Modeling the Watts test of adhesives

This example demonstrates how to model the curing process of adhesives using the cure modeling capabilities in Abaqus/Standard.

This example illustrates the following Abaqus features and techniques:

- the cure modeling capabilities;
- the use of the thermorheologically simple (TRS) material model to account for temperature dependence and dependence on degree of cure in a viscoelastic material;
- the use of the tangent thermal expansion to define the thermal expansion coefficient; and
- accounting for the thermal and chemical dependence of mechanical properties in a fully coupled temperature-displacement analysis.

This page discusses:

Products: Abaqus/Standard

Application description

Adhesives are commonly used in the aerospace, automobile, and electronics industries. Structural adhesives are preferred over mechanical fastening methods such as welding due to their special characteristics (for example, corrosion resistance, high strength to weight ratio, and reduced thermal and mechanical damage to the substrates).

When the adhesives are applied, they typically undergo a curing process. Cross linking of the polymer chains form during an irreversible chemical reaction, and the material turns from a viscous liquid to a rubbery solid and eventually cools to a glassy solid. The heat generated during the curing process can cause thermal expansion of the material, and the cross-linking of polymers can cause the material to shrink. The thermal and chemical strains developed during the curing process can potentially weaken the bonded components.

It is important to simulate the curing process to better design the curing conditions to reduce the residual strains and stresses in the adhesives. The Watts test (Watts and Cash, 1991) is a simple curing test that is designed to validate the cure modeling process by comparing simulation predictions with experimental measurements.

Geometry

The Watts test measures the polymerization shrinkage of materials. In the Watts test, a disc-shaped specimen is sandwiched between two glass plates, as shown in Figure 1. The top plate is a thin glass diaphragm that rests on the adhesive and a brass ring. The bottom plate is a thick glass slide that is centered within the brass ring. The brass ring serves as a support for the diaphragm as it deflects due to the shrinkage of the specimen. The dimensions of the adhesive and other parts of the assembly are shown in Figure 1.

Abaqus modeling approaches and simulation techniques

The Watts test is modeled with a curing step followed by a cooling step and a relaxation step.

Analysis types

A fully coupled temperature-displacement analysis models the deformation of the adhesive during the curing process, taking into account the thermal and the chemical dependencies of the mechanical properties. A quasi-static analysis performed after curing models the stress relaxation in the adhesive.

Mesh design

Axisymmetric elements are used to model the whole assembly, as shown in Figure 2. CAX4RHT elements are used to model the adhesive due to its nearly incompressible mechanical properties in the liquid state. CAX4RT elements are used to model the glass plates, brass ring, and air gap.

Materials

The Kamal equation (Reaction Kinetics) is used to define the cure kinetics of the adhesive, which controls the rate of cure as a function of cure and temperature. Table 1 lists the ccoefficients used in the Kamal equation. Table 2 list the other curing and thermal properties of the adhesive.

The history-dependent mechanical behavior of the adhesive can be characterized with a viscoelastic material model. Viscoelastic properties of adhesives can be measured with DMA (Dynamic Mechanical Analysis) methods, in which the specimens are subjected to small oscillatory strains at various combinations of frequencies and temperature.The same tests can also be performed for adhesives with various degrees of cure (conversion). Assuming the adhesive materials are thermorheologically simple, the time-temperature-cure superposition principles can be applied (Lindeman and Hedegaard, 2023), which enables the construction of a single master curve by shifting the test data in both the temperature-frequency space and the cure-frequency space. A shifting factor can then be characterized that is dependent both on temperature and the degree of cure as shown in Figure 3. The temperature and cure dependency of the viscoelastic model is modeled with the thermorheologically simple (TRS) material model (Temperature Effects). The instantaneous modulus of the adhesive is measured directly with the DMA test at various temperatures and degrees of cure, as shown in Figure 4 and Figure 5. The Young's modulus is small when the adhesive is in the liquid state, but increases rapidly after gelation when the adhesive turns from liquid to solid. The Young's modulus also increases as the material cools and transforms from a rubbery state to a glassy state. The Poisson's ratio is close to 0.5 when the adhesive is in the liquid state and decreases as the material solidifies. Figure 5 shows that the Poisson's ratio is not sensitive to the temperature change for this adhesive. Figure 6 shows the tangent thermal expansion coefficients at different temperatures and degrees of cure.

