

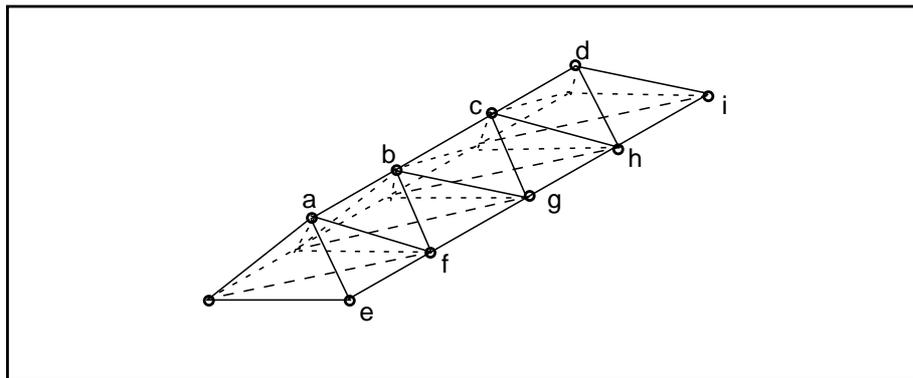
## 1.105 Solid Mechanics Laboratory Fall 2003

### Experiment 4 The linear, elastic behavior of a Truss.

The objectives of this experiment are

- To study the linear elastic behavior of a truss structure; to measure the structure's stiffness at two nodes.
- To compare measurement with theoretical prediction; in particular, to explore how behavior deviates from a frictionless pinned structure.
- To introduce the strain gage, the bridge circuit and its function, the op amp and its necessity, and the sensitivity of the instrumentation to temperature drift and other "disturbances".

The truss shown will be supported at its four corners and loaded at mid span. Two dial gages will be used to measure nodal displacements in the vertical direction. The strain gage instrumentation will measure the strain, and hence the load, in one member of the truss.



### Experiment Procedure

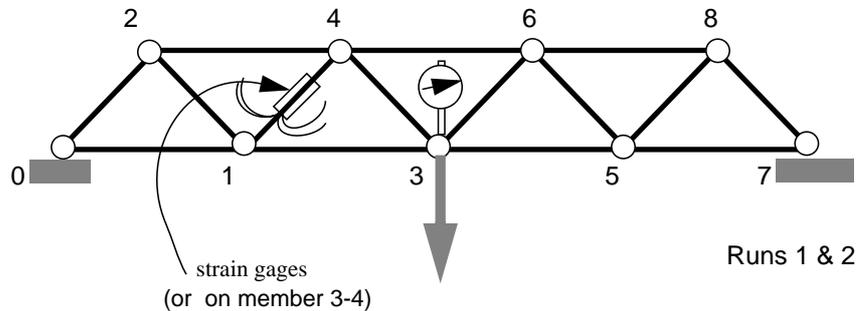
Measure all relevant dimensions of the structure. In this, envision the joints as frictionless pins located at the intersections of the members.

Make sure the structure rests on all four support points. Adjust one of the adjustment screws at the four corners if necessary to eliminate rocking.

The bucket should be suspended by an S hook slung on the chain and centering mechanism below the mid span nodes. Load the bucket up to, but do not exceed, 60 lbs.

Make sure you include a stop to limit excessive vertical displacement at the mid span nodes in case a member or joint fails. This should not be the case but we want to make sure we do not render the truss unusable in the future.

You will make two runs with the truss loaded at the center nodes. The figure shows the test set-up.



## Instrumentation Preparation

### Dial Gages

Two dial gages should be positioned to measure the vertical displacement of the two mid span nodes. Make sure the stands which support the gages are held fast against the bench by loading down their bases with the weights provided.

Do not try to zero the gage. Record your initial, no load (with bucket and chain attached) reading then, as you load, the subsequent readings. Leave the calculation of actual nodal displacements to later.

