeshings



Final (after 14 enrichment steps
7,529 mesh vertices and 34,117 mesh regions)

b) By mesh enrichments

Figure 15 The first updated and the final workpiece meshes in gear carrier simulations.

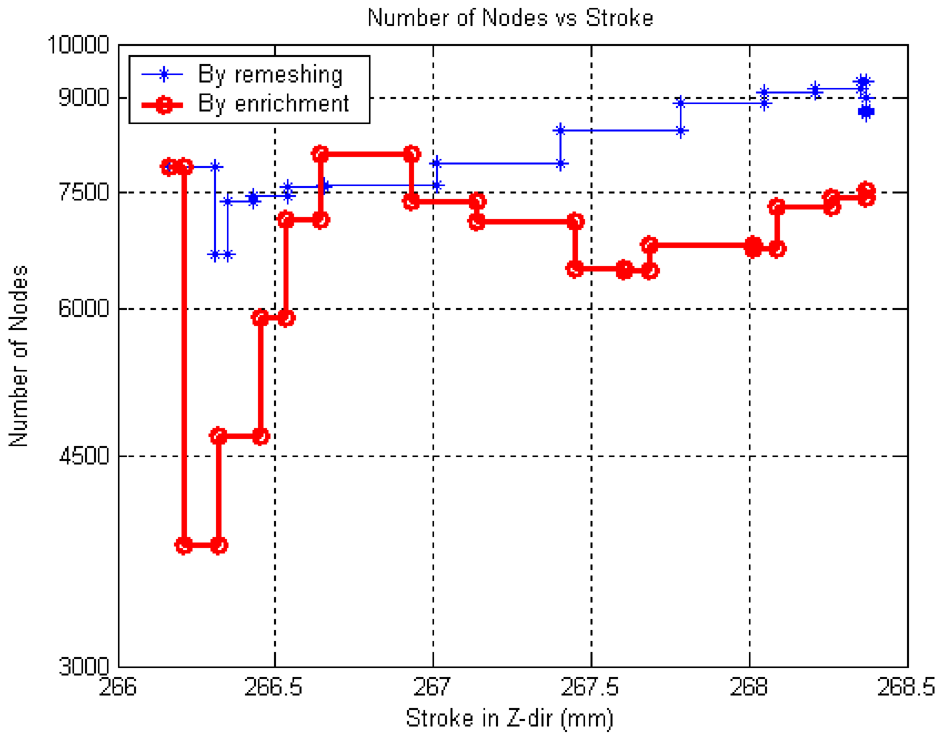


Figure 16 Number of nodes used in gear carrier simulations.

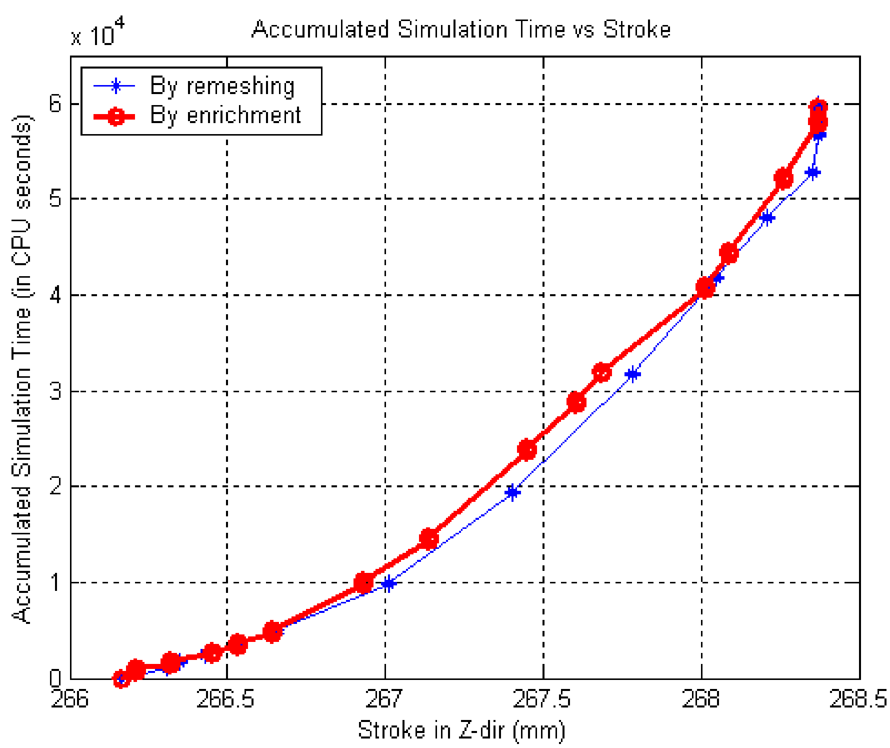


Figure 17 Accumulated simulation time in gear carrier simulations.

Table 3 Comparison summary of gear carrier simulations.

Mesh updating method	Remeshings	Mesh enrichments
Number of remeshing/mesh enrichment steps	18	14
Overall CPU run time (in seconds)	59,872	59,499
CPU time for remeshing/mesh enrichment process (including solution transfer, in seconds)	4,590	4,776
CPU time for solution transfer (in seconds)	660	108.17
Number of mesh vertices/regions in the final workpiece mesh	8,725 / 36,717	7,529 / 34,117
Min/Max mesh edge length in the final workpiece mesh	0.41880 / 1.8671	0.14236 / 4.97273
Min/Max temperature in the final workpiece (°F)	992.126 / 1,329.88	996.655 / 1,324.32
Min/Max effective strain in the final workpiece	0.57268 / 2.02913	0.36386 / 3.2454

It has been observed that for both the simulations, DEFORM substeps are taken at each analysis step after the first remeshing/mesh enrichment step (due to high localized deformations, which partially are corresponding to the portion with extensive geometric interference between the workpiece and the punch during the early simulation stage and the top portion of the workpiece during the late simulation stage corresponding to Z-stroke from 268.28mm to 268.3711mm). Since DEFORM's remeshing procedure result in relatively larger boundary edge length than the mesh enrichment procedure (as shown in Figure 18), larger DEFORM's substep sizes are taken during the early simulation stage in remeshing-based simulation. It leads to a little faster solution process in the remeshing-based simulation than the mesh enrichment based simulation during this period. However, during the late simulation stage, the workpiece mesh is adapted for a faster and better die filling at the top portion of the workpiece tooth.

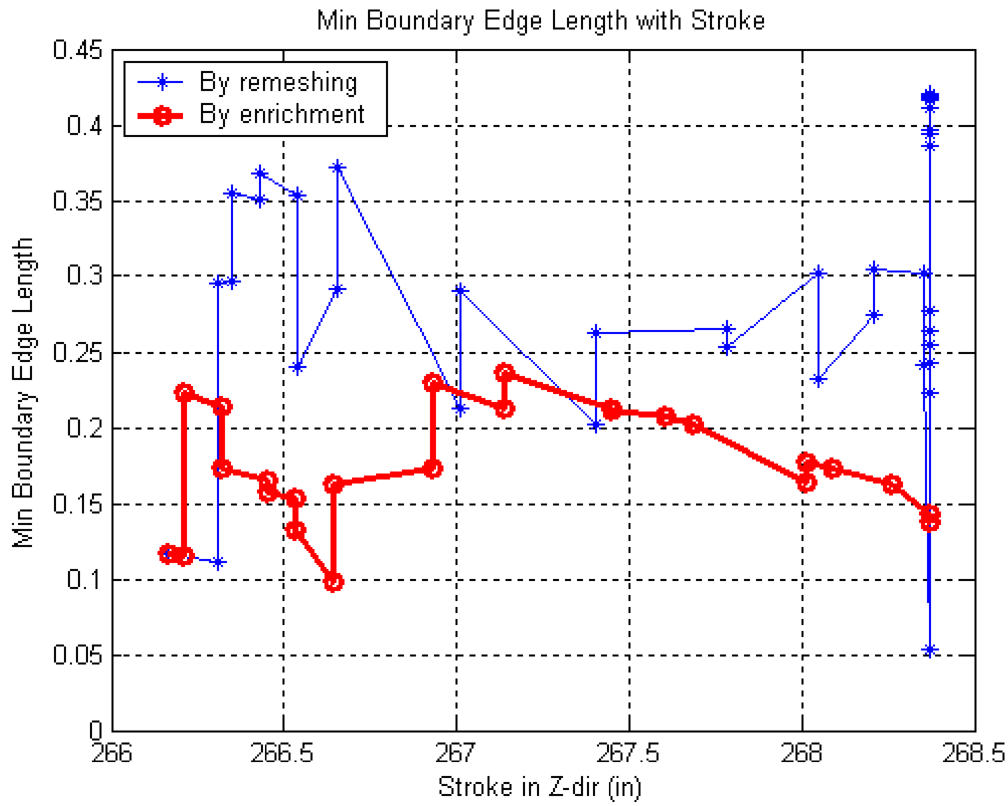


Figure 18 Minimum boundary edge length changes in gear carrier simulations.

Element quality control

The element quality of the workpiece mesh is effectively monitored and improved by the mesh enrichment procedure throughout the entire simulation. Figure 19 shows the largest dihedral angles of the workpiece mesh before and after the remeshing/mesh enrichment steps.

