Coupled Thermal-Structural Analysis of the Shippingport Nuclear Reactor Using Adaptive Remeshing in Abaqus/CAE

Summary

Mesh construction is a key consideration in the course of building a finite element model. The quality of the analysis results depends on the quality of the mesh; arriving at an acceptable solution requires judicious meshing choices. Specifically, the analyst must consider the type of elements and the density of the mesh, which is often varied throughout the model, with more refinement in critical regions. These considerations need to be balanced against the desire to minimize analysis cost in terms of preprocessing effort, analysis run time, and computer resources.

Beginning with Version 6.6 the adaptive Remeshing features in Abaqus allow Abaqus/CAE and Abaqus/Standard to work together automatically in an iterative fashion to determine an optimal mesh. The goal of this capability is to obtain a solution that satisfies discretization error indicator targets while minimizing the number of elements and, hence, the cost.

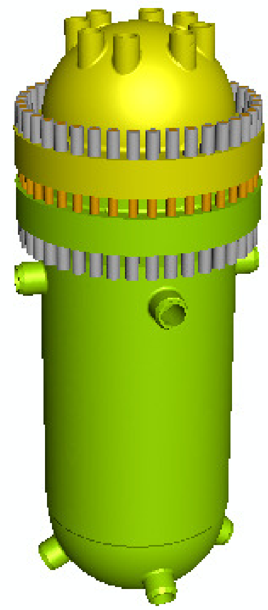
To demonstrate the adaptive remeshing technique, this technology brief describes how a sequentially coupled thermal-structural analysis is performed with a model of the Shippingport nuclear reactor.

Background

The Shippingport reactor, the first commercial nuclear generator in the United States, was in operation between 1957 and 1982. It was a pressurized water reactor in which the primary coolant loop used water under high pressure to transfer heat from the reactor core.

A short and rapid temperature change is considered to be a severe load case for a nuclear reactor. The simulation presented here considers the effect of a thermal transient in the primary coolant loop, specifically a 30°F decrease in the interior water temperature over a 45-sec period. The reactor vessel assembly is also subjected to a nominal operating pressure of 2×10^3 psi.

A simplified form of the complete reactor vessel assembly, as shown in Figure 1, is created in Abaqus/CAE. This simplified model includes the vessel, the closure head, the studs, the nuts, and the washers. For the mesh construction the structure contains several interesting features, including openings in the vessel, rapid thickness transitions, fillets, and small radii in the closure region.



Key Abaqus Features and Benefits

Automatic adaptive remeshing for Abaqus/Standard analyses submitted from Abaqus/CAE:

- Allows the mesh to vary topologically—the number of nodes and elements can increase or decrease.
- Eliminates the need to choose critical meshing regions a priori; the remeshing process will focus or coarsen the mesh automatically throughout the model to satisfy accuracy targets.
- Provides the ability to specify different remeshing rules in different regions of the model.
- Permits error indicator results to be visualized as a means of assessing mesh quality.

With the adaptive remeshing capability available in Abaqus, the quality of the simulation results can be improved without prior knowledge of how refined the mesh must be to obtain accurate results. Abaqus/CAE and Abaqus/Standard can work together to create a mesh that simultaneously satisfies user-defined error targets while minimizing the number of required elements.

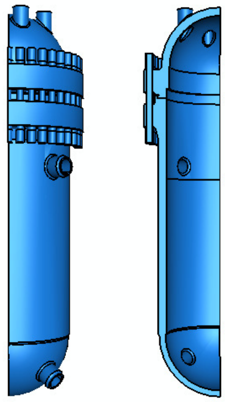


Figure 1: Quarter symmetric model of the Shippingport reactor created in Abaqus/CAE.

Finite Element Analysis Approach

A sequentially coupled thermal-structural analysis is carried out to simulate the response of the pressurized water reactor to the thermal transient. The heat transfer analysis is conducted first, and the temperature results are read into the stress analysis as part of the loading.