### Strain gage/op amp

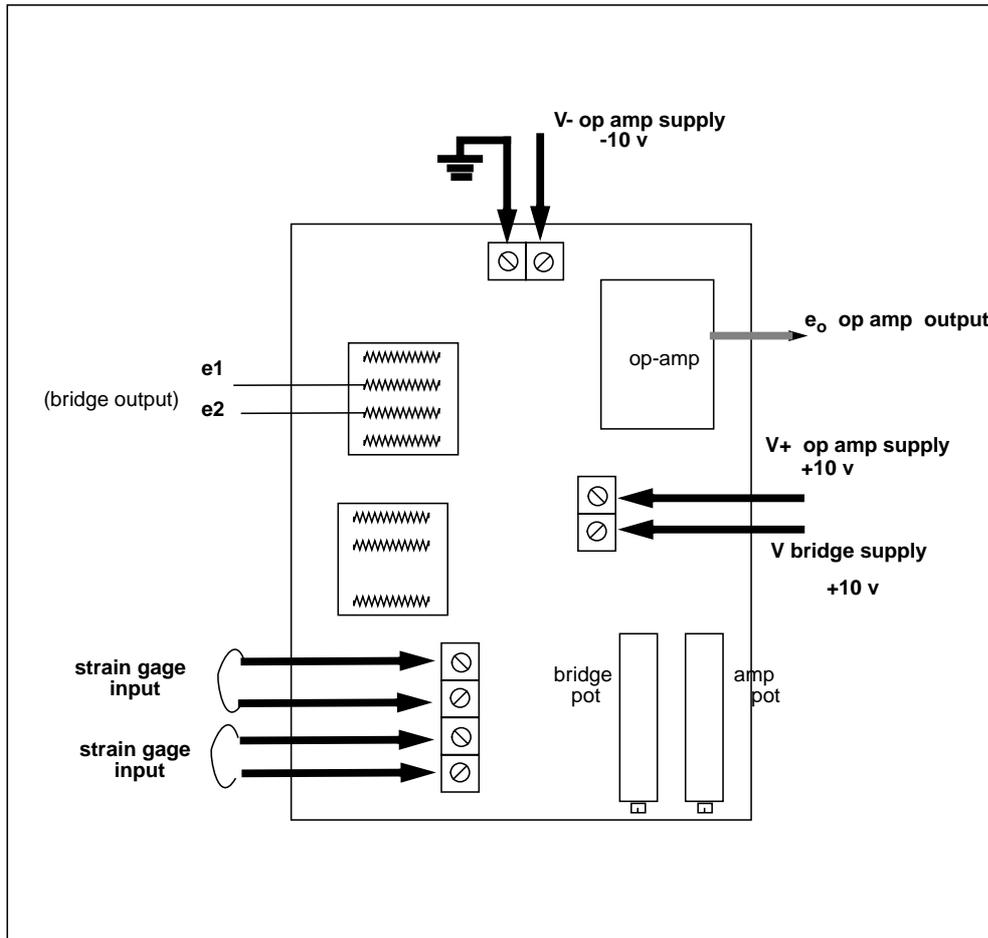
The measurement of the strain - hence the stress, hence the load - in a member is done using a strain gage - a physically small foil, electrical resistance fixed firmly to the member. As the member stretches (or contracts) the resistance increases (or decreases) a small amount. Actually two gages are used on one member to double the sensitivity.

An appendix describes the "bridge circuit" used to obtain a millivolt signal for a change in resistance of .01% and less!

Still the signal must be amplified. The circuit includes then an "op-amp" with a gain which you will measure.

The figure below shows the layout of the components, including the strain gage input terminals, the power supply input terminals, the (internal) bridge output points, and the op-amp output lead

wire. A variable resistance, a potentiometer for "balancing" the strain gage bridge is found lower



right; another for nulling the amplifier output is just to the right.

With the power supply **disconnected**, set the output of the +20v supply to positive one ( +1) volt, or some small amount. The -20v supply output terminal should then read minus one volt.

Connect the strain gage leads to the input terminals on the circuit board. The polarity doesn't matter nor does it matter which gage you connect to the top two terminals, which to the bottom two.

**Turn the power supply off** and connect the positive 20v supply terminal to both the V+ op amp supply and the V bridge supply. Use a short jumper wire at the circuit board input terminals to avoid stringing two leads.

Connect the "common" terminal of the power supply to the ground terminal of the circuit board. Connect the negative 20v supply terminal to the V- op amp supply terminal on the circuit board.

Check that you have the positive 20v supply going to the +10v op amp supply and the negative 20v supply going to the -10v op amp supply.

Turn on the power supply and adjust the +20v supply to +10 volts. NOTE: If you experience intolerable drift in bridge output signal due to temperature variations of the bridge resistors, you may reduce your supply voltage to reduce current flows, hence, to reduce heat generation ( $I^2R$ ), hence to reduce temperature changes.

Connect the ground of the digital multimeter to the ground on the board. Measure the voltages at the strain gage input terminals. Do they conform to what you expect?

Connect the digital multi meter to the bridge output terminals and balance the bridge using the potentiometer. Make sure you end up on the dc millivolt scale.

Connect the digital multimeter ground to ground on the board. (Any point will do). Measure the output of the op amp and using the op amp potentiometer, null the output of the amplifier.

Now generate an input to the op amp by offsetting the balance of the bridge until the output of the amplifier reads 400 mv. Using the multimeter, measure the output of the bridge and calculate the gain of the amplifier. Repeat this several times at different amplifier outputs.

Balance the bridge.

Check op-amp null.

Connect the digital multimeter to measure op-amp output. You are now ready to load the structure.

## Report

Start with a one paragraph executive summary of the purpose, the method, the results of the lab tests.

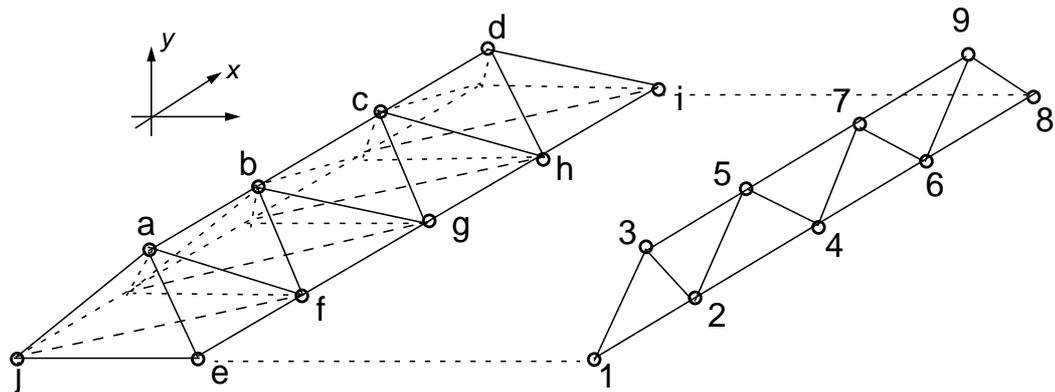
Include a short section on experiment procedure which, rather than reproduce the steps set out above, describes the method in your own words, making note of any particular difficulties you encountered and how you managed to overcome them. *Included in this section your op-amp calibration data and your calculation of amplifier gain.*