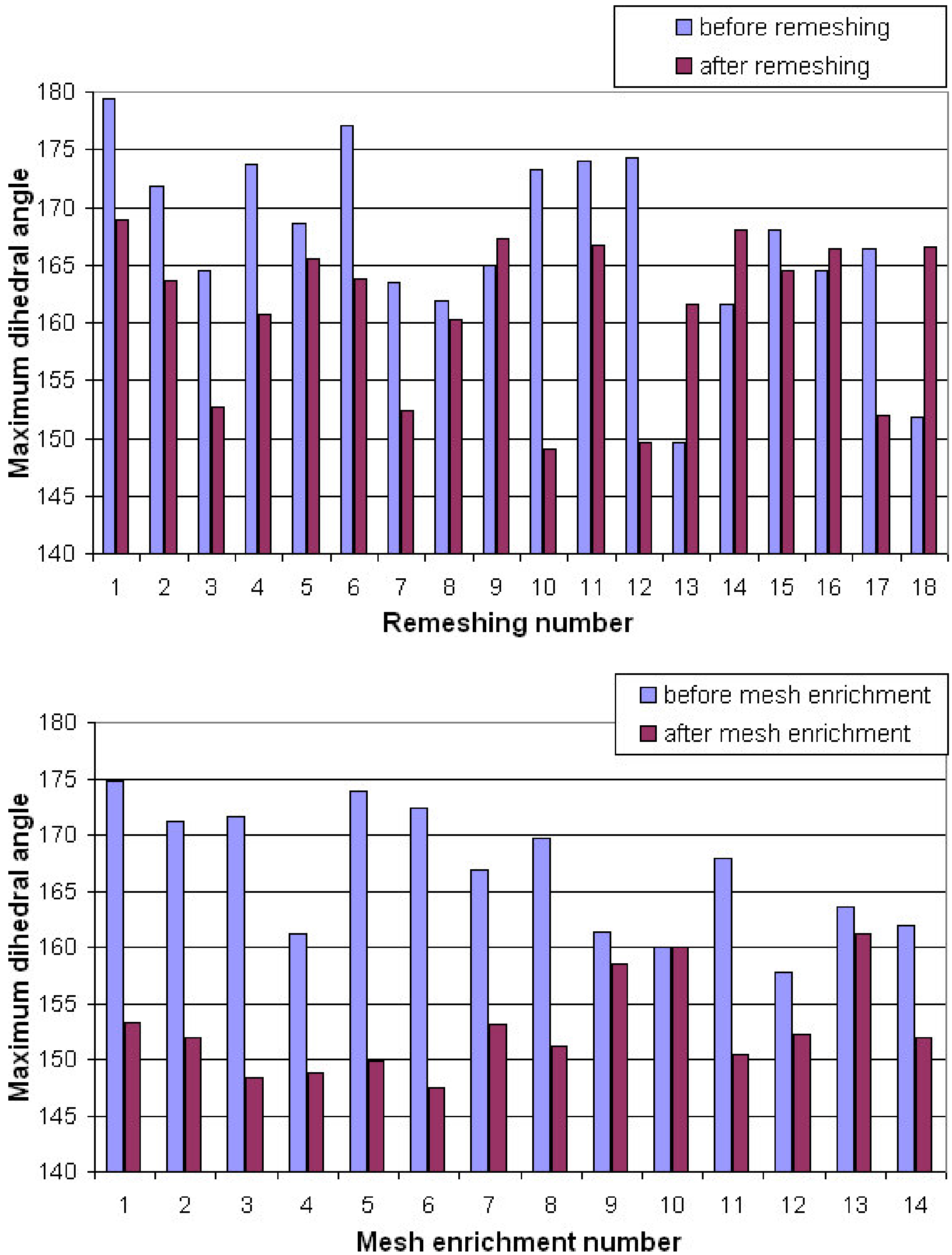


Figure 19 Element quality control for gear carrier simulations.

Consideration of solution transfer

For this plastic deformation problem, the field variables, including the nodal velocity, the nodal temperature, the elemental effective strain and the elemental damage factor, need to be transferred during the remeshing/mesh enrichment process. The accumulated L_2 strain norm of the workpiece mesh vs. Z-stroke is observed during both the simulations as shown in Figure 20. Similarly the global solution transfer applied in DEFORM's remeshing procedure has shown the tendency to diffuse the peak values of the history-dependent state variables.

The CPU time devoted to DEFORM's global solution transfer is 660 seconds while only 108.17 seconds are required by the local solution transfer applied in the mesh enrichment process.

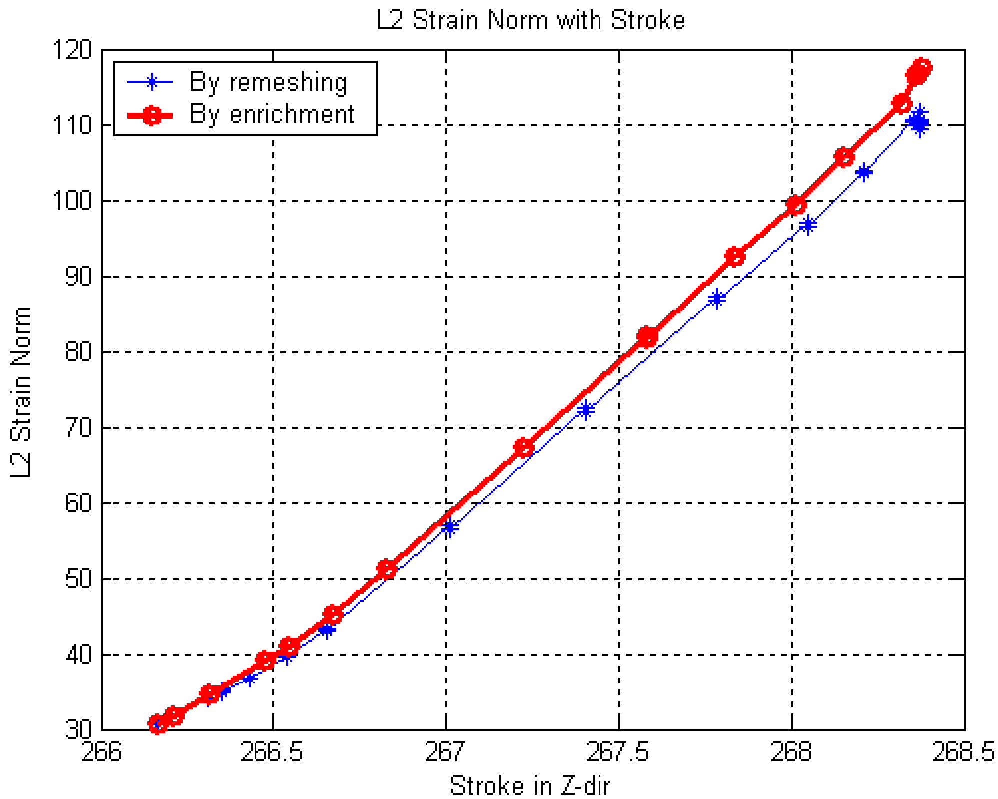
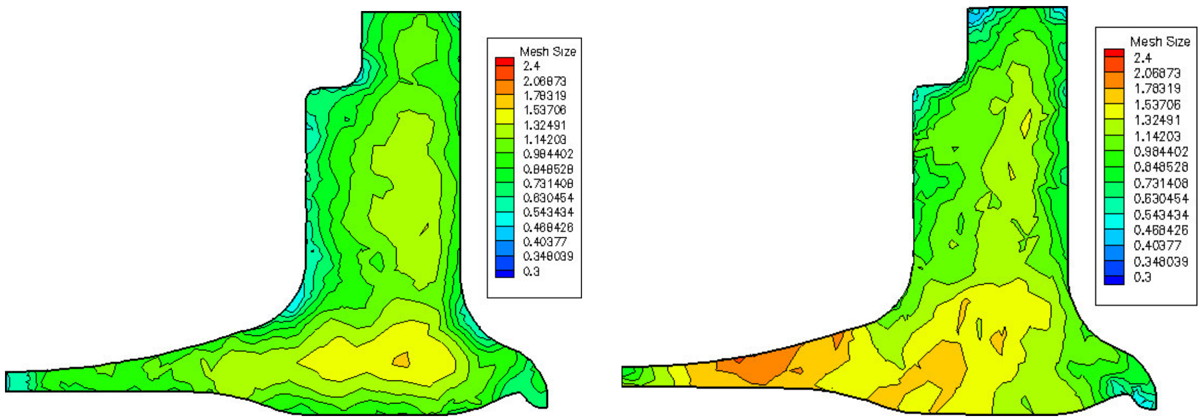


Figure 20 Accumulated L2 strain norm in gear carrier simulations.

