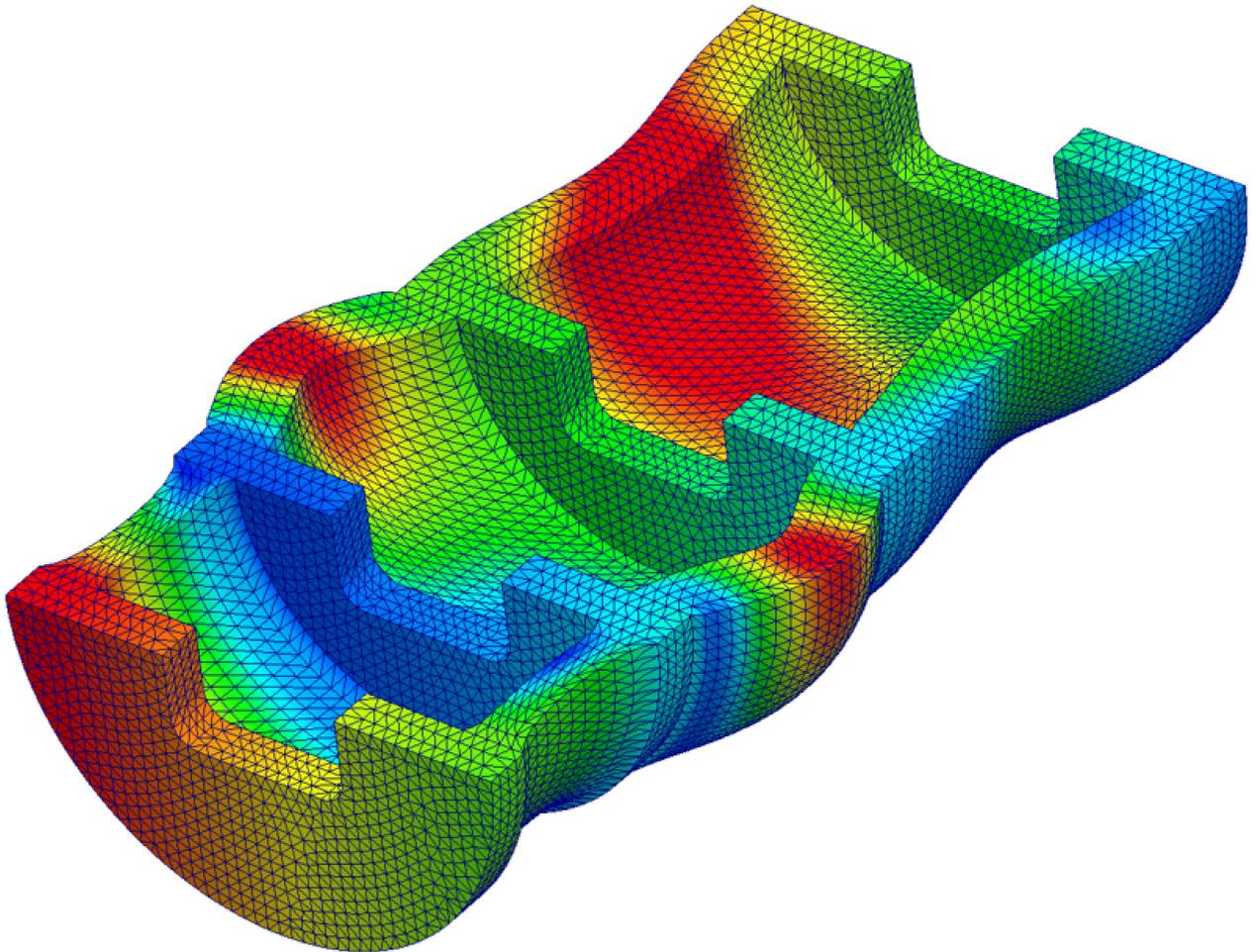


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2: Static analysis of a plate

Topics

- Using the SOLIDWORKS Simulation interface
- Linear static analysis with solid elements
- Controlling discretization error with the convergence process
- Finding reaction forces
- Presenting FEA results in a desired format

Project description

A steel plate is supported and loaded, as shown in Figure 2-1. We assume that the support is rigid. Rigid support is also called built-in support, fixed support, or fixed restraint. A 100000N tensile load is uniformly distributed along the end face, opposite to fixed face.

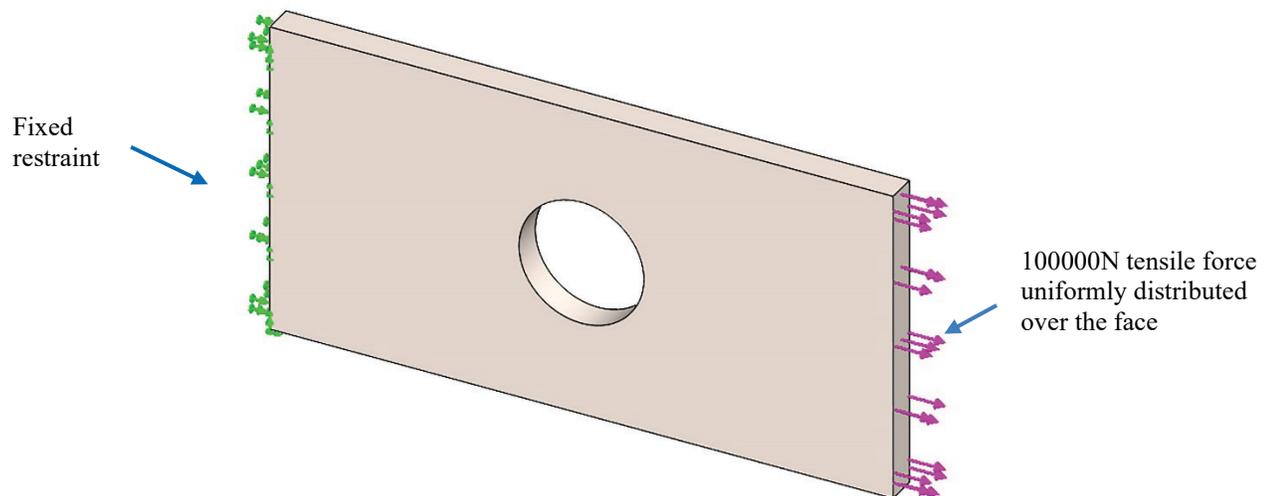


Figure 2-1: SOLIDWORKS model of a rectangular plate with a hole.

Symbols of loads and restraints are shown.

We will perform displacement and stress analysis using meshes with different element sizes. Note that repetitive analysis with different meshes does not represent standard practice in FEA. However, repetitive analysis with different meshes produces results which are useful in gaining more insight into how FEA works.

Procedure

In **SOLIDWORKS**, open part model HOLLOW PLATE. Verify that **SOLIDWORKS Simulation** is selected in the **Add-Ins** list (Figure 2-2).

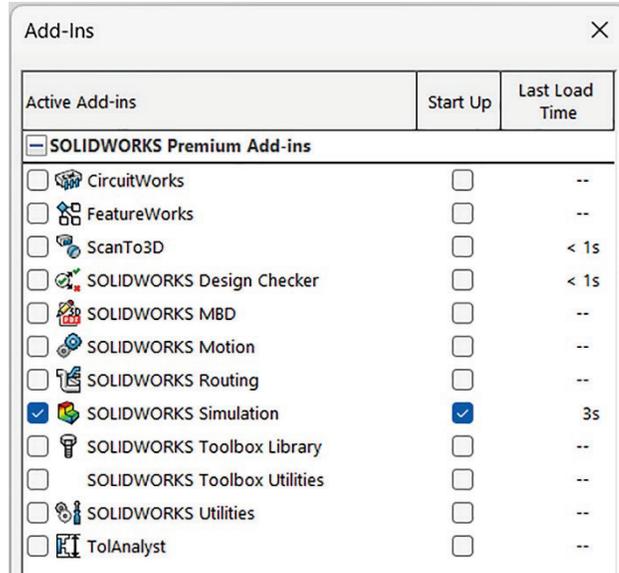


Figure 2-2: Add-ins list.

Verify that SOLIDWORKS Simulation is selected as Active Add-in and Start Up Add-in.

Once **Simulation** has been added, it shows in the main SOLIDWORKS menu and in the Command Manager.

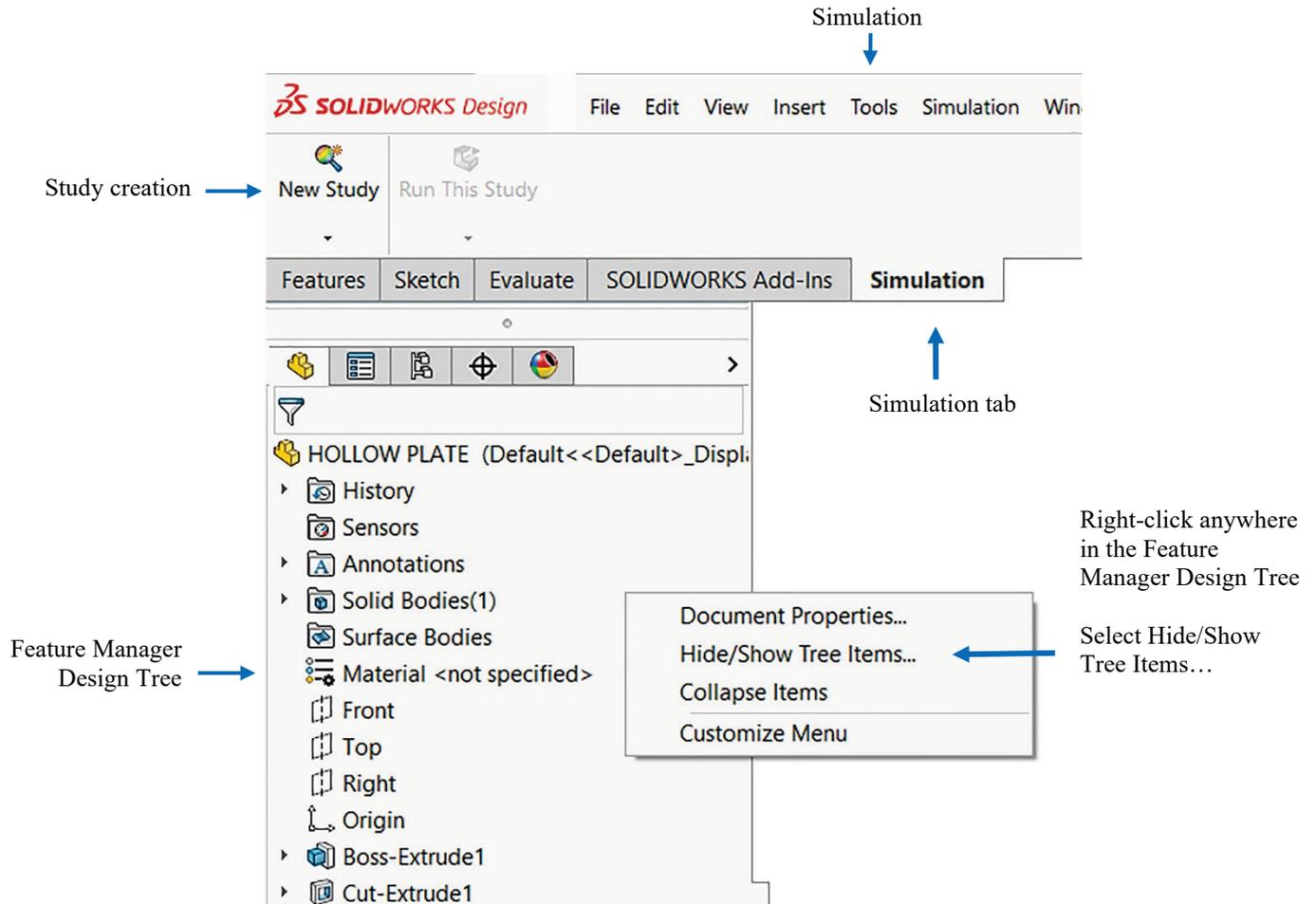


Figure 2-3: The Simulation tab is found in the Command Manager.

Selecting the Simulation tab in the Command Manager displays Simulation menu items (icons). Since no study has yet been created, only the Study creation icon is available; all others are grayed out. For convenience, pin down the top tool bar as shown. Command Manager with Large Buttons is shown in this illustration.

Note that **Feature Manager Design Tree** shown in Figure 2-3 displays **Solid Bodies** and **Surface Bodies** folders. These folders can be displayed by right-clicking anywhere in **Feature Manager Design Tree** to bring up the pop-up menu, and selecting **Hide/Show Tree Items**. This will invoke **System Options- Feature Manager** (not shown here). From there, **Solid Bodies** and **Surface Bodies** folders can be selected to show. We will need to distinguish between these two different bodies in later exercises. In this exercise these two folders do not need to show.

Before we create a study, let's review the **Simulation** main menu (Figure 2-4) along with its **Options** window (Figure 2-5).

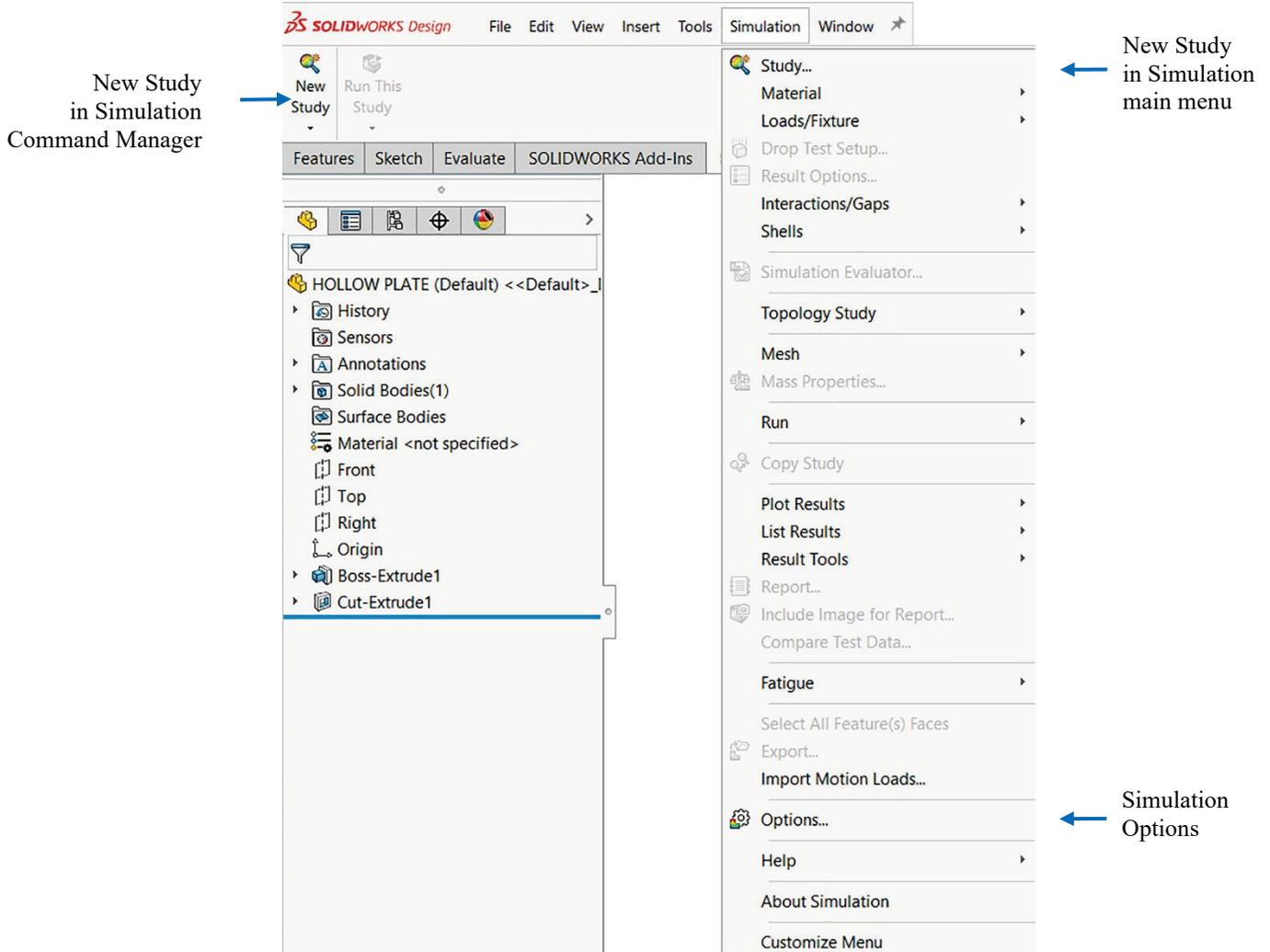


Figure 2-4: Simulation main menu.

