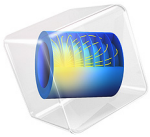


# Scordelis–Lo Roof Shell Benchmark

## *Introduction*

In the following example you build and solve a 3D shell model using the Shell interface. This example is a widely used benchmark model called the Scordelis–Lo roof. The computed maximum $z$-deformation is compared with the value given in Ref. 1.

## *Model Definition*

### GEOMETRY

The geometry consists of a curved face as shown in Figure 1. Only one quarter is analyzed due to symmetry.

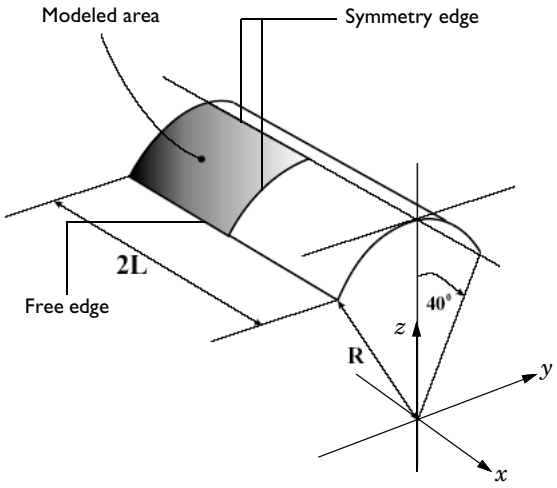



*Figure 1: The Scordelis-Lo roof shell benchmark geometry.*

- Roof length $2L = 50$ m
- Roof radius $R = 25$ m.

### MATERIAL

- Isotropic material with Young's modulus set to $E = 4.32 \cdot 10^8$ N/m$^2$.
- Poisson's ratio set to $\nu = 0.0$.

### CONSTRAINTS

- The outer straight edge is free.
- The outer curved edge is constrained against translation in the $y$ and $z$ directions.
- The straight edge on the top of the roof has symmetry edge constraints.
- The curved inner edge also has symmetry constraints.

### LOAD

A force per area unit of $-90$ N/m$^2$ in the $z$ direction is applied on the surface.

## *Results and Discussion*

The maximum deformation in the global $z$ direction with the default mesh settings is shown in Figure 2. The computed value is $-0.303$ m.

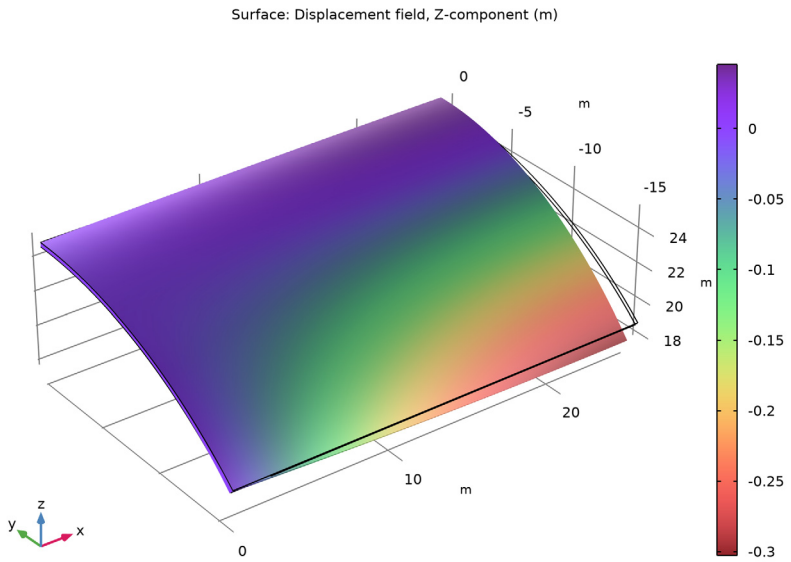



*Figure 2: z-displacement with 176 triangular elements.*

When changing to a mapped mesh, the more efficient quadrilateral elements are used. The result is $-0.301$ m as shown in Figure 3. With a very fine mesh, the value converges to $-0.302$ m, Figure 4. The reference solution quoted in Ref. 1 for the midside vertical displacement is $-0.3086$ m. The value $-0.302$ m is in fact observed in other published benchmark results treating this problem as the value that this problem converges toward.

A summary of the performance for different element types and mesh densities is given in Table 1. As can be seen, the results are good even with rather coarse meshes.