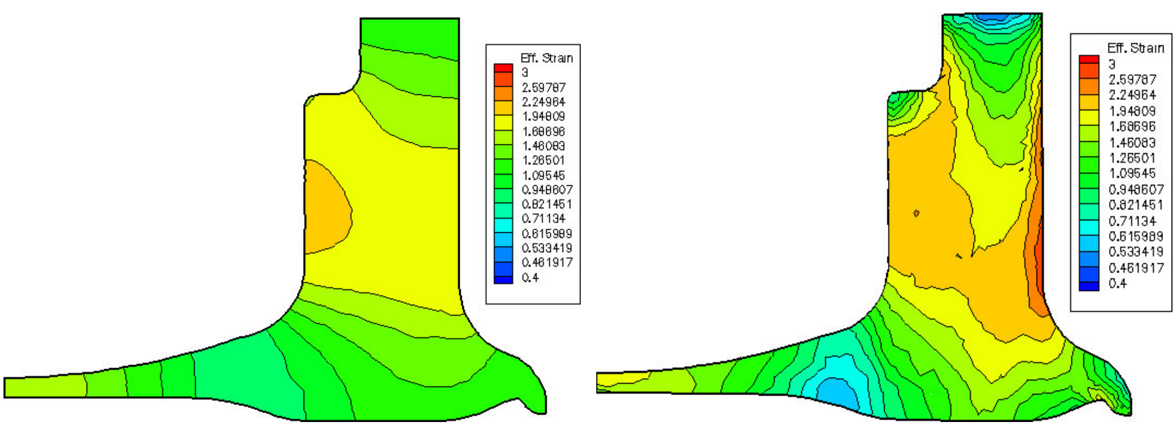
Interior distribution of mesh density and effective strain

The interior effective strain and mesh size distribution achieved in two simulations are shown in Figures 21 and 22. Figure 21 illustrates the profiles in plane of Y=0.0mm and Figure 22 shows the profiles in plane of X=34.0mm. As expected, desired mesh density is yielded at the portions with high strain gradients (such as at the top of the workpiece tooth) in the mesh enrichment based simulation.



By remeshings *By mesh enrichments*

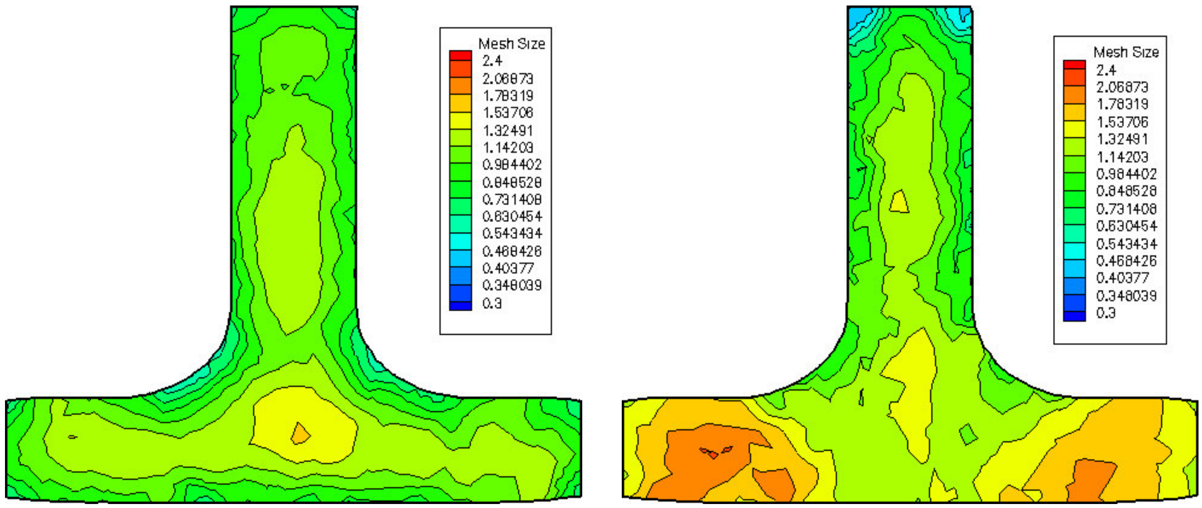
(a) Interior mesh size distribution



By remeshings *By mesh enrichments*

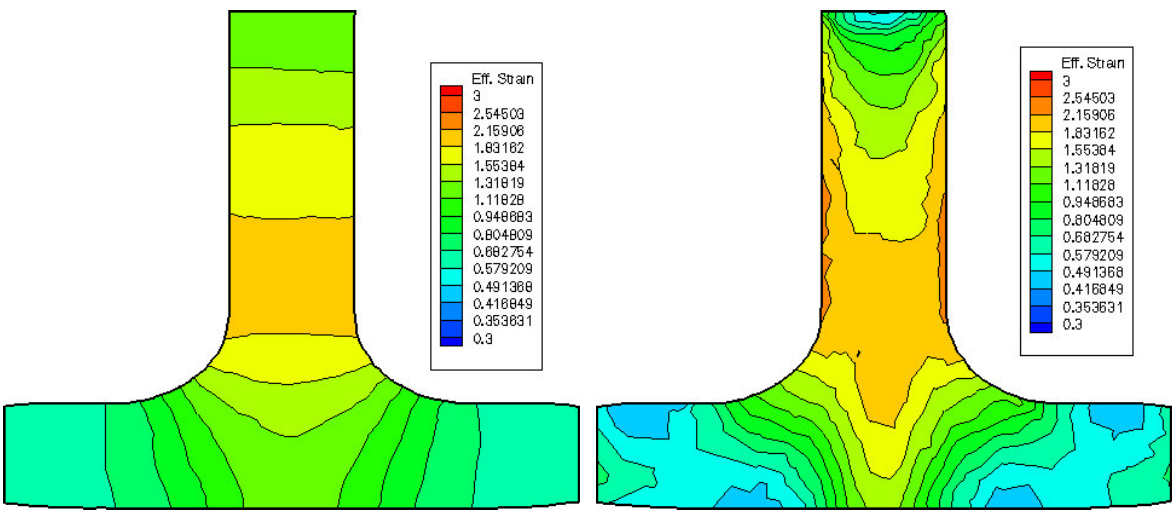
(b) Interior effective strain distribution

Figure 21 Interior mesh size and effective strain distributions at plane of Y=0 mm achieved in gear carrier simulations.



By remeshings *By mesh enrichments*

(a) Interior mesh size distribution



By remeshings *By mesh enrichments*

(b) Interior effective strain distribution

Figure 22 Interior mesh size and effective strain distributions at plane of X=34mm achieved in gear carrier simulations.

3.3 An Elasto-plastic Extrusion Problem

An extrusion problem with elasto-plastic material provided by GE is solved to compare the performance of the remeshing and mesh enrichment procedures on elasto-plastic deformation problems. The simulations starts from Z-stroke=0.574 inch and ends at Z-stroke=0.9742 inch. The starting workpiece mesh (at Z-stroke =0.574 inch) consists of 6,217 mesh vertices and 29,166 mesh regions as shown in Figure 23. The speed of the primary die is 0.1 inch/second and the initial time step size is 0.01 second/step. The allowed geometric interference is 0.01 inch.

The problem is solved after 13 DEFORM's remeshing steps with the final workpiece mesh consisting of 9,363 mesh vertices and 39,719 mesh regions. In mesh enrichment based simulation, 21 mesh enrichment steps are used and the final mesh consists of 7,855 mesh vertices and 35,752 mesh regions. The numbers of nodes of the workpiece mesh vs. Z-stroke are shown in Figure 24 and the final workpiece meshes are presented in Figure 25.

The remeshing/mesh enrichment based simulations take total 64,078 seconds and 60,520 seconds to complete respectively (in CPU time on *rushmore* of GE. The same simulations are being investigated on *monopoly* of SCOREC, RPI). The accumulated run time vs. Z-stroke is compared in Figure 26 and the simulation comparison is summarized in Table 4.

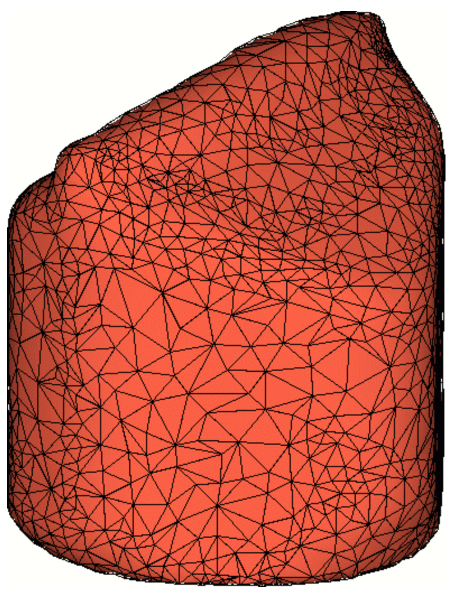


Figure 23 The starting workpiece mesh for the elasto-plastic extrusion simulation.

