# Simplifying Composites Process Modelling in Abaqus with COMPRO

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***Abstract****: Simulation of the manufacture of composite materials, commonly known as composites process modelling, has been gaining acceptance in industry since the mid-1990s. Starting from the early simple 1D and 2D representations of composite parts, process modelling of complex, fully configured 3D composite parts is now performed on a regular basis. Until recently, creating and running such simulations has required a high level of expertise not only in the manufacture of composite materials, but also in 3D finite element analysis.*

*Convergent Manufacturing Technologies has been enabling composite process modelling in Abaqus for over 15 years with its COMPRO libraries. Having established that composites process modelling with COMPRO is a valuable part of reducing risk in composites manufacturing, it became apparent that making these simulations easier and quicker to setup, with less expertise was necessary. To achieve this, Convergent created an Abaqus/CAE plug-in that walks the analyst through the workflow of creating a composites process model simulation, and automates many of the tasks required to set up the analysis with COMPRO. This CAE plug-in has lowered the level of expertise required to perform these analyses, enabled broader adoption across manufacturing organizations, and reduced the time for typical analyses by as much as 50%.*

***Keywords****: Composites, Process Modelling, Manufacturing, Multiphysics, Democratization.*

## 1. Introduction

Use of finite element analysis to simulate the manufacture of composite materials has grown steadily, but slowly, since the introduction of COMPRO2D in the mid-1990s (Hubert, 1995). Earlier composite process modeling efforts were largely analytical, focused on single mechanisms, or used simple numerical techniques (see Loos, 1983, Bogetti, 1991, Bogetti, 1992 for example). By the early 2000s, using finite element analysis in troubleshooting production issues and designing manufacturing processes had shown its potential for reducing the cost and risks associated with large-scale composites manufacturing (Fernlund, 1999). This lead to the integration of composite process modelling functionality into general finite element analysis packages like Abaqus.

Convergent Manufacturing Technologies introduced COMPRO for Abaqus in 2003. COMPRO adds composites process model functionality to Abaqus through the user-defined subroutine interfaces. This functionality includes capturing the thermochemical, thermomechanical, and flow behavior of thermoset and thermoplastic polymer matrix composites as they progress through the manufacturing process.

## 2. Composites Process Modelling

Composite materials and in particular polymer matrix composites (PMCs) such as carbon fiber or glass fiber reinforced plastics have many uses in modern industrial applications. The high specific stiffness of PMCs leads to structures that can be manufactured much lighter than the equivalent metallic structures. The inherent directionality of fiber reinforced plastics (FRPs) means that components can be engineered to have mechanical properties addressing the specific requirements of a given design. Different unprocessed composite parts can be mated before processing to create larger assemblies that require many fewer fasteners and subcomponents than conventional structures. These benefits, however, are offset by higher material expense, more complex engineering requirements, and higher manufacturing cost. Fortunately, process modelling can be used to reduce the cost and risks associated with manufacturing composite parts.

Use of thermoset polymer matrix composites in manufacturing begins with uncured matrix and fibers in some form. These “raw” materials must be placed in or onto a tool that will create the shape of the required part. Material placement can occur using a wide variety of techniques: hand or automated placement of pre-impregnated (“prepreg”) sheets, winding of fiber bundles (“tows”) through resin baths on to mandrels (“filament winding”) or pulling resin impregnated tows through dies (“pultrusion”), pumping liquid resin into prepared fiber forms (“resin transfer moulding”), and so on. The common thread in all these techniques is that the resin is initially in an uncured state and a combination of temperature, pressure, and time must be used to cure the resin into a solid, fully developed state. Thermoplastic PMCs are also used in industrial applications, but rather than curing, these plastics crystalize. The crystallization process shares many similarities with the polymerization process that thermoset systems go through, and many of the process modelling techniques described below are applicable for thermoplastic systems as well. For simplicity, however, only thermoset PMCs will be discussed further.

Polymerization is a chemical process. The resin systems change state as they cure, progressing from a “gooey” liquid-like form, through a gelatinous form, into a glassy form. As the resin cures, it gives off heat, it changes volume, and its mechanical properties change. The amount of polymerization that occurs can be typically quantified with a single value: the “degree of cure”. Degree of cure ranges from zero – no polymerization at all – to 1, at which state no further polymerization can occur.

Most of the material properties of PMCs are directly related to the degree of cure of the resin and the temperature of the system. Over the past 40 years, many researchers have investigated the behavior of PMCs, and have created countless models capturing these behaviors. By exercising material property models for each of the salient material properties in simulations of the particular manufacturing process, one can predict the final outcome. This is process modelling.