Adaptive remeshing is employed in both the heat transfer analysis and the stress analysis. Due to the symmetric design of the reactor, only one quarter of the structure is modeled, as shown in Figure 1. The stud bolts are tied to the nuts and the washers. Surface-to-surface contact with a small-sliding formulation is defined for the vessel and closure head seating ledges, the nut-to-washer interfaces, the washer-to-closure head interface, and the washer-to-vessel interface.

Remeshing Techniques

To incorporate adaptive remeshing into an Abaqus/CAE model:

1. Identify the regions of the model where remeshing is to be applied.
2. Define a remeshing rule, which includes:
   - Selecting output variables used to calculate error indicators.
   - Setting error indicator targets.
   - Selecting the element sizing method.
   - Setting any constraints on the element size.
3. Define the adaptivity process, which includes:
   - Selecting the number of remeshing iterations.
   - Setting job execution parameters.

Next, Abaqus/CAE submits a series of jobs to Abaqus/Standard. Each job communicates error indicator results back to Abaqus/CAE, which uses them in an element sizing function to compute new element sizes. You can size elements using a minimum/maximum algorithm or a uniform error distribution mesh sizing algorithm.

The minimum/maximum algorithm allows for a continuous variation in error targets between regions of high and low base solution values, providing the most flexibility for remeshing regions of rapid solution change. The uniform error distribution algorithm provides a single error target that is used for every element in the given region.

Each successive analysis job covers the same simulation history time period but uses a recomputed mesh generated by the adaptive remeshing process. Remeshing iterations are performed until the error targets are met or a maximum number of iterations are reached. As a result, an optimized mesh is created that provides a balance between computational cost and solution accuracy. The same mesh would be difficult to generate manually, even by experienced users.

Heat Transfer Analysis

The thermal portion of the analysis consists of two steps. The first step is a steady-state analysis in which the reactor is brought from an initial temperature of 70°F to a steady operating temperature distribution based on a 538°F outlet water temperature and a 508°F inlet water temperature.

The second step simulates the rapid cool down in the fuel core. The 30°F outlet temperature drop occurs over a 45-sec period—the inlet temperature remains the same. The transient response of the reactor is then monitored for 15 minutes. Figure 2 shows the surface regions where the thermal interactions are defined.

Table 1 shows the remeshing rules for the heat transfer analysis. Heat flux is chosen as the base solution variable on which the error is reported.

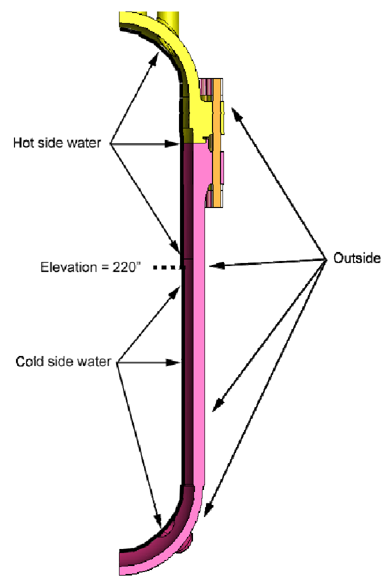


Figure 2: Thermal interaction regions.

Table 1: Remeshing rule parameters specified in the thermal analysis.

Component	Error indicator	Sizing method	Error target (%)
Stud	HFLERI	Uniform	10.0
Head	HFLERI	Uniform	5.0
Nut	HFLERI	Uniform	5.0
Washer	HFLERI	Uniform	5.0
Vessel	HFLERI	Uniform	5.0

Figure 3 shows the original mesh used in the first remeshing iteration of the adaptivity process, created in Abaqus/CAE with uniform seed sizes.

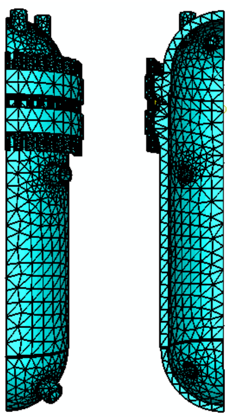


Figure 3: Original mesh used in the thermal and the structural analyses.

