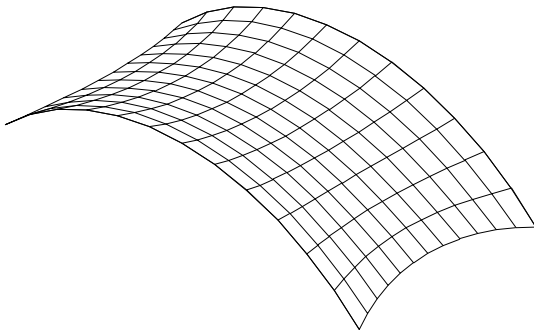


## Applying FEA to a tensile structure (Imperial)

The starting point for any FEA analysis is a good understanding of what results we expect. This can be from prior experience with similar structures, or by an estimate of the stresses. Then we can use the FEA to get more exact figures for the deflections and stresses, whilst using our broad picture of what the results should be as a reality check on the FEA results.

So first we will describe how a tensile structure reacts to loads, and then run through an estimation of the expected loads, and then look at an example of using FEA on a simple structure.

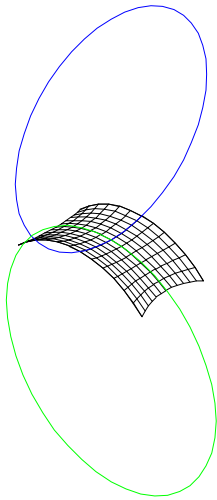


We will use a simple 120”by 240” barrel vault roof, between two arch supports, with cables on the bottom ends, as our model for this discussion.

The AutoCAD drawing this note was based on is also attached, called "Applying FEA Imp".

/cont

## How we expect a tensile structure to react to loads



A tensile structure's shape is maintained by the balance of two hoop stresses along the principle directions of curvature, shown in Blue and Green in the drawing.

These hoop stresses are the result of pre stressing the structure, using compensation, and of the structures shape, which determines the two hoop radii.

As loads are applied by wind suction, snow load, etc, they cause one of the hoop stresses to increase, and the other to decrease. (This change in stress will stretch or shrink the material, giving a different structural shape, but that's a further complication).

At some load value the structure will loose all hoop tension in one direction, and will then behave locally as an inflated structure. This can be the point where large deflections start.

So the pre-stress value is the main value that determines how the structure reacts to loads.

A high pre stress gives a stiff structure that will resist applied loads with low defections, but will need a strong material and supporting structure.

A low pre stress gives a structure that will deflect more with loads, but can be built with a weaker material and supporting structure.

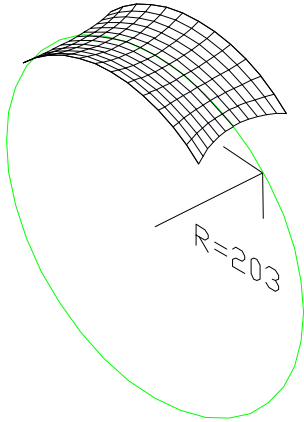
As a tensile structure, an external load will increase the fabric stress in one direction, and reduce it in the other.

Above a critical load, part or all of the structure will loose pre stress, and become an inflated structure, at least locally.

## Estimating Structural Stresses

An estimate of the pre-stress needed to cope with an applied pressure, with the membrane just about to go slack in one direction, can be obtained from the cylinder stress equation:

$$\text{Skin Stress} = \text{Hoop Radius} * \text{Pressure.}$$



So looking at the barrel vault shown,

applying a suction of 0.04 psi  
(equivalent to 45mph wind at CP=1)

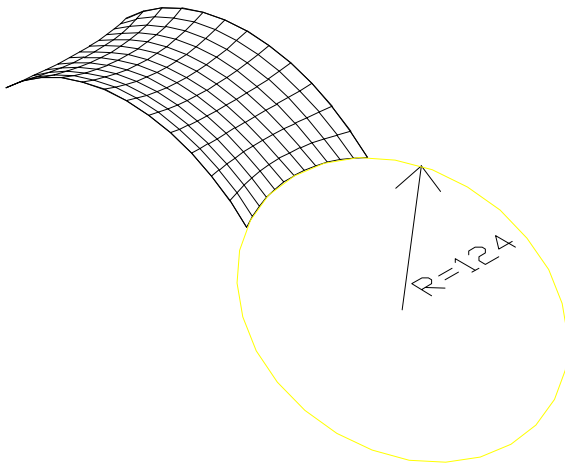
with a hoop radius of 203 inches in the hoop that will be  
withstanding suction,

giving a required pre-stress of approximately 8 lbs/inch.