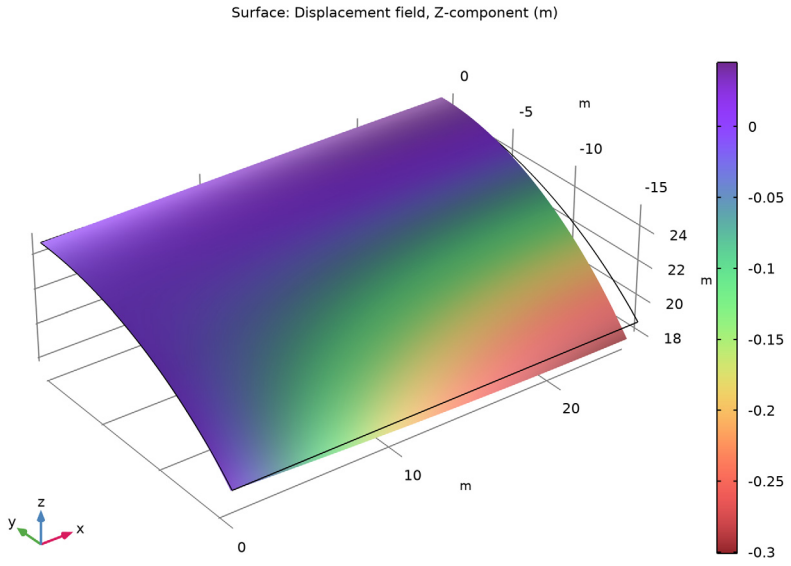



*Figure 3: z-displacement with 70 quadrilateral elements.*

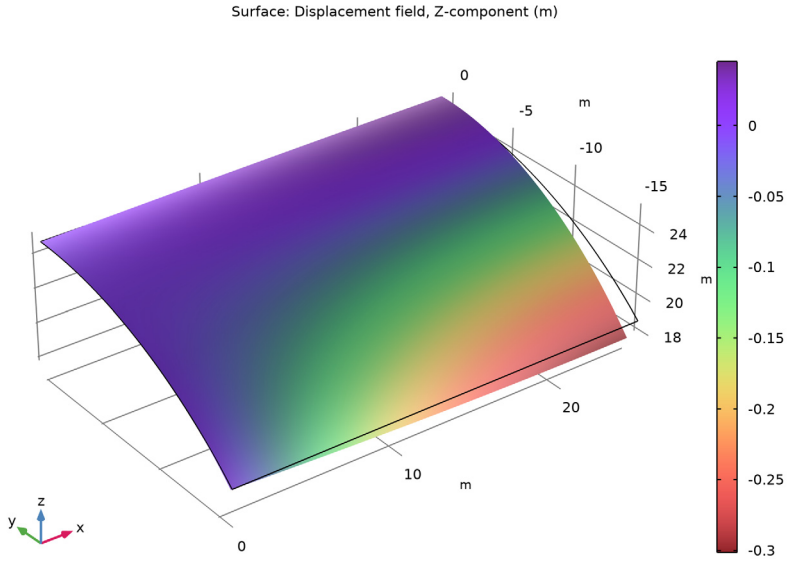



*Figure 4: z-displacement with 580 quadrilateral elements.*

TABLE 1: CONVERGENCE OF MIDPOINT VERTICAL DISPLACEMENT.

| MESH SIZE SETTING | ELEMENT TYPE | NUMBER OF ELEMENTS | MIDPOINT DISPLACEMENT |
|---|---|---|---|
| Coarser | Triangle | 64 | -0.304 |
| Coarser | Quadrilateral | 24 | -0.300 |
| Normal | Triangle | 176 | -0.303 |
| Normal | Quadrilateral | 70 | -0.301 |
| Extra fine | Triangle | 1384 | -0.302 |
| Extra fine | Quadrilateral | 580 | -0.301 |

## *Reference*

1. R.H. MacNeal and R.L. Harder, *Proposed Standard Set of Problems to Test Finite Element Accuracy*, Finite Elements in Analysis and Design, 1, 1985.

**Application Library path:** `Structural_Mechanics_Module/Verification_Examples/scordelis_lo_roof`

## *Modeling Instructions*

From the **File** menu, choose **New**.

### NEW

In the **New** window, click **Model Wizard**.

### MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Structural Mechanics>Shell (shell)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Stationary**.

6 Click **Done**.

### GEOMETRY 1

*Work Plane 1 (wp1)*

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, click **Go to Plane Geometry**.