Table 3 lists the properties of the brass ring, glass, and air.

Initial conditions

The initial temperature of the whole assembly is set to 22°C. The initial degree of cure for the adhesive is set to 0.0018.

Boundary conditions

Symmetric boundary conditions are applied at the nodes on the center-line. The bottom nodes of the glass slides are constrained in the vertical direction. Figure 2 shows the applied boundary conditions.

Loads

Thermal loads are applied to the exterior surfaces of the assembly (Figure 2) to simulate the curing conditions for the adhesive specimen. The film coefficient is set to 0.035 mW/mm^{2}K during the curing step and 0.05 mW/mm^{2}K during the cooling step. The sink temperature is set to 65°C during the curing step, which lasts 30 minutes. It is then set to 22°C during the cooling step, which also lasts 30 minutes. Thermal loads are removed after the cooling step when the temperature in the whole assembly reaches uniform room temperature.

Interactions

The interfaces between the adhesive and the glass (diaphragm and bottom slide) are assumed to be perfectly bonded (mechanically and thermally). Surface-to-surface contact is specified between the diaphragm and the top surfaces of the air and ring, and conductive heat transfer is specified between these surfaces. The bottom surfaces of the air and the brass ring are also assumed to be perfectly bonded to the top of the glass slide.

Analysis steps

The analysis consists of three steps. The first step is a coupled temperature-displacement step, in which the exterior of the assembly is heated to 65°C to activate the curing process. The second step is a cooling step, which is also modeled with the coupled temperature-displacement procedure. The sink temperature is dropped to 22°C, and a slightly higher film coefficient is used in this step. The final step is a quasi-static step in which the thermal load is removed and the residual stresses are relaxed.

Results and discussion

Figure 7 shows the cure history of the adhesive, and Figure 8 shows the temperature and cure history of the adhesive at a location near the center-line. An abrupt increase in the temperature is observed due to the high amount of heat produced when the material is cured. As a result, we also observe a fast increase of thermal expansion as shown in Figure 9. This exothermic reaction results in both a fast temperature increase and a high cure rate, which might cause potential problems in a real assembly when components are made with temperature-sensitive materials. However, exothermic reaction is not uncommon in a Watts test since a large amount of adhesive is used to facilitate the test measurements. Figure 10 shows the deflection of the glass diaphragm and the shrinkage of the adhesive, and Figure 11 shows the deflection profile of the diaphragm. The predicted deflection profile compares well with the test data presented in Lindeman and Hedegaard, 2023.

Acknowledgment

SIMULIA gratefully acknowledges 3M for providing input data used in this example.

Input files

watts_test.inp

Input file for the Watts test.

References

Watts, D. C., and A. J. Cash, "Determination of Polymerization Shrinkage Kinetics in Visible-Light-Cured Materials: Methods Development," *Dental Materials*, vol. 7, no. 4, pp. 281–287, 1991.

Lindeman, D., and A. Hedegaard, "31-Residual Stress Development in Curing Processes: Material Characterization and Modeling," *Advances in Structural Adhesive Bonding (Second Edition)* 1011-1033, 2023.

Tables

Table 1. Kamal model coefficients.

Z_1 (1/sec)	3.91×10^{15}
E_1/R (K)	1.34×10^{4}
m	1.15
n	1.2
b_1	0.0

Table 2. Other adhesive properties.

Density (ton/tmm^3)	1.26×10^{-9}
Heat of reaction (mJ/ton)	3.03×10^{11}
Cure shrinkage coefficient	0.043

Conductivity (mW/mm/K)	0.32
Specific heat (mJ/ton/K)	1.86×10^{9}

Table 3. Properties of brass, glass and air.