In your section on "results", you will compare experiment with theory. "Theory" includes:

- the results of a two-dimensional, matrix analysis of the structure, modeled as a truss. *You are to do the truss matrix analysis using Trussworks.* Please use the node numbering scheme shown in the figure on page 2, above. See comments on next page for instructions.
- the results of a two-dimensional matrix analysis of the structure modeled as a space frame made up of beam elements rigidly connected at the nodes. *The space frame matrix analysis is included in an appendix.*
- the results of a *fully three dimensional* matrix analysis of the structure using "Trussworks 3D". *This analysis is included in the appendix.* Note that distances were input 10 times actual (a work-around of a deficiency in the program) but this was compensated for by setting member area to be 10 times actual.

Re: constructing a two-dimensional truss model W

We showed in class how we might model the three-dimensional structure as a planar truss. In this, we fix the cross sectional area of the diagonal members, 1,3; 2,3; 4,5; etc. so that the stiffness of the top node, e.g., #3, in the x and y directions, is identical to that of node a in the fully three dimensional structure.



If we let  $A_{3d}$  be the Area of the 3D truss members, then for equivalence

$$A_{\text{diag-2d}} = 1.089 A_{3d}$$

In the same way we attempt to replicate the stiffness of the bottom members of the 3D structure in the horizontal direction by adjusting the cross sectional area of members 1,2; 2,4; ...etc. We found we should set

$$A_{\text{bot-2d}} = 2.35 A_{3d}$$

With these, you are to carry out a planar analysis of the truss.

Include then in your results:

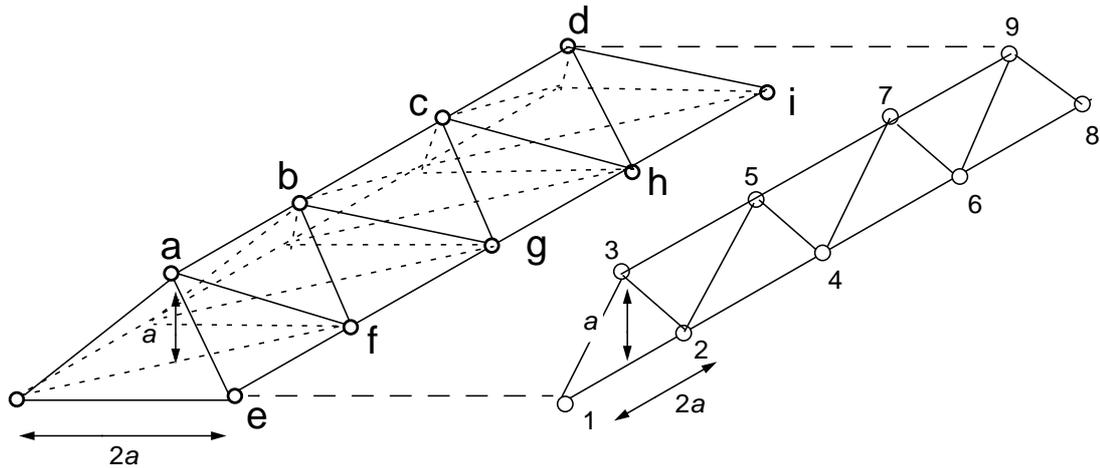
- A plot of load versus deflection for the two runs with the load applied at mid-span. Plot also the linear behavior as determined from theory - e.g., the 3D truss analysis.
- Compute the force in the member bearing the strain gages. (See Appendix) Compare this with the value determined from theory.
- A comparison of the two dimensional truss analysis with the two dimensional-space frame analysis.
- A comparison of the two dimensional analysis with the three dimensional analysis.

In a "conclusions" section, include recommendations for improvement of the experience.