*Work Plane 1 (wp1)>Plane Geometry*

In the **Model Builder** window, click **Plane Geometry**.

*Work Plane 1 (wp1)>Polygon 1 (pol1)*

1 In the **Work Plane** toolbar, click **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 In the table, enter the following settings:

| xw (m) | yw (m) |
|---|---|
| 0 | 25 |
| 25 | 25 |

4 Right-click **Polygon 1 (pol1)** and choose **Build All Objects**.

*Revolve 1 (rev1)*

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Work Plane 1 (wp1)** and choose **Revolve**.

2 In the **Settings** window for **Revolve**, locate the **Revolution Angles** section.

3 Click the **Angles** button.

4 In the **Start angle** text field, type `90`.

5 In the **End angle** text field, type `90+40`.

6 Locate the **Revolution Axis** section. Find the **Direction of revolution axis** subsection. In the **xw** text field, type `1`.

7 In the **yw** text field, type `0`.

8 Click **Build Selected**.

9 Click the **Zoom Extents** button in the **Graphics** toolbar.

*Form Union (fin)*

1 In the **Model Builder** window, click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, click **Build Selected**.

## SHELL (SHELL)

*Thickness and Offset 1*

1 In the **Model Builder** window, under **Component 1 (comp1)>Shell (shell)** click **Thickness and Offset 1**.

2 In the **Settings** window for **Thickness and Offset**, locate the **Thickness and Offset** section.

3 In the $d_0$ text field, type `0.25`.

*Symmetry 1*

1 In the **Physics** toolbar, click **Edges** and choose **Symmetry**.

2 Select Edges 3 and 4 only.

*Prescribed Displacement/Rotation 1*

1 In the **Physics** toolbar, click **Edges** and choose **Prescribed Displacement/Rotation**.

2 Select Edge 1 only.

3 In the **Settings** window for **Prescribed Displacement/Rotation**, locate the **Prescribed Displacement** section.

4 From the **Displacement in y direction** list, choose **Prescribed**.

5 From the **Displacement in z direction** list, choose **Prescribed**.

*Face Load 1*

1 In the **Physics** toolbar, click **Boundaries** and choose **Face Load**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Face Load**, locate the **Force** section.

4 Specify the $\mathbf{F}_A$ vector as

| | |
|---|---|
| 0 | x |
| 0 | y |
| -90 | z |

## MATERIALS

*Material 1 (mat1)*

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 In the table, enter the following settings:

| Property | Variable | Value | Unit | Property group |
|---|---|---|---|---|
| Young's modulus | E | 4.32e8 | Pa | Young's modulus and Poisson's ratio |
| Poisson's ratio | nu | 0 | 1 | Young's modulus and Poisson's ratio |
| Density | rho | 1 | kg/m³ | Basic |

## MESH 1

First, compute the results with the default triangular mesh.

*Free Triangular 1*

1 In the **Mesh** toolbar, click **More Generators** and choose **Free Triangular**.

2 In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **All boundaries**.

4 Click **Build All**.

## STUDY 1: TRI NORMAL

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Study 1: Tri Normal` in the **Label** text field.

3 In the **Home** toolbar, click **Compute**.

## RESULTS

*Vertical displacement*

In the **Settings** window for **3D Plot Group**, type `Vertical displacement` in the **Label** text field.

*Surface 1*

1 In the **Model Builder** window, expand the **Vertical displacement** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Shell> Displacement>Displacement field - m>w - Displacement field, Z-component**.

3 Locate the **Coloring and Style** section. Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Rainbow>SpectrumLight** in the tree.

5 Click **OK**.

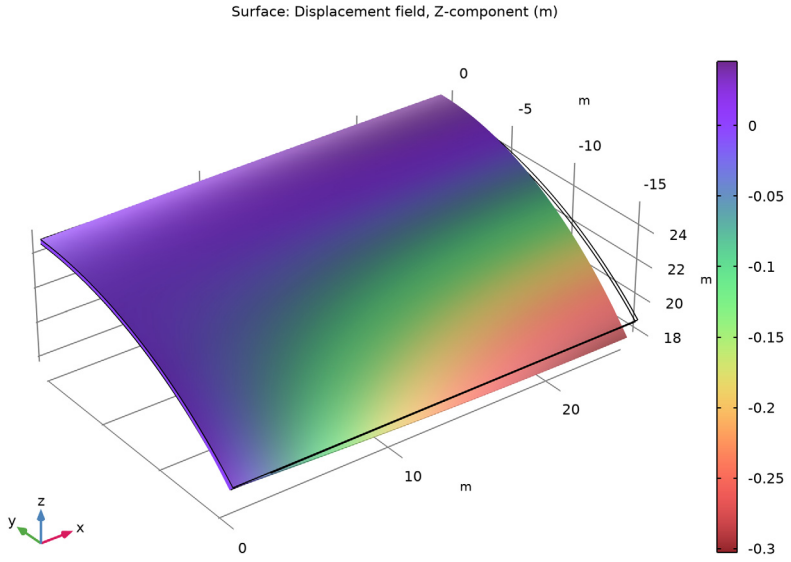
6 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