Like the Simulation Command Manager shown in Figure 2-3, only the New Study icon is available. Note that some commands are available both in the Command Manager and in the Simulation menu.

Simulation studies can be executed entirely from the **Simulation** drop-down menu shown in Figure 2-4. In this book we will use the **Simulation** main menu and/or Command Manager to create a new Study.

Click on the **Simulation Options** shown in Figure 2-4 to open the **Simulation Options** window (Figure 2-5); select **Default Options** tab and **Units** from the menu in **Default Options**.

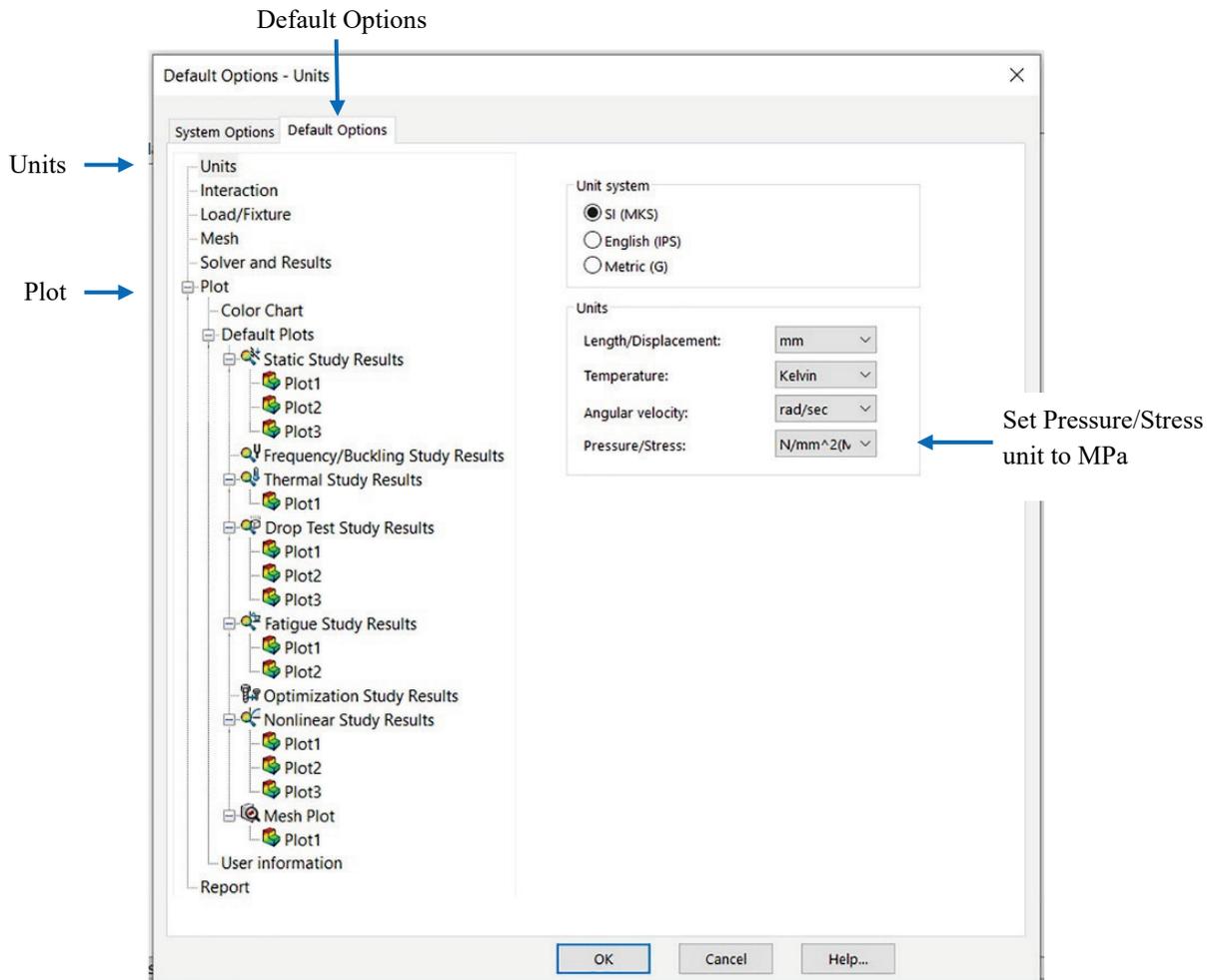


Figure 2-5: Simulation Options window.

The Options window has two tabs: system Options and Default Options. In this illustration, Default Options tab is shown. These selections will be valid for future studies and need to be made only once.

In the **Units** options, make the choices shown in Figure 2-5. In this book we will mostly use the SI system of units using MPa rather than Pa as a unit of stress and pressure. We will also use the IPS system.

Default Plots can be added, modified, deleted, or grouped into sub-folders which are created by right-clicking on the results folders, for example, **Static Study Results** folder, **Thermal Study Results** folder, etc.

In this chapter we will refer to **Default Options** (Figure 2-5) two more times to review choices in **Mesh** and in **Solver and Results**.

Creation of an FEA model starts with definition of a study. To define a new study, select **New Study** in either the **Simulation** tab in the Command Manager (Figure 2-3) or **Simulation** main menu (Figure 2-4). This opens the **Study Property Manager**. Note that the **New Study** icon in the **Simulation** Command Manager can also be used to open the **Study Advisor**. We will not be using the **Study Advisor** in this book. Name the study *tensile load 01* (Figure 2-6).

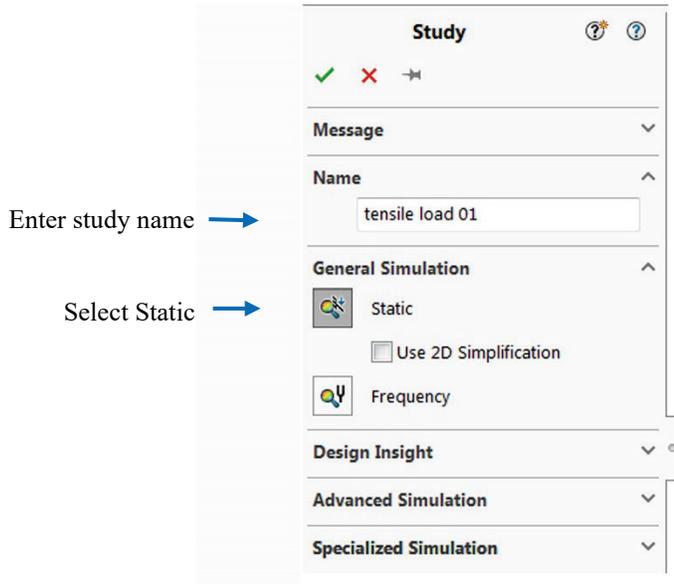


Figure 2-6: Creating a new study.

The study definition window offers choices of the type of study; here we select Static. Static and Frequency studies belonging to the group called General Simulation.

Once a new study has been created, **Simulation** Commands can be invoked in three ways:

- From the Simulation Command Manager (Figure 2-4)
- From the Simulation main menu (Figure 2-4); in this book, we will most often use this method

When a study is defined, **Simulation** creates a study window located below the **Feature Manager Design Tree** and places several folders in it. It also adds a study tab located next to **Model** and **Motion Study** tabs. The tab provides access to the study (Figure 2-7).

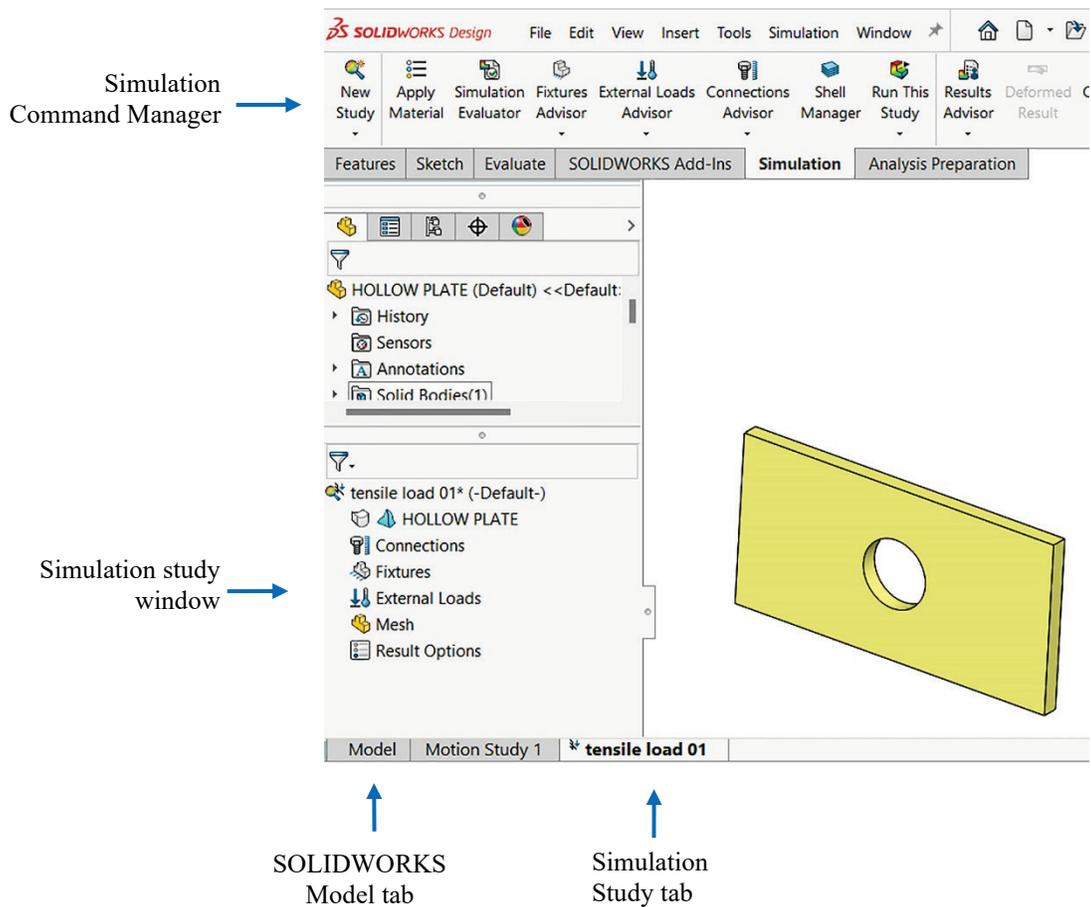


Figure 2-7: The Simulation window and Simulation tab.

You can switch between the SOLIDWORKS Model and Simulation Study by selecting the appropriate tab.

We are now ready to define the analysis model. This process generally consists of the following steps:

- CAD geometry idealization and/or simplification in preparation for analysis. This is usually done in SOLIDWORKS by creating an analysis specific configuration and making your changes there
- Material properties assignment
- Restraints definition
- Loads definition

In this case, geometry does not need any preparation, and we can start by assigning material properties.

If a material is defined for a SOLIDWORKS part model, the material definition is automatically transferred to the Simulation model. Assigning a material to the SOLIDWORKS model is a preferred modeling technique, especially when working with assemblies consisting of parts with different materials. We will do this in later exercises.

To apply material to the Simulation model, right-click the HOLLOW PLATE folder in the *tensile load 01* simulation study and select **Apply/Edit Material** from the pop-up menu (Figure 2-8).

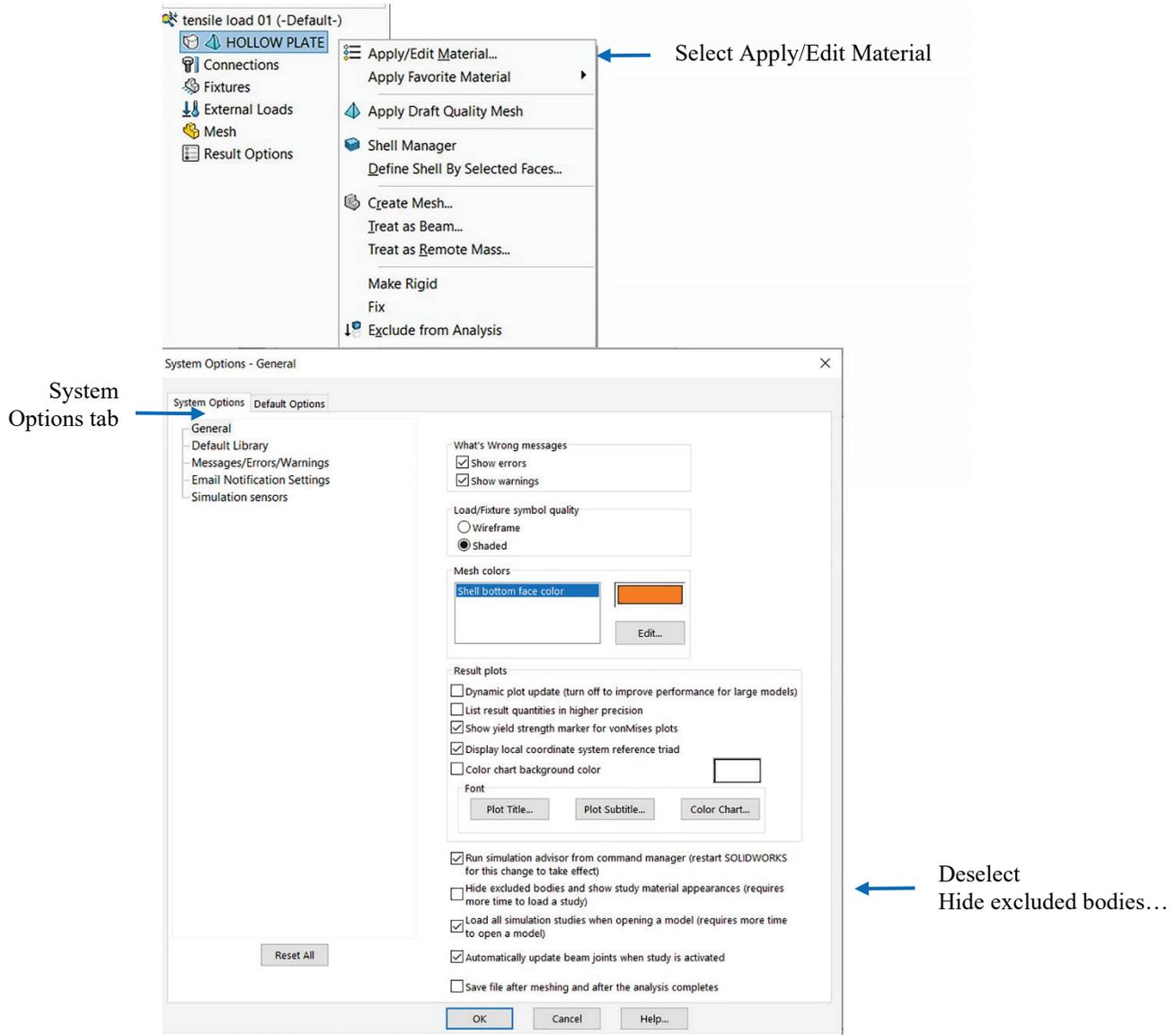


Figure 2-8: Assigning material properties.

The top window shows the first step in the process of applying material properties to the model. The bottom window shows modification to Simulation System Options; this needs to be done only once.

The action in Figure 2-8 opens the **Material** window in Figure 2-9.