Properties	Brass	Glass	Air
Density (ton/mm^3)	8.49×10^{-9}	2.42×10^{-9}	1.2×10^{-12}
Young's modulus (MPa)	106×10^{3}	71.5×10^{3}	1×10^{-6}
Poisson's ratio	0.32	0.21	0
Conductivity (mW/mm/K)	124	1.1	2.4×10^{-2}
Specific heat (mJ/ton/K)	3.8×10^{8}	7.5×10^{8}	1.006×10^{9}
Thermal expansion coefficient (K^{-1})	2.01×10^{-5}	3.25×10^{-6}	0

Figures

Figure 1. Watts test geometry.

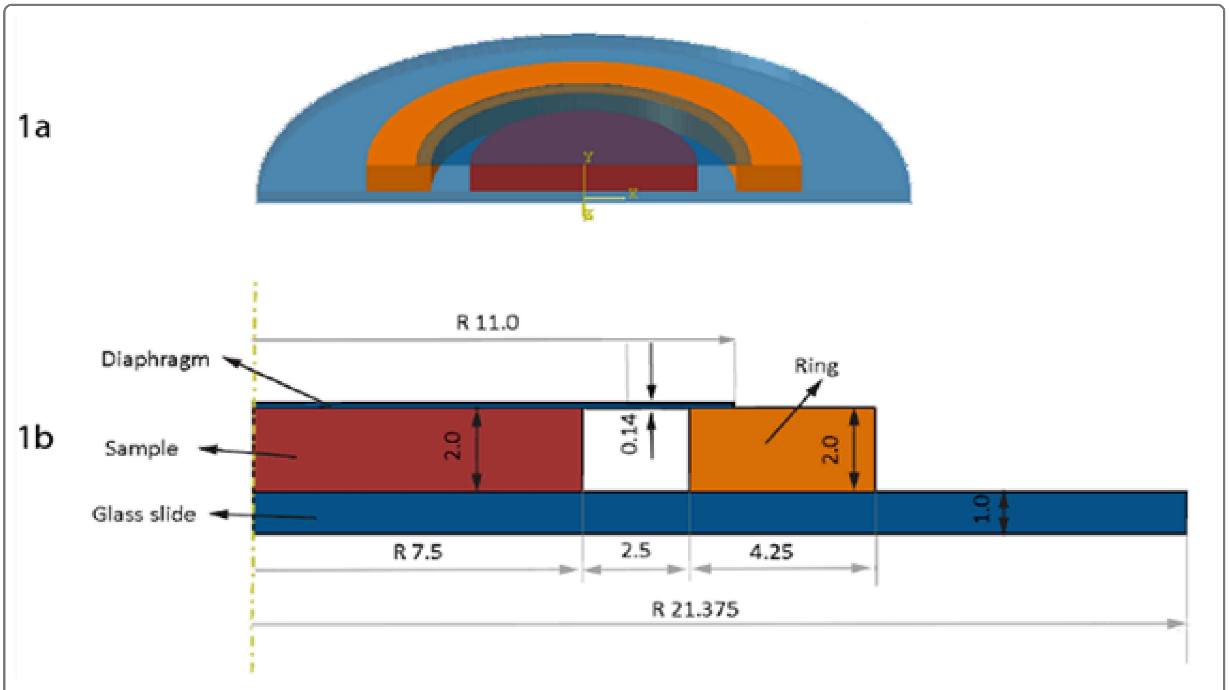

Figure 2. Axisymmetric mesh of the Watts test model and boundary conditions.