7 From the **Color table transformation** list, choose **Reverse**.

*Vertical displacement*

1 In the **Model Builder** window, click **Vertical displacement**.

2 In the **Vertical displacement** toolbar, click **Plot**.




*Tri Normal*

1 In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1: Tri Normal/Solution 1 (sol1)**.

2 In the **Settings** window for **Solution**, type `Tri Normal` in the **Label** text field.

Switch to the more effective quadrilateral mesh elements.

### TRI NORMAL

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, type `Tri Normal` in the **Label** text field.

### QUAD NORMAL

1 In the **Mesh** toolbar, click **Add Mesh** and choose **Add Mesh**.

2 In the **Settings** window for **Mesh**, type `Quad Normal` in the **Label** text field.

*Mapped 1*

1 In the **Mesh** toolbar, click **More Generators** and choose **Mapped**.

2 In the **Settings** window for **Mapped**, locate the **Boundary Selection** section.

3 From the **Geometric entity level** list, choose **Remaining**.

4 Click **Build All**.

### ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

### STUDY 2: QUAD NORMAL

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Study 2: Quad Normal` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

### RESULTS

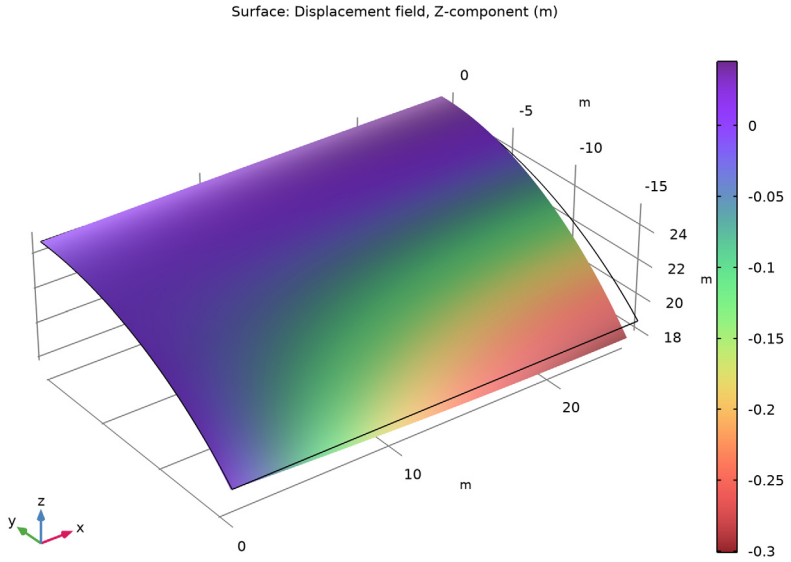
*Vertical displacement*

1 In the **Model Builder** window, under **Results** click **Vertical displacement**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2: Quad Normal/Solution 2 (sol2)**.

4 In the **Vertical displacement** toolbar, click **Plot**.




*Quad Normal*

1 In the **Model Builder** window, under **Results>Datasets** click **Study 2: Quad Normal/ Solution 2 (sol2)**.

2 In the **Settings** window for **Solution**, type `Quad Normal` in the **Label** text field.

Examine a well converged result with a fine quadrilateral mesh.

### QUAD NORMAL

In the **Model Builder** window, under **Component 1 (comp1)>Meshes** right-click **Quad Normal** and choose **Duplicate**.

### QUAD EXTRA FINE

1 In the **Model Builder** window, under **Component 1 (comp1)>Meshes** click **Quad Normal 1**.

2 In the **Settings** window for **Mesh**, type `Quad Extra fine` in the **Label** text field.

*Size*

1 In the **Model Builder** window, expand the **Quad Extra fine** node, then click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extra fine**.