Structural Analysis

The structural analysis also includes two steps. The closure preload and interior pressure loads are applied in the first step. The second step is based on the 15-minute thermal transient analysis described above; specifically, the temperatures calculated in this analysis are applied as a loading condition.

The adaptivity process starts with the same mesh as that shown in Figure 3. High stresses are expected in regions where the nozzles penetrate the closure head and vessel; therefore, these two components are partitioned into regions as shown in Figure 4 and Figure 5. The minimum/maximum algorithm is specified in the regions that contain the nozzles, and the uniform error distribution algorithm is used in the rest of the regions. The remeshing rules are defined with the parameters shown in Table 2. Element energy density is chosen as the base solution variable on which the error is reported.

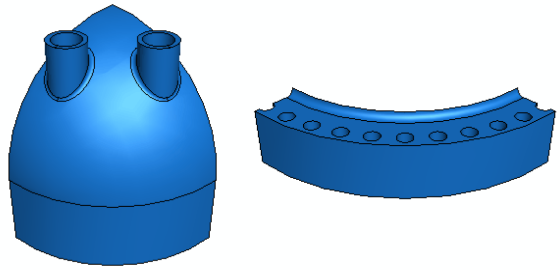


Figure 4: Two regions in the closure head where different remeshing rules are specified. The minimum/maximum algorithm is used in the region shown on the left (Head 1), and the uniform error distribution algorithm is used in the region shown on the right (Head 2).

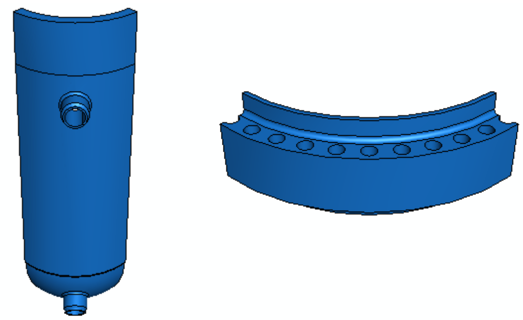


Figure 5: Two regions in the vessel where different remeshing rules are specified. The minimum/maximum algorithm is used in the region shown on the left (Vessel 1), and the uniform error distribution algorithm is used in the region shown on the right (Vessel 2).

Table 2: Remeshing rule parameters specified in the structural analysis.

Component	Error indicator	Sizing method	Error target (%)
Stud	ENDENERI	Uniform	10.0
Head 1	ENDENERI	Min/Max	20.0/2.0
Head 2	ENDENERI	Uniform	10.0
Nut	ENDENERI	Uniform	10.0
Vessel 1	ENDENERI	Min/Max	20.0/5.0
Vessel 2	ENDENERI	Uniform	10.0
Washer	ENDENERI	Uniform	10.0

Results and Conclusions

Thermal Analysis Results

During the thermal analysis the adaptivity process completed after the second remeshing iteration because all remeshing rules were satisfied. Table A1 of Appendix A shows the degree of freedom count and the heat flux error indicator (HFLERI) results of the first and second iterations. Figure 6 shows the meshes created for the vessel and closure head in the first and second iterations.

In the second iteration significant improvement in the temperature results is observed near the bolting flanges, as shown in Figure 7.

To emphasize the effectiveness of the adaptive remeshing, the analysis was rerun with the original mesh refined manually by simply halving the mesh seed sizes. Although the cost was higher in this case, the mesh was not refined as effectively as it was with adaptive remeshing. Additional solution details are provided in Table A2 of Appendix A.