Composites manufacturing is complicated, and consistently manufacturing in-spec parts is challenging. In general, there are four areas of concern: materials deposition, thermal management, quality management, and dimensional control (Fabris, 2014a, Fabris, 2014b, Fabris 2015)

The material deposition processes are quite varied. In all cases, however, resin and fiber are combined and placed in a certain arrangement on a tool. The details of how the fiber and resin are placed affect the variability in initial conditions, such as the local fiber orientations, fiber volume fraction, local initial stresses, and can even cause variability in the initial degree of cure for the resin system. Process models must be able to capture these variations in initial conditions in order to correctly predict the final state after processing is complete.

Often air is entrapped during the deposition process, and many resin systems evolve volatiles during cure. This leads to a need to evacuate these gases during manufacturing to avoid having voids in the final product. To accurately simulate this, a process model must include material models for the flow characteristics of the system, such as the resin viscosity, resin volatile generation, the fiber-bed permeability, as well as models for the mechanical behavior of both the resin and fiber systems in this liquid state. This stage of the process model relates to the quality management aspect: the prediction or prevention of porosity (bubbles of entrapped gas) and fiber orientation defects such as fiber waviness and ply wrinkling.

The chemical polymerization process gives off heat, and this heat must be managed during the process. Because heat is a driver for polymerization, too much heat can lead to increased polymerization rates, leading to even more heat, and this can cause all sort of complications, from non-uniformities in material properties within the part, to degradation of material properties, to actual fires during manufacturing. The cure behavior (“cure kinetics”), heat capacity, thermal conductivity, and density of both the resin and fiber systems must be captured by material models in order to accurately simulate the thermal response of the system. These properties relate to the thermal management aspect of the system.

Finally, the evolving mechanical properties of the resin affect the stresses and strains that occur during the manufacturing process. There are strain effects such as resin cure shrinkage and thermal expansion. There are pure mechanical effects such as changing modulus and Poisson’s ratio. There may be viscoelastic effects that depend not just on temperature and degree of cure but time as well. These factors combine to result in a produced part that may be warped, twisted, or generally not the expected shape. There may also be residual stresses in the final part that could lead to cracking, delamination, or premature failure. All these properties are part of the dimensional control aspects of process modelling. Figure 1 shows some problem types that can be examined using composites process modelling.

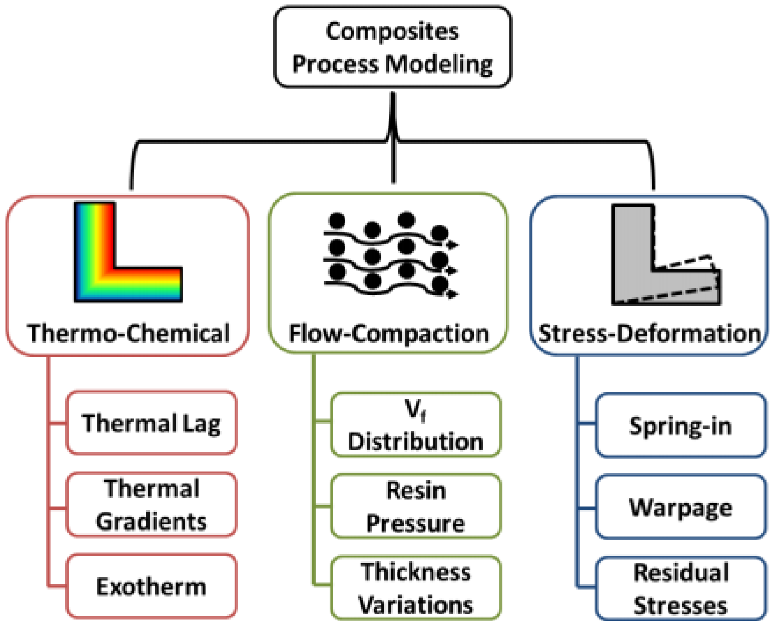


**Figure 1. Problem types in composite process modelling.**

Correctly capturing all the possible outcomes of a PMC manufacturing process with modelling is complicated. It requires a multi-physics approach, combining thermal, flow, and mechanical analyses. It requires comprehensive characterization of the materials involved, as a function of temperature and degree of cure. It also requires an expert user who understands these material processes as well as finite element analysis techniques in order to produce an accurate simulation.

## 3. Modelling Considerations

COMPRO for Abaqus provides all these process modelling capabilities to Abaqus. Sequentially coupled analyses of the thermal, flow, and stress/displacement problems are combined to predict outcomes for the whole manufacturing process. Creating the finite element model requires close attention to a significant number of details: element selection, meshing technique, orientation assignment, material assignment, boundary conditions, contact definitions, external loads, step definitions, and so on.