(Consisting of 6,217 mesh vertices and 29,166 mesh regions at Z-Stroke =0.574 inch)

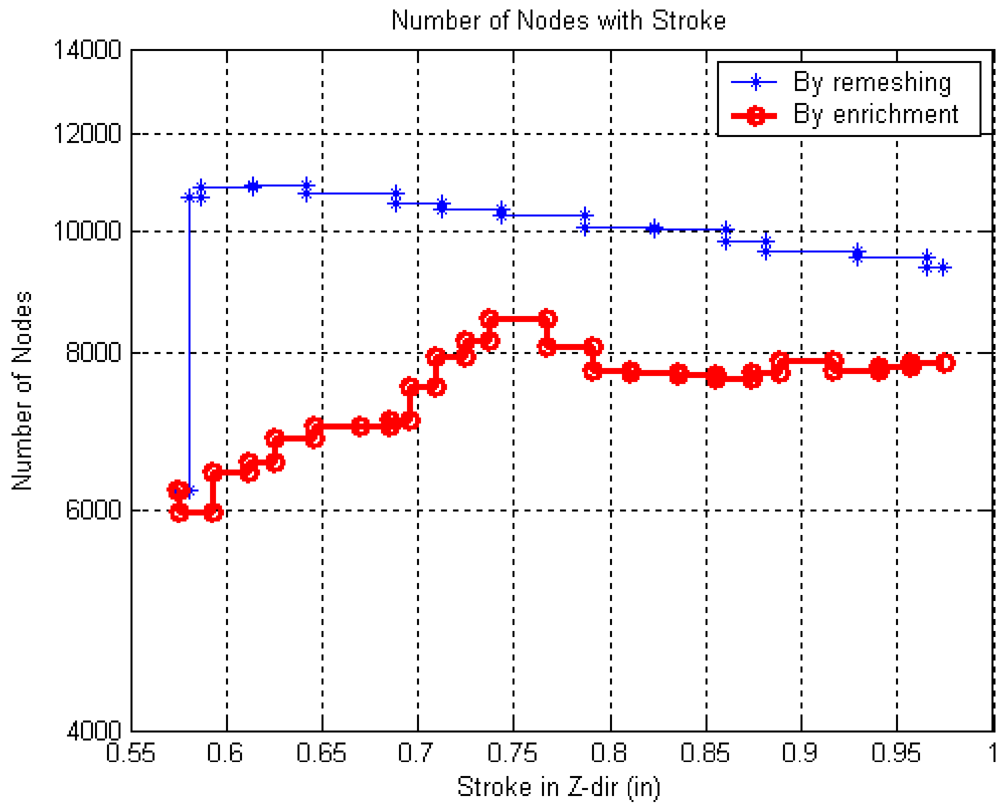
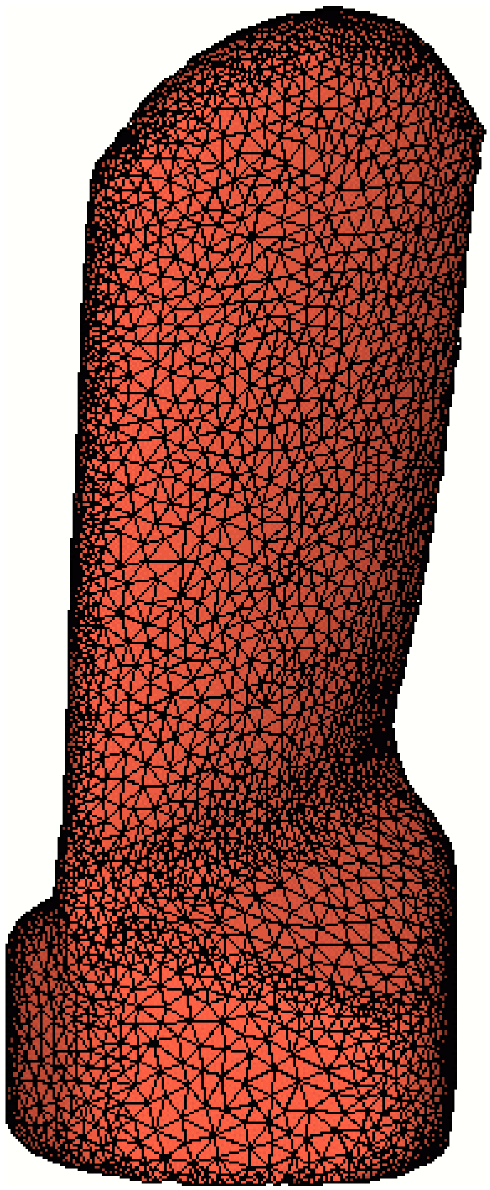
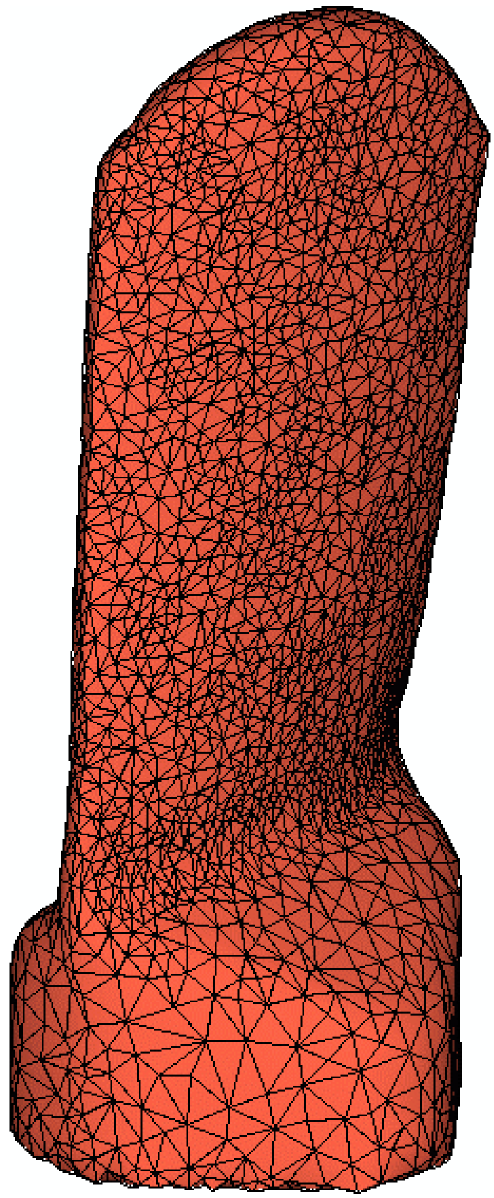


Figure 24 Numbers of nodes used in the elasto-plastic extrusion simulations.



a) By remeshings
(9,363 mesh vertices and 39,719 mesh regions)



b) By mesh enrichments
(7,855 mesh vertices and 35,752 mesh regions)

Figure 25 The final workpiece meshes achieved in elasto-plastic extrusion simulations.

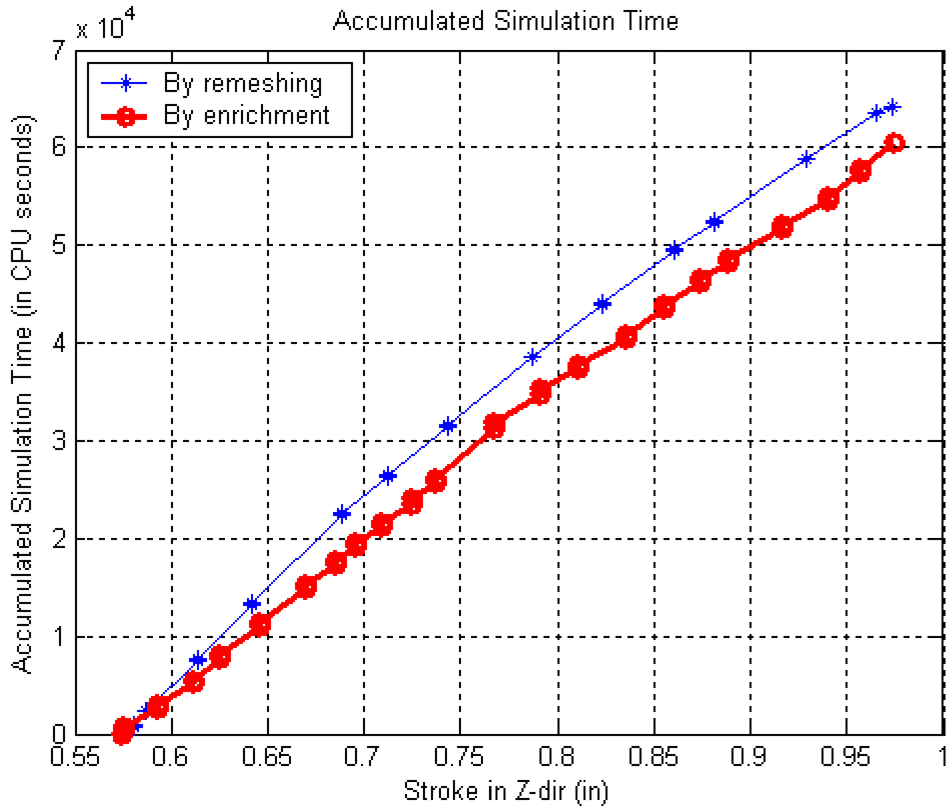


Figure 26 Accumulated simulation time of elasto-plastic extrusion simulations.

Table 4: Comparison summary of elasto-plastic extrusion simulations.