Above this loading we would expect parts of the structure to become inflated, with larger deflections.

We can estimate the cable tension from the equation:

$$\text{Cable Tension} = \text{Skin Stress} * \text{Catenary Radius}$$



For the prestress case we have a skin stress  
of 8 lbs/inch

Catenary radius of 124 inches.

giving a Cable tension of 992 lbs

The main structural reactions will be at the corners from the cable, plus a distributed load on the supporting frame from the membrane stress. These can easily be calculated.

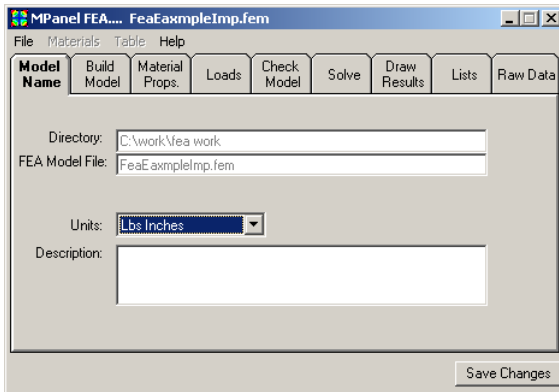
Note: the mesh hoop radiuses, and the catenary radius, can be obtained from the drawing as shown, or MPanel will report them by using the Info button on the mesh and on a 3Dpoly representing the edge cable.

/cont

## Running an FEA Analysis.

The FEA Interface program is organised as a series of Tabs. To run an analysis you go through the tabs in order

### Model Name

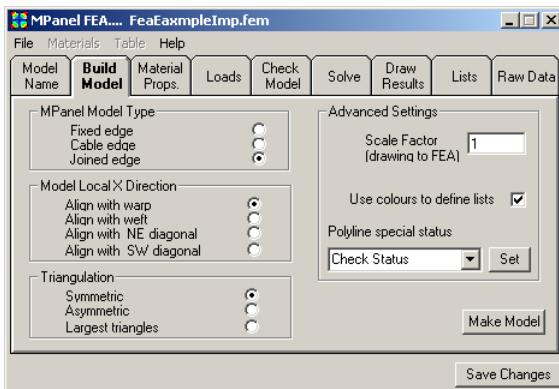


First we open the FEA Interface, and choose a file name. This will set the filename for the model file and the output file.

Also we choose a units system. This will start us off with some sensible default values. Here we choose to work in Lbs and Inches.

It is important to note that the AutoCAD model must be drawn in the units that have been specified in the FEA. This model is a 120 inch by 240 inch model. If it was drawn in feet, as a 10ft by 20ft model, then the FEA would read it as a 10 inch by 20 inch model. You may have to scale your AutoCAD model to suit.

### Build Model

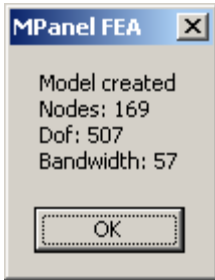


The model definition is the same as an MPanel model, and on model with some cable edges all fixed points must be specified with a 3D poly.

This is not an problem as we have the 3Dpolys defining the framework already in the drawing.

The FEA model will output the stress results in terms of a localX and localY direction. Usually we want the localX to align with the model warp, so we select this option.