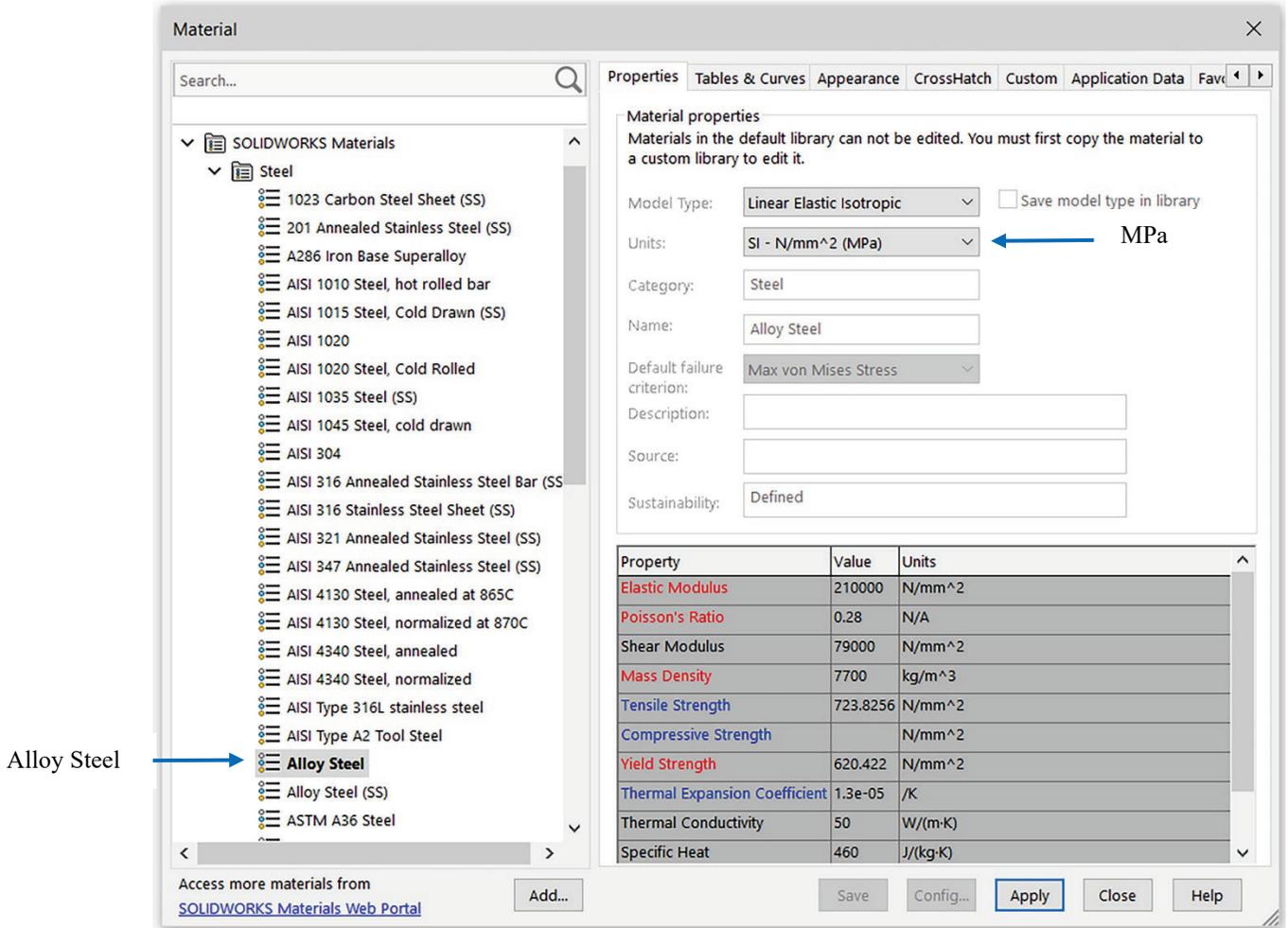


Figure 2-9: Material window.

Select Alloy Steel to be assigned to the model; select MPa as units.

Click Apply, and then click Close.

In the **Material** window, the properties are color coded to indicate the mandatory and optional properties. Red color (Elastic modulus, Poisson's ratio, Mass Density, Yield Strength) indicates a property that is mandatory based on the active study type and the material model. Blue color (Tensile strength, Compressive Strength, Thermal expansion coefficient) indicates optional properties. A black color description indicates properties calculated from the mandatory properties (Shear Modulus) or properties not applicable to the current study.

The analysis will not use volume loads; therefore, Mass Density will not be used.

In the **Material** window, open the **SOLIDWORKS Materials** menu, followed by the **Steel** menu. Select **Alloy Steel**. Select **SI** units under the **Properties** tab (other units could be used as well); **HOLLOW PLATE** folder in *tensile load 01* study now shows a check mark and the name of selected material to indicate that material has been assigned. If needed, you can define your own material by selecting **Custom Defined** material.

Material definition consists of two steps:

- Material selection (or material definition if a custom material is used)
- Material assignment (either to the entire model, to selected bodies of a multi-body part, or to selected components of an assembly)

Having assigned the material, we move to defining restraints. To display the pop-up menu that lists the options available for defining restraints, right-click the *Fixtures* folder in the *tensile load 01* study (Figure 2-10).

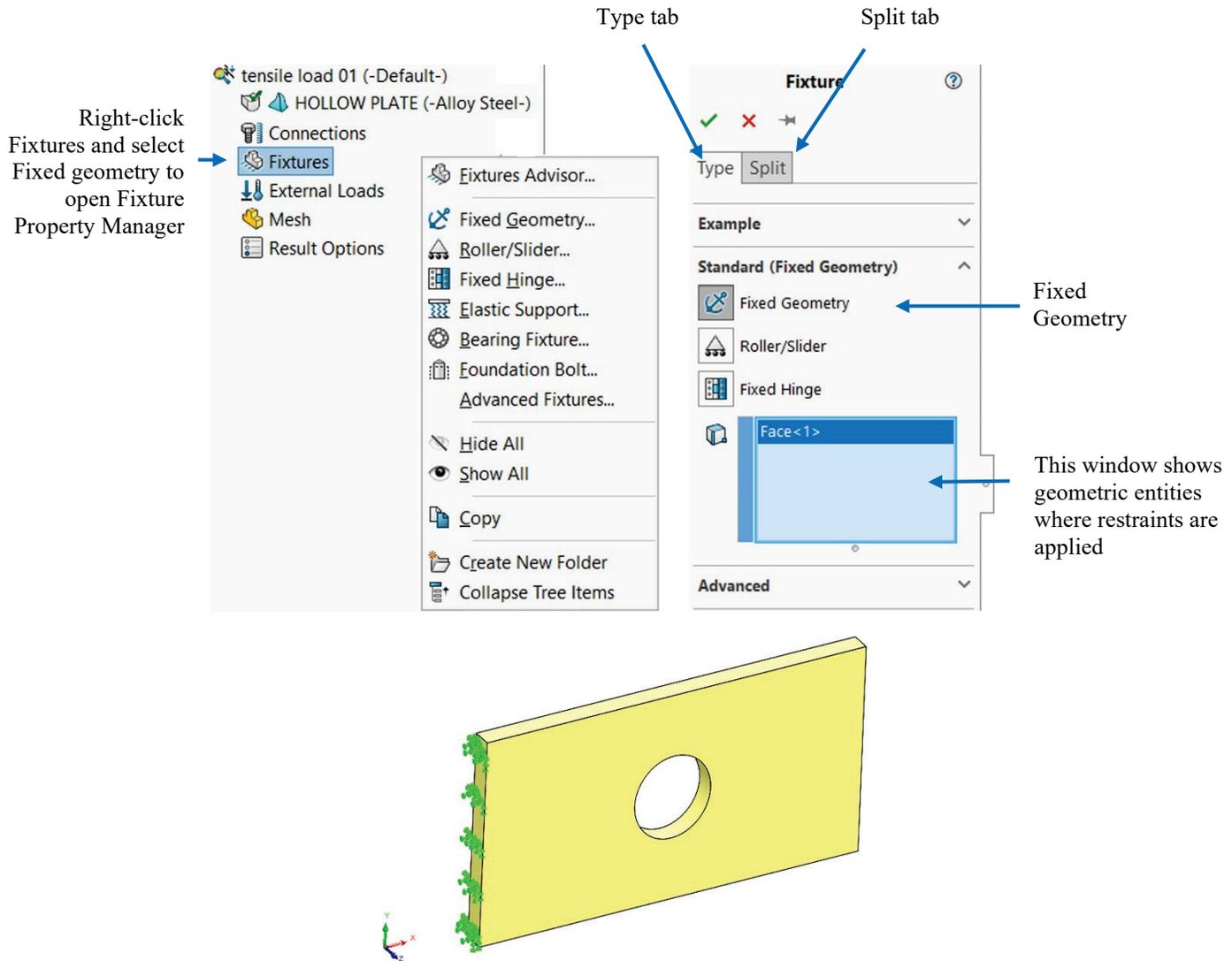


Figure 2-10: Pop-up menu for the Fixtures folder and Fixture definition window.

All restraints' definitions are done in the Type tab. The Split tab is used to define a split face where restraints are applied. The same can be done in SOLIDWORKS by defining a Split Line.

Once the **Fixtures** definition window is open, select the **Fixed Geometry** restraint type. Select the end-face entity where the restraint is to be applied. Click the green check mark in the Fixture Property manager window to complete the restraint definition.

Note that in **SOLIDWORKS Simulation**, the term “Fixture” implies that the model is firmly attached to the ground. However, aside from **Fixed Geometry**, which we have just used, all other types of fixtures restrain the model in certain directions while allowing movements in other directions. Therefore, the term “restraint” may better describe what happens when choices in the **Fixture** window are made. In this book we will switch between the terms “fixture” and “restraint” freely.

The existence of restraints is indicated by symbols shown in Figure 2-10. In the **Symbol** Settings of the Fixture window, the size of the symbol can be changed. Note that symbols shown in Figure 2-10 are distributed over the highlighted face meaning the entire face has been restrained. Each symbol consists of three orthogonal arrows symbolizing directions where translations have been restrained. Each arrow has a disk symbolizing that rotations have also been restrained. The symbol implies that all six degrees of freedom (three translations and three rotations) have been restrained. However, the element type we will use to mesh this model (second order solid tetrahedral element) has only translational degrees of freedom. Rotational degrees of freedom can't be restrained because they don't exist in this type of element. Therefore, disks symbolizing restrained rotations are irrelevant in our model. Please see the following table for more explanations.

Before proceeding, explore other types of restraints accessible through the **Fixture** window. Restraints can be divided into two groups: **Standard** and **Advanced**. Review animated examples available in the **Fixture** window and review the following table. Some less frequently used types of restraints are not listed here.

Standard Fixtures	
Fixed	Also called built-in or rigid support. All translational and all rotational degrees of freedom are restrained.
Immovable (No translations)	Only translational degrees of freedom are restrained, while rotational degrees of freedom remain unrestrained. If solid elements are used (like in this exercise), Fixed and Immovable restraints would have the same effect because solid elements do not have rotational degrees of freedom. Therefore, the Immovable restraint is not available if solid elements are used alone.
Roller/Slider	Specifies that a planar face can move freely on its plane but not in the direction normal to its plane. The face can shrink or expand under loading.
Fixed Hinge	Applies only to cylindrical faces and specifies that the cylindrical face can only rotate about its own axis. This condition is identical to selecting the On cylindrical face restraint type and setting the radial and axial components to zero.

Advanced Fixtures	
Symmetry	Applies symmetry boundary conditions to a flat face. Translation in the normal direction to the face is restrained and rotations about the axes aligned with the face are restrained.
Cyclic symmetry	Allows analysis of a model with cyclic patterns around an axis by modeling a representative segment. The geometry, restraints, and loading conditions must be identical for all other segments making up the model. Turbines, fans, flywheels, and motor rotors can usually be analyzed using cyclic symmetry.
Use Reference Geometry	Restrains a face, edge, or vertex only in certain directions, while leaving the other directions free to move. You can specify the desired directions of restraint in relation to the selected reference plane or reference axis.
On Flat Faces	Provides restraints in selected directions, which are defined by the three directions of the flat face where restraints are being applied.
On Cylindrical Faces	This option is similar to On flat face , except that the three directions of a cylindrical face define the directions of restraints.
On Spherical Face	Like On Flat Faces and On Cylindrical Faces . The three directions of a spherical face define the directions of the applied restraints.

When a model is fully supported (as it is in our case), we say that the model does not have any rigid body motions (the term “rigid body modes” is also used), meaning it cannot move without experiencing deformation.

Note that the presence of restraints in the model is manifested by both the restraint symbols (showing on the restrained face) and by the automatically created icon, **Fixture-1**, in the *Fixtures* folder. The display of the restraint symbols can be turned on and off by either:

- Right-click *Fixtures* folder and select **Hide All** or **Show All** in the pop-up menu shown in Figure 2-10
- or
- Right-click fixture icon and select **Hide** or **Show** from the pop-up menu.

Use the same method to control display of other Simulation symbols.

To define the load right-click the *External Loads* folder and select **Force** from the pop-up menu. This action opens the **Force** window as shown in Figure 2-11.

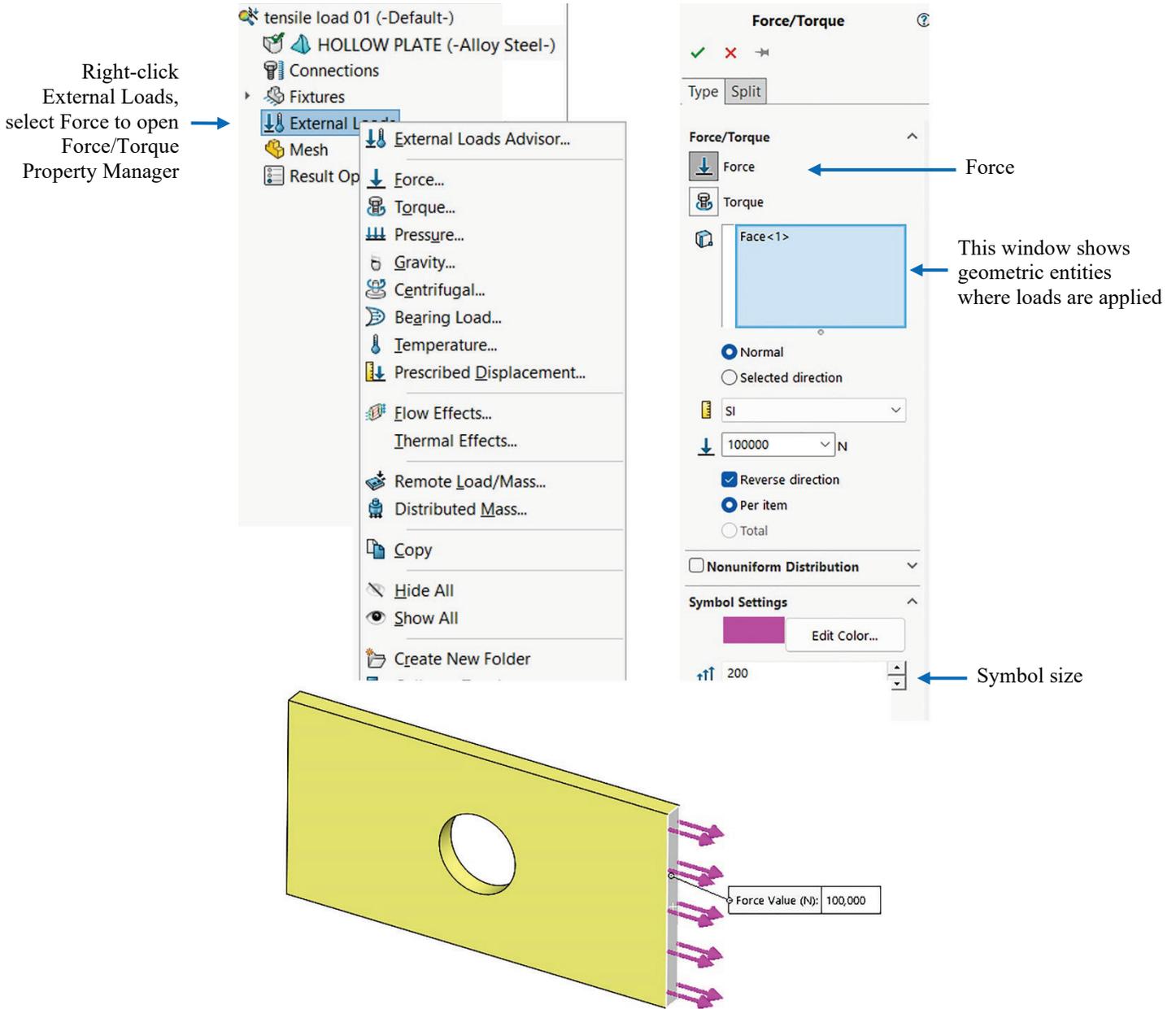


Figure 2-11: Pop-up menu for the External Loads folder and Force window.

The Force window displays the selected face where the tensile force is applied. If only one entity is selected, there is no distinction between Per Item and Total. In this illustration, load symbols have been enlarged by adjusting the Symbols Settings. Symbols of previously defined restraints have been hidden.

In the **Type** tab, select **Normal** to load the model with a 100000N tensile force uniformly distributed over the end face, as shown in Figure 2-11. Check the **Reverse direction** option to apply a tensile load.