## Appendix

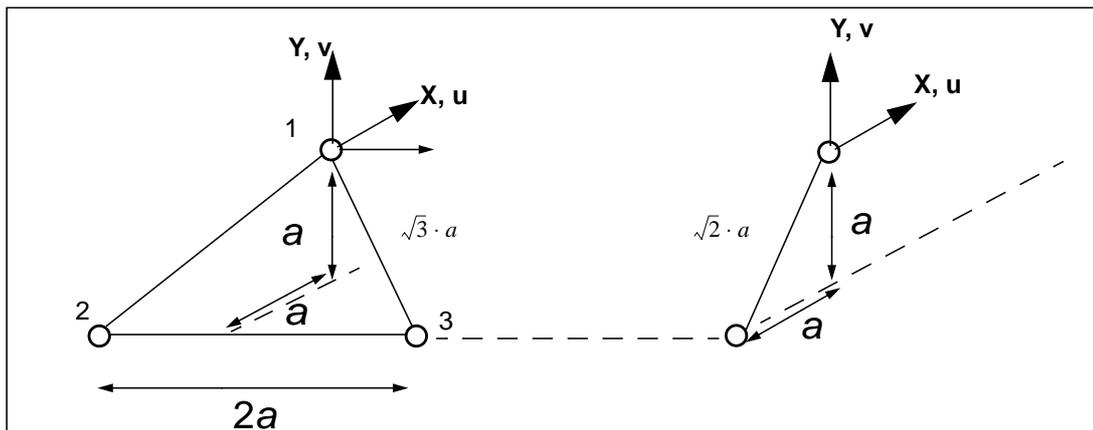
### A 2 dimensional model of the 3 dimensional truss.

In the lab, we load the truss structure, supported at its ends, at mid-span, and measure the deflection at a mid-span node (e.g., "g" in the figure below). We seek to construct an equivalent two dimensional model of the structure to analyze and determine the force-displacement behavior (as well as the forces in the members).

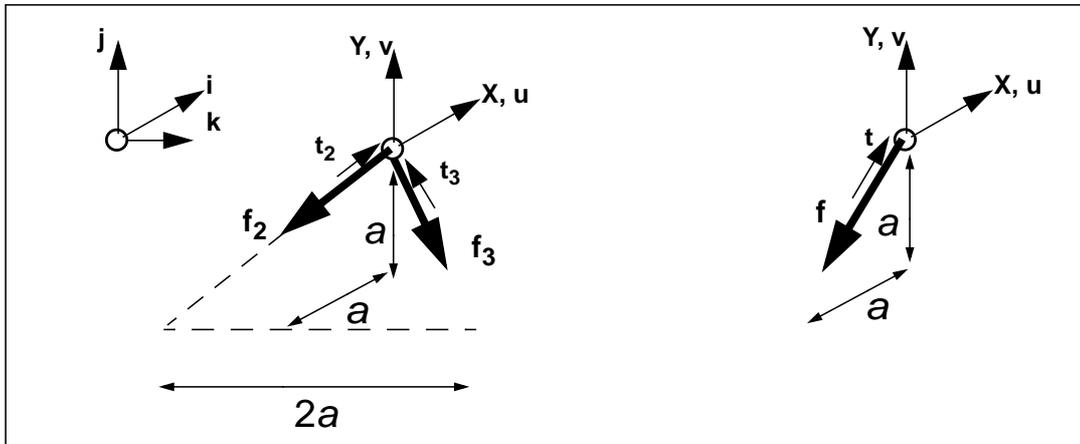


We need to establish an equivalent stiffness for the pairs of diagonal members joined at the top nodes and for the pairs of the bottom members.

For the pairs of diagonal members: We replace the two members shown on the left by a single member, inclined at  $45^\circ$ . We adjust this single member's cross-sectional area so that the stiffness matrix relating the two force components,  $\mathbf{X}, \mathbf{Y}$ , to the two displacements,  $\mathbf{u}, \mathbf{v}$ , is the same as in the fully three dimensional structure.



To get the stiffness matrix, we write out equilibrium, compatibility of deformation, and the constitutive equations, then back substitute and obtain the equilibrium equations in terms of displacements.



The unit vectors:

$$t_2 = 1/\sqrt{3} \cdot i + 1/\sqrt{3} \cdot j + 1/\sqrt{3} \cdot k$$

$$t_3 = 1/\sqrt{3} \cdot i + 1/\sqrt{3} \cdot j - 1/\sqrt{3} \cdot k$$

$$t = 1/\sqrt{2} \cdot i + 1/\sqrt{2} \cdot j$$

So equilibrium in matrix form gives

$$\begin{bmatrix} \phantom{0} \\ \phantom{0} \\ \phantom{0} \end{bmatrix} \cdot \begin{bmatrix} f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix}$$

3D structure

$$\begin{bmatrix} \phantom{0} \\ \phantom{0} \end{bmatrix} \cdot [f] = \begin{bmatrix} X \\ Y \end{bmatrix}$$

2D model

So compatibility is:

$$\begin{bmatrix} \delta_2 \\ \delta_3 \end{bmatrix} = \begin{bmatrix} \phantom{0} \\ \phantom{0} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix}$$

3D structure

$$[\delta] = \begin{bmatrix} \phantom{0} \\ \phantom{0} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix}$$

2D model

And with the force/deformation relations:

$$f_2 = k_{3D} \cdot \delta_2$$

$$f_3 = k_{3D} \cdot \delta_3$$

$$f = k_{2D} \cdot \delta$$

The stiffness matrices for the two are:

$$\begin{bmatrix} \quad & \quad \\ \quad & \quad \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix} \qquad \begin{bmatrix} \quad & \quad \\ \quad & \quad \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix}$$