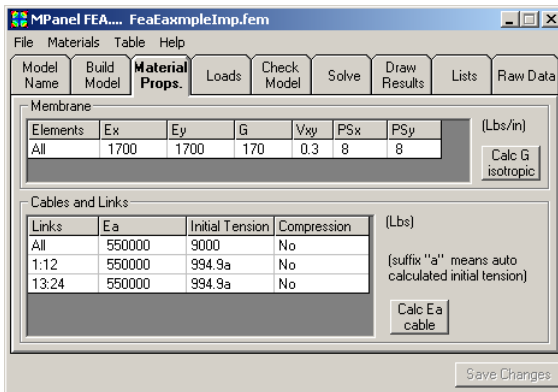
Then we select the model in AutoCAD, and make the model.



This window reports on the model build. The Bandwidth is an indication of how big the model looks to the FEA. Above a bandwidth of 150 the FEA solving becomes quite slow. But in this case it is just fine.

At this point the model file .fem is written to the disk.

## Material Properties



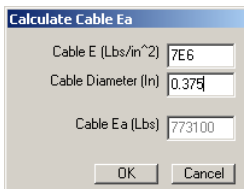
We start out with the default values that will be roughly correct for the unit system shown.

And then we alter the figures to suit our model case more exactly.

Ex and Ey are the stiffness values for the material, once it is pre stressed to the expected working stress. This value can be obtained from the fabric manufacturer, or from fabric tests, or from experience with similar materials.

Vxy is the Poisson ratio, which in a fabric is related to the crimp interchange. Values between 0 and 0.5 are suitable.

G is the shear stiffness value. On a loose weave fabric this may be close to zero, on a film it would be close to half the E value. This figure could be obtained from the manufacturer, or measured, but is often estimated as 10% of the E value.



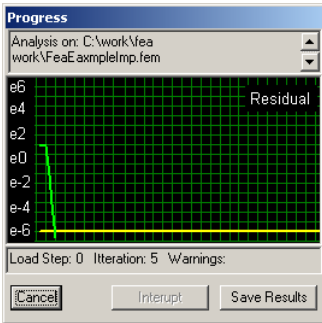
Ea is the cable effective E value. This is calculated from the cable area and the cable E, or it may be known from previous work. A calculator for Ea is provided, and is shown here with a 3/8 inch cable.

We change the Membrane pre stress values to the 8 lbs/inch that we choose earlier.



In a simple structure like this they will be pretty close to the final values, but in more complicated structures the model will have to move to achieve a pre stress balance.

So we make sure we are solving for load case 0. Then we run the solver.



This is the solver progress window.

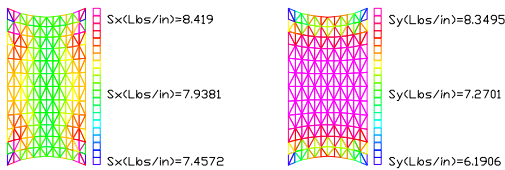
The green line is the graph of the residual.

The residual is a measure of how far the model is out of force balance. Typically when this figure is less than  $1E-3$  the model is pretty well force balanced, and the results are valid.

We have specified  $1E-6$  to make sure of the result.

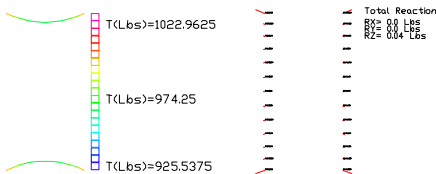
So now you click on Save Results, and an output file is written with the stress and displacement results.

## Draw Results



So now we plot out the results from the output file, to check the pre stress load case.

We will look at  $S_x$ ,  $S_y$ , the cable tension, and the reactions.



The model has adjusted the stresses a little to get a pre stress force balance.

$S_x$  values are all close to the initial pre stress of 8 lbs

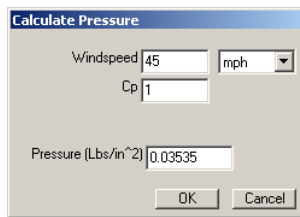
$S_y$  varies more, with the lowest figures near the cable corners, a difficult area to model.

The Cable tension agrees well with the estimate of 992 lbs

The reactions all look correct, and in particular the total reaction is zero. The total reaction should equal the total external load, so its value gives a good check that the solution was valid.