Generally, forces can be applied to faces, edges, and vertices using different methods, which are reviewed below:

Force normal	Available for flat faces only, this option applies load in the direction normal to the selected face.
Force in the selected direction	<p>This option applies a force or a moment to a face, edge, or vertex in the direction defined by the selected reference geometry.</p> <p>Moments can be applied only if shell elements are used. Shell elements have six degrees of freedom per node: three translations and three rotations. Nodes of shell element can take a moment load.</p> <p>Solid elements only have three degrees of freedom (translations) per node and, therefore, cannot take a moment load directly.</p> <p>If you need to apply moments to solid elements, they must be represented with appropriately applied forces.</p>
Torque	This option applies torque (expressed by traction forces) about a reference axis using the right-hand rule.

Try using the click-inside technique to rename the **Fixture-1** and **Force/Torque-1** items. Note that renaming using the click-inside technique works on all items in SOLIDWORKS Simulation.

The model is now ready for meshing. Before creating a mesh, let's make a few observations about defining the geometry, material properties, loads and restraints.

Geometry preparation is a well-defined step with few uncertainties. Geometry that is simplified for analysis can be compared with the original CAD model.

Material properties are most often selected from the material library and do not account for local defects, surface conditions, etc. Therefore, the definition of material properties usually has more uncertainties than geometry preparation.

The definition of loads is done in a few menu selections but involves many assumptions. Factors such as load magnitude and distribution are often only approximately known and must be assumed. Therefore, significant idealization errors can be made when defining loads.

Defining restraints is where severe errors are most often made. For example, it is easy enough to apply a fixed restraint without giving too much thought to the fact that a fixed restraint means a rigid support – a mathematical abstraction. A common error is over-constraining the model, which results in an overly stiff structure that underestimates displacements and stresses. The relative level of uncertainties in defining geometry, material, loads, and restraints is qualitatively shown in Figure 2-12.

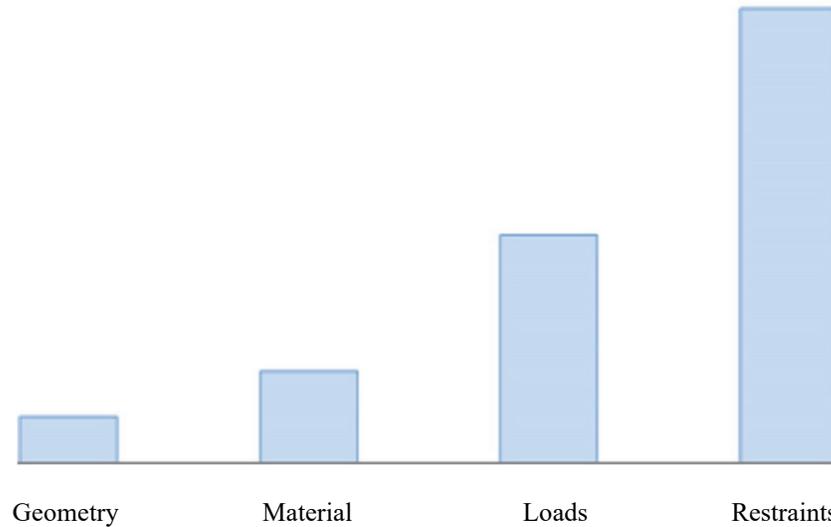


Figure 2-12: Qualitative comparison of uncertainty in defining geometry, material properties, loads, restraints.

The level of uncertainty (or the risk of error) has no relationship to the time required for each step, so the message in Figure 2-12 may be counterintuitive. In fact, preparing CAD geometry for FEA may take hours, while defining material properties and applying restraints and loads takes only a few clicks.

In all the examples presented in this book, we assume that definitions of material properties, loads, and restraints represent an acceptable idealization of real conditions. However, we need to point out that it is the responsibility of the FEA user to determine if all those idealized assumptions made during the creation of the mathematical model are indeed acceptable.

Before meshing the model, we need to verify under the **Default Options** tab, in the **Mesh** properties, that **High** quality, **Standard** mesh is selected (Figure 2-13). The **Options** window can be opened from the **Simulation** menu as shown in Figure 2-4. **Standard, High quality mesh is the default mesh in this book.**

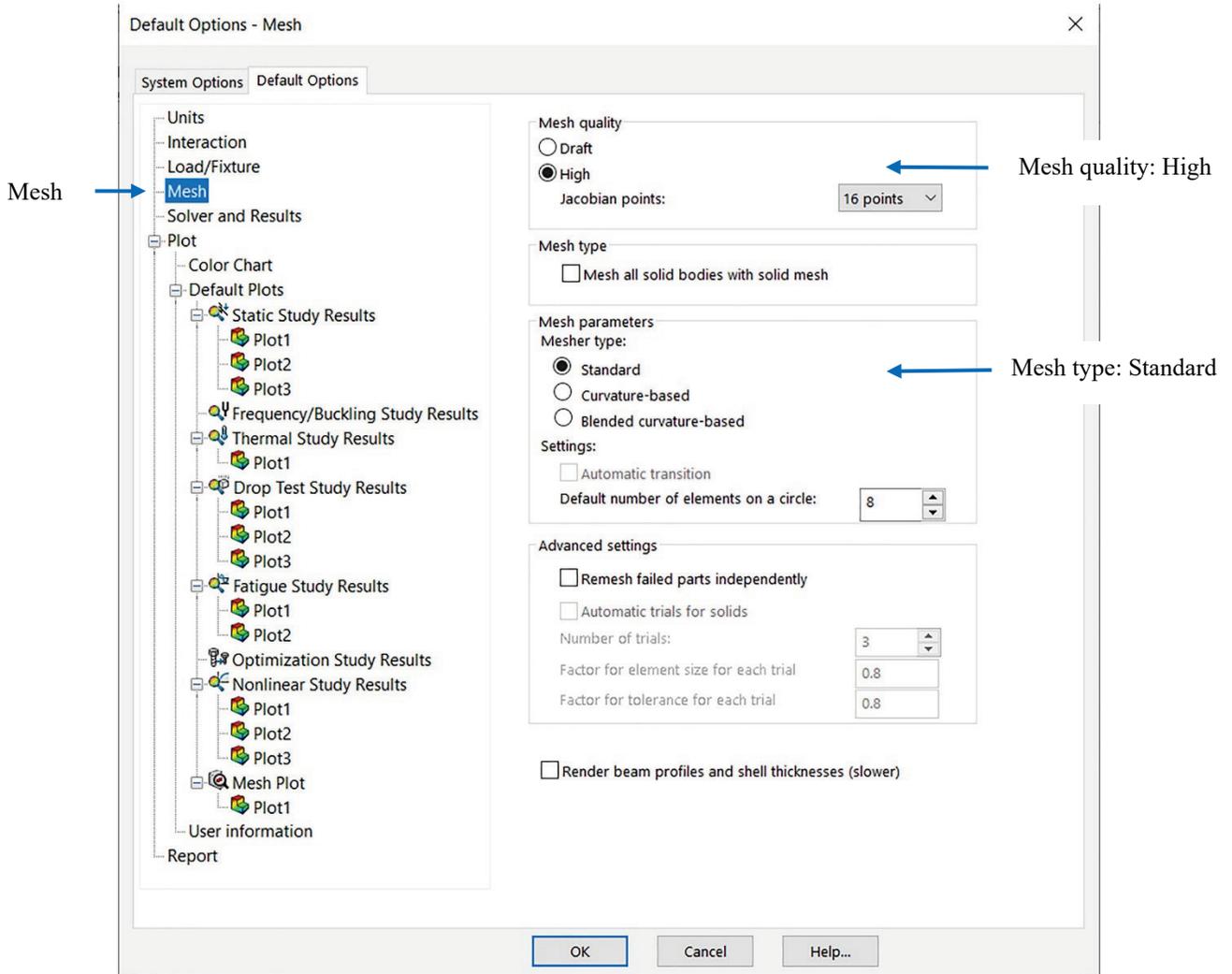


Figure 2-13: Mesh settings in the Default Options window.

High Mesh quality means that the second order elements are used. Standard mesh type is one of three types of mesh available. We will use curvature based meshes in later exercises.

The element order is visually indicated by a tetrahedron symbol next to Solid Body symbol in Study window. Tetrahedron with straight edges indicates the first order element. Tetrahedron with curvilinear edges indicates the second order element (Figure 2-14). If more than one body is present in a Simulation study, they can be meshed with different element orders. The current study has only one body called HOLLOW PLATE after the study name.

The difference between **High** and **Draft** mesh quality is:

- Draft quality mesh uses first order elements
- High quality mesh uses second order elements

Differences between first and second order elements were discussed in Chapter 1.

The difference between **Curvature based** mesh and **Standard** mesh will be explained in Chapter 3. Now, right-click the *Mesh* folder to display the pop-up menu (Figure 2-14).

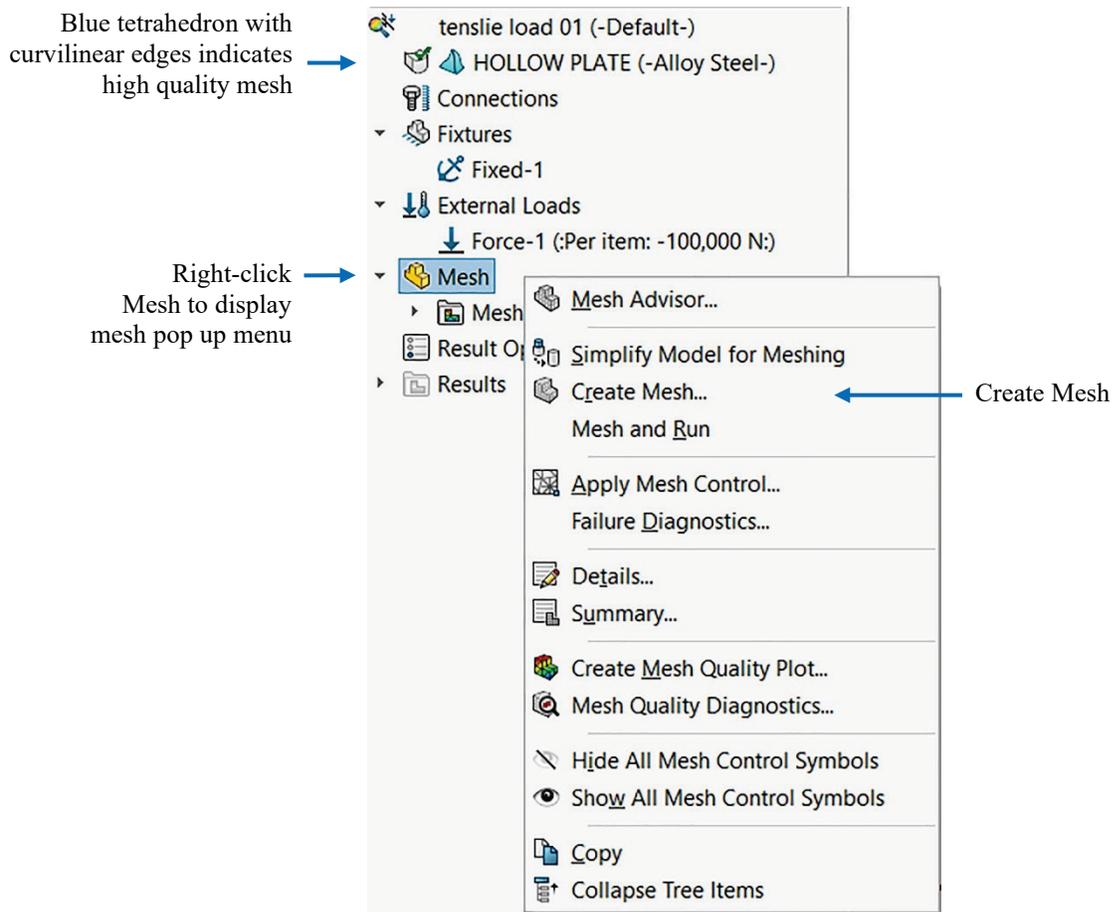


Figure 2-14: Mesh pop-up menu.

Select Create Mesh from the pop-up menu.

In the pop-up menu, select **Create Mesh**. This opens the **Mesh** window (Figure 2-15) which offers a choice of element size and element size tolerance.

This exercise demonstrates the impact of mesh size on results. Therefore, we will solve the same problem using four different meshes: coarse, medium, fine, very fine. Figure 2-15 shows the respective selection of meshing parameters to create the meshes. All four studies use the High Quality (second order) elements.

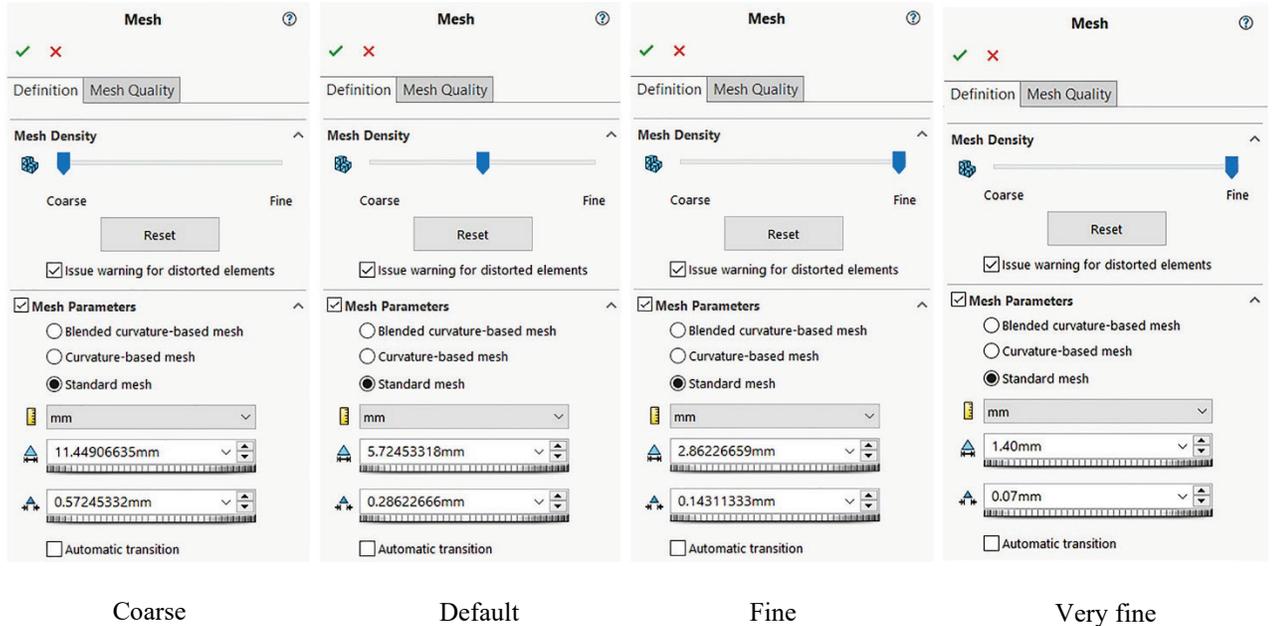


Figure 2-15: Four meshes: coarse, default, fine, very fine.

Show Mesh Parameters to see the element size. In all cases use Standard mesh. Note different Mesh Density slider positions in the four windows. Very fine mesh uses element size that is out of the range of slider.

The default mesh is what Simulation proposes for meshing the model. The element size of 5.72 mm is established automatically based on the geometric features of the model. The 5.72 mm size is the characteristic element size in the mesh, as explained in Figure 2-16.

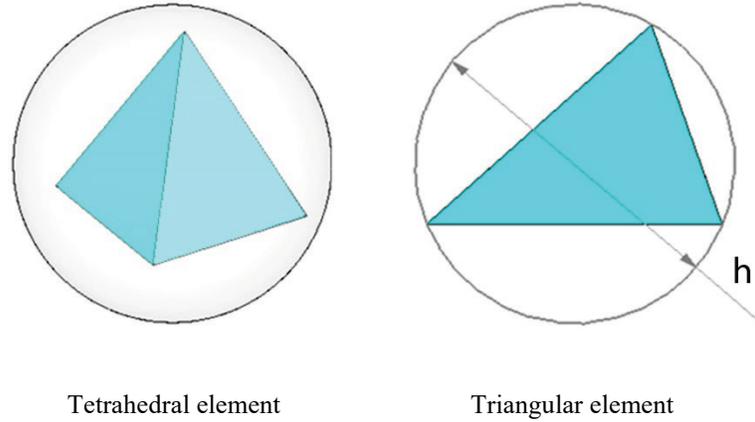


Figure 2-16: Characteristic element size of a tetrahedral element and a triangular element.