Composite materials are orthotropic, exhibiting different characteristics in different directions. In particularly, capturing the though-thickness response of curing PMCs is important to accurately model their behavior. Typical structural analysis of PMCs, however, employs shell elements which lack the though-thickness capabilities required. As such, the first major characteristic of process modelling is the use of continuum elements and solid sections.

Composite materials often consist of layers ("plies") of similar materials placed one on top of another, sometimes at different angles or orientations. The need to capture this layering and variation in orientations results in the second characteristic, the requirement to use hexahedral ("brick") elements.

Given the need to use brick elements instead of tetrahedral ("tet") elements, meshing composite parts becomes more challenging. Meshes must be regular, with element faces parallel with the tool faces. Table 1 shows which Abaqus element types are recommended for the different stages of analysis. The number of elements through-thickness is important in order to capture various bending and shear effects. Composite parts, however, are often very thin. The requirement to have a minimum number of through-thickness elements on a thin part tends to lead to either having elements with very large aspect ratios or a very large number of elements. A balance must be struck between numerical robustness (small aspect ratios) and numerical efficiency (short run-times). In analyses using COMPRO, the recommended guidelines are a minimum of 4 higher-order elements through the thickness of composite parts, with aspect ratios no larger than 10:1 in flat areas and 5:1 in curved regions (COMPRO for ABAQUS Modeling Guidelines, 2014). These guidelines change somewhat depending on the orientation definition method and element type.

**Table 1. Recommended element types for composites process modelling with COMPRO.**

| Analysis Type | Recommended Element Type |
|---|---|
| Thermo-chemical (heat transfer) | DC3D20 |
| Flow-compaction | C3D20P |
| Stress/deformation | C3D20 |

Capturing the orientation of the fibers is a challenging exercise, and external tools, such as Composites Modeler for Abaqus/CAE, are available to aid establishing the orientation for different regions. Orientations can be specified using global orientation definitions or local definitions such as OFFSET TO NODES. Abaqus/CAE has a useful feature to assign discrete orientation definitions to individual elements based on local geometric features. Figure 2 shows an example of capturing the material orientation changes in curved regions.

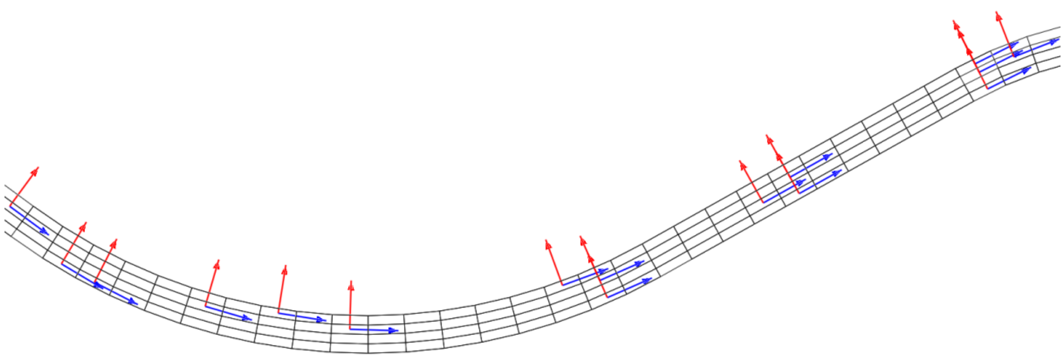

**Figure 2. Example of integration point orientation changes in curved regions.**

Standard material definitions in Abaqus are not sufficient to capture all the behaviors of composite materials in process modelling. Convergent has created a material data file standard (CCA-XML) which is supported by COMPRO. In order to relate materials defined in Abaqus input files to the CCA-XML material files, a mapping must be created between the Abaqus material definitions and the CCA-XML materials. This is handled through an external file that COMPRO for Abaqus uses to provide additional analysis control.

Initial conditions, boundary conditions, contact definitions, and external loads must also be carefully defined. Since sequentially-coupled analyses are used to simulate the different phases of the manufacturing process, these definitions are unique to the type of analysis being performed. For example, thermal boundary conditions like film interfaces (for manipulating the heat transfer coefficients at surfaces) are only used in thermal analyses. Resin pressure and fiber volume fractions must be defined for flow analyses but not for stress/deformation analyses.