## Loads

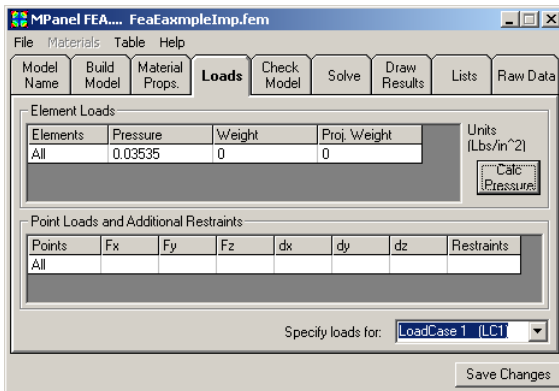
Now we will look at some load cases. First we look at the suction load caused by a 45mph wind.



The 'Calculate Pressure' dialog box is shown. It has a title bar 'Calculate Pressure'. Inside, there are three input fields: 'Windspeed' with the value '45' and a unit dropdown set to 'mph'; 'Cp' with the value '1'; and 'Pressure (Lbs/in^2)' with the value '0.03535'. At the bottom are 'OK' and 'Cancel' buttons.

The pressure calculator works out the pressure that 45 mph will apply, in the correct units, for a given coefficient of pressure. In this case it is 0.035 psi.

The coefficient of pressure to use may be specified in local building codes, or may be known from wind tunnel tests. A value of 1 is probably conservative.

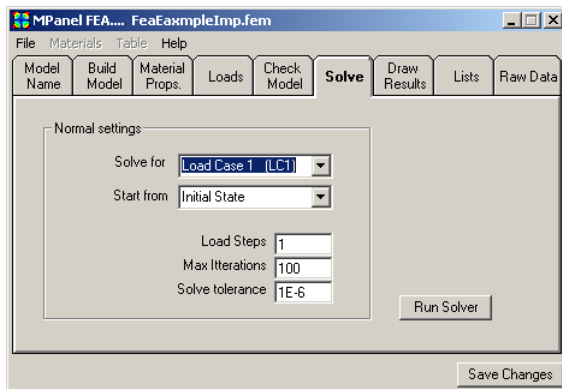


The 'MPanel FEA... FeaExampleImp.fem' dialog box is shown. It has a title bar and a menu bar (File, Materials, Table, Help). Below the menu bar are several tabs: Model Name, Build Model, Material Props., Loads, Check Model, Solve, Draw Results, Lists, and Raw Data. The 'Loads' tab is active. It contains two tables. The first table is 'Element Loads' with columns: Elements, Pressure, Weight, Proj. Weight, and Units (Lbs/in^2). The row for 'All' elements shows Pressure: 0.03535, Weight: 0, and Proj. Weight: 0. There is a 'Calc Pressure' button to the right of this table. The second table is 'Point Loads and Additional Restraints' with columns: Points, Fx, Fy, Fz, dx, dy, dz, and Restraints. The row for 'All' points is empty. At the bottom, there is a dropdown menu 'Specify loads for:' set to 'LoadCase 1 (LC1)' and a 'Save Changes' button.

The value is entered in the pressure column, and applied to All elements.

(You can also apply to just part of the structure, but that's a more advanced analysis).

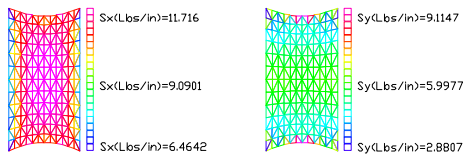
This is defining Load Case 1.



The 'MPanel FEA... FeaExampleImp.fem' dialog box is shown, now with the 'Solve' tab active. It has a title bar and a menu bar (File, Materials, Table, Help). Below the menu bar are several tabs: Model Name, Build Model, Material Props., Loads, Check Model, Solve, Draw Results, Lists, and Raw Data. The 'Solve' tab is active. It contains a section 'Normal settings' with a dropdown menu 'Solve for:' set to 'Load Case 1 (LC1)', a dropdown menu 'Start from:' set to 'Initial State', and three input fields: 'Load Steps' with the value '1', 'Max Iterations' with the value '100', and 'Solve tolerance' with the value '1E-6'. There is a 'Run Solver' button and a 'Save Changes' button at the bottom.