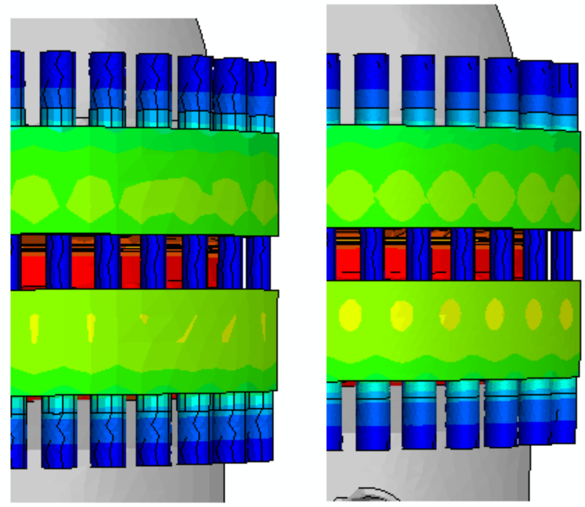
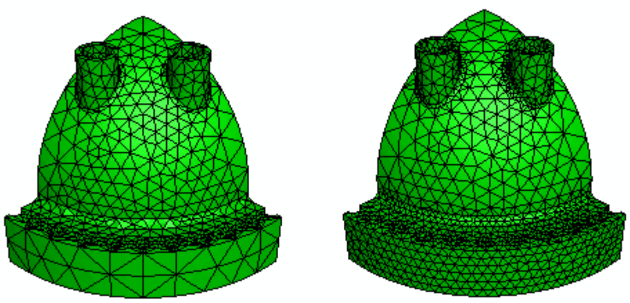
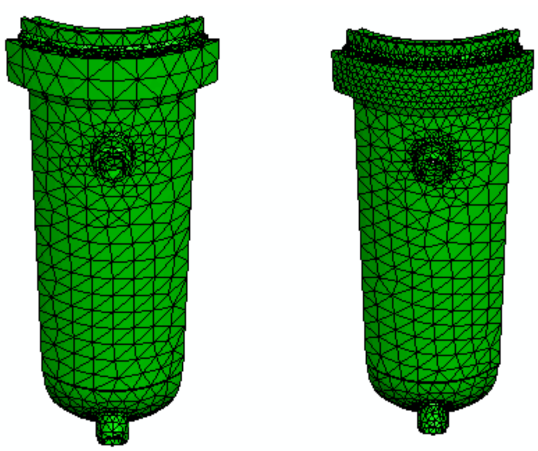


Figure 7: Temperature distribution near the closure assembly after the first (left) and second (right) remeshing iterations.



Closure head.



Vessel.

Figure 6: Meshes created in the first (left) and second (right) remeshing iterations during the thermal analysis.

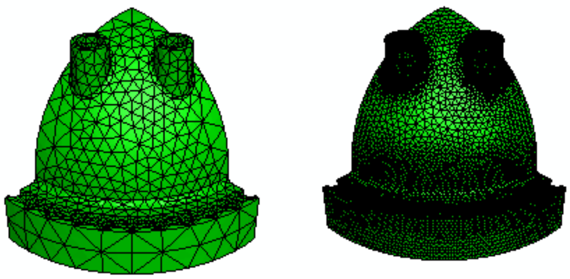
Structural Analysis Results

In the structural analysis the adaptivity process is run with two remeshing iterations. Table A3 of Appendix A shows the estimate of the error indicators and the element count in each remeshing region. To emphasize the effectiveness of the remeshing, the error indicators are again calculated for a manually refined mesh (uniform global seed sizes used in all components); Table A4 of Appendix A shows the results. The adaptive remeshing improves the accuracy of the results more effectively than uniform refinement, especially in regions where high stresses are focused in small areas such as in the stud bolts.