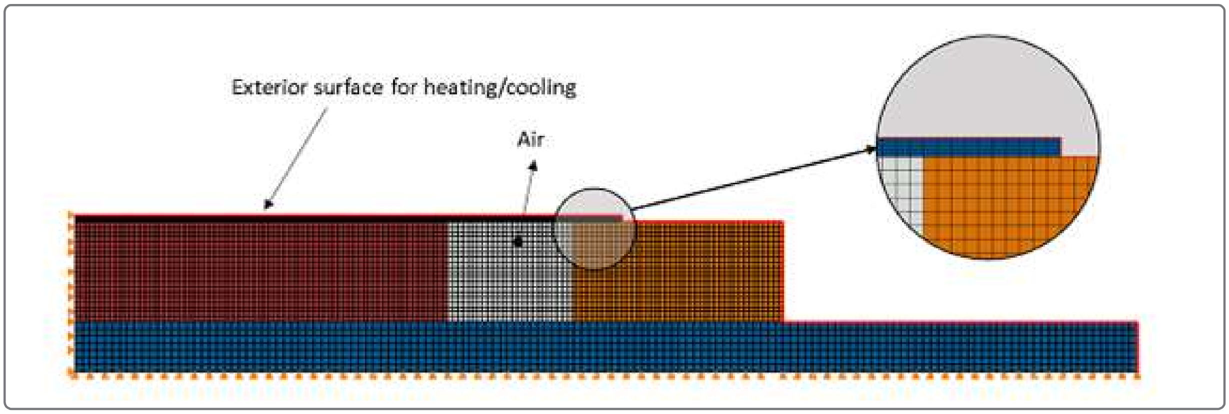

Figure 3. Shift function of the adhesive.

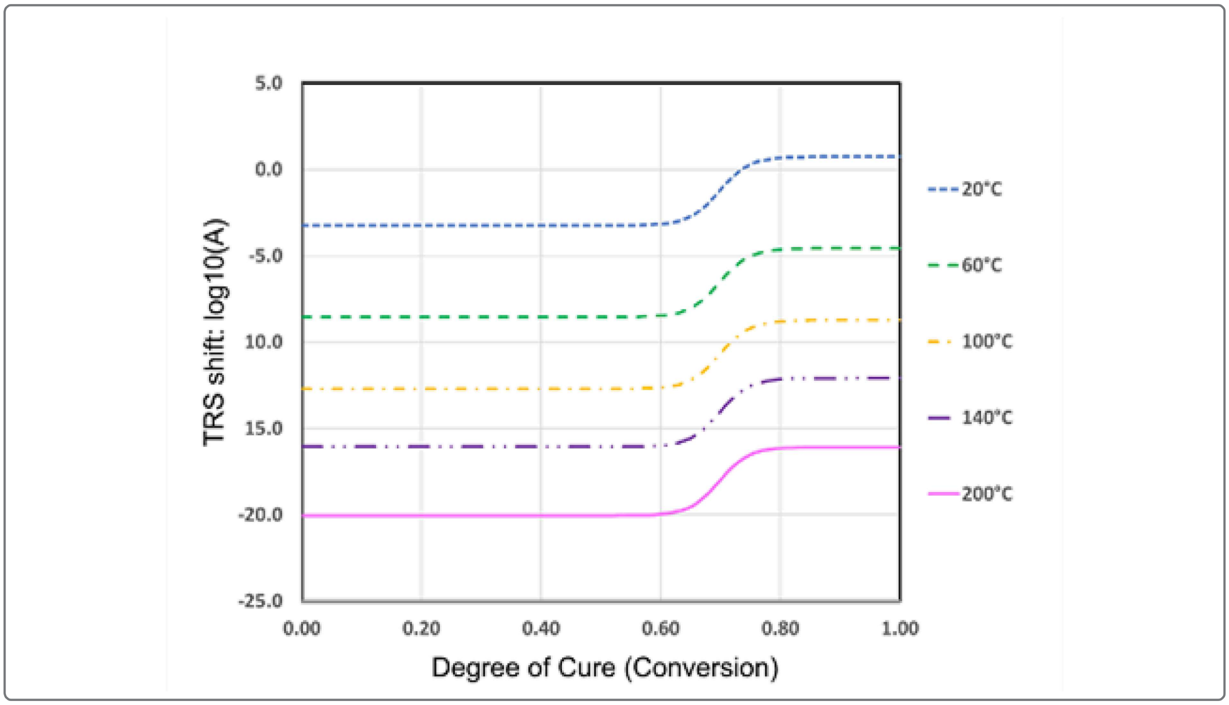

Figure 4. Young's modulus of the adhesive.