So, for equivalent stiffness,

$$k_{2D} = ??? \ k_{3D}$$

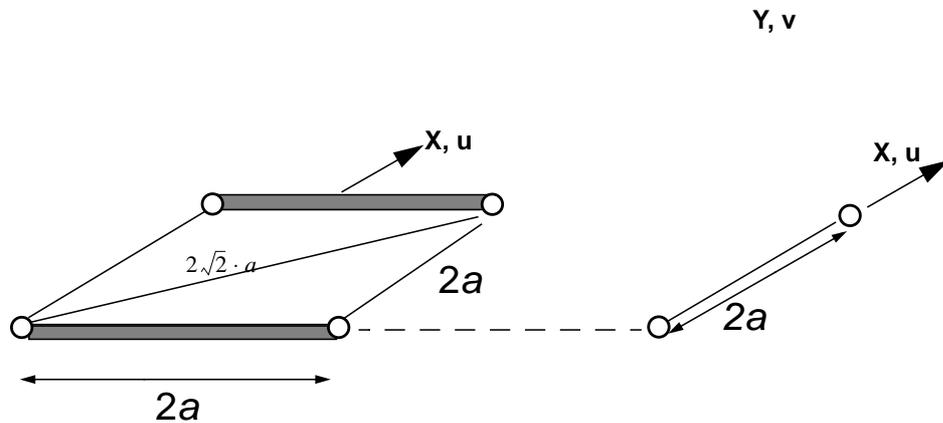
and, since the lengths are related by

$$L_{2D} = ????? \ L_{3D}$$

the cross-sectional areas must be in the ratio

$$A_{2D} = ????? \ A_{3D}$$

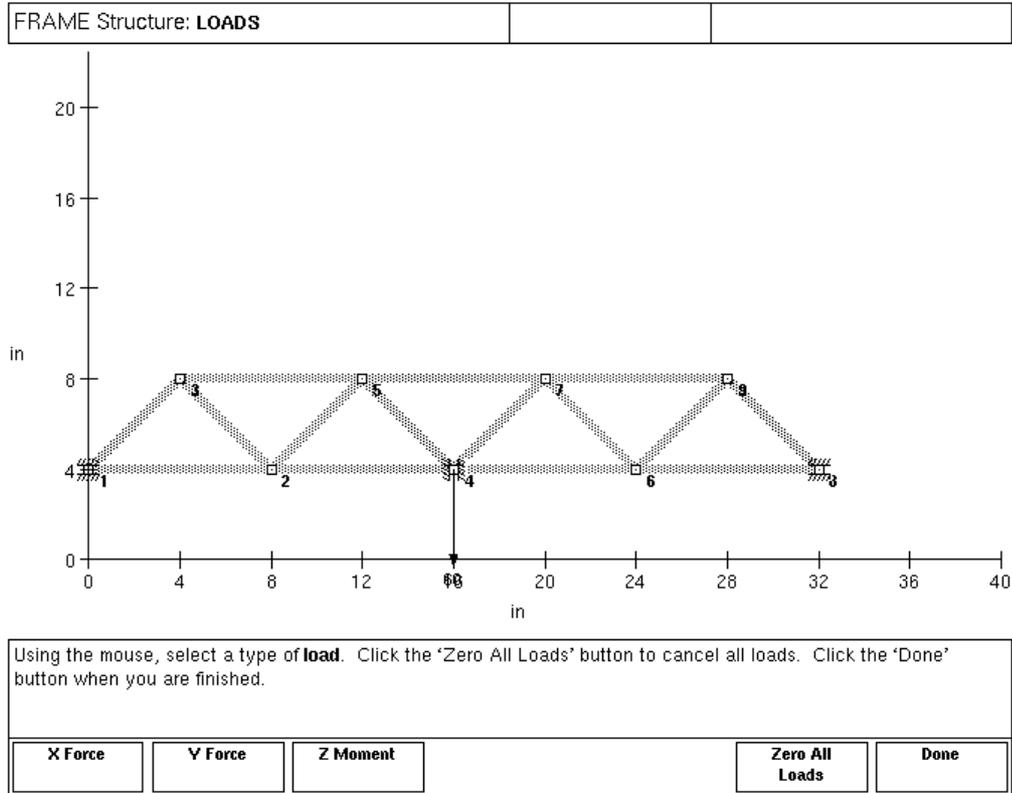
The same process is followed to obtain an equivalent stiffness for the bottom, parallel members (plus the diagonal). Again we show the 3D structure on the left and the 2D model on the right.



We assume the deformation is such that the shaded members move as rigid bodies and translate in the X direction.

Important note: To obtain the force in the member instrumented with the strain gages, we must calculate  $f_2$  (or  $f_3$ ), of the three dimensional structure in terms of the  $f$  of the two-dimensional model. This will be done in class.