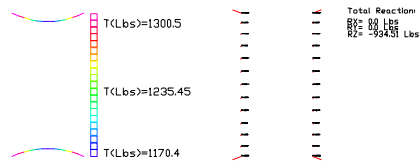
Then we solve in the same manner as before, except that now we solve for load case 1.

Now we can look at the results for this load case.



The  $S_x$  has increased, and the  $S_y$  decreased, as expected.

The membrane is still in tension, but the  $S_y$  is dropping down close to zero.

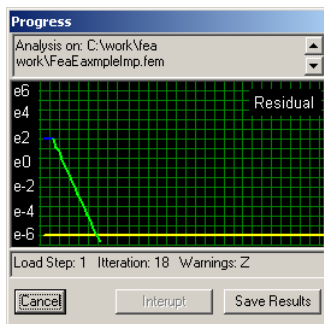


The cable tensions have increased, and the reactions now show a resultant force in Z, which will equal the projected area times the applied pressure.

There is zero X and Y reactions as the model is symmetrical.

## Load Case 2

Now let's change the pressure load to 0.074 psi, equivalent to 65 mph wind suction, save the changes, and run the solver as before. We called this load case 2.



Now the solution has some warnings.

The Blue graph line indicates large displacements, with some damping being applied.

The Z warning means zero stress in some elements.

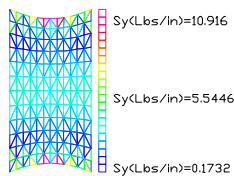
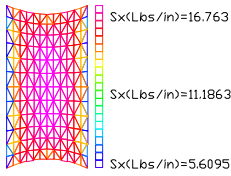
In these situations the model takes more iterations to solve.

Usually allowing enough iterations will get a solution.

In some cases we need to split the load into several smaller load steps to get a solution.

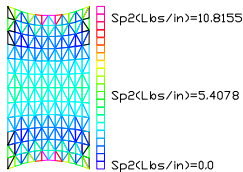
And in some combinations of loads and properties, the model will not solve... the residual will not come down to our desired figure of  $1E-6$ .

But in this case we have a valid solution as the residual has come down to  $1E-6$



Now the  $S_y$  is close to zero on much of the structure.

The elements that have gone slack are best shown up by plotting the Second Principle stress.



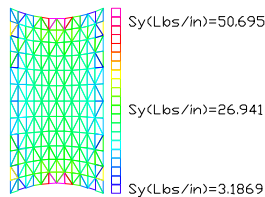
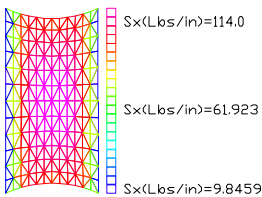
FeoExampleImp.fem  
 Element: 20  
 Node: 10  
 Pressure: 0.7  
 Pressure: 0.7  
 Pressure: 0.7

This is the lowest stress in the element, irrespective of direction, and the slack fabric is marked in white/black. This will be wrinkled fabric.

### Load Case 3

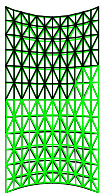
Lets now go to an extreme case, and look at loading the structure to 0.7 psi. This is equivalent to a wind of 200 mph.

There is no real requirement to solve at this high a pressure, but it is instructive to see what happens to the model.



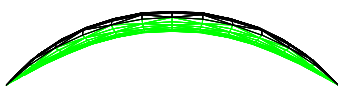
Now the  $S_x$  and the  $S_y$  are both increasing, although some areas of the model still have slack fabric.

To see what is happening we plot out the displaced shape twice, with a scale factor of 1 in white/black, and with a scale factor of zero in green.

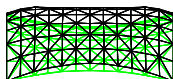


FeoExampleImp.fem  
 Element: 20  
 Node: 10  
 Pressure: 0.7  
 Pressure: 0.7  
 Pressure: 0.7

This gives us a comparison between the displaced shape and the original shape.



Looking closer at the displaced shape, in side and front views, we can see that under this extreme loading the membrane has completely inverted, and is now operating as an inflated structure.



Under more normal loading, just parts of the structure may invert, but this illustrates an extreme case.