4 Click **Build All**.

### ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

### STUDY 3: QUAD EXTRA FINE

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Study 3: Quad Extra fine` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

### RESULTS

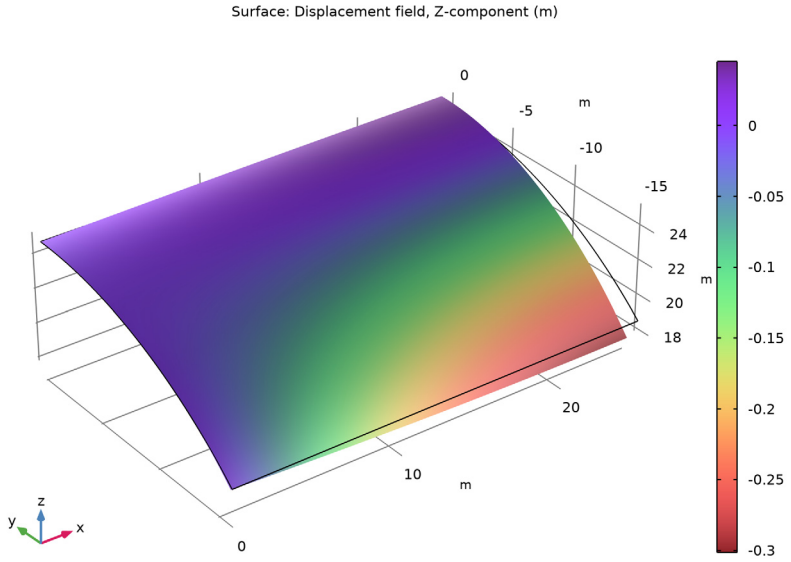
*Vertical displacement*

1 In the **Model Builder** window, under **Results** click **Vertical displacement**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3: Quad Extra fine/Solution 3 (sol3)**.

4 In the **Vertical displacement** toolbar, click **Plot**.




*Quad Extra fine*

1 In the **Model Builder** window, under **Results>Datasets** click **Study 3: Quad Extra fine/ Solution 3 (sol3)**.

2 In the **Settings** window for **Solution**, type `Quad Extra fine` in the **Label** text field.

Examine a well converged result with a triangular mesh.

### TRI NORMAL

In the **Model Builder** window, under **Component 1 (comp1)>Meshes** right-click **Tri Normal** and choose **Duplicate**.

### TRI EXTRA FINE

1 In the **Model Builder** window, under **Component 1 (comp1)>Meshes** click **Tri Normal 1**.

2 In the **Settings** window for **Mesh**, type `Tri Extra Fine` in the **Label** text field.

*Size*

1 In the **Model Builder** window, expand the **Tri Extra Fine** node, then click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extra fine**.

4 Click **Build All**.

### ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

### STUDY 4: TRI EXTRA FINE

1 In the **Model Builder** window, click **Study 4**.

2 In the **Settings** window for **Study**, type `Study 4: Tri Extra fine` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

### RESULTS

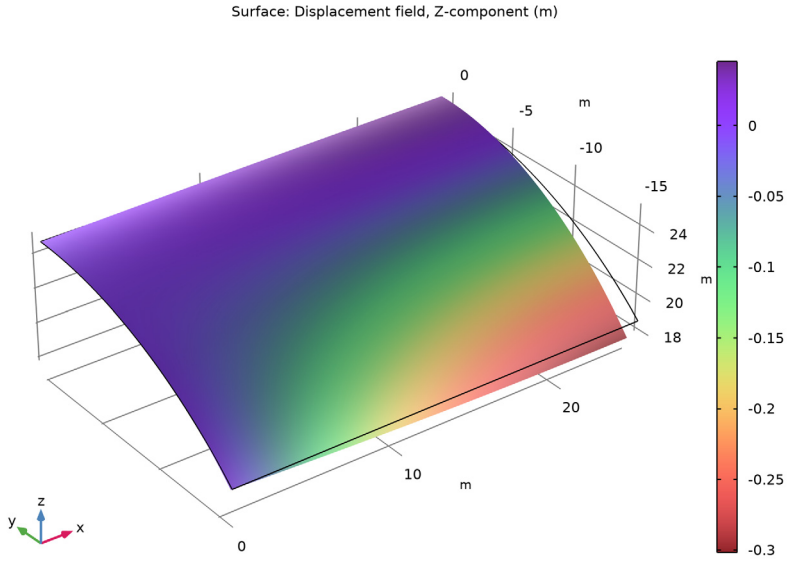
*Vertical displacement*

1 In the **Model Builder** window, under **Results** click **Vertical displacement**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 4: Tri Extra fine/Solution 4 (sol4)**.