The characteristic element size of a tetrahedral element can be defined as diameter h of a circumscribed sphere. This is easier to illustrate with a 2D analogy of a circle circumscribed on a triangular element.

Element size influences the accuracy of results. The smaller the elements, the lower the discretization error, but the meshing and solving time takes longer.

Right-click the Mesh folder again and select **Create...** to open the **Mesh** window. With the **Mesh** window open, set the slider all the way to the left (as illustrated in Figure 2-15, left) to create a coarse mesh, and click the green checkmark button. The mesh will be displayed as shown in Figure 2-17.

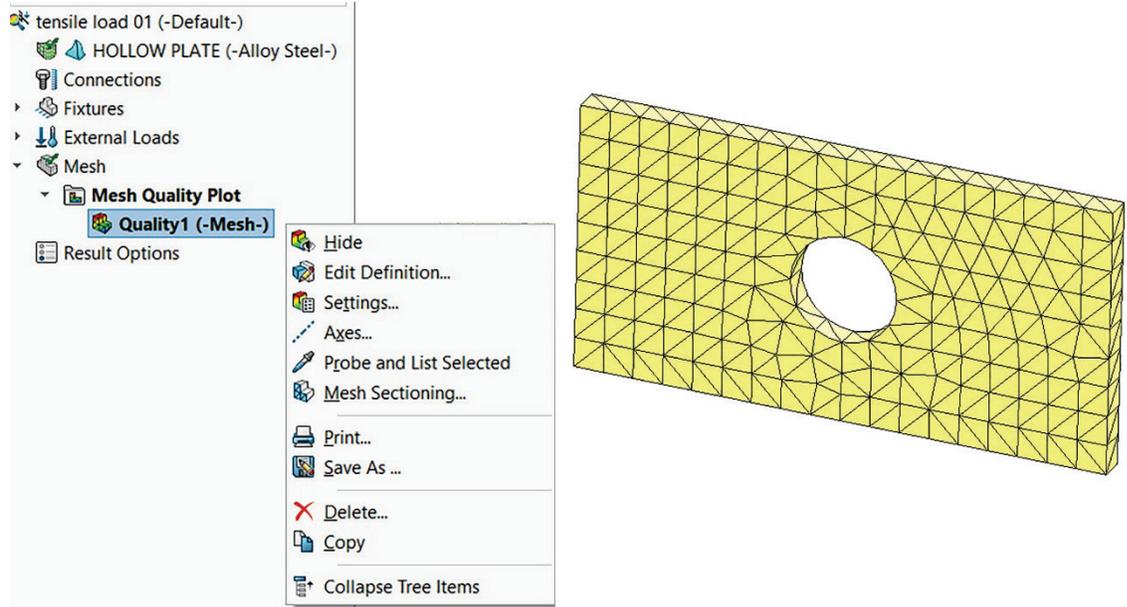


Figure 2-17: A coarse mesh created with second order, solid tetrahedral elements.

You can control the mesh display by selecting Hide Mesh or Show Mesh from the pop-up menu in Mesh Quality Plot. Here the plot is named Quality1. Activate the above pop-up menu by right-clicking Quality1 plot.

The presence of a mesh is reflected in the appearance of the solid folder and the mesh folder in a **Simulation** study (Figure 2-18).

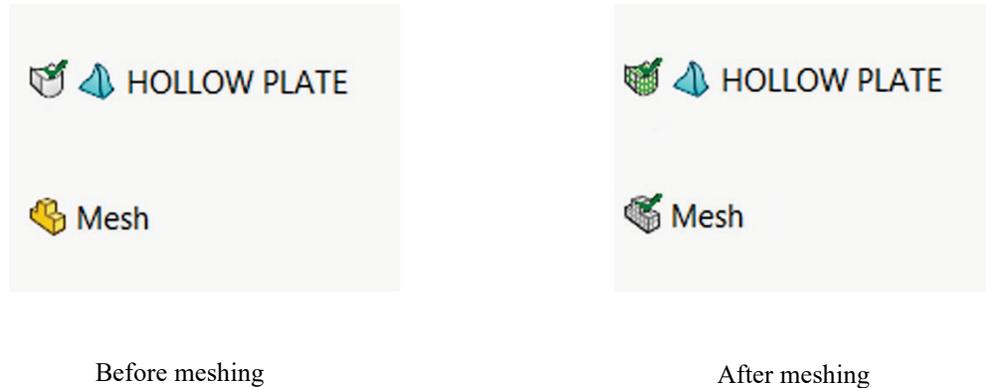


Figure 2-18: Solid folder and Mesh folder in a Simulation study before and after meshing.

After meshing, cross hatching is added to the Solid Body symbol. Assigning material properties adds a green check mark to the Solid Body symbol.

After meshing, cross hatching and a green check mark are also added to Mesh folder.

Blue tetrahedron with cured edges, visible next to Solid Body symbol, denotes that second order elements are used.

When **Solid** folder contains more than one body, **High Quality** and **Draft Quality** meshes may be individually selected for each body. We do not use this option in this exercise.

To start the solution, right-click the *tensile load 01* study folder which displays a pop-up menu (Figure 2-19). Select **Run** to start the solution.

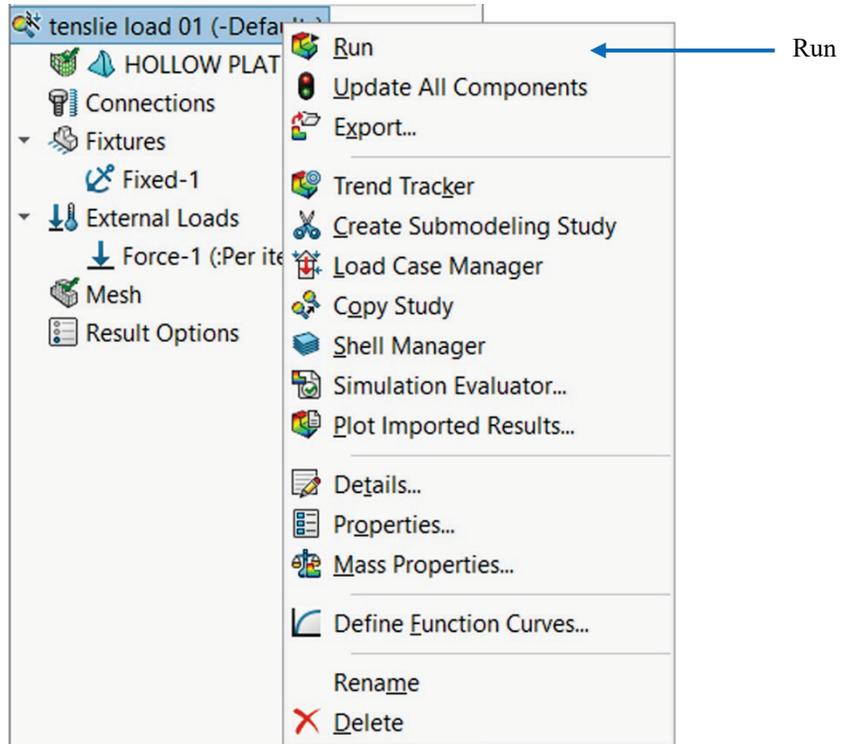


Figure 2-19: Pop-up menu for the *tensile load 01* study.

*Start the solution by right-click the *tensile load 01* folder to display this pop-up menu. Select **Run** to start the solution.*

The solution can be executed with different properties, which we will investigate in later chapters. You can monitor the solution progress while the solution is running (Figure 2-20).

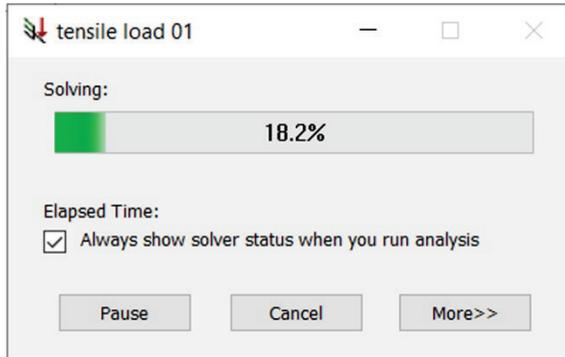


Figure 2-20: Solution Progress window.

The solver reports solution progress while the solution is running.

If a solution fails (not in this exercise), a failure is reported (Figure 2-21).

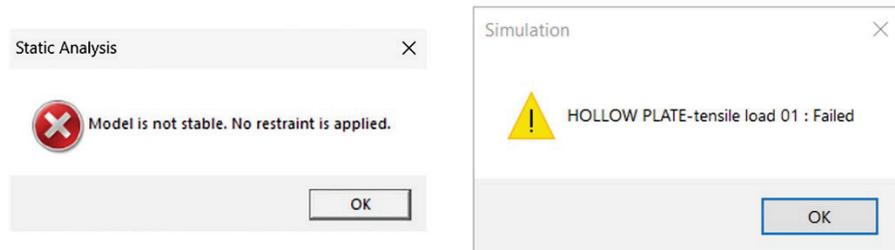


Figure 2-21: Failed solution warning windows.

Here, a solution of a model with no restraints was attempted. Once the error message has been acknowledged (left), the solver displays the outcome of the run (right).

When the solution is completed successfully, **Simulation** creates a *Results* folder with result plots which are defined in **Simulation Default Options** as shown in Figure 2-5.

In a typical configuration three plots are created automatically in the *Static* study:

- *Stress1* showing von Mises stresses
- *Displacement1* showing resultant displacements
- *Strain1* showing equivalent strain

You can add more plots to the *Results* folder. You can also create subfolders in the *Results* folder to group plots (Figure 2-22).

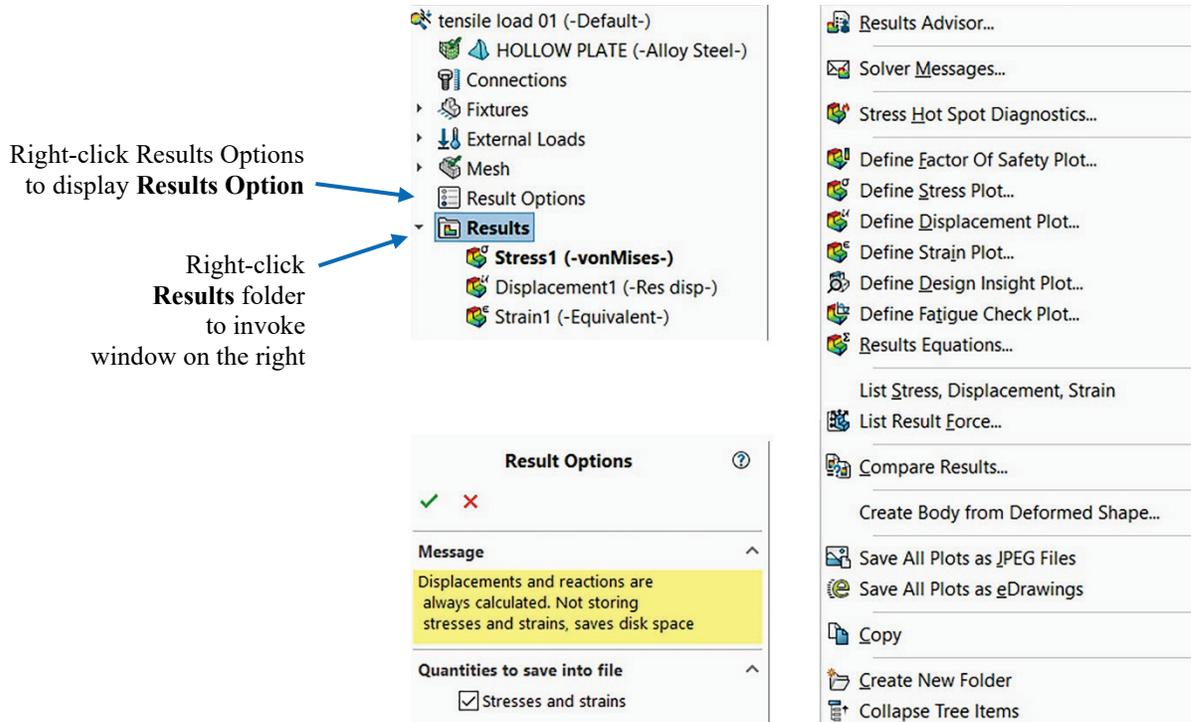


Figure 2-22: More plots and folders can be added to the *Results* folder.

Right-clicking on the Results folder activates this pop-up menu from which plots may be added. Three plots are automatically created if Results Options include these three plots: Stress, Displacement, Strain. You may define additional plots.

The **Results Options** window shown in Figure 2-22 has different choices depending on the type of study. In a **Static** study, deselecting **Stress and strain** disables calculation of stress and strain which reduces calculation time and the size of solution database. This may be important in analysis of very large models.

To display stress results, double-click on the **Stress1** icon in the *Results* folder or right-click it and select **Show** from the pop-up menu. The stress plot is shown in Figure 2-23.

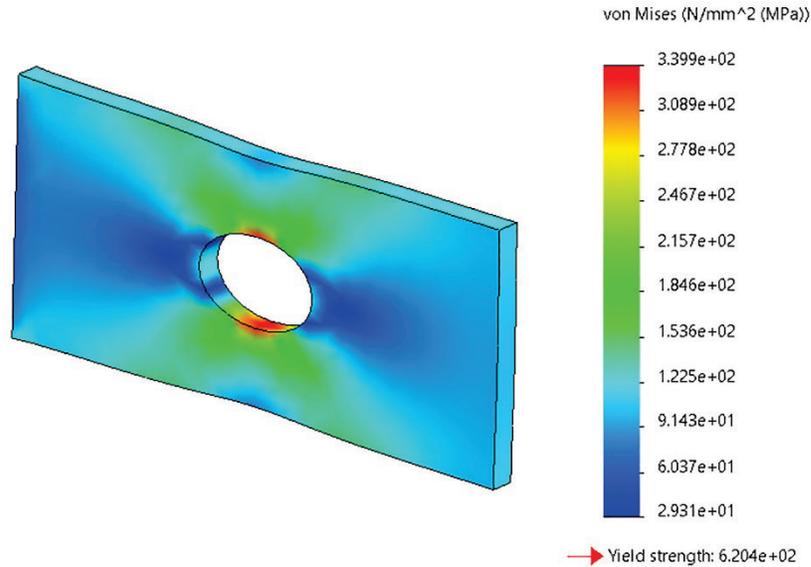


Figure 2-23: Stress plot displayed using default settings.

Von Mises stress results are shown by default in the stress plot window. Note that results are shown in [MPa] as was set in the Default Options tab shown in Figure 2-5. The highest stress 345 MPa is below the material yield strength, 620 MPa.

Once the stress plot is showing, right-click the stress plot icon to display the pop-up menu featuring different plot options (Figure 2-24).