If a full process simulation is to be performed, then the analyses must be tied together to transfer the appropriate information between the different analysis types. The full thermal history of all the integration points generated by the thermochemical analysis must be transferred to the flow-compaction analysis. The fiber volume fraction changes calculated by the flow analysis must be transferred (along with the thermal history) to the stress/deformation analysis. In each case, the appropriate initial conditions, boundary conditions, contact definitions, and external loads must be used.

Juggling everything required to perform a robust simulation is challenging. It is easy to overlook any step, or be completely unaware of specific steps or requirements of the step. Many of the steps require hand-editing of the Abaqus input file or the COMPRO analysis file since Abaqus/CAE does not support all the required features and some of the analysis configuration is completely external to Abaqus.

To reduce this complexity and in turn reduce the level of expertise required to perform these analyses, the COMPRO Plug-in for CAE has been created.

## 4. COMPRO Plug-in for CAE

The “COMPRO Plug-in for CAE” is a graphical plug-in for Abaqus/CAE that reduces much of the complexity of performing a successful composites process simulation in Abaqus. The plug-in is not able to completely remove all the stumbling blocks, but it provides a workflow that the analyst can use to guide the creation of a simulation, it automates many of the “book-keeping” steps related to running sequentially coupled analyses, and it completely removes the need to hand-edit any input files. Table 2 lists the typical workflow for creating a process model simulation, and the primary interface used for the particular steps.

**Table 2. Workflow and interface for process simulation.**

| Workflow Step | Primary User Interface |
|---|---|
| 1. Create part and tool geometry | Abaqus/CAE |
| 2. Add materials | COMPRO Plug-in |
| 3. Create and assign sections | Abaqus/CAE |
| 4. Assign material orientations | Abaqus/CAE |
| 5. Create assembly | Abaqus/CAE |
| 6. Define analysis steps | COMPRO Plug-in |
| 7. Assign initial and boundary conditions | Abaqus/CAE |
| 8. Mesh geometry | Abaqus/CAE |
| 9. Run analysis | COMPRO Plug-in |
| 10. Post-process results | Abaqus/CAE + COMPRO Plug-in |

The COMPRO Plug-in provides a simple interface for mapping COMPRO (CCA-XML) materials to materials defined in the Abaqus/CAE file. It lists all the materials defined in Abaqus/CAE, and allows the user to pick the associated COMPRO file. When the eventual job files are created, the COMPRO Plug-in will create the appropriate entries in the COMPRO configuration file to ensure the mapping is accurate. This interface is shown in Figure 3.

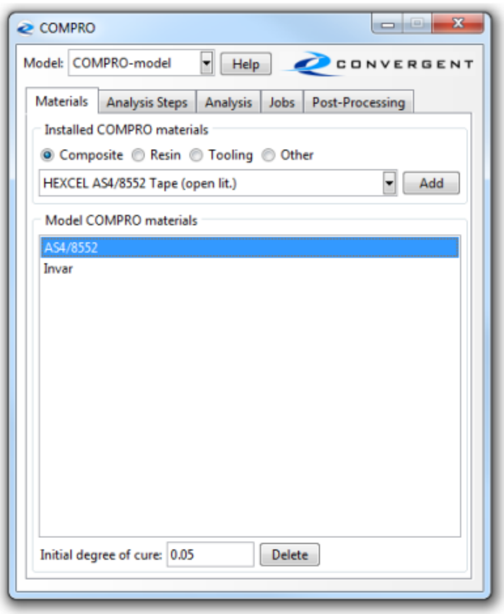


**Figure 3. COMPRO Plug-in material mapping dialog.**

Handling the different analysis types can be tedious. The COMPRO Plug-in makes this easy by providing some simple ways to create and manage the steps. In creating the steps, it creates the Abaqus/CAE features necessary to support the analysis type, and it also handles the details of running the steps sequentially – applying the appropriate initial conditions, boundary conditions, contact interfaces, and loads. It also will automatically switch element types, so that the mesh only needs to be created once. The recommended element types will be used in the appropriate analysis type without the analyst having to do any extra work. See Figure 4 for the interface to handle steps. Furthermore, the plug-in provides a simple way for the analyst to switch the "active step". Choosing an "active step" will cause Abaqus/CAE to turn on and off the appropriate features (initial conditions, boundary conditions, etc.) automatically. This streamlines the analyst's work, removing the need to try to figure out why a certain boundary condition (such as a thermal film) cannot be applied (if the stress/deformation step is active, for example).

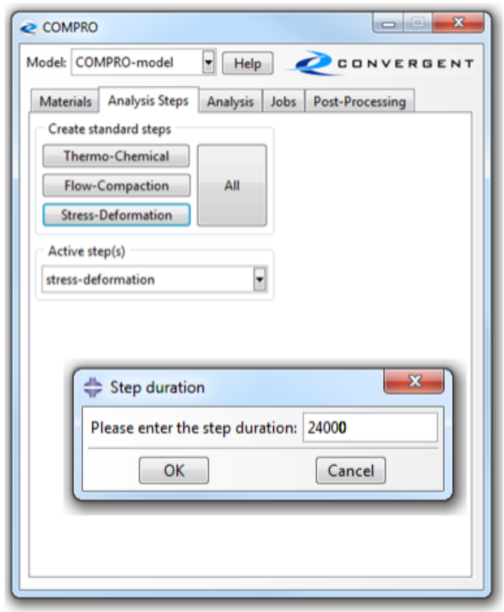


**Figure 4. Analysis step control in the COMPRO Plug-in.**

The COMPRO Plug-in also handles job control. That is, it will automatically create the appropriate input files for each of the analysis types, and handle transferring the appropriate state data between them. See Figure 5 for the interface. In addition, the plug-in will perform validation checks on the model, and warn the analyst about missing information or possible issues such as dangerous aspect ratios. This validation review can catch many simple errors, reducing the amount of troubleshoot required to have a successful analysis. Additionally, the analyst can write the input files for manual review.

To take advantage of all the job control that the plug-in provides, the actual analyses must be run from within the plug-in. This ensures the state data is transferred correctly, and it provides a mechanism for monitoring the progress of the different stages of analysis. Figure 6 shows the job monitoring capabilities of the plug-in.

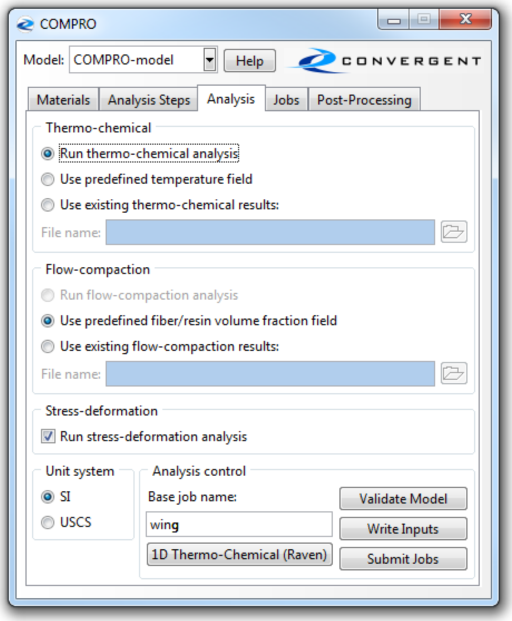


**Figure 5. COMPRO Plug-in job controls.**

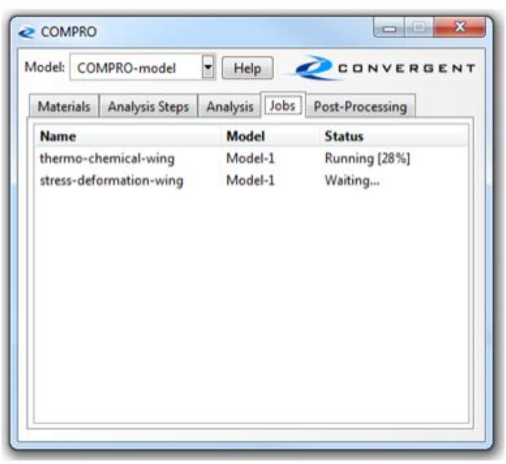


**Figure 6. COMPRO Plug-in job monitoring.**

The final tasks the COMPRO Plug-in assists the analyst with are some common post-processing operations. Automating these steps helps indicate to the analyst what common important outputs are. The plug-in will create plots of the thermal history and degree of cure history for the whole model, showing the upper and lower bounds as a function of time. This is helpful to determine if the temperature requirements of the process cycle have been satisfied, and to get a measure of how much thermal gradient exists in the analysis at all times during the analysis. Both of these measures are critical both in ensuring a good analysis, but also indicate whether a good part will be produced from these processing conditions. The other post-processing step that has been automated is creating a point cloud of the final deformed part shape. This point cloud can then be imported into a CAD program such as CATIA V5. Using a tool such as CATIA V5's Realistic Shape Optimizer (RSO), it is possible to modify a design based on the output of the process model ("tooling compensation") to ensure that the as-manufactured part shape closely matches the as-designed shape.

