Fluid-Structure Interaction Analysis of a Prosthetic Aortic Valve using Abaqus/Explicit Smoothed Particle Hydrodynamics

Abaqus Technology Brief

Acknowledgement

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Summary

Durability is a key measurement of prosthetic heart valve function. Assessment of fatigue life requires accurate estimates of the stresses induced during the cardiac cycle. Finite element (FE) studies have been used to estimate peak stresses in valves [1], and computational fluid dynamics (CFD) studies have been used to model blood flow around valves [2]. Fluid-structure interaction (FSI) studies are less common, in part because the closure of the valve creates CFD domain pinching.

The smoothed particle hydrodynamic (SPH) analysis method in Abaqus/Explicit overcomes this difficulty. In this Technology Brief, the SPH technique will be used to determine the FSI response of a generic prosthetic heart valve.

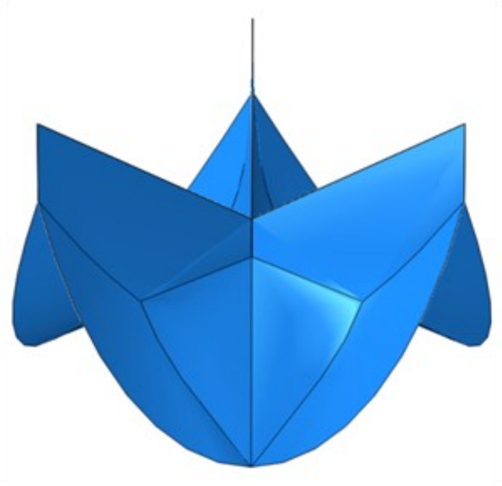
Background

There are two principal modes of aortic valve disease: aortic stenosis, in which the valve no longer fully opens, and aortic regurgitation, in which the valve no longer fully closes. Either condition can eventually require the implantation of a prosthetic valve to replace the underperforming original.

Surgically implanted or transcatheter-delivered bioprosthetic aortic valve leaflets undergo dynamic cyclic loading and large deformation during the cardiac cycle. This can cause fatigue failure of the leaflets, compromising valve function and potentially affecting the patient. Accurate stress analysis of the valve during operation is therefore essential for designing durable aortic valves and improving patient outcomes.

The operating conditions of the aortic valve are complex. The pressure on the aorta side of the leaflets is lower than that on the ventricular side when the ventricle is pumping oxygenated blood into the aorta, and the pressure on both sides varies depending on the stage of the cardiac cycle. This can be modeled by applying dynamic pressure loads (corresponding to loads measured in the aorta and left ventricle) directly onto the leaflets, which is an improvement in accuracy compared to previous analyses that used only static load conditions.

Even this method, however, does not account for the inertial and viscous effects of blood contacting the leaflets during flow. CFD can model the behavior of the blood, and a coupled fluid-structure interaction (FSI) analysis can capture the effect of the blood on the valve during the cardiac cycle.



Key Abaqus Features and Benefits

- Abaqus/Explicit Smoothed Particle Hydrodynamics capability for analyses involving extreme deformation
- Robust hyperelastic material modeling
- General contact capability for simplified definition of contact interactions

There is a final condition during the cycle that presents a challenge to coupled FSI: the fluid domain pinches during valve closure, which is a condition most CFD packages cannot handle. The Smoothed Particle Hydrodynamics (SPH) analysis technique, available in Abaqus/Explicit 6.11-1, addresses this challenge and makes modeling heart valves for the entire cardiac cycle possible, thus increasing the accuracy of prosthetic valve stress analysis.

Analysis Approach

Smoothed Particle Hydrodynamics

SPH offers several advantages over CFD and coupled Eulerian-Lagrangian methods in tracking free surface boundaries, handling small material-to-void ratios, and modeling extreme deformation with fragmentation. The latter capability makes it ideal for simulating the behavior of blood during valve closure and pressure changes.