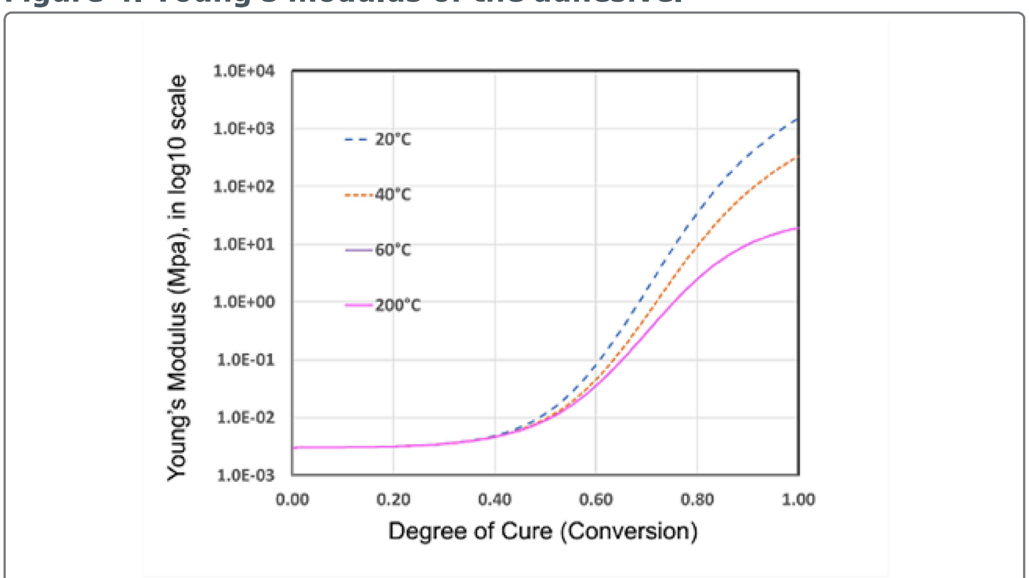

Figure 5. Poisson's ratio of the adhesive.

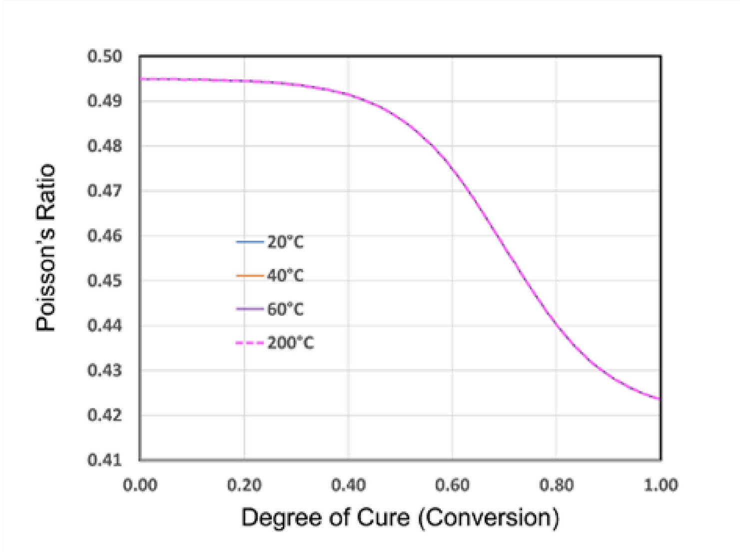

Figure 6. Tangent thermal expansion coefficient of the adhesive.