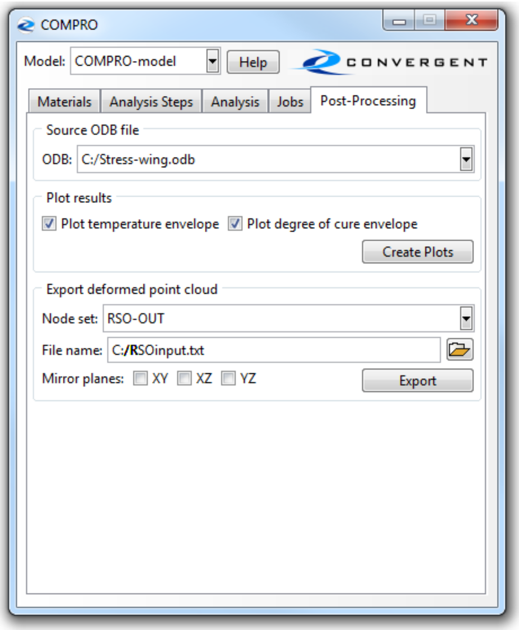


**Figure 7. COMPRO Plug-in post-processing options.**

## 5. Case Study

To illustrate the benefits of using tools like the COMPRO Plug-in, consider the simulation of a generic but relatively complex aerospace part, shown in Figure 8. This part is a sandwich panel consisting of CFRP face-sheets (10 plies each) and 0.5" thick Nomex honeycomb core. The part is built up by hand on an Invar tool with a 0.5" thick tool skin. The part is approximately 6 ft long and 1 ft high and wide.

There are often several manufacturing outcomes which are assessed through simulation, and in this specific case the part was evaluated with respect to thermal and dimensional requirements.

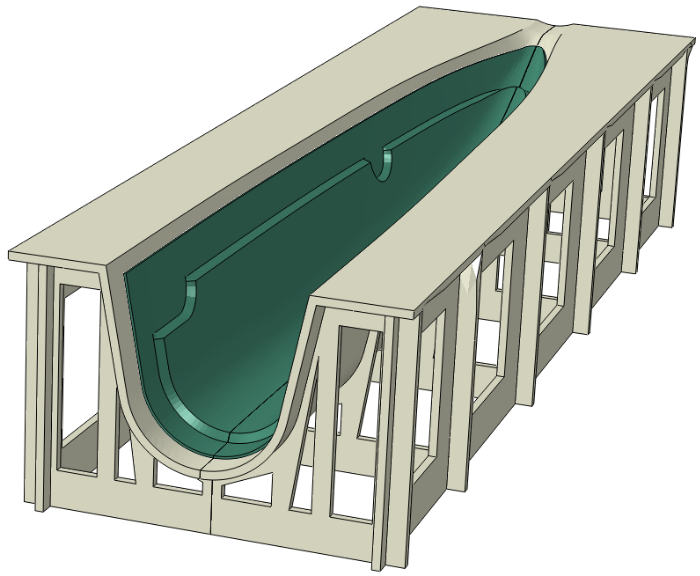

**Figure 8. Representative aerospace part simulated with composite process modelling.**

The tool and part geometry and the part layup have been fully defined by the design team in CATIA. To create an appropriate model in Abaqus, the part tool-side surface is meshed with quadrilateral elements, the tool is meshed with tetrahedral elements, then the part mesh and layup are exported using Composites Link, and the tool mesh is exported separately. In this case, the part surface mesh is ~8,000 elements and the tool mesh is ~60,000 elements.

The typical workflow for putting the simulation together in Abaqus/CAE uses Composites Modeler for Abaqus to extrude the part surface mesh to quadratic hexahedral elements, creating appropriate thicknesses and element orientations. In this case ~60,000 brick elements were created for the part solid mesh. Note that only half the part and tool are meshed, taking advantage of the longitudinal symmetry of the physical part. The mesh is shown in Figure 9.