SPH is part of a larger family of meshless numerical methods that define a body by a collection of points, instead of using nodes and elements. The SPH method implemented in Abaqus 6.11-1 uses a cubic spline kernel for interpolation, applying either a fixed or a variable "smoothing" length to particles. Internally, particle connectivity is determined based on smoothing length. The particles can contact Lagrangian bodies (in this case, the valve leaflets) through the Abaqus/Explicit general contact feature. In addition, particles can be "glued" to Lagrangian bodies through *TIE constraints. SPH supports an extensive library of solid and fluid materials, including user materials.

For this particular simulation, a finite volume of blood near the aortic valve was modeled with one-node PC3D elements. All particles had the same volume initially. There were 4956 particles, each with a radius of 1 mm.

Material Modeling

A generic aortic valve was meshed with shell (S4) elements. The valve had a diameter of 26mm and a thickness of 0.5mm. The junction between the aorta and the left ventricle was represented with a rigid tube, and two rigid plates were used to apply pressure on either side of the fluid particles (Figure 1).

The material for the valve was modeled with the Marlow isotropic hyperelastic representation, the general first-invariant hyperelastic material model in Abaqus. This model can exactly duplicate physical test data from one of several standard modes of loading (uniaxial, biaxial, or planar). It works well in situations where extensive data for one of the test modes is available. For the present analysis, uniaxial tensile test was used. (Figure 2).

Boundary and Loading Conditions

Translational degrees of freedom were fixed for the valve edges. Left ventricle and aorta pressure profiles were applied to the end plates (Figure 3) [1]. The pressure profiles start from the point at which the pressure inside the left ventricle and the aorta are the same since the initial condition of the valve was stress-free. The same pressure was applied to the fluid as an initial condition. The end plates were not allowed to rotate, and because the finite volume of fluid is incompressible, the two rigid plates were constrained to have the same displacement along the axial direction using an equation constraint.

As a reference model, a second analysis was run with the same (uniform) pressure profiles directly applied on the valve leaflets without the fluid. All other conditions were the same as the FSI model.