Mesh updating method	Remeshings	Mesh enrichments
Number of remeshing/mesh enrichment steps	13	21
Overall CPU run time (in seconds)	64,078	60,520
Number of mesh vertices/regions in the final workpiece mesh	9,363 / 39,719	7,855 / 35,752
Min/Max mesh edge length in the final workpiece mesh	0.02045 / 0.12293	0.01294 / 0.25537
Min/Max temperature in the final workpiece (°F)	813.78 / 1,764.04	832.808 / 1,809.21
Min/Max effective strain in the final workpiece	0.22369 / 2.96483	0.03836 / 3.50068
Min/Max effective stress in the final workpiece	20.980 / 301.602	23.9607 / 302.12

Boundary mesh size and time step control

The changes in the minimum boundary edge length of the workpiece mesh are shown in Figure 27. The minimum boundary edge length in the remeshed workpiece mesh ranges from 0.017 to 0.021 inch while in the enriched workpiece mesh ranges from 0.010 to 0.022 inch. When the enriched workpiece mesh contains relatively short boundary edges, time step size smaller than the initial value is usually adopted to avoid potential substeps as shown in Figure 28. Consider the estimation of the allowed maximum time step size is based on both the boundary edge length and the nodal velocity of the workpiece, a larger minimum boundary edge length does not necessarily lead to a larger time step size as can be seen in Figures 27 and 28. With the boundary edge length control and adaptive time step adjustment adopted in the enrichment-based simulation, unacceptably small time step sizes and DEFORM's substeps have been effectively avoided.

Element quality control

The element quality of the workpiece mesh is monitored during the analysis steps and improved based on the controlled local mesh modifications throughout the enrichment-based simulation. Figure 29 shows the largest dihedral angles of the workpiece mesh before and after remeshing/mesh enrichment steps. From the figure one can notice that in the mesh enrichment based simulation the largest dihedral angle of the workpiece mesh is controlled around or under 175° by the application of the simulation monitoring function while most of DEFORM's remeshing steps are triggered till the largest dihedral angle approaches to 180°. This partially explains why more mesh enrichment steps are taken than remeshing steps.

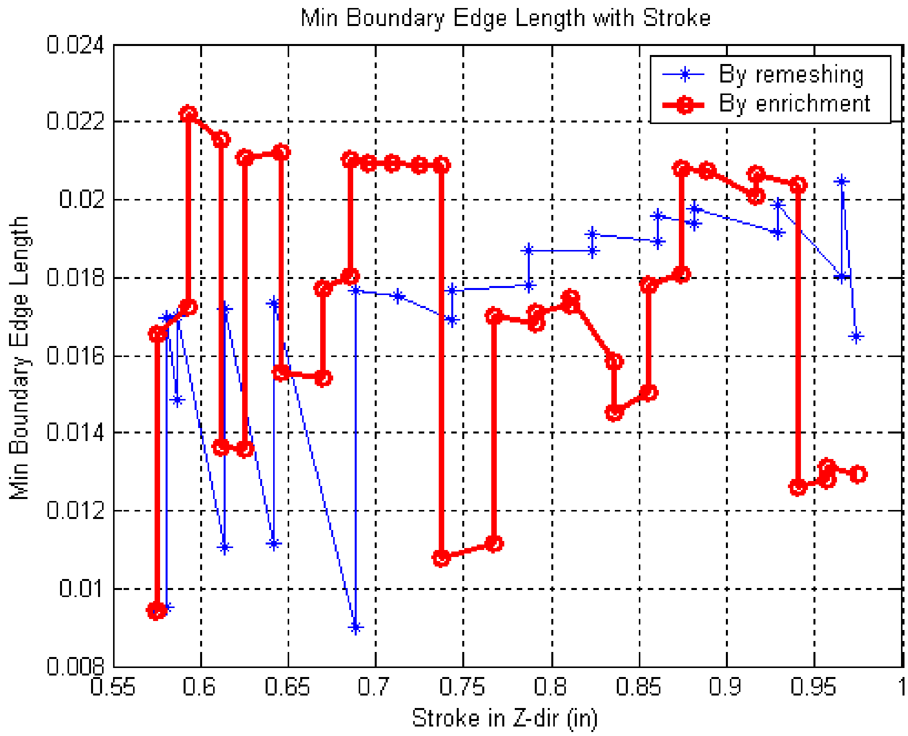


Figure 27 Minimum boundary edge length changes during the simulation

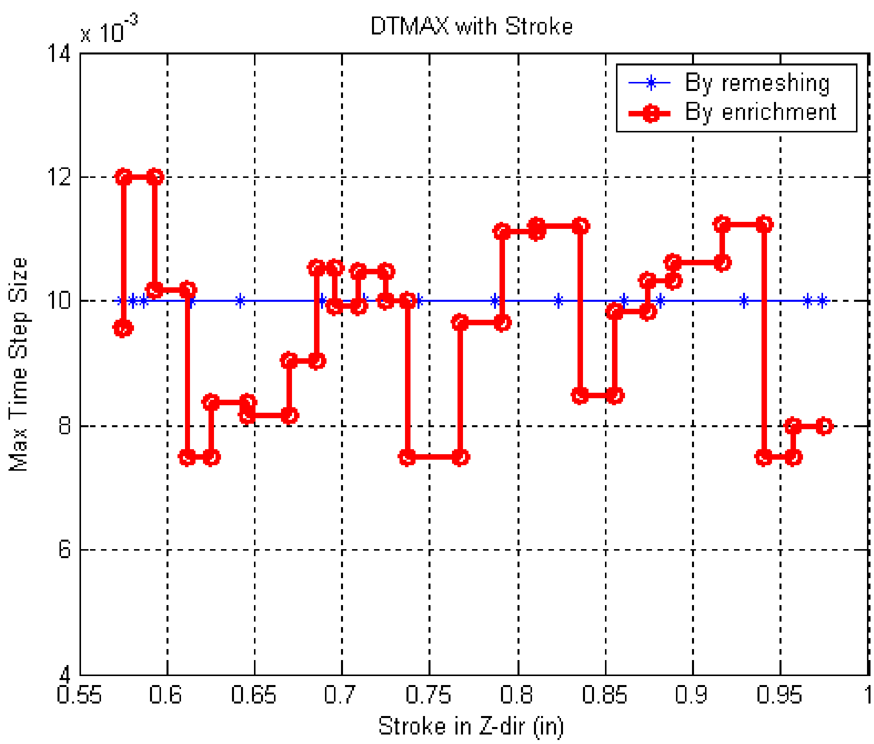


Figure 28 Maximum time step size used in elasto-plastic extrusion simulations.

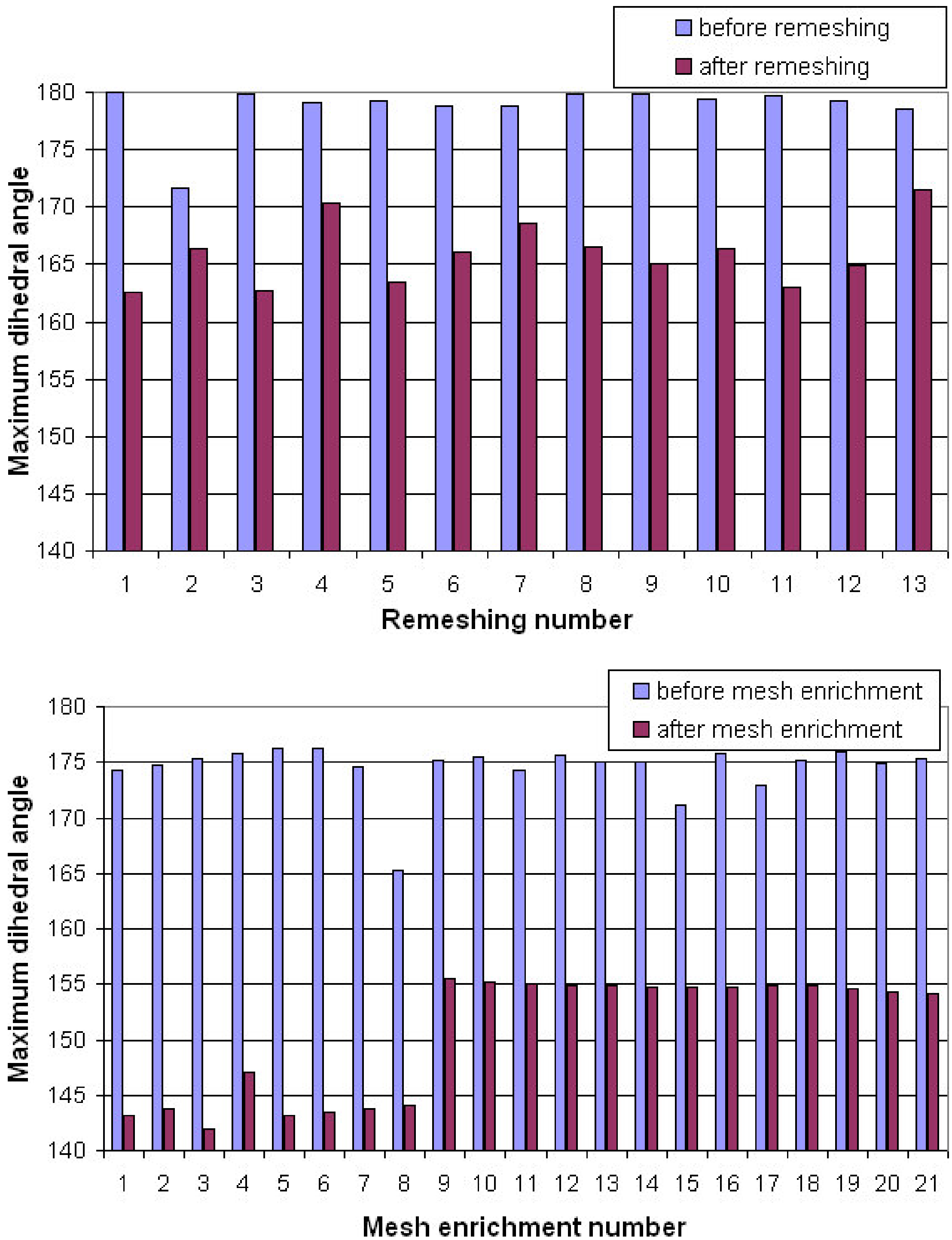


Figure 29 Element quality control in elasto-plastic extrusion simulations.