4 In the **Vertical displacement** toolbar, click **Plot**.




*Tri Extra fine*

1 In the **Model Builder** window, under **Results>Datasets** click **Study 4: Tri Extra fine/ Solution 4 (sol4)**.

2 In the **Settings** window for **Solution**, type `Tri Extra fine` in the **Label** text field.

Investigate how well the elements perform with a very coarse mesh.

### TRI NORMAL

In the **Model Builder** window, under **Component 1 (comp1)>Meshes** right-click **Tri Normal** and choose **Duplicate**.

### TRI COARSER

1 In the **Model Builder** window, under **Component 1 (comp1)>Meshes** click **Tri Normal 1**.

2 In the **Settings** window for **Mesh**, type `Tri Coarser` in the **Label** text field.

*Size*

1 In the **Model Builder** window, expand the **Tri Coarser** node, then click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Coarser**.

4 Click **Build All**.

### ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

### STUDY 5: TRI COARSER

1 In the **Model Builder** window, click **Study 5**.

2 In the **Settings** window for **Study**, type `Study 5: Tri Coarser` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

### RESULTS

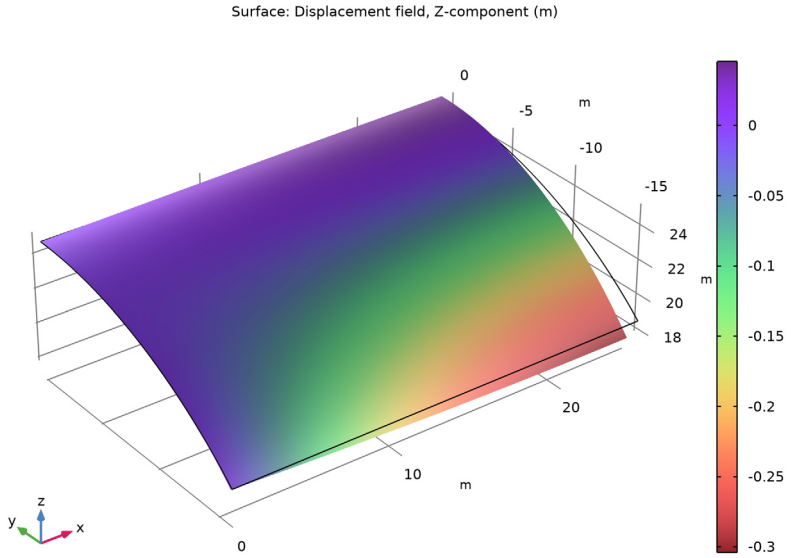
*Vertical displacement*

1 In the **Model Builder** window, under **Results** click **Vertical displacement**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 5: Tri Coarser/Solution 5 (sol5)**.

4 In the **Vertical displacement** toolbar, click **Plot**.




*Tri Coarser*

1 In the **Model Builder** window, under **Results>Datasets** click **Study 5: Tri Coarser/ Solution 5 (sol5)**.

2 In the **Settings** window for **Solution**, type `Tri Coarser` in the **Label** text field.

### QUAD NORMAL

In the **Model Builder** window, under **Component 1 (comp1)>Meshes** right-click **Quad Normal** and choose **Duplicate**.

### QUAD COARSER

1 In the **Model Builder** window, under **Component 1 (comp1)>Meshes** click **Quad Normal 1**.

2 In the **Settings** window for **Mesh**, type `Quad Coarser` in the **Label** text field.

*Size*

1 In the **Model Builder** window, expand the **Quad Coarser** node, then click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Coarser**.

### ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

### STUDY 6: QUAD COARSER

1 In the **Model Builder** window, click **Study 6**.

2 In the **Settings** window for **Study**, type `Study 6: Quad Coarser` in the **Label** text field.

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

4 In the **Home** toolbar, click **Compute**.

### RESULTS

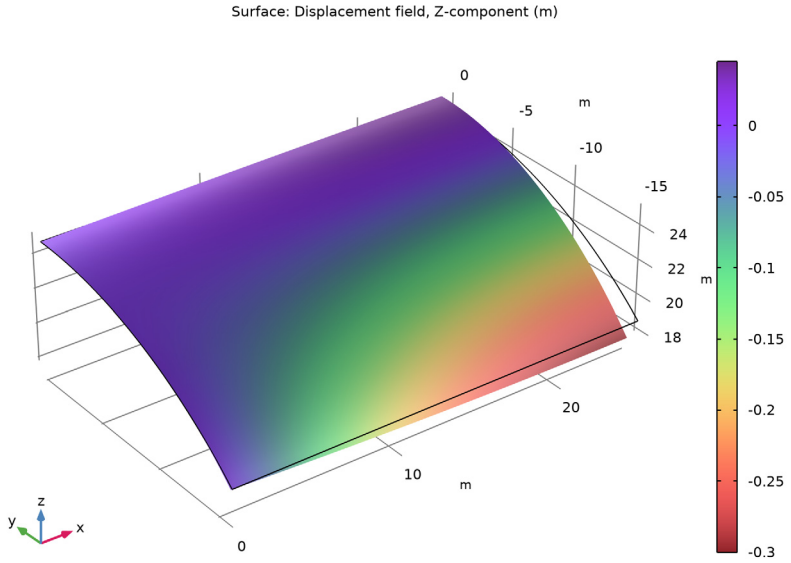
*Vertical displacement*

1 In the **Model Builder** window, under **Results** click **Vertical displacement**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 6: Quad Coarser/Solution 6 (sol6)**.

4 In the **Vertical displacement** toolbar, click **Plot**.




*Quad Coarser*

1 In the **Model Builder** window, under **Results>Datasets** click **Study 6: Quad Coarser/ Solution 6 (sol6)**.

2 In the **Settings** window for **Solution**, type `Quad Coarser` in the **Label** text field.

The following section compares the maximum deformation of the midpoint, in the vertical direction, for different element types and mesh densities.

*Point Evaluation 1*

1 In the **Results** toolbar, click **Point Evaluation**.

2 Select Point 3 only.

3 In the **Settings** window for **Point Evaluation**, locate the **Expressions** section.

4 In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Tri Normal |

5 Click **Evaluate**.

6 Right-click **Point Evaluation 1** and choose **Duplicate**.

*Point Evaluation 2*

1 In the **Model Builder** window, click **Point Evaluation 2**.

2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.

3 From the **Dataset** list, choose **Quad Normal (sol2)**.

4 Locate the **Expressions** section. In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Quad Normal |

5 Click ▼ next to = **Evaluate**, then choose **Table 1 - Point Evaluation 1**.

6 Right-click **Point Evaluation 2** and choose **Duplicate**.

*Point Evaluation 3*

1 In the **Model Builder** window, click **Point Evaluation 3**.

2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.

3 From the **Dataset** list, choose **Quad Extra fine (sol3)**.

4 Locate the **Expressions** section. In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Quad Extra fine |

5 Click ▼ next to = **Evaluate**, then choose **Table 1 - Point Evaluation 1**.

6 Right-click **Point Evaluation 3** and choose **Duplicate**.

*Point Evaluation 4*

1 In the **Model Builder** window, click **Point Evaluation 4**.

2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.

3 From the **Dataset** list, choose **Tri Extra fine (sol4)**.

4 Locate the **Expressions** section. In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Tri Extra fine |

5 Click ▼ next to = **Evaluate**, then choose **Table 1 - Point Evaluation 1**.

6 Right-click **Point Evaluation 4** and choose **Duplicate**.

*Point Evaluation 5*

1 In the **Model Builder** window, click **Point Evaluation 5**.

2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.

3 From the **Dataset** list, choose **Tri Coarser (sol5)**.

4 Locate the **Expressions** section. In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Tri Coarser |

5 Click ▼ next to = **Evaluate**, then choose **Table 1 - Point Evaluation 1**.

6 Right-click **Point Evaluation 5** and choose **Duplicate**.

*Point Evaluation 6*

1 In the **Model Builder** window, click **Point Evaluation 6**.

2 In the **Settings** window for **Point Evaluation**, locate the **Data** section.

3 From the **Dataset** list, choose **Quad Coarser (sol6)**.

4 Locate the **Expressions** section. In the table, enter the following settings:

| Expression | Unit | Description |
|---|---|---|
| w | m | Midpoint displacement, Quad Coarser |

5 Click ▼ next to = **Evaluate**, then choose **Table 1 - Point Evaluation 1**.