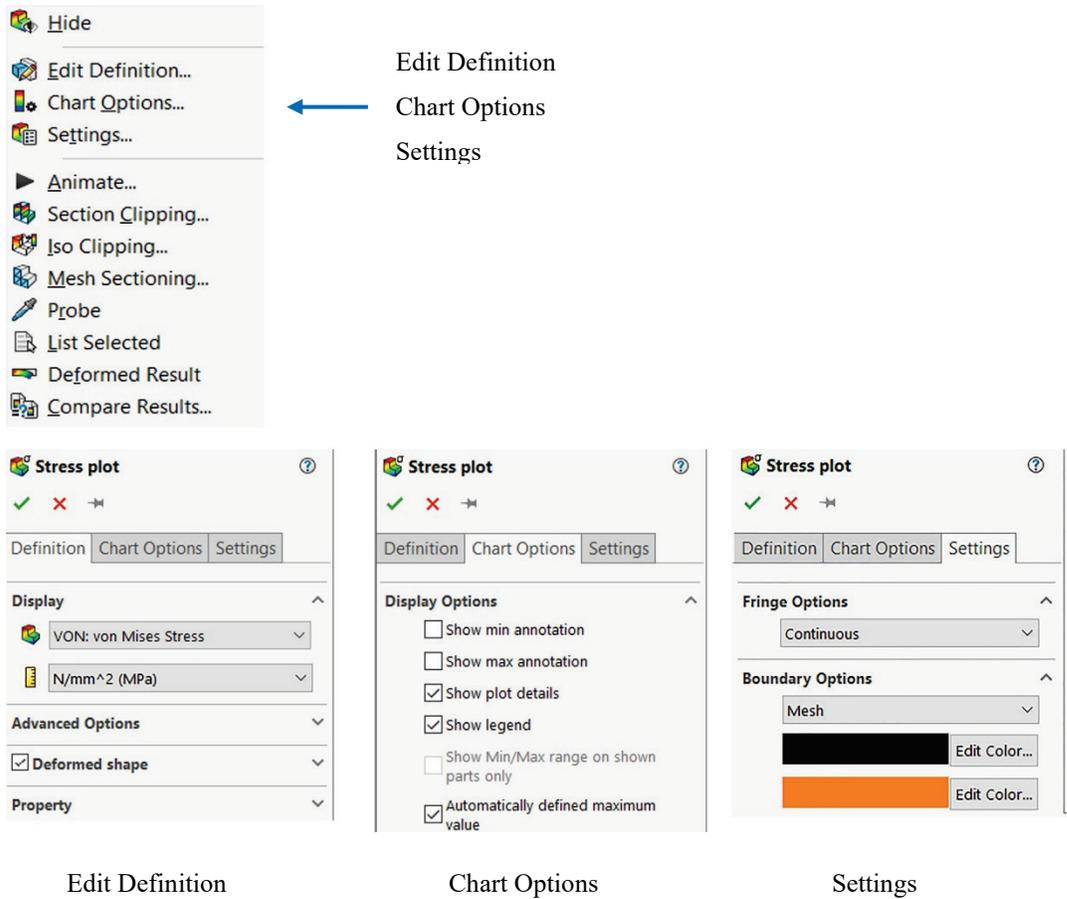


Figure 2-24: Plot display options.

Plots can be modified using selections from the pop-up menu (top). The same windows may also be invoked by right clicking the color legend of a result plot. Settings tab is shown here for Boundary Options: Mesh

Explore all selections offered by these three windows shown in Figure 2-24. Select scientific, floating, and general format and color Options in **Chart Options**. Note that you may switch between **Definition**, **Chart Options** and **Settings** either by using the pop-up menu shown in Figure 2-24 or by using tabs at the top of these windows.

Use **Edit Definition** to change units if necessary. **Chart Options** offers control over the format of numerical results, such as scientific, floating, and general, and offers a different number of decimal places. Explore these choices. In this book, results will be presented using different choices that are most suitable for the desired plot. In many plots in this book **Color Options** will be **User Defined** to replace dark blue color with grey color which shows better in print. Figure 2-24 shows the **User Defined** menu. Position of the color legend may be modified for improved layout.

The default type of **Fringe Options** in the **Settings** window is **Continuous** (Figure 2-24). Change this to **Discrete** through the **Default Options** window, by selecting **Plot** (Figure 2-5). This way you will not have to modify the future plots individually. In this book we will be using **Discrete Fringe Options** to display fringe plots. The already created plots will not change after changing the **Default Options**.

Since the above change does not affect already existing plots, we now examine how to modify the stress plot using the **Settings** window shown in Figure 2-25. In **Settings**, select **Discrete** in **Fringe options** and **Mesh** in **Boundary options**. In **Chart Options** select floating numerical format with one decimal place.

The edited stress plot is shown in Figure 2-25.

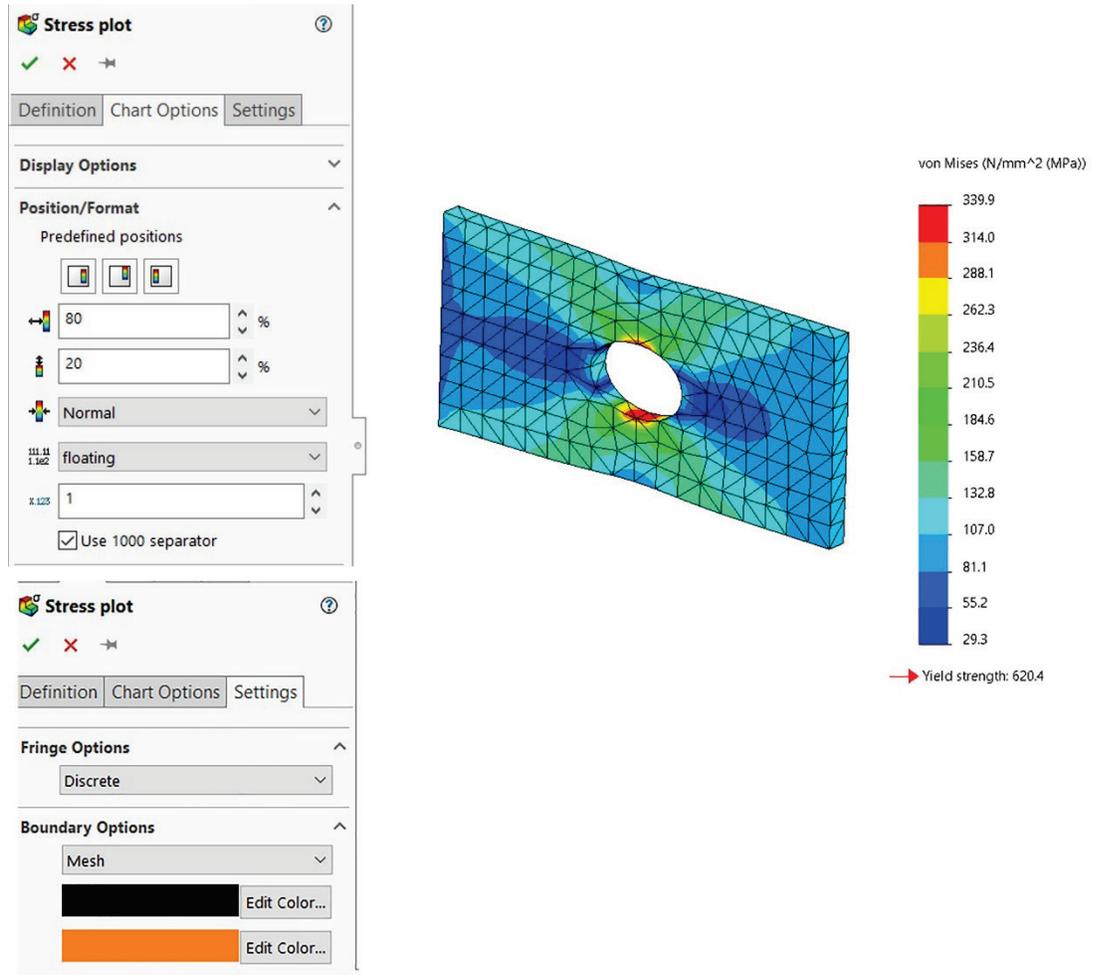


Figure 2-25: The modified stress plot is shown with floating numerical format with one decimal place selected in Chart Options and with discrete fringes and the mesh superimposed on the plot selected in Settings.

The stress plot in Figure 2-25 shows node values, also called averaged stresses. Element values (or non-averaged stresses) can be displayed by proper selection in the **Stress Plot** window in **Advanced Options**. Node values are most often used to present stress results. See Chapter 3 and the glossary of terms in Chapter 23 for more information on node values and element values of stress results.

Before you proceed, investigate stress plot with other selections available in the windows shown in Figure 2-24.

We now review the displacement and strain results. All these plots are created and modified in the same way. Sample results are shown in Figure 2-26 (displacement) and Figure 2-27 (strain).

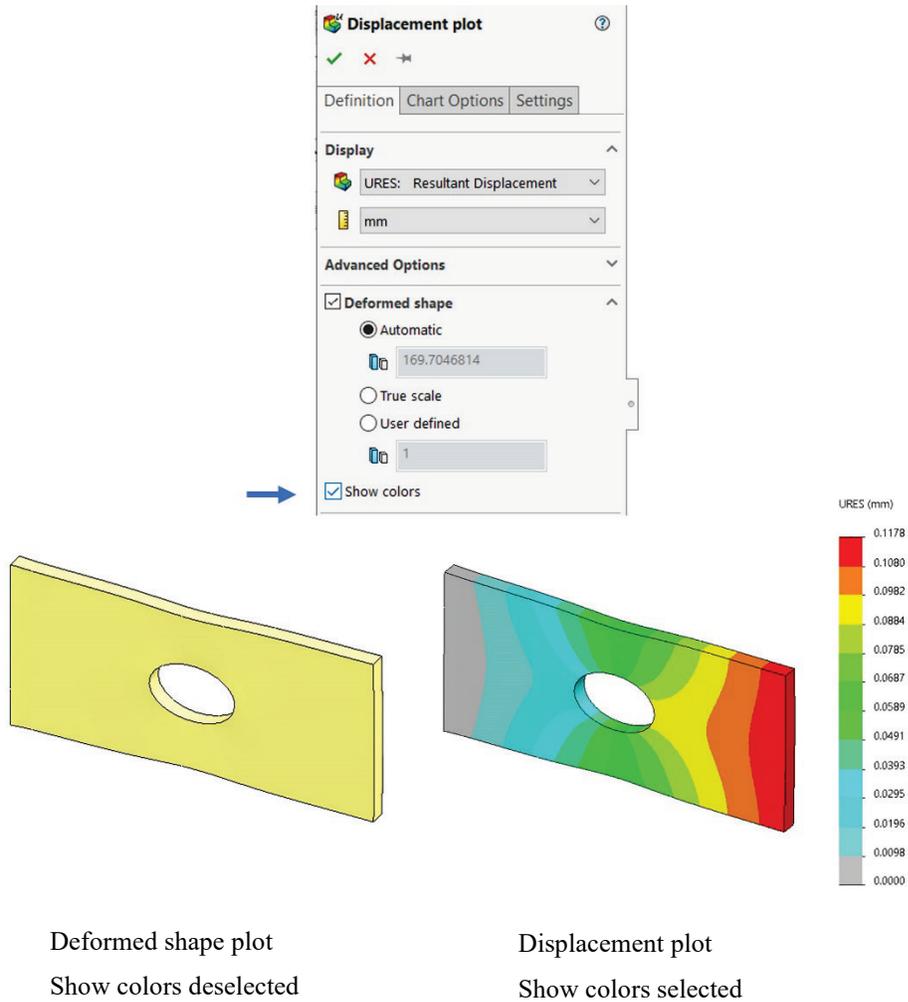


Figure 2-26: Deformed shape plot (left) and Displacement plot (right).

A Displacement plot can be turned into a Deformation plot by deselecting Show Colors in the Displacement Plot Definition window. The same window has the option of showing the model with an exaggerated scale of deformation as shown above. Both plots show the deformed shape; this option may also be deselected. The blue color in the Displacement plot has been replaced with a gray color for better appearance in this illustration. That was done in Chart Options, Color Options, User defined. Numerical format specifies floating with four decimal places.

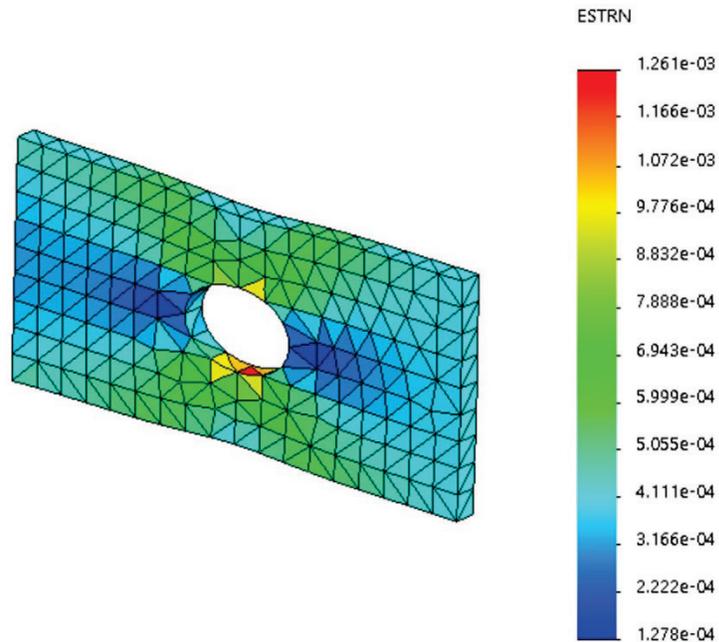
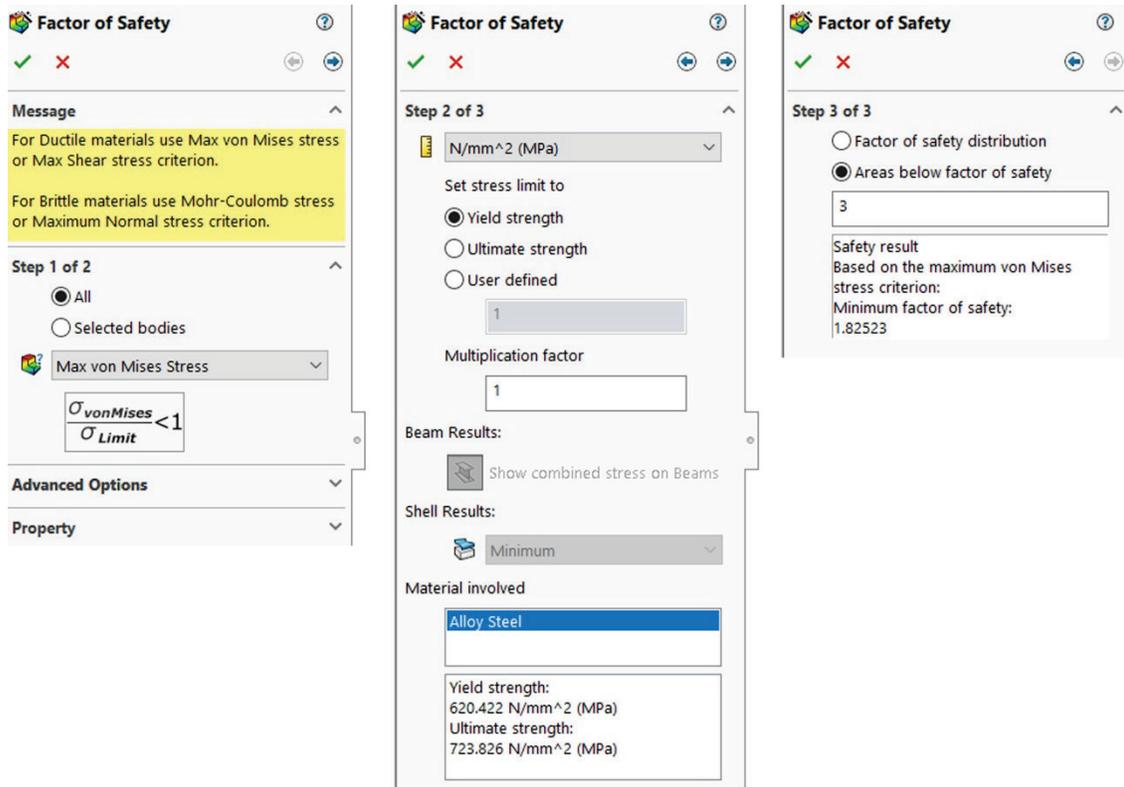


Figure 2-27: Strain plot.

Strain plot is shown using Element values. The mesh is also shown.

The plots in Figures 2-23, 2-25, 2-26, 2-27 all show the deformed shape in an exaggerated scale. You can change the display from deformed to undeformed or modify the scale of deformation in the **Displacement Plot**, **Stress Plot**, and **Strain Plot** windows, activated by right-clicking the plot icon, then selecting **Edit Definition**.

Now, construct a **Factor of Safety** plot using the menu shown in Figure 2-22. The definition of the **Factor of Safety** plot requires three steps. Follow steps 1 through 3 using the selection shown in Figure 2-28. Refer to Chapter 1 and review Help to learn about failure criteria and their applicability to different materials.



Step 1

Use von Mises Stress criterion.
Review Property options to insert text and/or use specific views for the plot

Step 2

Select stress limit: Yield strength
Select Multiplication factor: 1

Step 3

Select Areas below factor of safety, enter 3

Figure 2-28: Three windows show the three steps in the Factor of Safety plot definition. Select the Max von Mises Stress criterion in the first window. Use right arrow to move to the next two windows.

To move through steps, click on the right and left arrows located at the top of the Factor of Safety dialog.

Step 1 selects the failure criterion; Step 2 selects display units, sets the stress limit and sets multiplication factor; Step 3 selects what will be displayed in the plot. Here we select areas below the factor of safety 3. Click the green check mark to display the plot.

Review Help to learn more about failure criteria.