Consideration of solution transfer

For this elasto-plastic deformation simulation, the field variables, including the nodal velocity, the nodal temperature, the elemental effective strain, the elemental damage factor and the stress tensor, are considered to be transferred during the remeshing/mesh enrichment steps. The accumulated L_2 strain norms in the two simulations are compared in Figure 30 as an evaluation of the solution transfer accuracy based on the local transfer procedure adopted in enrichment-based simulation and the global transfer procedure used in remeshing-based simulation. Similarly larger accumulated L_2 strain norm is observed in the enrichment-based simulation.

The interior distributions of the velocity and temperature in the final workpiece meshes are compared in Figure 31. One can see the distributions are very close between the two simulations.

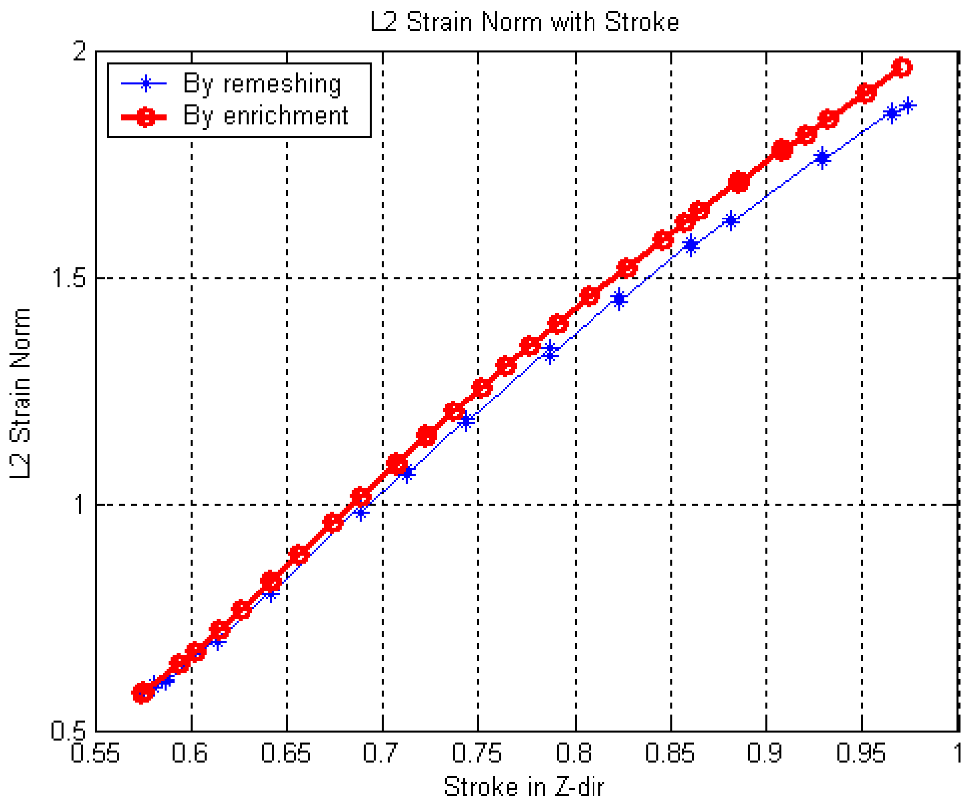
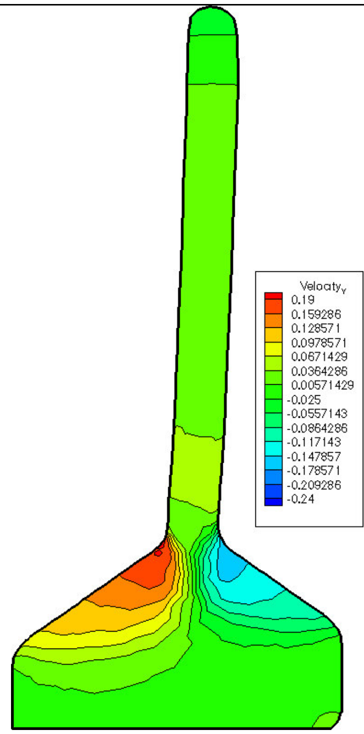
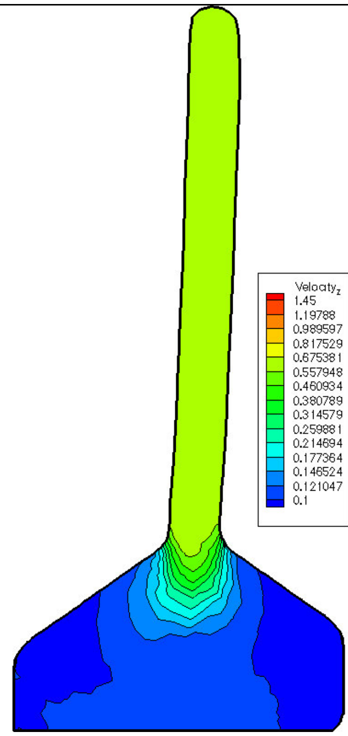
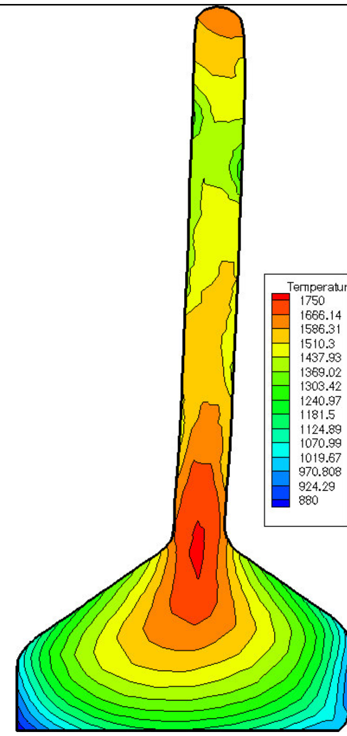


Figure 30 Accumulated L_2 strain norm in elasto-plastic extrusion simulations.

<table>
<tr><th>Velocity in Y-direction</th><th>Velocity in Z-direction</th><th>Temperature</th></tr>
<tr>
<td>

By remeshings</td>
<td>

By remeshings</td>
<td>

By remeshings</td>
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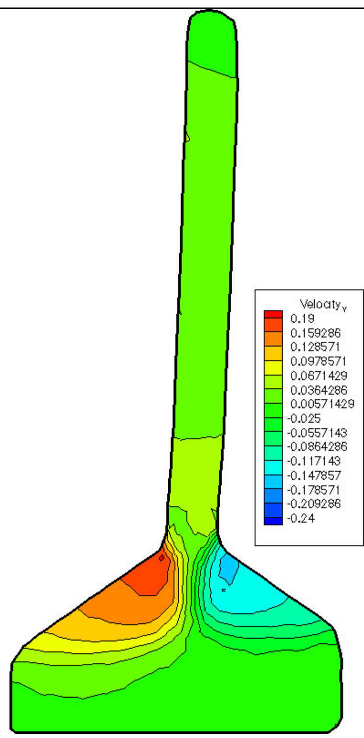
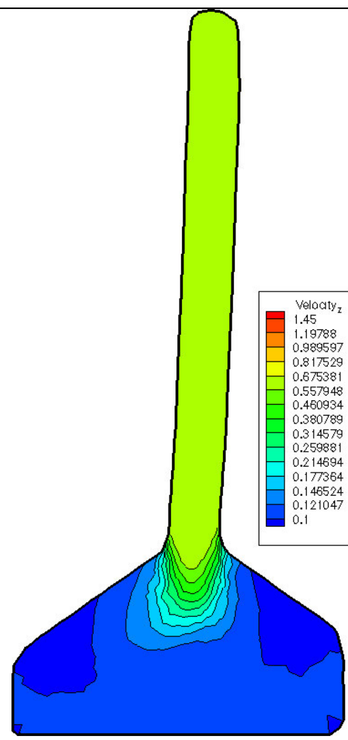
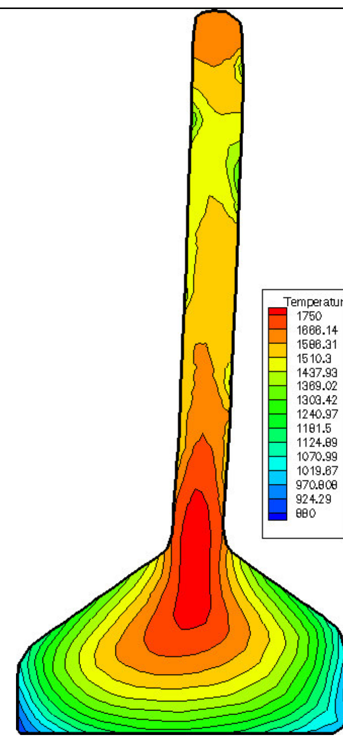
<td>