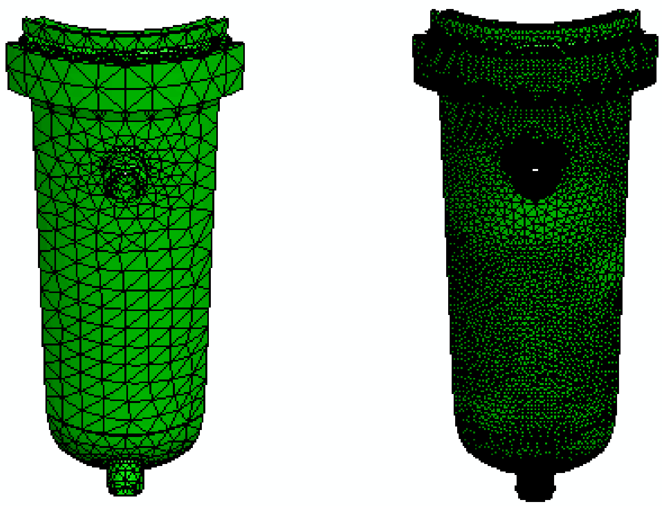
The results of only two remeshing iterations are presented in this technology brief. At least one more iteration is necessary if all remeshing rules are to be satisfied.

Figure 8 shows the closure head and the vessel meshes created in the first and second remeshing iterations.

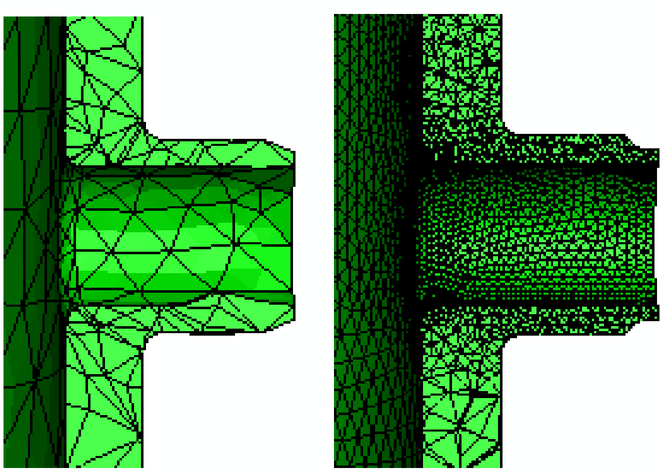
Figure 9 compares the Mises stresses obtained in the first and second remeshing iterations. Figure 10 shows a comparison of the Mises stresses inside the outlet nozzle. Figure 11 shows the time history of Mises stress at a representative point location where the outlet nozzle penetrates the vessel. The stress increases quickly at the beginning of the second step (during the applied thermal transient) and becomes almost constant at the end of the step. Lower stresses are reported with a finer mesh.



Closure head.



Vessel.



A 45° cut of the vessel near the outlet nozzle.

Figure 8: Meshes created in the first (left) and second (right) remeshing iterations during the structural analysis.

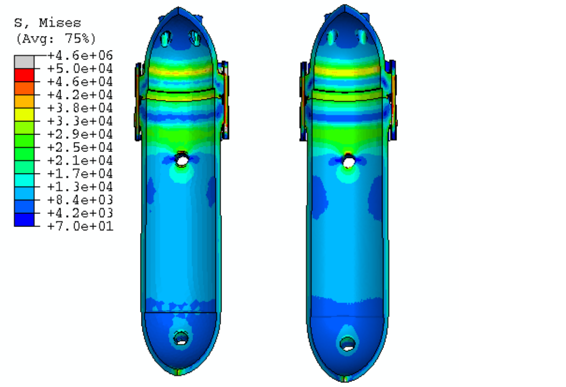


Figure 9: Mises stress results from the mesh created in the first (left) and second (right) remeshing iterations.

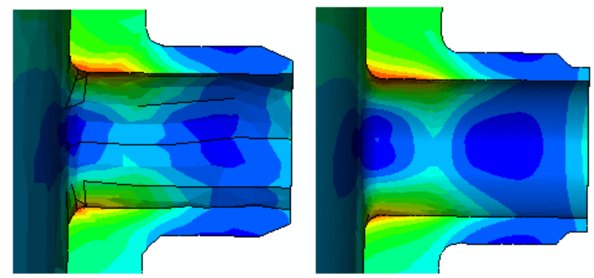


Figure 10: Mises stress in the outlet nozzle from the mesh created in the first (left) and second (right) remeshing iterations.