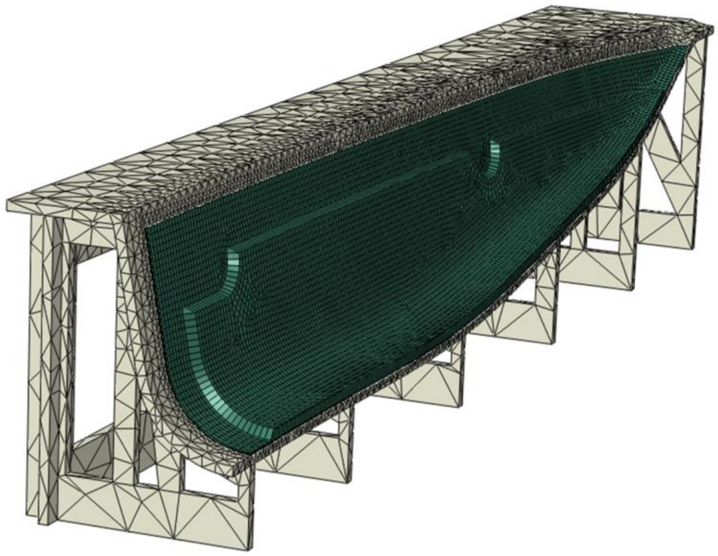

**Figure 9. Half-symmetry mesh of part and tool.**

At this point in the setup workflow, materials must be created in Abaqus/CAE. In order to use COMPRO, Abaqus must use CCA-XML material data files. In the “manual” workflow, user material input cards are created in Abaqus/CAE, and then COMPRO is manually configured to link those materials to CCA-XML material files. Using the COMPRO Plug-in, however, it is a simple matter of selecting materials from a drop-down and the plug-in takes care of the details of adding them to the CAE database and managing the COMPRO configuration. For example, see Figure 3. Once the materials are available in the CAE data tree, they can be assigned to layup definitions as normal.

A significant source of time savings is not apparent to novice users: when performing thermal analyses, there is no appropriate layered element available in Abaqus. In order to capture the effect of stack sequence, smearing factors must be calculated and applied to each stack sequence. In the “manual” workflow, correctly applying these calculations can be a difficult book-keeping exercise. Using the COMPRO Plug-In, however, these calculations are automatically performed, and the smearing factors are inserted in the configuration file as needed, entirely without user intervention.

The next steps in the setup workflow are native to CAE: creating and assigning the various sections, orientations, and creating the assembly of parts.

At this point, the model has been configured, but no load, boundary conditions, or analysis steps have been defined. The COMPRO Plug-in helps with this step, allowing the analyst to easily create the required steps (thermo-chemical, flow-compaction, and/or stress-deformation), including additions that are specific to individual analysis types – such as the tool removal step of stress-deformation analyses.

Further native CAE workflow steps are necessary, defining the boundary conditions and loads for each analysis type. The plug-in can be used to easily switch between the analysis steps, and it will ensure that the appropriate loads and boundary conditions are enabled for the current context.

Finally, the analyses are ready to be run. In the manual workflow, each analysis must be set up separately and many details must be handled. Managing the different element types required by each analysis type is one example. Additionally, the analyses types must be run sequentially, with the thermal analysis occurring first, then the temperature history must be transferred to the stress analysis before that is run. If a flow-compaction analysis is run, the thermal history is fed to that, and then the fiber-volume changes must be transferred along with the thermal history to the stress analysis (see Figure 10). In each case, different input files must be created with the appropriate boundary conditions, loads, element types and so on.

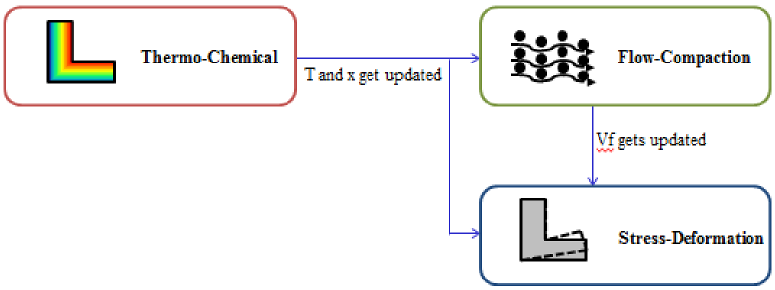


**Figure 10. Schematic of sequentially coupled steps in composites process modeling.**

The COMPRO Plug-in performs all these tasks transparently. It handles the changes to element types, it handles changes to boundary conditions (thermal analyses use tied contact surfaces instead of master-slave type contact surfaces), it ensures the appropriate loads and boundary conditions are active in the correct analyses, it handles transferring the required information between the different analyses, and it manages the running of the analyses themselves. Many details which are easy to get wrong or overlook are automatically handled by the plug-in, reducing time and effort in setting up and running the model. This also reduces the number of mistakes and the time associated with subsequent debugging and re-running of simulations.

Once all the required simulations have been run, the COMPRO Plug-in assists in creating appropriate post-processing results such temperature and cure envelopes and deformation point clouds. Figure 11 shows a plot of the temperature and cure envelopes for this part, showing the highest and lowest temperatures in the part over the course of the analysis. Figure 12 shows the part deformation as a point cloud, which can then be brought back into CATIA to morph the tool surface to compensate for this processing-induced deformation.

Using the COMPRO Plug-in to create these data reduction results has two distinct advantages: it saves time, and it standardizes the forms of post-processing, guiding the analyst to examine similar analyses in the same manner, allowing for easy comparison between analyses.

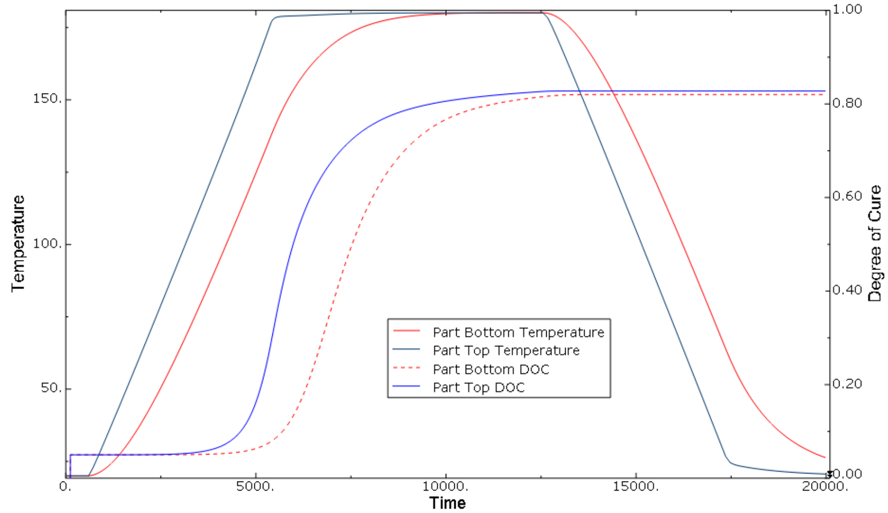


**Figure 11. Temperature and degree of cure envelopes for the case study.**

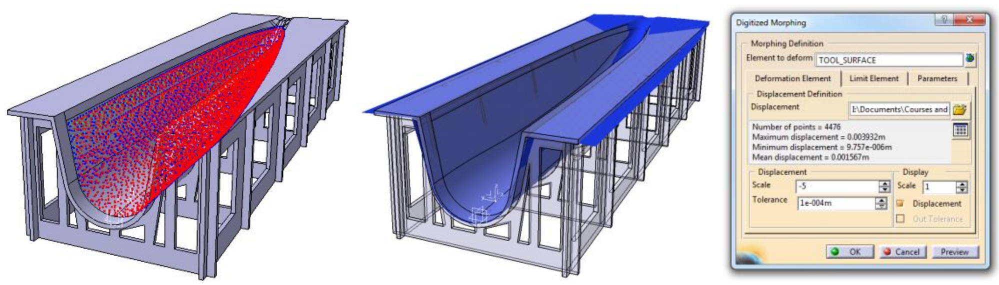


**Figure 12. Deformation point cloud used for tooling compensation, and using this point cloud to modify the shape of the tool surface in CATIA.**

For a model of this complexity, an expert analyst could setup, debug, run, and post-process the simulations in approximately 150 hours using COMPRO without the COMPRO Plug-in for CAE. With the plug-in, however, that expert analyst can perform the whole workflow in less than 100 hours. A significant portion of the time savings is realized by reducing the opportunities to make hard-to-find mistakes in the analysis setup, and by automating many of the tedious, time-consuming tasks.

Non-expert users see a more significant benefit. Such analysts might take 300 hours or more to complete an analysis like this without the plug-in (if at all), and the risk of errors would be significant. With the workflow guidance, error-checking, and detail-handling of the plug-in, however, Convergent has observed that instead of doubling, the analysis time for non-experts becomes on average a modest 50% increase over experts.

## 6. Summary

Manufacturing composite materials is a complicated process and simulating the manufacturing process is no less complicated. Adoption of composite process modeling in industry has been hampered by this complexity, requiring analysts with a high degree of expertise in both composites manufacturing as well as finite element analysis. The modeling process itself was very manual, very detail-oriented, and prone to error.

In the first step to simplify the process, lower the barrier to entry, and increase the adoption of this powerful analysis tool, Convergent has created a workflow automation tool for Abaqus/CAE, the COMPRO Plug-in for CAE. This tool provides workflow guidance for analysts, and automates many of the mundane "book-keeping" tasks that unnecessarily made the analysis creation process complicated and lengthy, and eliminates many of the errors that can occur during the model setup. The plug-in allows the analyst to concentrate on important aspects of the model – the design and process model results – without needing to be concerned about tedious aspects of the analysis itself while avoiding unnecessary debugging time and effort.

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