By mesh enrichments</td>
<td>

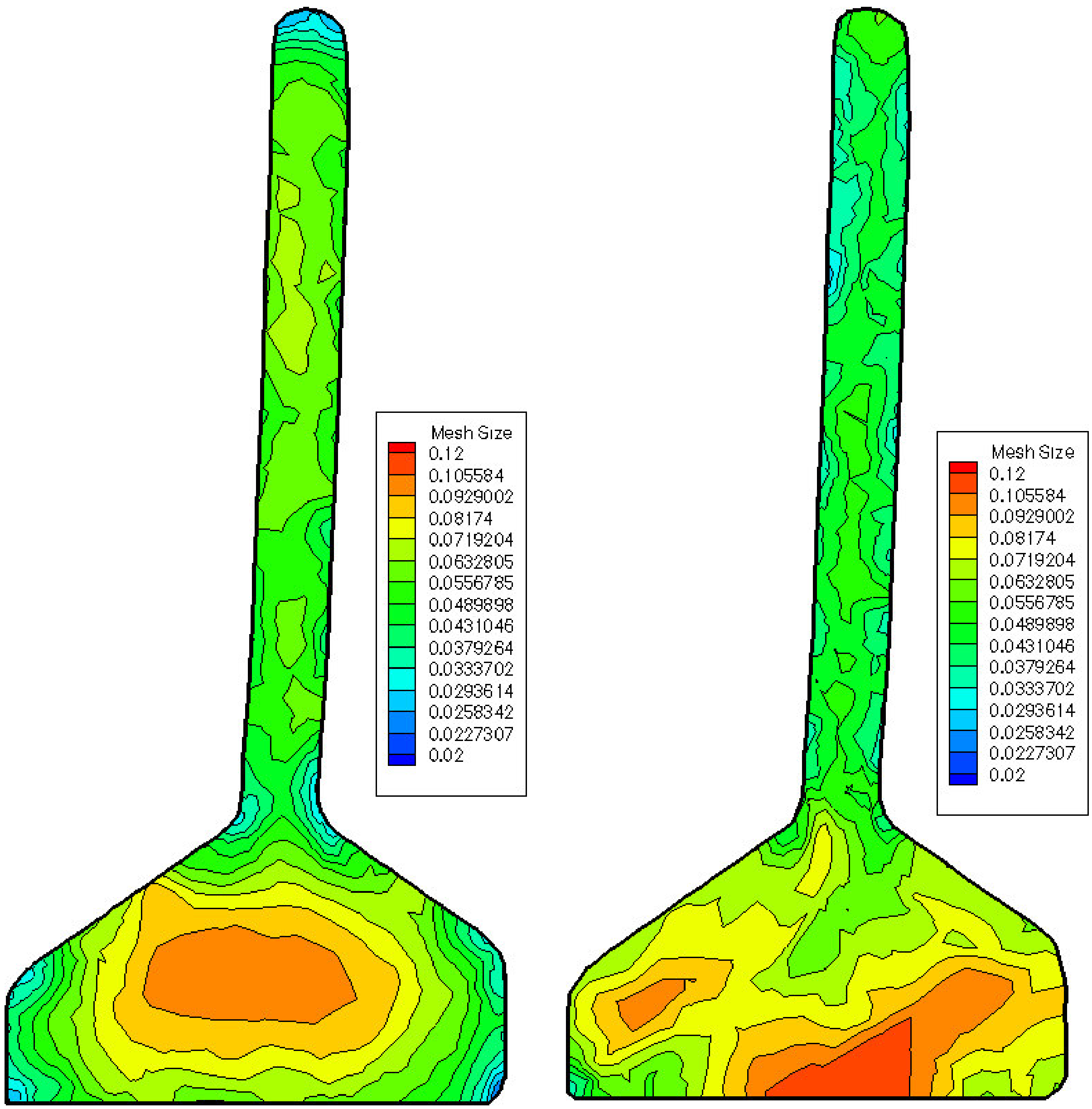
By mesh enrichments</td>
<td>

By mesh enrichments</td>
</tr>
</table>

Figure 31 Comparison of the interior distributions of selected node-based fields.

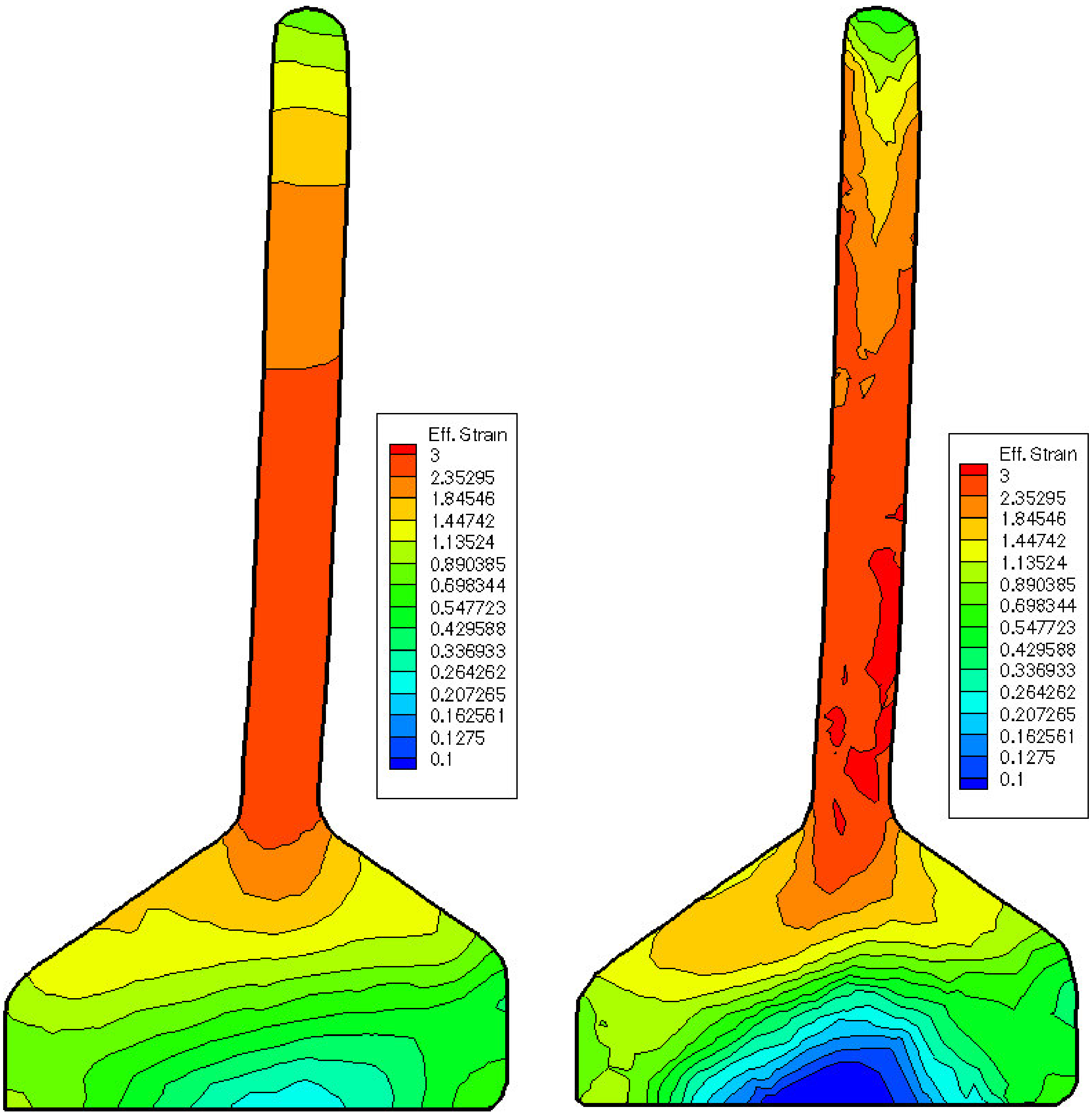
Simulation results

The interior mesh size and effective strain distributions in the final workpiece meshes are compared in Figures 32 and 33. It can be seen that in the remeshing-based simulation, smaller mesh size is used around the boundary features with high curvature and larger mesh size inside the workpiece domain, while in the enrichment-based simulation the mesh is adapted according to the strain gradients and geometric approximation. The interior effective Mises stress distributions are compared in Figure 34.