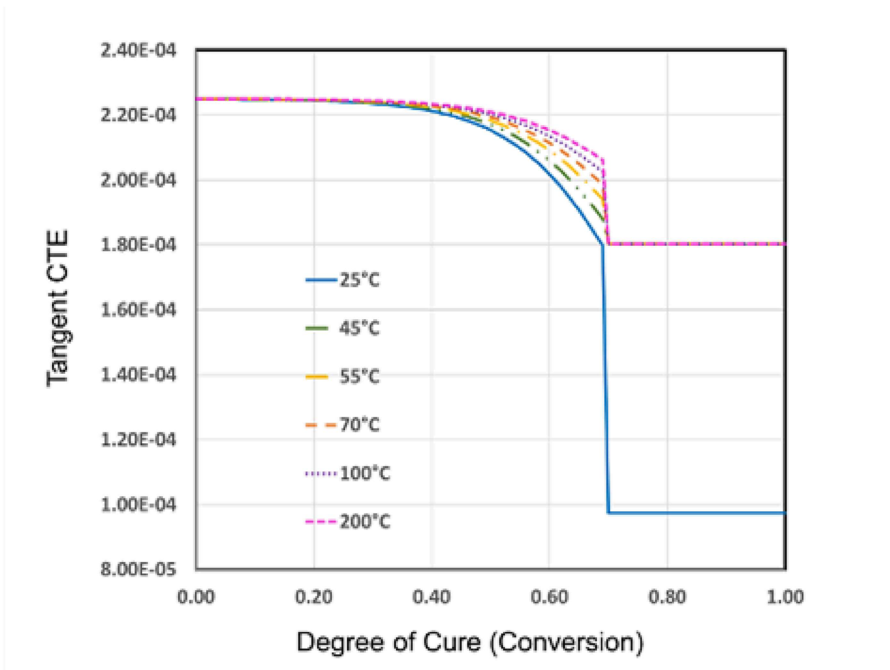

Figure 7. Conversion history of the adhesive during curing.

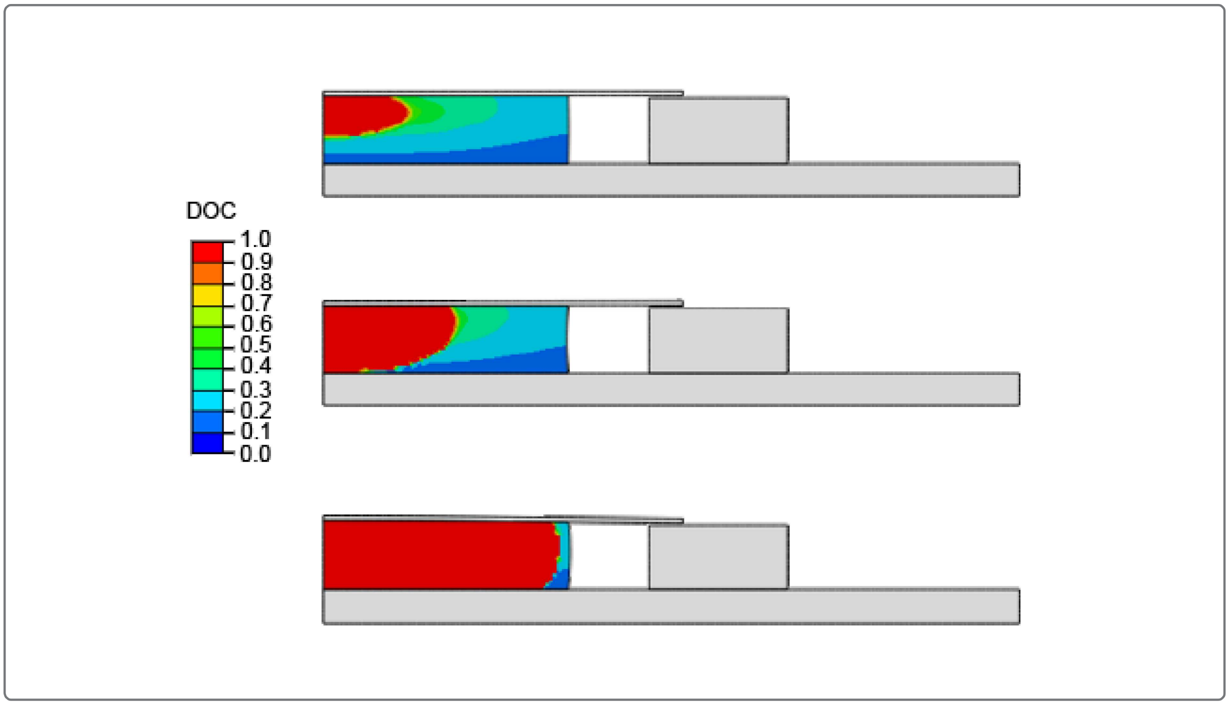

Figure 8. Temperature and cure history at the center of the specimen.