The factor of safety plot in Figure 2-29 shows the area where the safety factor is below the specified.

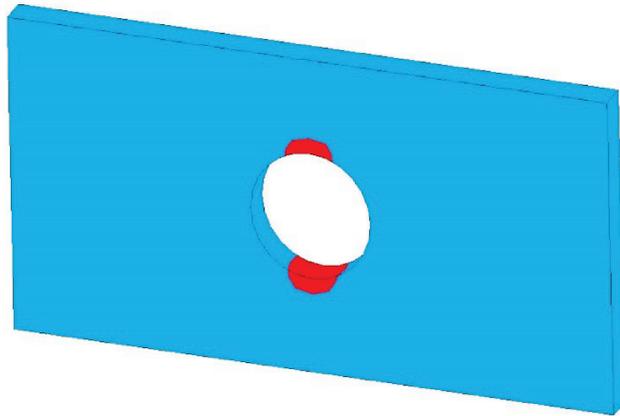


Figure 2-29: The red color displays the areas where the factor of safety is below 3.
The irregular shape of red areas is caused by a coarse mesh used in this study. Mesh is not shown.

We have completed the analysis with a coarse mesh and now wish to see how a change in mesh density will affect the results. Therefore, we will repeat the analysis three more times using medium, fine and very fine meshes respectively. We will use the settings shown in Figure 2-15. All four meshes used in this exercise are shown in Figure 2-30.

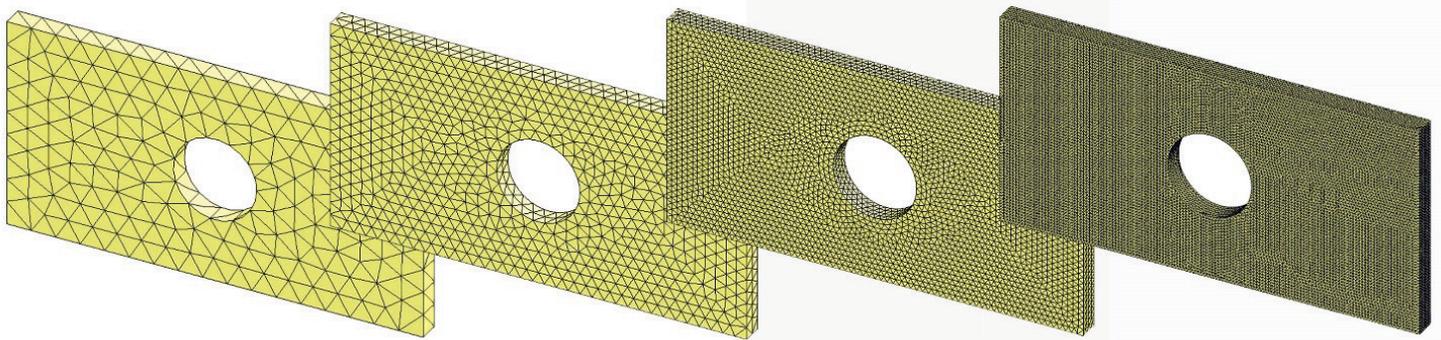


Figure 2-30: Four meshes: coarse, medium, fine, very fine.
Four meshes are used to study the effects of reducing the element size on results.

To compare the results produced by different meshes, we need more information than what is available in plots. Along with the maximum displacement and the maximum von Mises stress, for each study we need to know:

- The number of nodes in the mesh
- The number of elements in the mesh
- The number of degrees of freedom in the model

The information on the number of nodes and number of elements can be found in **Mesh Details** accessible from the menu in Figure 2-14. The mesh **Details** window is shown in Figure 2-31.

Mesh Details	
Study name	tensile load 01 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points for High quality mesh	16 points
Element size	11.4491 mm
Tolerance	0.572453 mm
Mesh quality	High
Total nodes	2768
Total elements	1472
Maximum Aspect Ratio	6.5595
Percentage of elements with Aspect Ratio < 3	99.9
Percentage of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0
Number of distorted elements	0
Time to complete mesh(hh:mm:ss)	00:00:00

Figure 2-31: Mesh Details window.

Right-click the Mesh folder and select Details from the pop-up menu to display the Mesh Details window. Information on the number of degrees of freedom is not available here.

Another way to find the number of nodes and elements and the only way to find the number of degrees of freedom is to use the pop-up menu shown in Figure 2-32. Right-click the *Results* folder and select **Solver Messages** to display the window shown in Figure 2-32.

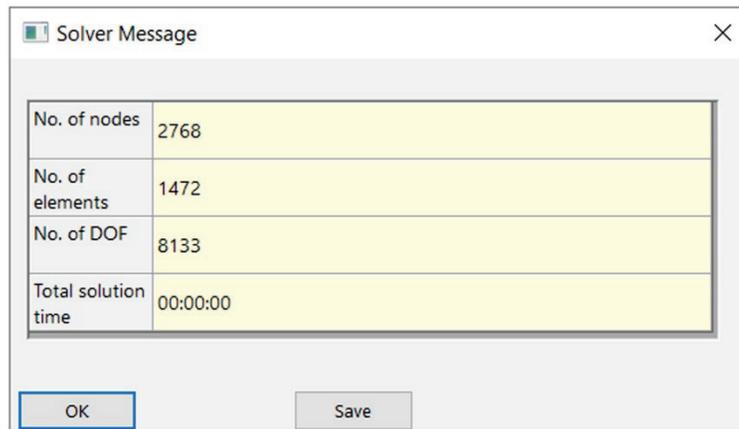


Figure 2-32: The Solver Message window lists information pertaining to the solved study.

The solution time was below 0.01s. You may click Save button to save this message.

Now create and run three more studies: *tensile load 02* with the default element size (medium), *tensile load 03* with a fine element size, and *tensile load 04* with element size 1.4mm as shown in Figure 2-15 and Figure 2-30. To create a new study, we could repeat the same steps as before, but an easier way is to copy the original study. To copy a study, follow the steps in Figure 2-33.

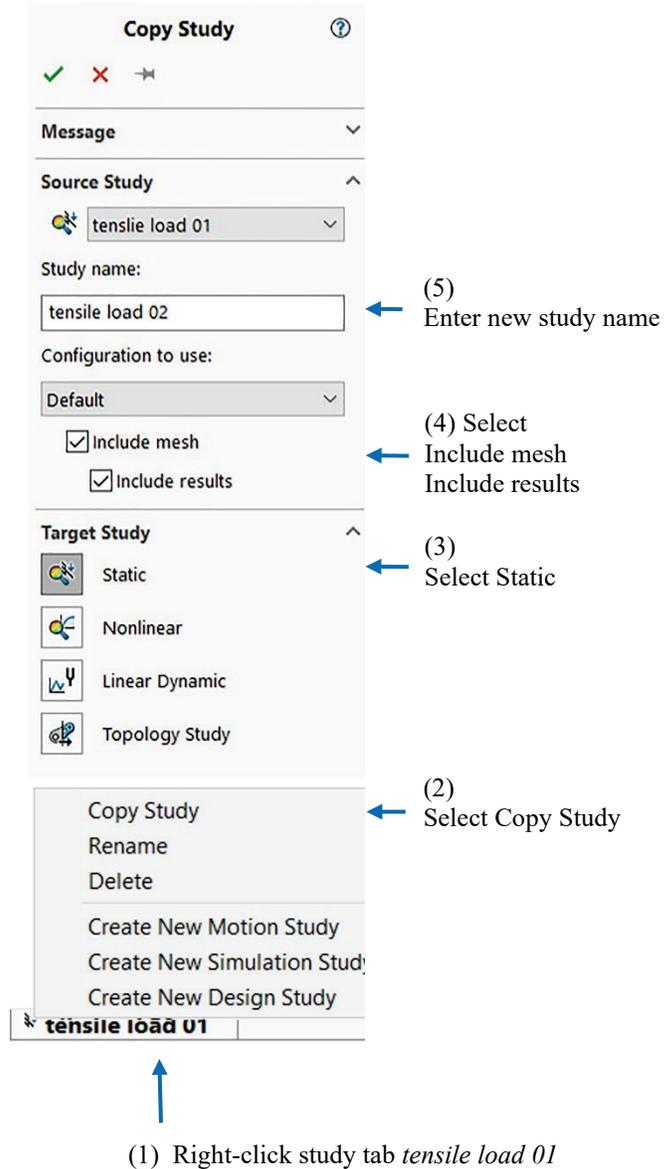


Figure 2-33: A study can be copied following the above steps.

All definitions in a study (material, restraints, loads, mesh) can also be copied individually from one study to another by dragging and dropping them into a new study tab. Selecting Include Mesh and Include results copies mesh and all result plots. Mesh and plots will be later overwritten but definitions of plots will stay the same.

A study is copied complete with results and plot definitions. Before remeshing with default element size, you must acknowledge the message shown in Figure 2-34.

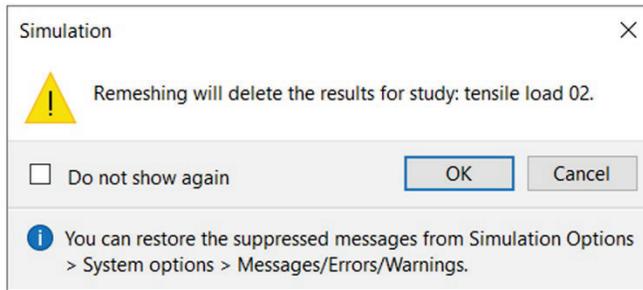


Figure 2-34: Remeshing deletes existing results in the study.

The summary of results produced by the four studies is shown in Figure 2-35.

Study	Element size	Number of nodes	Number of elements	Number of DOF	Max. resultant displacement	Max. von Mises stress
	mm				mm	MPa
<i>tensile load 01</i>	11.45	2768	1472	8133	0.117813	339.9
<i>tensile load 02</i>	5.72	12222	7040	36111	0.118035	369.9
<i>tensile load 03</i>	2.86	84112	54969	250851	0.118070	377.1
<i>tensile load 04</i>	1.4	599383	416218	1791606	0.118084	377.8

Figure 2-35: Summary of results produced by the four meshes.

All results are based on the same problem. Differences in the results arise from the different mesh refinements.

The actual numbers in this table may vary slightly depending on the type of solver and the release of the software.

Figure 2-36 shows the maximum resultant displacement and the maximum von Mises stress as a function of the number of degrees of freedom. The number of DOFs increases with mesh density.

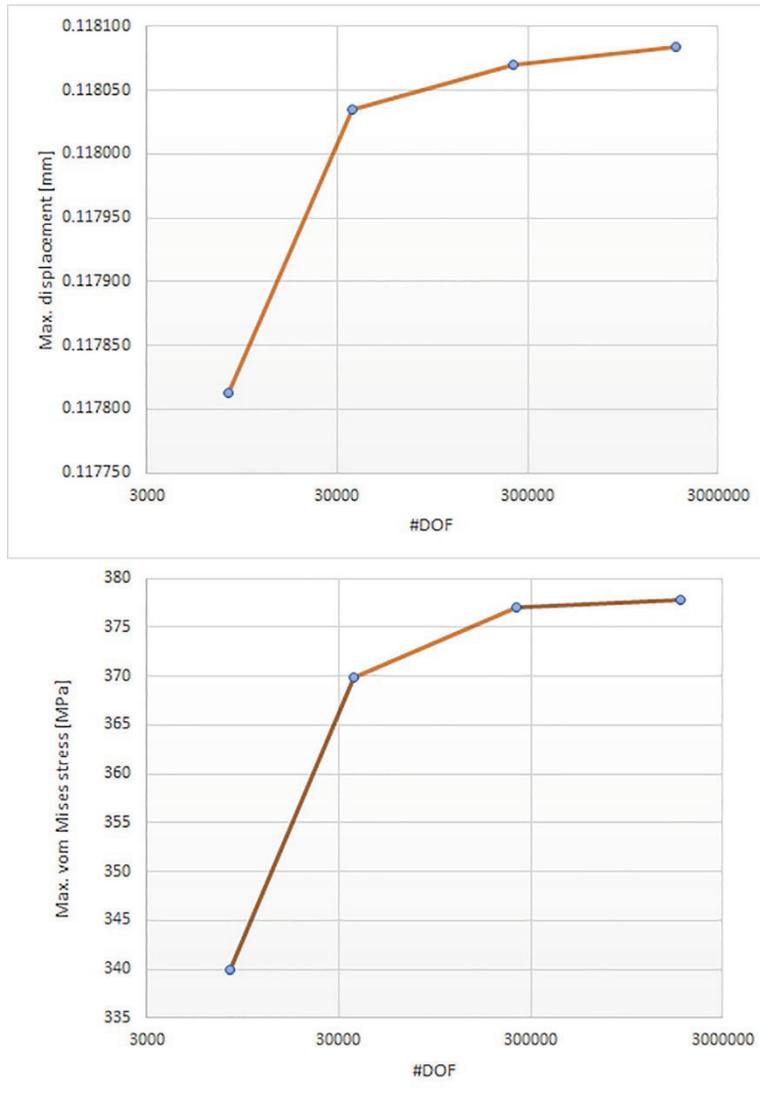


Figure 2-36: Max. displacement and max. von Mises stress as a function of the number of DOF.

Both curves are graphed as a function of the number of degrees of freedom in the model. The four points on the curves correspond to four models solved. Straight lines connect the four points only to visually enhance the graphs.

Having noted that the maximum displacement increases with mesh refinement, we can conclude that the model becomes “softer” when smaller elements are used. With mesh refinement, a larger number of elements allows for better approximation of the real displacement and stress field. Therefore, we can say that the artificial restraints imposed by element definition become less imposing with mesh refinement.

Displacements are the primary unknowns in structural FEA, and stresses are calculated based on displacement results. Therefore, stress also increases with mesh refinement. If we continued with mesh refinement, we would see that both the displacement and stress results converge to a finite value which is the solution of the mathematical model. Differences between the solution of the FEA model and the mathematical model are due to discretization errors, which diminish with mesh refinement.

We will now repeat our analysis of the HOLLOW PLATE by using prescribed displacements in place of a load. Rather than loading it with a 100000N force that caused a 0.118 mm displacement of the loaded face, we will apply a prescribed displacement of 0.118 mm to this face to see what stress it causes. For this exercise, we will use only one mesh with the default (medium) mesh density.

Define fifth study, called *prescribed displ.* The easiest way to do this is to copy one of the already completed studies, for example study *tensile load 02*. The definition of material properties, the fixed restraint to the left-side end-face and mesh are all identical to the previous design study. We need to delete the current **External Loads** (right-click the load icon and select **Delete**) and apply in its place a prescribed displacement.

To apply the prescribed displacement to the right-side end-face, right-click the **Fixtures** folder and select **Advanced Fixtures** from the pop-up menu. This opens the **Fixture** definition window. Select **On Flat Face** from the **Advanced** menu and define the displacement as shown in Figure 2-37. Check **Reverse direction** to obtain displacement in the tensile direction. Note that the direction of a prescribed displacement is indicated by a restraint symbol.

Prescribed displacement may also be defined from the **External Loads** folder by selecting **Prescribed Displacement** from the pop-up menu. This opens the same **Fixture** definition window. Figure 2-37 illustrates both methods of defining prescribed displacement.