## Space Frame 2D Matrix Analysis



NODE	COORDINATES		DISPLACEMENTS		
	x	y	u	v	q
	in	in	in	in	rad
1	0.000E+00	4.000E+00	-1.148E-03	0.000E+00	-1.183E-03
2	8.000E+00	4.000E+00	-8.605E-04	-9.150E-03	-1.008E-03
3	4.000E+00	8.000E+00	2.695E-03	-4.719E-03	-1.030E-03
4	1.600E+01	4.000E+00	0.000E+00	-1.445E-02	0.000E+00
5	1.200E+01	8.000E+00	1.347E-03	-1.223E-02	-5.838E-04
6	2.400E+01	4.000E+00	8.605E-04	-9.150E-03	1.008E-03
7	2.000E+01	8.000E+00	-1.347E-03	-1.223E-02	5.838E-04
8	3.200E+01	4.000E+00	1.148E-03	0.000E+00	1.183E-03
9	2.800E+01	8.000E+00	-2.695E-03	-4.719E-03	1.030E-03

NODE	APPLIED LOADS	REACTIONS
------	---------------	-----------

	Fx	Fy	Mz	Fx	Fy	Mz
	lb	lb	lb ft	lb	lb	lb ft
	=====	=====	=====	=====	=====	=====
1	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.000E+01	0.000E+00
2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
3	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
4	0.000E+00	-6.000E+01	0.000E+00	0.000E+00	0.000E+00	0.000E+00
5	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
6	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
8	0.000E+00	0.000E+00	0.000E+00	0.000E+00	3.000E+01	0.000E+00
9	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00

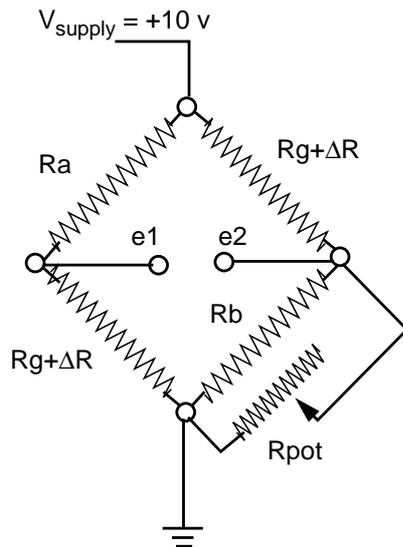
MEMBER	LENGTH	PROPERTIES			
i-j	L	A	E	I	Ymax <sup>1</sup>
	in	in <sup>2</sup>	psi	in <sup>4</sup>	in
	=====	=====	=====	=====	=====
1-2	8.000E+00	2.883E-02	2.900E+07	6.570E-05	4.782E-02
1-3	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
2-3	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
2-4	8.000E+00	2.883E-02	2.900E+07	6.570E-05	4.782E-02
2-5	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
3-5	8.000E+00	1.227E-02	2.900E+07	1.198E-05	3.125E-02
4-5	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
4-6	8.000E+00	2.883E-02	2.900E+07	6.570E-05	4.782E-02
4-7	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
5-7	8.000E+00	1.227E-02	2.900E+07	1.198E-05	3.125E-02
6-7	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
6-8	8.000E+00	2.883E-02	2.900E+07	6.570E-05	4.782E-02
6-9	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02
7-9	8.000E+00	1.227E-02	2.900E+07	1.198E-05	3.125E-02
8-9	5.657E+00	1.336E-02	2.900E+07	1.418E-05	3.259E-02

1. These values for Ymax are off by a factor of 2.

MEMBER	SHEAR	TENSILE	BENDING MOMENT		TENSILE	MAX BEND
i-j	FORCE	FORCE	node i	node j	STRESS	STRESS
	lb	lb	lb ft	lb ft	psi	psi
1-2	-1.715E-02	2.999E+01	2.247E-03	9.190E-03	1.040E+03	8.026E+01
1-3	5.586E-03	-4.241E+01	-2.247E-03	-3.865E-04	-3.174E+03	-6.197E+01
2-3	3.168E-03	4.239E+01	-6.171E-04	-8.762E-04	3.173E+03	-2.417E+01
2-4	-5.673E-02	8.993E+01	-1.102E-03	3.892E-02	3.119E+03	3.399E+02
2-5	2.079E-02	-4.235E+01	-7.471E-03	-2.329E-03	-3.170E+03	-2.061E+02
3-5	-8.628E-03	-5.997E+01	1.263E-03	4.490E-03	-4.887E+03	1.405E+02
4-5	-2.377E-02	4.232E+01	9.138E-03	2.065E-03	3.168E+03	2.521E+02
4-6	5.673E-02	8.993E+01	-3.892E-02	1.102E-03	3.119E+03	-3.399E+02
4-7	2.377E-02	4.232E+01	-9.138E-03	-2.065E-03	3.168E+03	-2.521E+02
5-7	0.000E+00	-1.198E+02	-4.226E-03	4.226E-03	-9.767E+03	1.323E+02
6-7	-2.079E-02	-4.235E+01	7.471E-03	2.329E-03	-3.170E+03	2.061E+02
6-8	1.715E-02	2.999E+01	-9.190E-03	-2.247E-03	1.040E+03	-8.026E+01
6-9	-3.168E-03	4.239E+01	6.171E-04	8.762E-04	3.173E+03	2.417E+01
7-9	8.628E-03	-5.997E+01	-4.490E-03	-1.263E-03	-4.887E+03	-1.405E+02
8-9	-5.586E-03	-4.241E+01	2.247E-03	3.865E-04	-3.174E+03	6.197E+01

## Strain-gage Circuit Analysis

Two strain gages are fixed to one of the members. They both will measure the extension or contraction along the length. A bridge circuit is used to avoid attempting to measure the small difference of two large numbers and their placement in the bridge also should eliminate the effects of bending - although we anticipate that to be small.