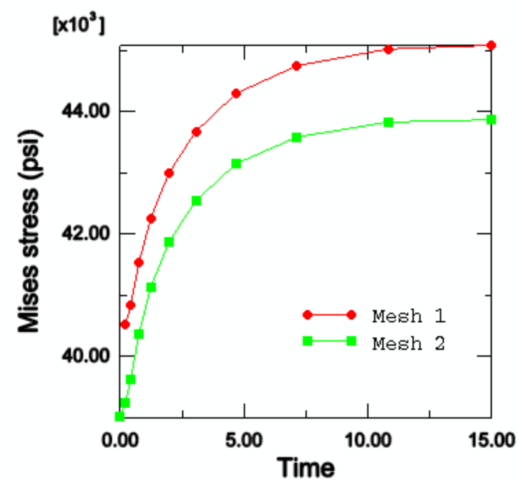


Figure 11: Mises stresses at a location where the outlet nozzle intersects the vessel.

Conclusion

This technology brief demonstrates the adaptive remeshing feature available in Abaqus. The technique is applied to improve mesh accuracy, based on error indicators, in a sequentially coupled thermal-structural analysis of the Shippingport reactor. The results are compared to those generated by uniformly sized meshes with approximately the same number of degrees of freedom. More accuracy is observed with the adaptive remeshing process.

Appendix A

This appendix presents detailed error indicator and element count results for the thermal analysis and the structural analysis.

Thermal Analysis

Table A1: Remeshing results after the first and second remeshing iterations in the thermal analysis

First mesh iteration: 77,046 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	6.50	Yes	10,023
Head	5.73	No	10,761
Nut	5.50	No	4,338
Vessel	5.65	No	10,343
Washer	26.89	No	1,462
Second mesh iteration: 140,045 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	6.92	Yes	9,645
Head	4.25	Yes	16,879
Nut	4.28	Yes	6,754
Vessel	3.29	Yes	14,874
Washer	2.75	Yes	19,180

Table A2: Error indicator and element count results for manually refined mesh in the thermal analysis.

User-defined mesh: 173,229 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	4.59	Yes	34,409
Head	4.78	Yes	17,518
Nut	1.16	Yes	10,968
Vessel	3.57	Yes	22,818
Washer	16.01	No	4,462

Structural Analysis

Table A3: Remeshing results after the first and second remeshing iterations in the structural analysis.

First mesh iteration: 312,113 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	76.43	No	9,510
Head	56.08/36.16	No	2,581
Head 2	64.95	No	7,772
Nut	82.10	No	4,338
Vessel	99.93/35.40	No	2,722
Vessel 2	73.83	No	6,475
Washer	85.08	No	1,462
Second mesh iteration: 3,399,662 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	23.35	No	30,995
Head	18.53/21.79	No	117,982
Head 2	26.97	No	69,498
Nut	69.31	No	19,692
Vessel	17.10/135.49	No	123,874
Vessel 2	24.74	No	60,679
Washer	51.75	No	14,994

Table A4: Error indicator and element count results for manually refined mesh in the structural analysis.

User-defined mesh: 2,687,255 degrees of freedom			
Component	**Error indicator result (%)**	**Rule satisfied**	**Element count**
Stud	65.67	No	37,199
Head	30.31/22.23	No	59,734
Head 2	38.09	No	38,195
Nut	67.60	No	10,968
Vessel	42.04/181.98	No	161,971
Vessel 2	32.31	No	35,115
Washer	66.63	No	4,462

References

1. Naval Reactors Branch, Division of Reactor Development, United States Atomic Energy Commission, “The Shippingport Pressurized Water Reactor,” Addison Wesley Publishing Company, 1958.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, see the following sections of the Abaqus 6.13 documentation:

- Analysis User’s Guide
  – “Adaptive remeshing,” Section 12.3
- Abaqus/CAE User’s Guide
  – “Understanding adaptive remeshing,” Section 17.13