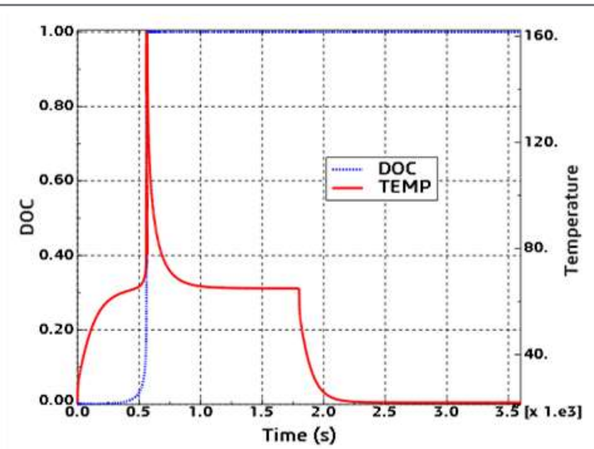

Figure 9. Time history of strains in element 681.

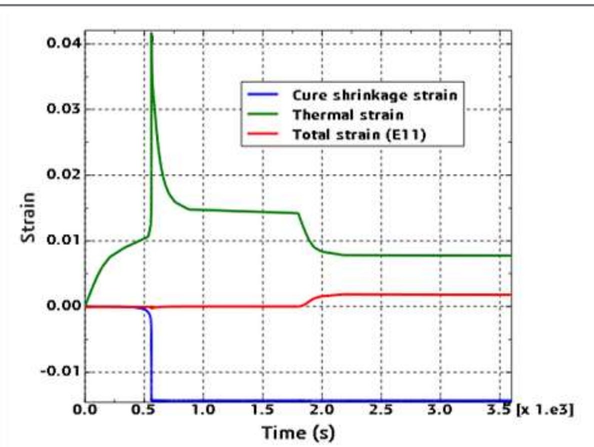

Figure 10. Deformation of the specimen at the end of the cooling step.

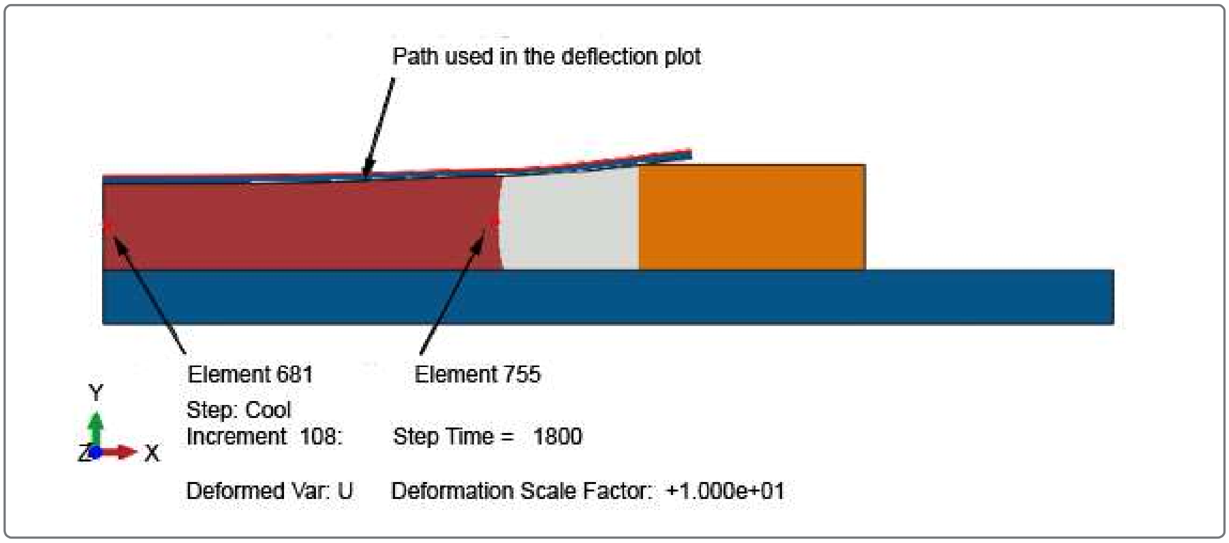

Figure 11. Predicted deflection profile.