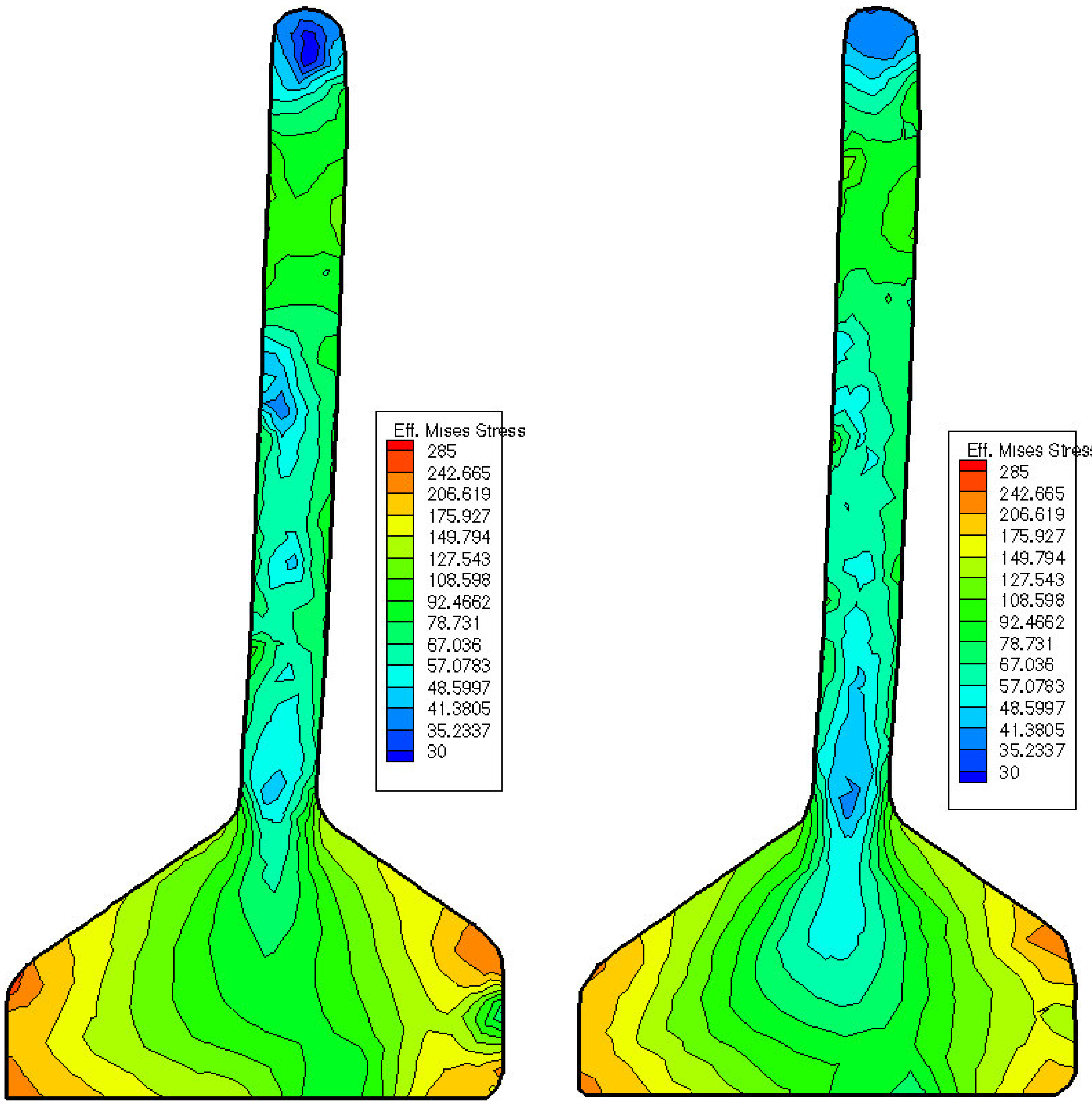
By remeshings *By mesh enrichments*

Figure 32 Interior mesh size distributions achieved in elasto-plastic extrusion simulations.



By remeshings *By mesh enrichments*

Figure 33 Interior effective strain distributions achieved in elasto-plastic extrusion simulations.



By remeshings *By mesh enrichments*

Figure 34 Interior effective Mises stress distributions achieved in elasto-plastic extrusion simulations.

The load stroke curves of the two simulations are compared in Figure 35. A big undulation in Z load is observed around Z-stroke =0.68 inch in the remeshing-based simulation. The estimated loads at the simulation completion (Z-stroke =0.9742 inch) for the two simulation are 523.99 klbf and 481.79 klbf respectively (we suggest to compare the estimated load with the actual load used in the practice if possible. For further investigation on the load difference, another remeshing-based simulation will be run with a finer workpiece on *rushmore* and the simulations are being run on *monopoly* of SCOREC, RPI).

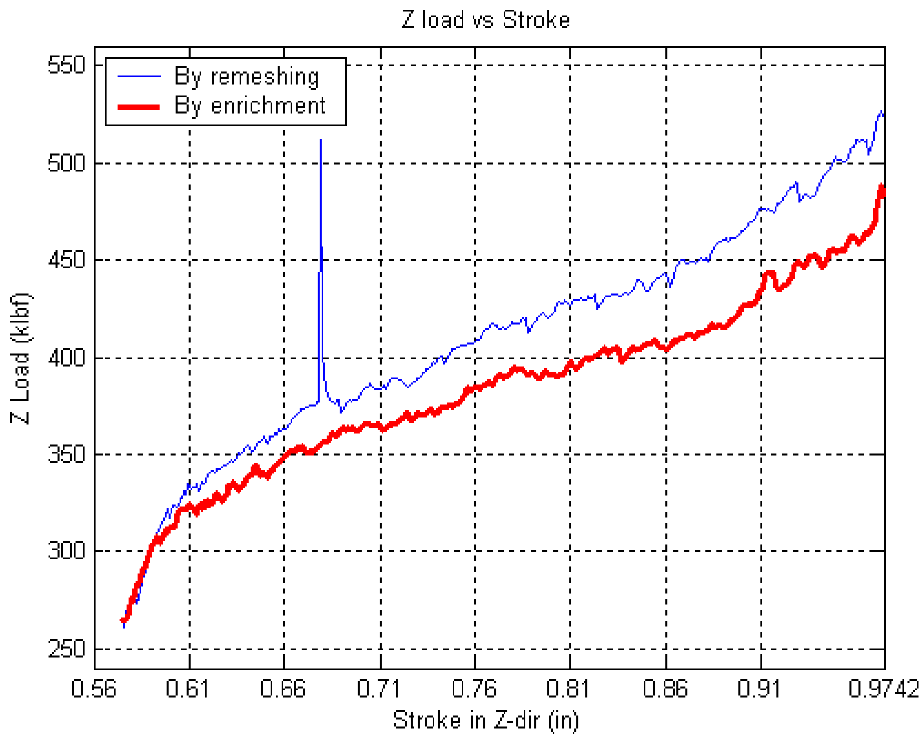


Figure 35 Load stroke curves achieved in elasto-plastic extrusion simulations.

4. CLOSING REMARKS AND FUTURE WORK

Three different industrial forming problems have been investigated using DEFORM's remeshing procedure and SCOREC-GE's mesh enrichment procedure respectively in this study. Based on the comparison of the simulation process and results, one can observe that:

1. The mesh enrichment procedure enables the simulations to perform more efficiently than DEFORM's remeshing procedure by updating the workpiece mesh in accordance with the mesh discretization and geometric approximation requirements. The efficiency comparison on three simulations is summarized in Table 5.

2. The element quality can be effectively monitored and stably improved based on the controlled application of local mesh modifications in the mesh enrichment procedure. The element quality control evaluated based on the worst element shape (measured by the mean ratio) and the largest dihedral angle of the workpiece meshes during the remeshing and mesh enrichment based simulations is summarized in Table 6. In the mesh enrichment based simulations, the enrichment steps are successfully triggered before the element distortion becomes too large.

3. Adaptive time step adjustment helps to reduce/avoid substeps in mesh enrichment based simulations. No substeps have been used in the steering link simulation and only 1 substep has been observed in the GE's elasto-plastic extrusion simulation.

Table 5 Summary of simulation efficiency comparison.

Simulation performed	**Steering Link**		**Gear Carrier**		**GE's Elasto-plasctic Extrusion**	
	By Remeshings	By Enrichments	By Remeshings	By Enrichments	By Remeshings	By Enrichments
# of Mesh Updates	35	21	18	14	13	21
Total Run CPU Time (in seconds)	99,537 *(monopoly)*	89,905 *(monopoly)*	59,872 *(monopoly)*	59,499 *(monopoly)*	64,078 *(rushmore)*	60,520 *(rushmore)*
# of mesh vertices in final workpiece mesh	13,893	15,789	8,725	7,529	9,363	7,855
# of mesh regions in final workpiece mesh	61,787	66,795	36,717	34,117	39,719	35,752

Table 6 Summary of element shape control comparison.

Simulation performed	**Steering Link**		**Gear Carrier**		**GE's Elasto-plasctic Extrusion**	
	By Remeshins	By Enrichments	By Remeshings	By Enrichments	By Remeshings	By Enrichments
Minimum worst element shape **before** mesh updates	0.00000	0.00020	0.00002	0.00181	0.00000	0.00042
Minimum worst element shape **after** mesh updates	0.00367	0.01674	0.00538	0.01665	0.00371	0.02748
Maximum worst element shape **after** mesh updates	0.02389	0.05959	0.05094	0.05298	0.01860	0.07435
Maximum largest dihedral angle **before** mesh updates	180.000°	178.271°	179.458°	174.788°	180.000°	176.190°
Maximum largest dihedral angle **after** mesh updates	171.586°	164.220°	168.882°	161.263°	171.448°	155.442°
Minimum largest dihedral angle **after** mesh updates	157.58°	146.948°	149.094°	147.495°	162.508°	141.947°

Through the simulation comparison, some future efforts have been identified as follows:

1. To further improve the efficiency of the mesh enrichment process, especially during the phases of error estimation, mesh size specification and application of local mesh modifications;
2. To apply the surface curvature control over the free workpiece surface for further control of the geometric approximation errors.

ACKNOWLEDGMENTS

The assistance from D. Mika, P. R. Myers and A. Majorell of GE during this study is highly appreciated.