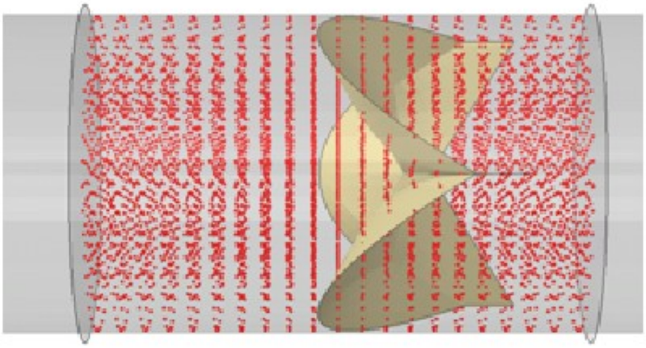


Figure 1: Aortic valve model with SPH particles

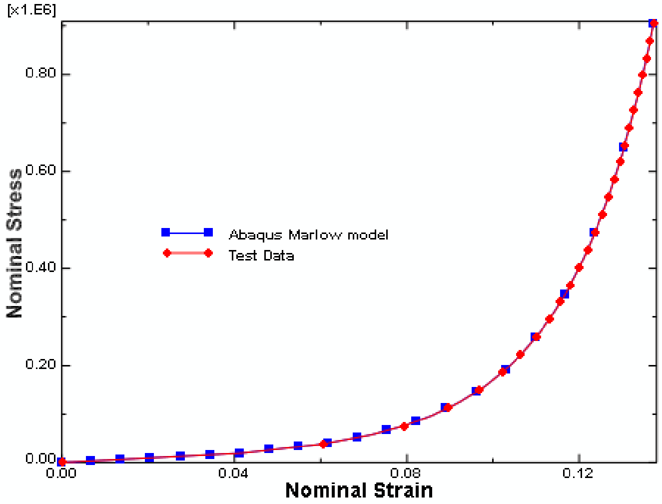


Figure 2: Leaflet material test data and Marlow model representation

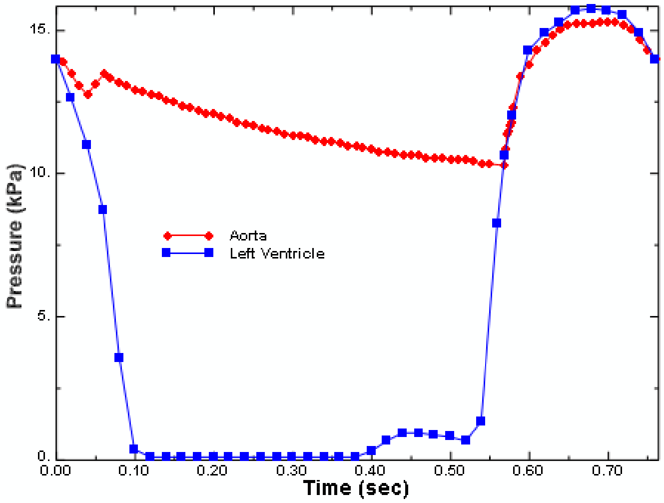


Figure 3: Pressure load profiles [1]

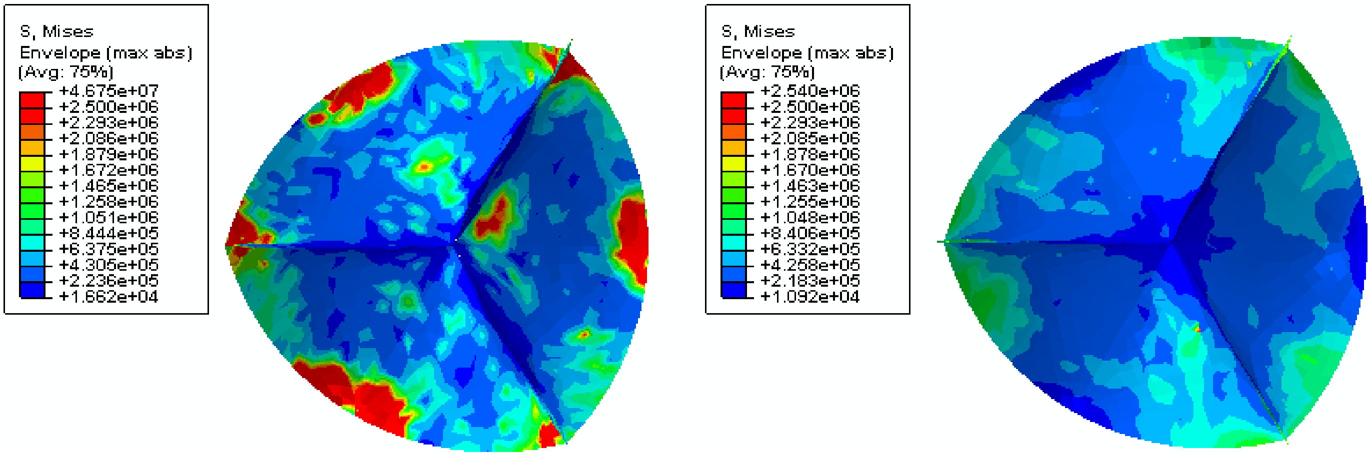


Figure 4: Mises stress on the leaflets during diastolic phase, SPH model (left) and reference model (right)

Results and Conclusions

Peak stress in the valve leaflets occurs during the diastolic phase, when the valve leaflets are closed. Higher stresses are observed in the FSI analysis using SPH than the reference model (Figure 4). In addition, the distribution of stresses is also different. Stress hot spots are observed in the middle of the leaflets as well as near the corners where two leaflets meet. This shows that, in addition to the pressure loads, the inertia effect of the fluid also influences the stress analysis results.

The present SPH simulation capability is an important step toward providing prosthetic valve designers with increased simulation accuracy and the data needed to design more durable valves.

References

1. H. Kim, J. Lu, M. S. Sacks and K. B. Chandran, "Dynamic Simulation of Bioprosthetic Heart Valves Using a Stress Resultant Shell Model", Annals of Biomedical Engineering, Vol. 36, No. 2, 2008
2. W. Sun, K. Li, and E. Sirois, "Simulated Elliptical Bioprosthetic Valve Deformation: Implications for Asymmetric Transcatheter Valve Deployment", Journal of Biomechanics 43(16), 2010,

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus 6.12 documentation reference:

- 'Smoothed particle hydrodynamic analyses,' Section 15.1 of the Analysis User's Manual

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