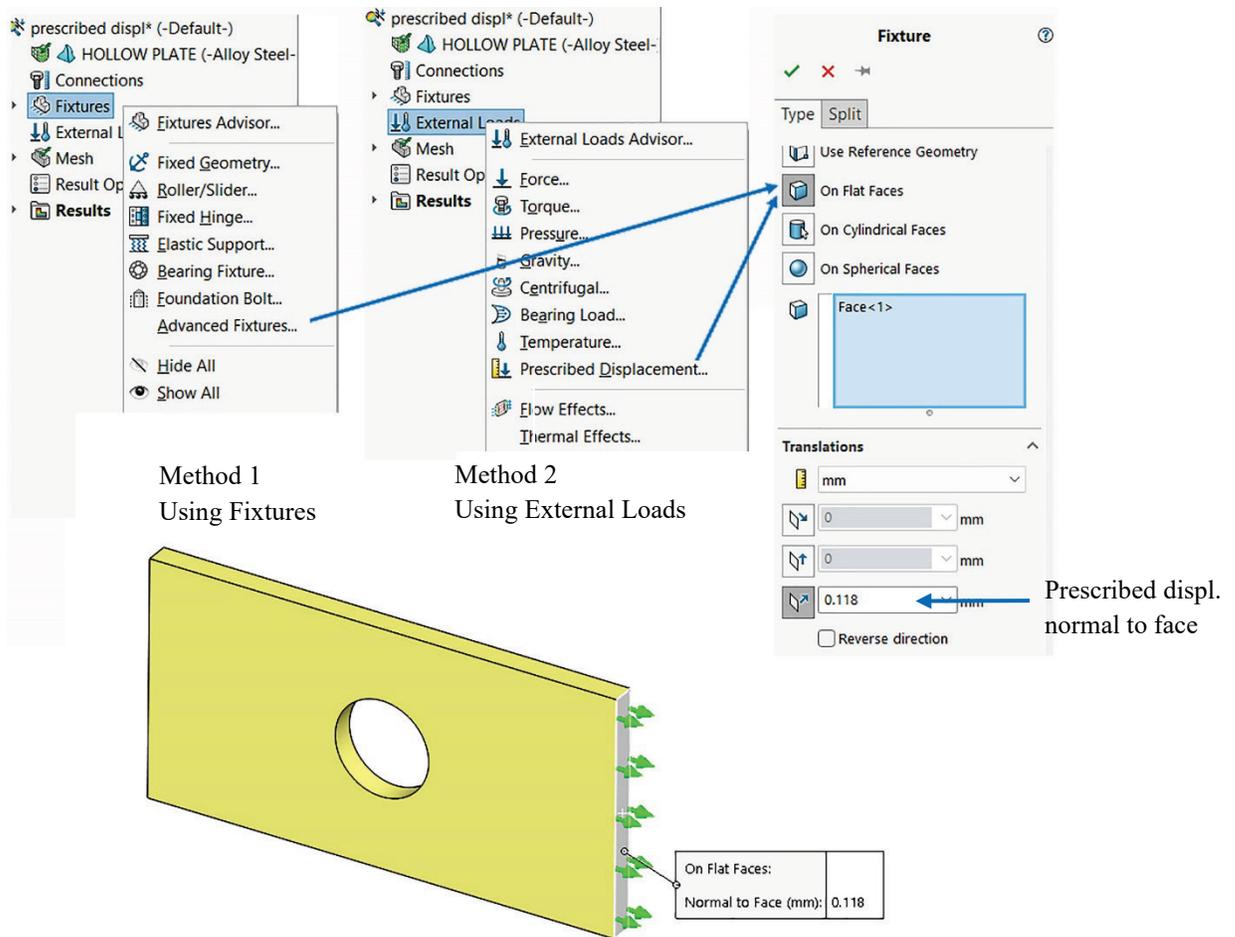


Figure 2-37: Two methods of defining prescribed displacement.

The prescribed displacement of 0.118 mm is applied to the same face where the tensile load of 100000N was applied in previous studies.

Verify that the arrows (shown here in black color) are pointed away from the selected face. Fixed restraints symbols on the other side are not shown.

Once again, note that the visibility of all loads and restraints symbols is controlled by right clicking the symbol and making the desired choice (**Hide/Show**). All load symbols and all restraint (fixture) symbols may also be turned on/off all at once by right clicking the **Fixtures** or **External loads** folders and selecting **Hide all/ Show all** from the pop-up menu.

Once a prescribed displacement is defined to the end face, it overrides any previously applied loads to the same end face. While it is better to delete the load to keep the model clean, a load has no effect if a prescribed displacement is applied to the same entity in the same direction.

Figure 2-38 compares stress results for the model loaded with force to the model loaded with prescribed displacement.

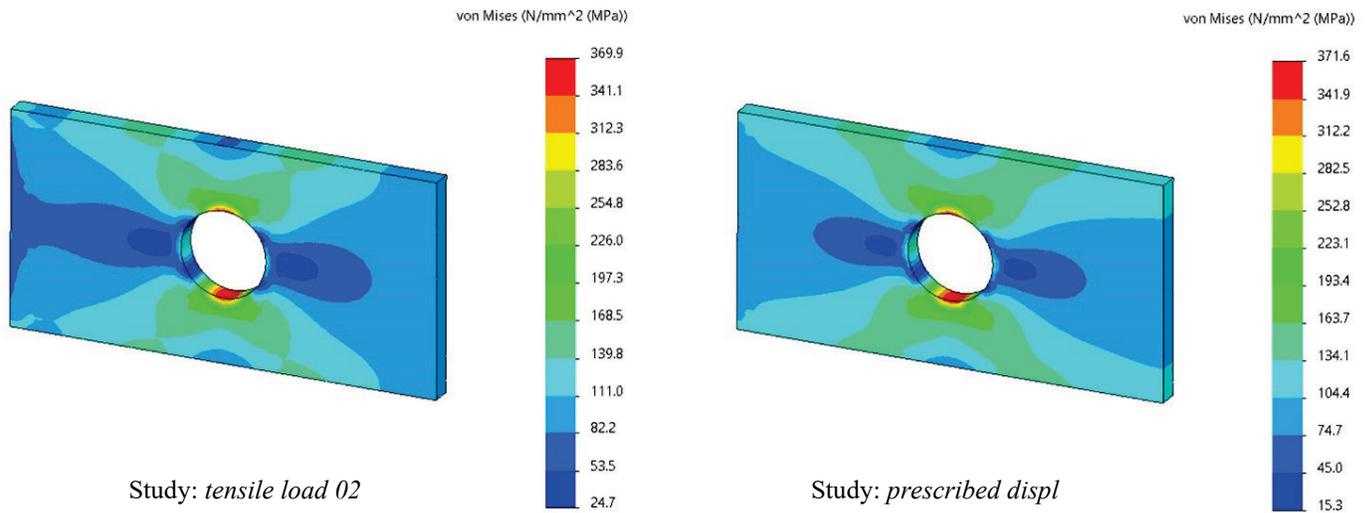


Figure 2-38: Comparison of von Mises stress results using force load and prescribed displacement load.

Von Mises stress results with a force load (left) and with a prescribed displacement (right).

Results produced by applying a force load and by applying a prescribed displacement load are similar but not identical. The reason for this discrepancy is that in the model loaded by force, the loaded face does not remain flat. In the prescribed displacement model, the face remains flat. Also, while the prescribed displacement of 0.118 mm applies to the entire face in the prescribed displacement model, it is only seen as the maximum displacement in one location in the model loaded by force. Plot the displacement along the edge of the end face in study *tensile load 02* by following the steps in Figure 2-39.

(1) Right-click the Displacement plot and select **List selected** to open the **Probe Result** window

(2) Select the edge on the loaded side to open **Probe Result** window

(3) Update

(4) Plot

Node	Value (mm)	X (mm)
8	1.151e-01	100.00000000
3485	1.153e-01	100.00000000
181	1.154e-01	100.00000000
10783	1.156e-01	100.00000000
182	1.158e-01	100.00000000
10565	1.160e-01	100.00000000
183	1.162e-01	100.00000000
12897	1.164e-01	100.00000000

Figure 2-39: Plotting displacement along the edge of the force loaded face in study *tensile load 02*.

Right click the resultant displacement plot in the tensile load 02 study to invoke a pop-up menu shown in the top left corner. Follow steps 1 through 4 to produce a graph of displacements along the loaded edge. Repeat this exercise for a model loaded with prescribed displacement to verify that the displacement is constant along the edge.

We conclude the analysis of the HOLLOW PLATE by examining the reaction forces using the results of study *tensile load 02*. In the study *tensile load 02*, right-click the *Results* folder. From the pop-up menu, select **List Result Force** to open the **Result Force** window. Select the face where the fixed restraint is applied and click the **Update** button. Information on reaction forces will be displayed as shown in Figure 2-40.

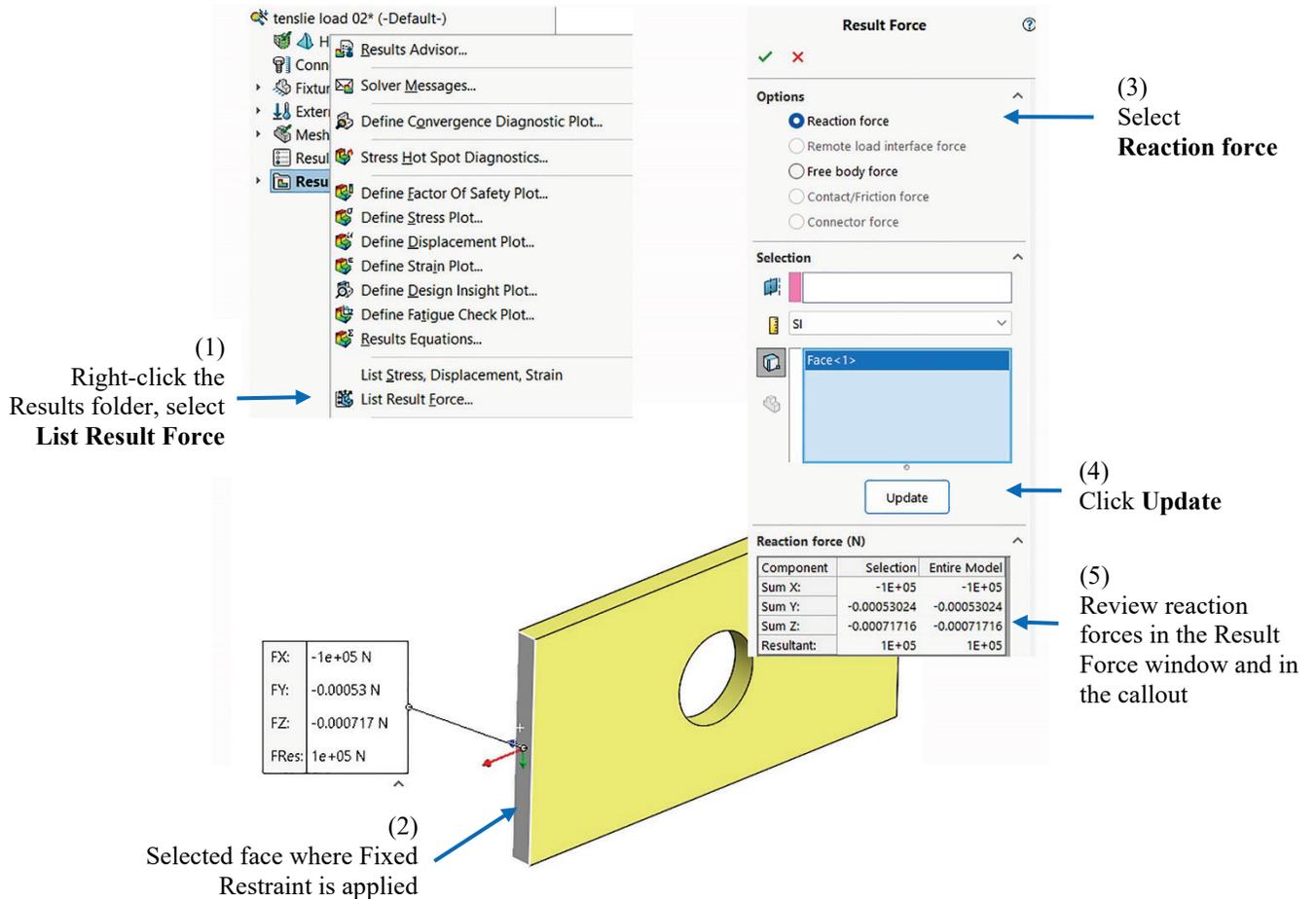


Figure 2-40: Result Force window.

Right-click the *Results* folder and follow steps 1 through 4 to analyze and display reaction forces. Reaction forces can also be displayed in components other than those defined by the global reference system. To do this, reference geometry such as a plane or axis must be selected.

A note on where **Simulation** results are stored: By default, mesh data and results of all studies are stored in files with extension CWR, separate from model but in the same folder. For example, results of study *tensile load 02* have been stored in the file: HOLLOW PLATE-tensile load 02.CWR. The location of CWR files is specified in the **Default Options** window (Figure 2-41). It is recommended to store CWR files separately from models.

When an already solved study is opened, the CWR file is extracted into several different files depending on the type of study. Upon exiting **SOLIDWORKS Simulation** (which is done by means of deselecting **Simulation** from the list of add-ins, or by closing the model), all files are compressed allowing for convenient backup of **Simulation** results.

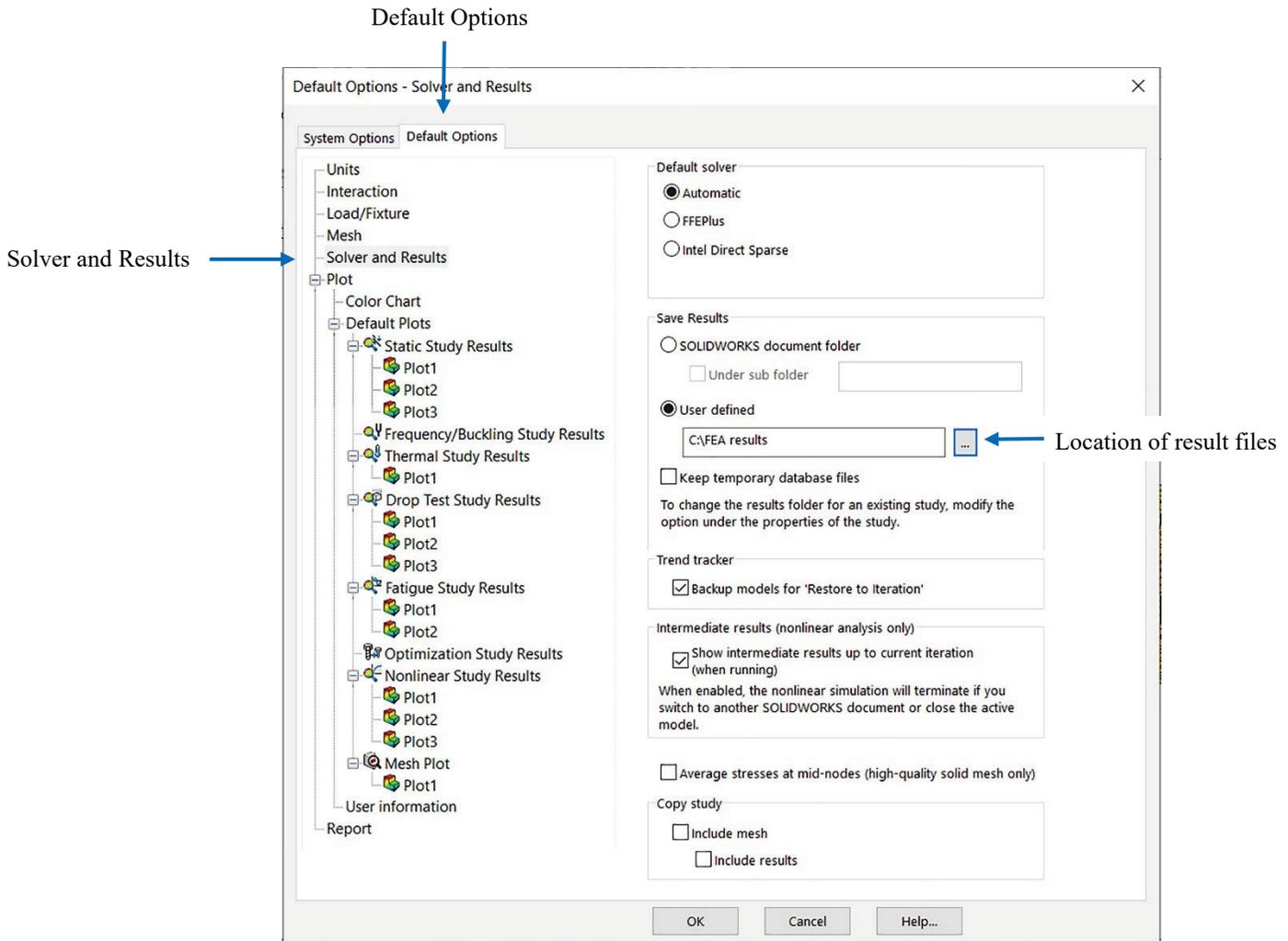


Figure 2-41: Location of solution files.

You may use the *SOLIDWORKS* document folder, or a user defined folder as shown here. Using the above settings the solution files will be in folder *C:\FEA results*.

Models in this chapter

Model	Configuration	Study Name	Study Type
HOLLOW PLATE.sldprt	<i>Default</i>	<i>tensile load 01</i>	Static
		<i>tensile load 02</i>	Static
		<i>tensile load 03</i>	Static
		<i>tensile load 04</i>	Static
		<i>prescribed displ</i>	Static

Notes: