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A Study of the Process of Using Pro/ENGINEER Geometry Models to Create Finite Element Models

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A Study of the Process of Using Pro/ENGINEER Geometry Models to Create Finite Element Models

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Abstract

Methods for building Pro/ENGINEER models which allowed integration with structural and thermal mesh generation and analyses software without recreating geometry were evaluated. This study was not intended to be an in-depth study of the mechanics of Pro/ENGINEER or of mesh generation or analysis software, but instead was a first cut attempt to provide recommendations for Sandia personnel which would yield useful analytical models in less time than an analyst would require to create a separate model. The study evaluated a wide variety of geometries built in Pro/Engineer and provided general recommendations for designers, drafters, and analysts.

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Introduction

The process of performing finite element analysis of systems or components consists generally of four steps: 1) geometry definition, 2) mesh creation from the geometry, 3) application to the mesh of properties and boundary and load conditions, 4) performing the finite element calculations, and 5) examining the results of the analysis. This study examines the link between the first two steps. The reason for the study is that the past decade has seen a tremendous growth in the capabilities of electronic design (geometry) definition, with such computer software as Pro/ENGINEER [1] now being able to routinely define solid geometries. These electronic databases can create traditional blueprints for manufacturing purposes, but can also transfer information electronically to computerized manufacturing processes and to finite element analysts. Potentially, this electronic transfer of information can save the analyst a significant amount of time in both steps 1 and 2.

In addition, the mesh generation codes have also improved significantly in the last decade. Many different codes now have the capability of automatically generating shell meshes on general surfaces, and some have (or are close to having) the ability to mesh general-shaped solids automatically with either tetrahedral or hexahedral elements.

Because things are changing so quickly, analysts and drafters may not have experience in how to best use these new tools. This study was undertaken to understand some of the mechanisms which would enhance the process of creating finite element models using today's electronic tools and using electronic design definition as input to the analyst. Since Sandia has chosen Pro/ENGINEER as its standard design definition computer program, Pro/ENGINEER was examined in some detail.

In order to understand the details and the significance of the different phases of this study, we believe that the reader needs to have a basic understanding of several areas. These areas include a brief background of the finite element process, a current status of mesh generation capabilities (including current problem areas), a description of different Pro/ENGINEER capabilities and how they apply to the finite element analysis process, and an understanding of how these technological changes might affect the interrelationship between the work of the designer, the drafter, the analyst, and the manufacturer. The reader is encouraged to thoroughly study these introductory sections in order to understand the significance of things that were done in the main study.

Background

The process of performing finite element analysis of systems or components has in the past been challenging. The analyst could be called on to give either a very preliminary estimate of a structural or thermal response, or a very detailed prediction of that same

response. To perform the evaluation, the analyst was typically given a geometry definition, either in paper or electronic form, some materials information, and some load information. The analyst took this information and made enough assumptions about the problem to allow a finite element model to be built which would result in an acceptable answer within the available amount of time. Thus, a limited time to perform an analysis was a third constraint.

Often, the geometry information was given to the analyst in paper form. The analyst needed to make decisions based on experience to determine how much of the detail (such as bolt holes, cut-outs, etc.) to include in order to have an acceptable level of accuracy in the analysis. Then the analyst recreated, in some form, a simplified version of the geometry which had already been created by a drafter. This process, of reconstructing the geometry for the finite element model, and then of creating the finite element model, took up to 80% of the analyst's time and efforts.

With the more prevalent use of solid modeler design definition programs, such as Pro/ENGINEER [1], and with the more powerful codes and computers used by the analyst, it is now more feasible to attempt an analysis which directly utilizes an electronic solid model definition of the design. However, this is only beneficial if the analyst does not have to recreate or significantly modify the geometry to be compatible with the required analysis. Typically, the analyst would still like to ignore much of the detail (such as bolt holes, cut-outs, etc.) because that detail doesn't contribute to the accuracy of the solution, even though that detail may be integrated into the Pro/ENGINEER model.

There are also instances where it may be inefficient for the analyst to work with a solid geometry for some reason. Two examples of this are 1) thin structures, which can be accurately analyzed using 3-dimensional shell elements at a lower computational cost and model size than when using solid elements; and 2) axisymmetric structures, which may be adequately analyzed using a 2-dimensional axisymmetric model representing the cross-section.

In either recreating a geometry or using a solid geometry from Pro/ENGINEER, the analyst must know ahead of time what types of analyses are going to be required. This is dependent on the current state of mesh generation and analysis technology. For instance, current mesh generation technology only allows acceptable automatic mesh generation of general solid geometries using tetrahedral (tet) elements, even though hexahedral (hex) elements typically provide a better answer with fewer elements. Thus, if hex elements are required, the analyst will have to modify the geometry provided from Pro/ENGINEER, to accommodate the non-automatic mesh generation. In addition, tet elements tend to have problems even beyond their lower accuracy. Low order tet elements tend to exhibit shear locking and excessive stiffness, while higher order tet elements cannot be used in explicit analyses (dynamic analyses requiring very small time steps). So the analyst must choose the type of mesh generation based partly on the type of analysis.

Another consideration is model size. Three-dimensional models can very quickly become too large to run either because of calculation time or memory size, both of which are

limitations of the current generation of computers. A "small" 3-dimensional mesh of 100x100x100 cells results in a model size of a million elements, while traditional finite element models to date have been less than 100,000 elements. Therefore, it is prudent wherever possible to model structures as 2-dimensional, even when a 3-dimensional calculation may yield more accurate results. This again may require modification of solid geometry provided from Pro/ENGINEER.

A final consideration is that typically it takes much less time and effort for a drafter to "build" a Pro/ENGINEER model than it does for an analyst to "build" an analysis model. Therefore, it is reasonable (from an overall design-to-analysis process) to focus first on things which can be done in Pro/ENGINEER to facilitate the analyst's model building. This is despite the fact that the drafter is almost always funded by the designer rather than the analyst, and therefore might feel reluctant to do any model modification for the analyst unless agreed to by the designer.

Problems with Current Mesh Generation

Current mesh generation technology and the meshing process have some known obstacles. These include 1) problems meshing large geometries with small features, 2) problems meshing complex non-standard geometric shapes, 3) problems using solid geometries to create shell models, 4) problems modeling the connectivity between different parts of assemblies, 5) problems handling tolerances, and 6) problems transferring geometry information from solid modeler codes such as Pro/ENGINEER into mesh generation codes.

Traditional mesh generation technology can automatically mesh low order shapes, specifically, points, lines, four-sided surfaces, and 6-sided solids. In two dimensions, current paving techniques now exist to also mesh general geometries with three- and four-sided elements. These techniques are relatively robust. In three dimensions, current techniques now exist for automatically meshing general shapes with tetrahedral (tet) elements, but not the more desirable hexahedral (hex) elements. However, these three-dimensional mesh generation codes are not robust enough to always successfully mesh every geometry, and they have increasing difficulty with increased geometry complexity. Specifically, having many small features in a large complex geometry often causes mesh generation codes to fail, because they cannot complete the transitions well from small elements (around the small features) to large elements and back again (to the next small feature). The same problem may also occur in a part with no "small" features, but with lots of complexity. That is, transitioning from feature to feature can eventually fail because the mesh generation codes usually start at one location and "sweep" toward another location. An analyst may need to break up a single three-dimensional part into several "sub-parts" in order to successfully mesh the part.

Another area where current mesh generation has problems is in creating a shell model from a three-dimensional geometry. A shell finite element has no thickness, but assumes the stiffness of something which has half of the thickness on either side of the element

(that is, it is assumed to be positioned at the midplane of the thickness). Because they have no thickness, parts modeled with shell elements which are supposed to physically interface with other parts will now be geometrically separated by a gap. Defining these new interfaces can often be difficult. Furthermore, solid model design definition codes (such as Pro/ENGINEER) do not easily or automatically provide this midplane surface location to the mesh generation codes in the first place. Thus, an analyst may have to create geometry to be used in making the shell element model, and may also have to create geometry to define the interfaces in the shell element model.

Often an analyst is asked to model an assembly, which has multiple connected parts. Typically the interfaces between parts are an area where analysts must make assumptions. A Pro/ENGINEER assembly contains the bolt holes and the separate bolts or other fasteners which hold the parts together, but which are not of interest to the analyst. An analyst may choose to model a rigid interface in order to simplify the analysis, and in doing so will need to suppress or ignore the details and assume a simplified connection mechanism or geometry. Also, the file which describes the assembly of parts in a Pro/ENGINEER model contains the positioning information between parts. If that file is not available to the analyst (perhaps the assembly is not completed at the time of the analysis) or if it contains too many unwanted part references, then the analyst may have to manually position the parts of interest, which is an undesirable task.

Tolerances present another aspect that may require modification of the geometry provided to the analyst. While a structural analyst usually works with the nominal geometry and tolerances, a thermal analyst is usually more interested in looking at one end or the other of the tolerance range. Although tolerance information is in a Pro/ENGINEER drawing, the geometry which is passed to the analyst is nominal position information. Thus, it is more difficult to use a Pro/ENGINEER model directly to build a thermal model.

Some problems exist in importing a Pro/ENGINEER model into a mesh generation code. Specifically, all of the current commercial mesh generation codes import the surfaces of the Pro/ENGINEER representation of a solid, rather than the actual solid representation, and then rebuild their own representation of that solid. This additional step is not always successful, due usually to complexity in the model or differences in assumptions of how to represent a solid. Even when a solid representation is successfully recreated, differences in tolerance assumptions between the two codes can cause problems in meshing an imported geometry.

Pro/Engineer Capabilities Examined

As stated in the introduction, this study was a first-cut, rather than in-depth, look at what could be done in Pro/ENGINEER to aid the design-to-analysis process. The capabilities which were examined included feature/part suppression, including simplified model representation and layering capabilities. Other options investigated include thin shell generation, mid-plane surface generation, and cross-sectional cuts. We also examined philosophical issues such as model reconstruction specifically for the analyst, and the sequence in which a Pro/ENGINEER model of a new design should be built in order to make the analysis process and design definition process as efficient as possible.

Suppression

In Pro/ENGINEER, features, layers, and parts can be suppressed, simplifying the construction of a finite element model which uses Pro/ENGINEER geometry.

Feature suppression is a capability in Pro/ENGINEER by which a feature (a cut, a hole, a fillet, a chamfer, etc.) can be made inactive in the part description, without removing it permanently from the model. This can be done on a feature-by-feature basis for a part by choosing from a table or by interactively selecting that feature with a cursor. Any feature can be suppressed; however, if a second feature depends on or references that suppressed feature, Pro/ENGINEER will ask for further guidance about what to do with the dependent feature, and may force the suppression of that dependent feature as well. This is an example of a parent-child relationship, where the child cannot remain active without the parent being active.

A feature in Pro/ENGINEER (v. 16 or later) is also automatically added upon creation to a Pro/ENGINEER-defined grouping, or layer. These layers are defined by the drafter and often are grouped to include such things as cuts, surfaces, rounds, etc. Suppression can be done not only to individual features, but also to entire layers. This can be useful. For instance, if a part with bolt holes has all of the bolt holes in a single layer, all holes can be suppressed with a single command. However, Pro/ENGINEER does not currently appear to allow the user to automatically allocate similar feature types to different user-defined layers as the features are created. Pro/ENGINEER would group all holes in the same layer with the bolt holes, including those that need to be included in the finite element model. This would prohibit the possibility of suppressing the entire layer. Even though features can be moved manually from one layer to another after creation, the limitation in the auto-layering means that this capability only has limited usefulness at the present time.

A third type of suppression is the suppression of entire parts which make up a Pro/ENGINEER assembly. Again, there could be a parent-child relationship between parts, since often the positioning of one part is taken from a specific location on another

part (such as bolts and bolt holes). Furthermore, Pro/ENGINEER allows multiple use of a single part in an assembly, and so suppression of that part would suppress all uses of that part in the assembly.

Another capability of Pro/ENGINEER which relates to suppression is the Simplified Representation capability. A simplified representation is essentially a secondary model representation which may have different parts (features) suppressed than are desired for the actual model. For instance, the complete model representation may not have any features suppressed except for a cross-section feature. In that same Pro/ENGINEER database, one simplified representation might have everything suppressed except for the main structure (no bolt holes, fillets, etc.) to be used in finite element analysis, and another might have the cross-section feature unsuppressed for showing internal structure. Unfortunately, interface codes which read Pro/ENGINEER files and translate the model to the mesh generation code do not allow the user to "choose" from among simplified representations, unless the interface code is invoked from inside Pro/ENGINEER rather than from inside of the mesh generation code.

Other Capabilities of Pro/ENGINEER

The thin shell capability is a feature in Pro/ENGINEER by which thin structures are specifically created to carry enough information to be able to automatically generate a mid-plane surface between the inner and outer surfaces of the thin structure. The automatic mid-plane generation is a capability in Pro/MESH which automatically pairs inner and outer surfaces of thin structures and creates the mid plane. (Pro/MESH is an optional module of Pro/ENGINEER which provides limited shell and tetrahedral element mesh generation capability inside of Pro/ENGINEER.) However, if the structure was not created in Pro/ENGINEER with the thin shell capability, the inner and outer surfaces must be manually paired by the user in order for the mid plane surface to be generated.

Slicing the model with a plane really is an additional model feature, which in many cases the drafter has already defined and suppressed, but which the analyst will almost always want. These cuts allow the visibility of the interior of the model. In many cases, they are at the centerline of symmetric parts. An analyst will, if possible, want to take advantage of symmetry in order to keep the analysis model size as small as possible, and therefore will want every symmetric part that is built in Pro/ENGINEER to have that feature created and active before the model is given to the analyst.

Philosophical Issues

Although they are not capabilities of Pro/ENGINEER, two philosophical issues were also explored in this study. First, it is possible that for some geometries or models it might take less of a drafter's time to create for the analyst a new, separate Pro/ENGINEER model which does not have any undesired detail in it. This assumes, of course, that the detailed model already exists and is too complicated to simplify easily.

On the other hand, if the analyst can provide input before the Pro/ENGINEER model is built, it may be desirable for the drafter to build a model first to the level of detail required for the analyst (not including every detail such as bolt holes and fillets), and then continue to add the necessary detail after giving the model to the analyst. This second issue may be especially important for new system design, since a global system analysis (with only major structure modeled) is the first analysis required in order to predict load inputs for the individual components of that system. Once those loads are defined, then the individual components can be designed, the specific details of the parts can begin to be defined in Pro/ENGINEER, and more detailed analyses of the components can be attempted. This would be an important and beneficial change from the traditional process. In the past, the analyst was usually not provided with a model until after much design detail for every part had already been defined in Pro/ENGINEER. This meant that the analyst or the drafter then had to take back out the details which weren't desired for at least the first analyses, and the analyst's input was not available for the initial component design.

Main Study

The study was broken into four phases. The purpose of the first phase was to try to understand the mechanics of the capabilities in Pro/ENGINEER and to understand how those mechanics interacted with the process of transferring/translating the Pro/ENGINEER model to the mesh generation code. This phase involved creating a controlled test part, with specific details, transferring that part to the MSC/PATRAN [1] mesh generation code (referred to herein as PATRAN), and generating a finite element mesh. We looked at two structures in this phase, a solid structure and a shell structure. The second phase was done to understand any differences in the way Pro/ENGINEER features were either translated to the codes or handled by the codes during mesh generation. It involved translating several representative Pro/ENGINEER models to several different mesh generation codes and meshing the models in each code. The third phase applied as many different capabilities of Pro/ENGINEER (and of PATRAN) to best understand and facilitate the design-to-analysis process for a wide variety of existing

(actual part/assembly) Pro/ENGINEER models being translated to and meshed by PATRAN. The fourth phase was an attempt to find and categorize or understand how to handle problematic geometries, or those models which were still very difficult to mesh even after applying all of the capabilities learned in the previous three phases.

Phase 1—Basic Understanding of Pro/ENGINEER and the Transfer Process to PATRAN

The first part examined was made specifically for this study, and is shown in Figure 1. This part was created in Pro/ENGINEER with chamfers, fillets, bolt holes, an additional parent hole, and a corresponding child slot. The desire was to import to PATRAN a model of only the basic geometry plus the child slot, without any of the other features. Two different processes were attempted, the first being the use of suppression capabilities of Pro/ENGINEER, and the second being the use of a simplified representation in Pro/ENGINEER.

We used the suppression capability of Pro/ENGINEER to individually suppress the bolt holes, fillets, and chamfers. When we attempted to suppress the parent hole, Pro/ENGINEER forced us to also suppress the child slot.

The resulting Pro/ENGINEER model was opened and imported by PATRAN, and in fact none of the suppressed features were present in the imported geometry. The resulting solid model in PATRAN was easily meshed automatically with tetrahedral elements. However, it did not include the desired child slot (Figure 2).

We went back to Pro/ENGINEER and attempted to use the simplified geometry capabilities. In creating a simplified geometry, Pro/ENGINEER did allow us to suppress the parent hole while keeping the child slot. Unfortunately, PATRAN did not seem to be able to automatically import the simplified representation, but instead imported the main Pro/ENGINEER geometry model. In order to transfer the solid simplified representation from Pro/ENGINEER to PATRAN, a special interface to Pro/ENGINEER (provided with PATRAN) had to be used. This interface executed Pro/ENGINEER and added (for that execution) a PATRAN export capability to a version of Pro/ENGINEER which had the Pro/DEVELOP option. With this executable of Pro/ENGINEER, we made the simplified representation the active model, and exported the model to a PATRAN interface file. This interface file was then imported into PATRAN. The resulting model was the desired solid model, with all of the features suppressed except for the child slot (Figure 3). This solid model was again easily meshed automatically in PATRAN with tetrahedral elements.

Figure 1: Unmodified Sample Part

Figure 2: Sample Part After Suppression of Parent Hole

Figure 3: Simplified Representation of Sample Part With Parent Hole Suppressed

The second part translated to PATRAN was a shell structure, similar to the environmental case of many warheads. This part was a thin-shelled, generally axisymmetric structure with flanges, small bolt holes, larger clearance holes, bosses specifically for the purpose of reinforcement at bolt holes, and some small radii (at flanges). Although any type of analysis is possible with this part, use of solid elements is not feasible because the thin shell requires a large number of elements to capture bending accurately and have reasonable aspect ratios in the elements for accurate results. The goal was to provide a geometry to PATRAN which was a quarter-circumference shell representation of the mid-plane surface of the actual part, simplified to eliminate bosses, bolt holes, and most fillets. Figure 4 shows 1/4 of the solid model. The only automated way of generating a mid-plane surface in Pro/ENGINEER is to create the features using the "thin shell" capability, and then using the Pro/MESH capability to automatically pair inner and outer surfaces and then generate the mid plane between those surfaces. Inner and outer surfaces can still be paired even if the "thin shell" capability is not used, but only if it makes geometric sense. In this instance, the outer surface of the shell structure was a single surface, while the inner surface was actually several surfaces, broken up because of the flanges. Thus, for this part, pairing was not feasible without making major modifications to the Pro/ENGINEER model. Instead, a new set of Pro/ENGINEER surface features was added to the model. Specifically, mid points between inner and outer surfaces were created and curves were drawn between the midpoints. Then the curves

were swept into datum surfaces. The difficulties in providing a shell representation were three-fold: 1) how to model flange midplanes and have them connect to shell midplanes, 2) how to handle varying thickness sections, and 3) how to handle varying radius sections. The latter two are really the same issue: for non-linear variations, the linear discrete creation of lines between two points is inexact and tedious.

Figure 4: Typical Warhead Environmental Case with Flanges and Holes

Despite the crude way of enhancing the Pro/ENGINEER model for use by the analyst, a shell model was successfully created of this part. This model was easily imported into PATRAN and meshed with shell elements. It took the drafter approximately 1/2 a day to make the modifications. It would have taken at least that long for a more expensive analyst to have reduced the solid model in PATRAN to a shell model.

Conclusions From First Phase of the Study

The process of creating the finite element models for these two parts resulted in the same two conclusions. First, the way the drafter builds the Pro/ENGINEER model affects how easy it is to arrive at an appropriate geometry for mesh generation. If the drafter can understand the needs of the analyst before making the Pro/ENGINEER model, considerable time could be saved in the design-to-analysis process. Second, for the purposes of this process it is efficient if both the drafter and the analyst are capable of doing simple suppressions of part features inside of Pro/ENGINEER. The drafter should communicate with the analyst to learn what is not of interest to the analyst and suppress

those features, and/or automatically suppress such common features as bolt holes, fillet radii, threads, etc. The analyst should gain enough familiarity with Pro/ENGINEER to suppress any additional simple features which were not suppressed by the drafter.

Phase Two—Detailed Examination of Translation to Several Mesh Generation Codes Using Actual Parts

Three different mesh generation codes were used in examining this issue: PATRAN, Algor/Houdini [3], and Pro/MECHANICA [4]. CUBIT [5], the Sandia in-development mesh generation code, was not used because it did not have a user-friendly interface and because it had difficulty meshing even simple parts. Tet elements were used in PATRAN and in Pro/MECHANICA. In Houdini, both tet and hexahedral elements were used. (In Houdini, the method of creating a hex mesh is to create a tet mesh and then subdivide the elements, causing a large number of elements and a large number of skewed elements. Consequently, the hex mesh may be less desirable than the tet mesh.)

We used analytical engineering judgment to determine which features of the model to suppress in Pro/ENGINEER. The model was then imported to the mesh generation code, and an attempt was made to generate a mesh. This attempt balanced quality of the mesh against total number of elements in the mesh.

First Part (Housing with threads)

A housing was examined as the first part (Figure 5). The housing was non-axisymmetric and included bolt holes, threads, small step changes in thickness, small radii of curvature, fillets, and several midsize cutouts. The most likely analysis would use a 3D model meshed with solid elements. However, a shell model might be possible if only a crude analysis were desired. This part was imported only to PATRAN and Pro/MECHANICA.

As a test, the unmodified Pro/ENGINEER model was imported to PATRAN (167 surfaces) and Pro/MECHANICA. The model did not import to PATRAN as a solid, but instead imported as a collection of surfaces. The model did import to Pro/MECHANICA as a solid, even though Pro/MECHANICA did complain about improper geometry. Pro/MECHANICA worked unsuccessfully for over 6 hours to attempt to mesh the complete geometry. (A complex part can typically be meshed with <100,000 elements in PATRAN in under an hour.) In this instance, the warning message did not give clear enough information to know what to fix in Pro/ENGINEER, even though fixing the geometry might have allowed Pro/MECHANICA to more easily mesh the geometry.

Figure 5: Housing with Threads and Holes

For the next attempt, Pro/ENGINEER was used to suppress the threads, the bolt holes, and all of the small fillet radii. The small step change in thickness was not suppressed because it was a part of the initial design definition feature, rather than being a separate feature which could be suppressed. This simpler model was again imported to PATRAN, and again the model did not enter PATRAN as a solid but as a collection of surfaces. The problem with the geometry appeared to be the detailed creation of complex midsize cutouts very near the edge of a surface.

By suppressing some of the complex features which defined the midsize cutouts, the geometry with the modified cutouts was successfully imported into PATRAN as a solid. PATRAN was easily able to create a tetrahedral mesh, but because of the very small change in thickness a large number of elements were required to capture that structurally unimportant feature. PATRAN meshed the geometry using about 20,000 tet elements. This model was also imported into Pro/MECHANICA, and a solid mesh of about 2,200 elements was created (Pro/MECHANICA uses higher order elements, and therefore can provide adequate answers with a geometrically coarser mesh).

Using the geometry manipulation features of PATRAN, we were able to disassemble the solid, modify and recreate the appropriate surfaces in such a way as to eliminate the very small step change in wall thickness, and then recreate the solid. This simple task required an extra 1-2 hours of effort by the analyst. However, when the recreated solid was

meshed in a manner similar to before, the resulting model size was only 5,500 elements (as opposed to the previous 20,000 element model). In general, not all parts could be as easily reconstructed by the analyst, and thus having the drafter provide a model without the step change would allow a much smaller, cheaper model.

Evaluation of this process suggests an important point for defining an efficient process. The drafter created a very small step change in thickness in the model, but did so as part of the initial design definition in the "sketcher" feature of Pro/ENGINEER, thus not allowing for either possible changes in the design or for simplification by/for the analyst. It would have been much more flexible, and only slightly more work, to have defined this (and other design features) as separate features in Pro/ENGINEER. That is, if a complex geometry is created with a single Pro/ENGINEER command, then suppression is not possible, and any design changes require recreation of the entire part rather than of a small portion of the part.

The second problem, that of the creation of the complex midsize cutouts near the edge of large surfaces (small features in large features), appears to be a combination of inaccuracies in the Pro/ENGINEER representation and inaccuracies in the process of importing the model to the mesh generation codes. It is recommended that the drafter/designer attempt to avoid designs which have very small unnecessary features associated with a large part (either as part of the design or as part of the creation of the Pro/ENGINEER model). These small features may cause problems for the analyst, and may also cause problems in the manufacture of the parts.

This part also re-emphasized that the capability of suppressing small features (bolt holes, threads, fillets) in Pro/ENGINEER allows the analyst to create a still valid model that can be meshed with fewer elements and thus is less costly than for a fully detailed model. The final PATRAN model only had 1/4 of the surfaces of the full unsuppressed model, and the remaining surfaces were larger than those suppressed, thus allowing larger and therefore fewer elements.

Second Part (Optical Firing Set Housing)

The second assembly was actually three parts, including a shell-like case structure and a cover for the case (Figure 6). The cover had an O-ring groove, and was welded on the other side to the case. Although the design is very simple, the cover analysis would probably require solid elements in order to predict the stresses around the groove. Thus a shell model is not possible.

Figure 6: Optical Firing Set Housing and Cover

The Pro/ENGINEER model was manipulated to suppress bolt holes and fillets, and the resulting model was imported to PATRAN and Algor/Houdini. Both mesh generation codes easily generated all-tetrahedral meshes, and Houdini also easily created both a hybrid mesh and an all-hexahedral mesh. Of course, the hexahedral mesh was essentially created by breaking the tet elements into hex elements, so the resulting mesh had even more skewed elements than the tet mesh. In addition, the all-hex mesh had nearly eight times the number of elements of the all-tet mesh.

This part was included as an example of a part which shows the limitations of the current mesh generation codes. The analyst visually could easily choose a method of creating a new model, or of breaking up the existing model, such that an extremely simple all-hex mesh could be created for this geometry. However, the mesh generation codes create a much more complex mesh because they don't have the visual intuition of a human. If an all-hex mesh had been required, the simplest solution may have been to have the drafter recreate the part using that visual intuition, in conjunction with an analyst, so that a simple all hex-mesh was possible.

Third Part (NIF Building 1)

The third model examined in this phase was an assembly of an early design of the target chamber for the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). This was a complex assembly of complex parts (Figure 7), for which a customer wanted a very quick-turnaround analysis of random vibration response.

The assembly included a cylindrical building with a dome roof. The dome roof was stiffened with beams. Inside the building, the structural design looked vaguely like a typical sport stadium. There were two structures, called grandstands by the designers, which changed height with radius, in a stair step design, similar to bleachers in a stadium. These grandstands also had other holes, and were supported by discrete posts. There were holes in the building walls for functional purposes. The walls were made of concrete while the grandstands were proposed to be made of steel.

The Pro/ENGINEER model was simplified by eliminating holes in the building walls and detail cuts in the grandstands. This was a conceptual design, so there were no bolt holes/small radii to cause mesh generation problems. However, the very complex bleacher geometry was made in the initial geometry definition using the "sketcher" mode of Pro/ENGINEER, and so was not suppressible inside of Pro/ENGINEER.

Figure 7: Early Concept of the NIF Target Chamber Building

When the assembly was imported into PATRAN, the grandstands came into PATRAN as individual solids. However, the bleachers were undesirable because they did not add significantly to the structure and yet modeling the individual steps would have added significantly to the size of the model. Therefore, the solids were disassembled in PATRAN, the bleacher surfaces were deleted and replaced with a single sheet surface, and the solids were reassembled easily.

The building did not translate into PATRAN as a solid. The problems were twofold: 1) the geometry of the two center beams on the dome roof were imported incorrectly, causing an incorrect geometry, and 2) PATRAN could not correctly interpret the enclosed volume as a volume rather than a solid. The incorrect geometry was deleted and recreated easily inside of PATRAN. The building was broken into two solids inside PATRAN, and so became two parts of which neither had an enclosed volume. These two parts were easily reassembled into solids with congruent contacting surfaces.

The reassembled solids were meshed automatically by PATRAN, using a coarse mesh requirement. The interface capabilities of the ABAQUS [6] finite element code were used to "weld" the parts together at all contacting surfaces. Using this model, a modal analysis and a random response analysis were done using ABAQUS.

The building model was also imported to Pro/MECHANICA. Unfortunately, the enclosed volume was treated as a solid, rather than a void, and so the model was not taken

further. Also, Pro/MECHANICA could not easily import an assembly. One method to get around that is to merge different parts of an assembly in Pro/ENGINEER into a single part. However, this does not allow the user to specify different materials for different (pre-merged) parts. Since the different parts of this assembly were of different materials, this attempt also was not taken further.

A possible method of overcoming the enclosed volume problem would have been for the analyst to ask the drafter to add a feature which suppressed half of the building. This is usually desirable from a visual standpoint anyway, so that one can see into the interior of the design (a cut-away). In fact, for this model that feature had already been created, but was not a part of the default model. The analyst did not know that there would be a problem, and therefore did not inquire about it. The drafter also did not realize that this cut-away might be beneficial to the analyst, so did not include it in the default model. The lessons to be learned are: 1) for symmetric structures, half of the Pro/ENGINEER model should always be suppressed before giving the model to the analyst; 2) enclosed volumes will not import correctly to current mesh generator codes; 3) analysts should be trained enough in what is possible in Pro/ENGINEER so that they are able to ask for simple modifications by the drafter rather than (in a more complicated way) attempting to do modifications outside of Pro/ENGINEER; and 4) effective communication between the drafter and the analyst as the model is being prepared for the analyst is crucial.

Conclusions from Phase Two Part Study

All of the mesh generation codes which were used (PATRAN, Algor/Houdini, and Pro/MECHANICA) had the same basic capabilities for modifying geometry, and for importing models from Pro/ENGINEER. It also appeared that the same features caused mesh generation difficulties for all codes. Thus, for the rest of the study only PATRAN was used.

We also learned that enclosed volume Pro/ENGINEER models should never be given directly to the analyst. Further, complex cuts should not be done as part of the initial geometry definition in Pro/ENGINEER, if possible. Instead, an initial "structural" geometry should be created, and then "simple" features (cuts, protrusions, rounds, etc.) should be added sequentially in such a way that features not useful for analysis can be suppressed without losing the basic structural geometry of the model.

Other things learned in this phase included the fact that for some geometries it may be more beneficial for the drafter to create a new, separate Pro/ENGINEER model specifically for the analyst, which either doesn't have all of the detail of the full model or which might be created in a specific way to enable the analyst to take advantage of mesh generation code capabilities. Also, small features in large parts should be avoided in creation of the initial large part, and small features such as bolt holes or fillets should be suppressed before the model is given to the analyst. However, in all instances the analyst should be trained enough to know what to ask for, and communication between the drafter and the analyst should take place while the Pro/ENGINEER model is being modified by the drafter.

Phase Three—General Pro/ENGINEER-to-PATRAN Translation and Model Mesh Generation

Over 100 separate parts and assemblies from the W76 were included in this phase of the study. The intent was to apply the capabilities examined in the first two phases to: 1) determine their applicability to general designs and 2) to learn about any other capabilities which were important but missed in the first two phases. In addition, parts which in the past 3-5 years had been problematic geometries for less advanced mesh generation capabilities were remeshed with the current version of PATRAN, to verify that the design-to-analysis procedure was going in the correct direction.

The parts which were studied fell into three categories: simple shell-like solids (such as washers), simple solid structures (such as bolts), and more complex structures. Most were in the first two groups. That is, most were easily meshed with tetrahedral elements after suppressing fillets and other small features. Some of the shell-like structures were simple enough to manually pair surfaces and then create a mid-plane surface, which was also imported into PATRAN and easily meshed using shell elements. However, it would have been simpler (for the analyst) if the drafter had created the shell-like structures with the "thin" capability, because the surfaces would have then paired automatically.

Although many of the parts were simple, the names of the parts were not. The part files and the assembly files all had cryptic names. This was somewhat of a nuisance for doing single part analyses, because it was difficult to find the part of interest, or to know whether it was an important part or a standard bolt part file. The problem was worse for assembly files, because their names did not indicate the level of the assembly (i.e., top level assembly, major sub-assembly, or a sub-sub-assembly). Without communication with the drafter, it was nearly impossible (for a major system) for the analyst to find and read the top level assembly (which reads all other assembly files), or to know which assembly file went with each sub-assembly. If possible, the drafter should give both part and assembly files more descriptive names that would be recognizable to the designer and to the analyst. If not, then the drafter should provide, and the analyst should ask for if necessary, a list of names of all files provided to an analyst along with short descriptions of what is contained/defined in those files.

In at least one part, we saw an anomaly which was caused by the inaccuracies/approximation of Pro/ENGINEER in the creation of the part. That is, a visually insignificant variation from the exact requested geometry was seen at the edges of a cutout region (Figure 8). This "dirty" geometry prevented PATRAN from meshing the part. We were not able to determine exactly how that part was initially created in Pro/ENGINEER, and so cannot make recommendations on how to avoid the problem.

One part which we had modeled in 1993 was included in this study. The part was the Fireset Housing Assembly (FSA) housing for the PRESS program (Pit Reuse and Enhanced Safety and Surety). In 1993, a solid model of hexahedral elements was built to

Figure 8: Example of an Incorrect Geometry Created in Pro/ENGINEER

examine the effect of static loads on the housing. The part was essentially an offset tower design, with an offset cylinder sitting on top of a larger diameter cylinder (Figure 9). In 1993, capabilities did not exist to automatically mesh a general shaped body, and so the geometry had to be broken down by the analyst into 6-sided solids with congruent sides in order to be properly meshed. That finite element model took over two months to build. As part of this study, the same exact Pro/ENGINEER part file was simplified with Pro/ENGINEER to suppress threads, fillets, bolt holes, chamfers, and other small design features, and then was imported into PATRAN. Using the automatic tetrahedral mesh generation capability, a credible tet mesh was created in a couple of hours. This model would have been sufficient to have answered the static load questions being asked in 1993, which took over two months to answer. Of course, an explicit dynamic calculation would not have been possible because the elements created were not the lower-order hexahedral elements required by explicit solvers. But this still is a clear example that the technological advances in the last three years have greatly increased the productivity of the analyst, even without using conventions to create an analysis-ready Pro/ENGINEER model. The conclusions/recommendations of this study build upon these technological advances to help the design-to-analysis process be even more streamlined. That is, the knowledge of the need to suppress, and of how to suppress, the structurally insignificant features of this model allowed the resulting finite element model to mesh automatically with many fewer elements than otherwise would have been required.

This phase of the study did not uncover any new significant recommendations, but did verify the effectiveness of the already known recommendations.

Phase Four—Problematic Geometries

Several of the parts which were discussed in the first three phases of this study were actually problematic geometries. The initial shell structure of phase one does not lend itself to an automatic design-to-analysis process, but may require special work to be done

Figure 9: PRESS Fire Set Assembly Housing

by a drafter specifically for the analyst. This is also true of beam models (such as frame structures), where the analyst may desire a curve at the “center” of the beam.

There are also two examples, discussed above in phases 2 (NIF building) and 3, where the geometry representation was incorrect by the time it was imported into the mesh generator, thereby preventing the recreation of the original Pro/ENGINEER solid. These may only occur in complex geometries with complex cuts. It may be that using the Pro/ENGINEER capability (“info”/“geometry check”) to check geometries (to make sure they can regenerate properly) would catch these problems. In fact, in several of the problem geometries, a regeneration suggested problems with the geometry even though the regeneration “succeeded”. These problems with geometry nearly always caused problems with mesh generation.

Thirdly, some of the geometries were just much too complex (had too much detail) for being useful for a first-order (approximate) finite element model. Suppression of some features was impossible because of parent-child relationships or because they were created in the sketcher as part of the original cross-section creation. In these instances, it may be most efficient to have the drafter create a new, much simpler model specifically for use by the analyst (although we did not take advantage of that for this study).

Discussion of Results

Several things are obvious in looking at the results of this study. First, the environment was artificial in that no customer was actually asking for specific analysis to be done. Thus, the choice of parts to examine was mostly random, and the acceptability of the finite element mesh for good analysis answers was not tested. However, the purpose of the study was to give first-cut recommendations which would provide the most (or any) time savings in the design-to-analysis process, and the process was sufficiently tested in this study to achieve that goal.

Most of the rest of the results and recommendations are common sense issues. Unfortunately, when deadlines draw near and when there are multiple organizations and pots of money feeding into the completion of a project, sometimes common sense gets left behind. Thus we will discuss the implications of the results here.

It is obvious that an analyst is interested in and needs a different level of detail than the designer or the manufacturer. At the first level, this can be achieved inside of Pro/ENGINEER by suppressing detail features, so as to just leave the basic structure active. Of course, this assumes that the drafter created the basic structure first, and then added the details. As was shown in this study, this is not always the case. It is easy, but usually not prudent in the long run, for a drafter to sketch up a complicated sketch with lots of details and create a solid model from that complicated sketch, but it is then impossible to get rid of that detail.

Even this first level of suppressing detail features brings up the question of who should be manipulating the Pro/ENGINEER model. Rarely does an analyst have a budget to support a drafter, and so in the past the analyst took whatever the drafter gave them and then worked independently from that point on. This must change. Usually both the drafter and the analyst are "working for" the designer, and therefore it is most cost effective in the project for the drafter to "clean up" the model for the analyst using his/her expertise in Pro/ENGINEER. Of course, this also should not be done in a vacuum, but instead should be done with constant communication with the analyst, to determine the analyst's needs. Indeed, that communication should take place starting as early in the design definition process as possible, since we have seen that a drafter could create a part in such a way that elimination of the "unwanted" details for the analyst was impossible. Further, if an analyst suggests or requests either changes in how the model is made (assuming the final result is the same) or modifications or new model creation specifically to benefit the analyst, it is usually cost effective for the drafter to make the modifications. Otherwise, the analyst will have to make the same geometry modifications, using a mesh generation tool which does not have the same level of sophistication and efficiency in geometry manipulation as Pro/ENGINEER, or clumsily using Pro/ENGINEER as a less-experienced user than the drafter.

It is also obvious that analysts need to be trained enough in the capabilities of Pro/ENGINEER that they know what can be asked for, and drafters should be trained

enough in the language/requirements of the analyst that they can understand what the analyst is asking for and why. Also, it may be more efficient for the analyst to run Pro/ENGINEER to suppress, for example, a forgotten but obnoxious feature, rather than going through the process of communicating to the drafter, having the drafter do the suppression, and then transferring a new file or set of files. Thus, the analyst should have at least basic training in how to use Pro/ENGINEER.

The analyst should not assume that they have to do all of the geometry manipulation specific to a finite element model, because in many cases the drafter can do the same thing more efficiently. On the other hand, the drafter should not assume (without asking) that certain features should be suppressed before giving the model to the analyst. The drafter **should** assume that the part they are building may have to be analyzed, and therefore should build in the **capability** of being able to suppress model details, by using the simplest possible features, cuts, etc. The communication allows the drafter to provide a Pro/ENGINEER model to the analyst which is best suited to the type of analysis that the analyst requires.

Finally, it seems obvious that geometries created in Pro/ENGINEER should at least be valid Pro/ENGINEER geometries. Pro/ENGINEER has a capability of creating invalid geometries. It will complain about them, and suggest that the drafter do a geometry check and correct the problem, but it does not require correction. However, these invalid geometries most likely will cause problems for the analyst, and so it is very important for the drafter to fix those geometries.

Thus, although there are some specific Pro/ENGINEER capabilities which can be used to benefit the design-to-analysis process, the first-cut time savings in the process can be obtained by communication, training, building a Pro/ENGINEER model using the simplest building blocks possible, and creating valid geometries.

If we compare the two months required in 1993 for a finite model creation to the single afternoon required at the time of this study, we see that the design-to-analysis process is getting better and more efficient just because the tools are more efficient. Obviously, the time savings may not always be that dramatic, but it is important to keep in mind that we are trying to provide recommendations for a changing process and technology. The specific details of Pro/ENGINEER or the mesh generation codes will probably be different three years from now, but communication and training will still help the process to be much more efficient.

Because technology is changing, it is also obvious that some recommendations made as part of this report may need to be changed to keep up with the technological advances. Most solid modeler programs and mesh generation programs have major releases twice a year. We suggest that these recommendations be reviewed at least yearly to account for new versions of computer codes which may have enhanced capabilities.

Specific Recommendations (for 1997)

For the drafter:

1. If possible, consult with analyst before creating model
2. Ask questions of a Pro/ENGINEER expert if you are not sure how to create or do something or if you don't understand what the program is doing
3. For new systems designs, create each part of an assembly in a simplified state (no bolt holes, fillets, etc.) and provide the model to the analyst before continuing to detail the parts of the assembly
4. Do not create complex, detailed geometry in sketcher mode or with complex cuts
5. Create many simple features rather than few complex features
6. Create small features (small steps, small radii, etc.) in large parts as separate features rather than in the large part (sketcher) definition
7. If reasonable without losing accuracy, position parts of an assembly relative to global rather than local coordinates (do not do for small parts in large assemblies)
8. Use the "thin" option to create solids wherever possible
9. Create mid-plane surfaces for all "shell" structures which may be analyzed
10. Suppress half of symmetric structures in model for analyst
11. Use the "info"/"geometry check" capability of Pro/ENGINEER to make sure that the created geometries are valid even in Pro/ENGINEER
12. Communicate with the analyst and work with them before providing them a model
13. Use a simplified representation when suppressing features which cause parent-child relationship problems, or to maintain different levels of suppression for the analyst, designer, and drafter in the same model
14. Coordinate suppression of bolt holes, fillets, and other details with analyst

For the analyst:

1. Learn the basics of Pro/ENGINEER--how to open a model and suppress simple features
2. Ask questions of an expert for your mesh generation code if you are not sure how to do something or if you don't understand what the program is doing
3. Assume that the drafter can create/modify geometry faster than you, so ask them to help
4. If minor changes in the design make it easier to analyze, ask the designer if those changes are possible before meshing the model, get the drafter to incorporate the changes, and then do the analysis
5. If you are modeling more than a single part in the same model, always get an assembly file as well as the part files
6. Use the capabilities of PATRAN to break solids with planes, as necessary, to get best mesh densities
7. If you need to manually position a new part into an existing finite element model, contact Arlo Ames (Org. 9622) or his equivalent to help obtain a transformation matrix from the Pro/ENGINEER files

For the designer:

1. Consider the cost of analysis and manufacture in the cost of the part design--the "ultimate" design may not be easy to analyze or make, while minor changes might save in both areas
2. Consult with an analyst before making design decisions on important parts, rather than handing the analyst a finished product to model
3. Symmetric or 2 1/2 D designs (parts extruded into the third dimension) are easier to analyze than fully 3D complex parts
4. When asking for an analysis, include the drafter in the communication
5. Make sure the analyst has the support of a drafter, and that the budgets reflect the time and cost savings of having drafting support for the analyst

Summary

The goal of the project documented in this report was to study and evaluate methods for building Pro/Engineer models which allowed integration with structural and thermal analyses software without recreating geometry. This study was a first cut attempt to provide recommendations for Sandia personnel which would yield useful analytical models in less time than an analyst would require to create a separate model. The study examined a wide variety of geometries built in Pro/Engineer and evaluated capabilities of Pro/ENGINEER which could be used to benefit an analyst. These capabilities included feature suppression, which was a major time-saver. In addition, the process of going through the study pointed out the value of training for the drafter and analyst, and of communication between all parties of the design process. Specific recommendations were made for the designer, drafter, and analyst which will benefit the design-to-analysis process. These recommendations should be examined periodically to account for technological advances in solid modeling and finite element modeling.

References

1. **Pro/ENGINEER**, Parametric Technologies, (1996).
2. **MSC/PATRAN, Version 5.0**, MacNeal-Schwendler Corp., (1996).
3. **Houdini**, Algor, (1996).
4. **Pro/MECHANICA**, Parametric Technologies, (1996).
5. **CUBIT**, Sandia National Laboratories, (1996).
6. Hibbit, Karlsson, and Sorensen, **ABAQUS/Standard User's Manual, Version 5.4**, HKS, (1990).

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