The values of the resistances are:

$$R_a = 352 \pm 5\% \text{ ohms}$$

$$R_b = 561 \pm 5\% \text{ ohms}$$

$$R_g = 350 \pm 0.2\% \text{ ohms}$$

$$R_{pot} = 1 \text{ kohm (max)}$$

The output of the bridge as a function of the change in resistance,  $\Delta R$ ,

$$e_1 - e_2 = (V_{supply}/2)(\Delta R/R_g)$$

The strain as a function of change in resistance is given by

$$\epsilon = (1/F_{gage})(\Delta R/R_g)$$

where  $F_{gage}$  is the "gage factor" stated by the manufacturer<sup>1</sup> to be

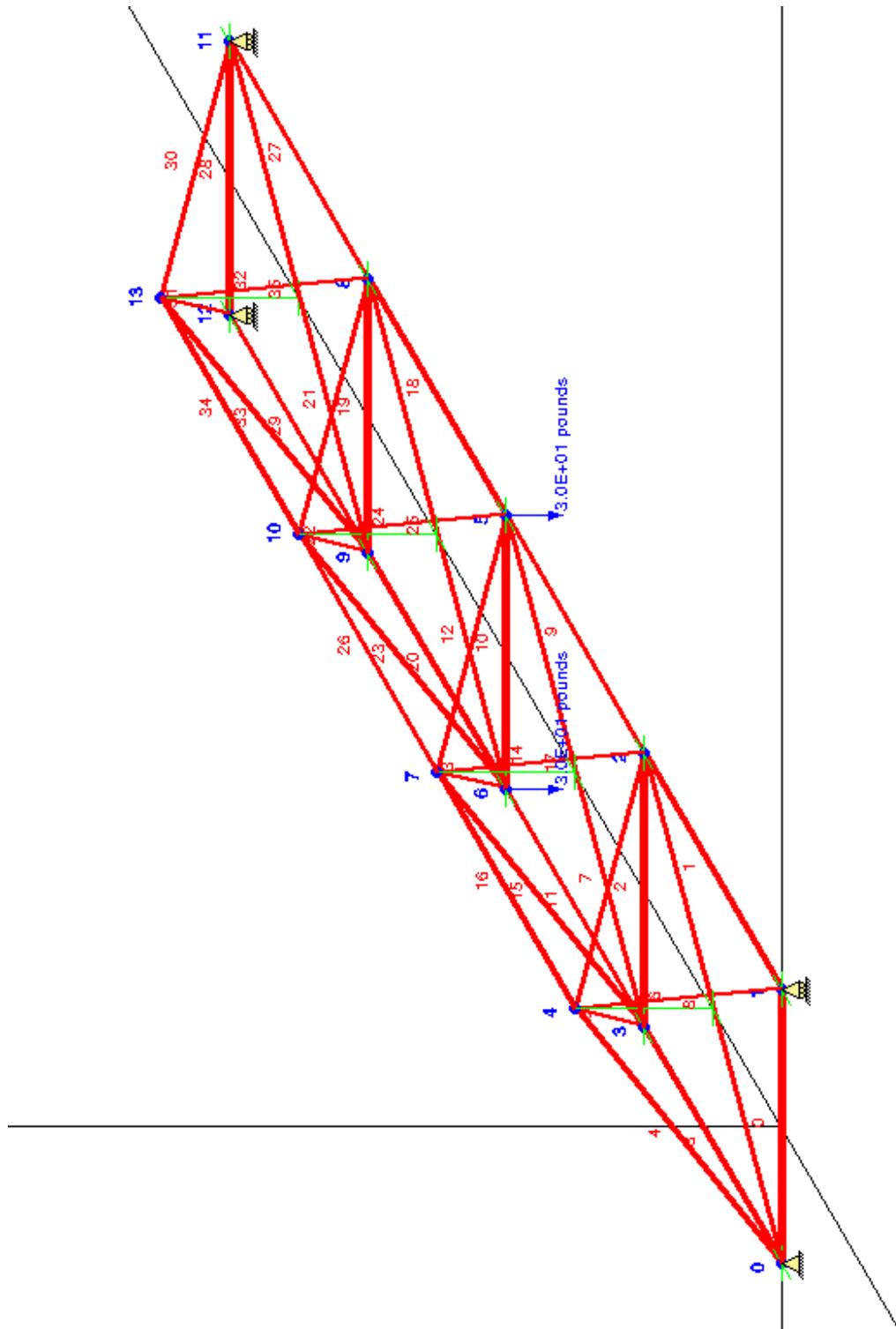
$$F_{gage} = 2.07 \pm 0.5\%$$

With these, you can compute the strain in the member, given the voltage difference  $e_1 - e_2$ .

The voltage difference  $e_1 - e_2$  is obtained from your measured values at the op-amp output by dividing by the amplifier gain.

1. BLH Electronics, Inc.

### 3D Results



## Structure 3D Output

Node Coordinates(x,y,z) and Nodal Displacements(u,v,w) - inches

	x	y	z	u	v	w
Node 0:	-4.00E+01	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 1:	+4.00E+01	+0.00E+00	+0.00E+00	+2.60E-04	+0.00E+00	+1.19E-03
Node 2:	+4.00E+01	+0.00E+00	-8.00E+01	+1.14E-03	-8.43E-03	+9.31E-04
Node 3:	-4.00E+01	+0.00E+00	-8.00E+01	+1.22E-03	-8.56E-03	-2.60E-04
Node 4:	+0.00E+00	+4.00E+01	-4.00E+01	+6.26E-04	-4.42E-03	-2.91E-03
Node 5:	+4.00E+01	+0.00E+00	-1.60E+02	+1.77E-03	-1.36E-02	+7.20E-05
Node 6:	-4.00E+01	+0.00E+00	-1.60E+02	+2.45E-03	-1.36E-02	-1.12E-03
Node 7:	+0.00E+00	+4.00E+01	-1.20E+02	+1.61E-03	-1.12E-02	-1.72E-03
Node 8:	+4.00E+01	+0.00E+00	-2.40E+02	+3.00E-03	-8.56E-03	-7.87E-04
Node 9:	-4.00E+01	+0.00E+00	-2.40E+02	+3.08E-03	-8.43E-03	-1.98E-03
Node 10:	+0.00E+00	+4.00E+01	-2.00E+02	+2.61E-03	-1.12E-02	+6.73E-04
Node 11:	+4.00E+01	+0.00E+00	-3.20E+02	+4.23E-03	+0.00E+00	-1.04E-03
Node 12:	-4.00E+01	+0.00E+00	-3.20E+02	+3.96E-03	+0.00E+00	-2.24E-03
Node 13:	+0.00E+00	+4.00E+01	-2.80E+02	+3.60E-03	-4.42E-03	+1.87E-03

Applied Loads(Lx, Ly, Lz) and Reaction Forces(Rx, Ry, Rz) - pounds

	Lx	Ly	Lz	Rx	Ry	Rz
Node 0:	+0.00E+00	+0.00E+00	+0.00E+00	-4.26E-14	+1.69E+01	-5.68E-14
Node 1:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+1.30E+01	+0.00E+00
Node 2:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 3:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 4:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 5:	+0.00E+00	-3.00E+01	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 6:	+0.00E+00	-3.00E+01	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 7:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 8:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 9:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 10:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00
Node 11:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+1.69E+01	+0.00E+00
Node 12:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+1.30E+01	+0.00E+00
Node 13:	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00	+0.00E+00

Member Properties

	L in	A in <sup>2</sup>	E lbs/in <sup>2</sup>
Member 0 - 1:	+8.00E+01	+1.33E-01	+3.00E+07
Member 1 - 2:	+8.00E+01	+1.33E-01	+3.00E+07
Member 2 - 3:	+8.00E+01	+1.33E-01	+3.00E+07

Member 3 - 0:	+8.00E+01	+1.33E-01	+3.00E+07
Member 0 - 4:	+6.92E+01	+1.33E-01	+3.00E+07
Member 4 - 3:	+6.92E+01	+1.33E-01	+3.00E+07
Member 4 - 1:	+6.92E+01	+1.33E-01	+3.00E+07
Member 4 - 2:	+6.92E+01	+1.33E-01	+3.00E+07
Member 0 - 2:	+1.13E+02	+1.33E-01	+3.00E+07
Member 2 - 5:	+8.00E+01	+1.33E-01	+3.00E+07
Member 5 - 6:	+8.00E+01	+1.33E-01	+3.00E+07
Member 6 - 3:	+8.00E+01	+1.33E-01	+3.00E+07
Member 5 - 7:	+6.92E+01	+1.33E-01	+3.00E+07
Member 7 - 6:	+6.92E+01	+1.33E-01	+3.00E+07
Member 7 - 2:	+6.92E+01	+1.33E-01	+3.00E+07
Member 7 - 3:	+6.92E+01	+1.33E-01	+3.00E+07
Member 4 - 7:	+8.00E+01	+1.33E-01	+3.00E+07
Member 3 - 5:	+1.13E+02	+1.33E-01	+3.00E+07
Member 5 - 8:	+8.00E+01	+1.33E-01	+3.00E+07
Member 8 - 9:	+8.00E+01	+1.33E-01	+3.00E+07
Member 9 - 6:	+8.00E+01	+1.33E-01	+3.00E+07
Member 8 - 10:	+6.92E+01	+1.33E-01	+3.00E+07
Member 10 - 9:	+6.92E+01	+1.33E-01	+3.00E+07
Member 10 - 6:	+6.92E+01	+1.33E-01	+3.00E+07
Member 10 - 5:	+6.92E+01	+1.33E-01	+3.00E+07
Member 6 - 8:	+1.13E+02	+1.33E-01	+3.00E+07
Member 7 - 10:	+8.00E+01	+1.33E-01	+3.00E+07
Member 8 - 11:	+8.00E+01	+1.33E-01	+3.00E+07
Member 11 - 12:	+8.00E+01	+1.33E-01	+3.00E+07
Member 12 - 9:	+8.00E+01	+1.33E-01	+3.00E+07
Member 11 - 13:	+6.92E+01	+1.33E-01	+3.00E+07
Member 13 - 12:	+6.92E+01	+1.33E-01	+3.00E+07
Member 13 - 8:	+6.92E+01	+1.33E-01	+3.00E+07
Member 13 - 9:	+6.92E+01	+1.33E-01	+3.00E+07
Member 10 - 13:	+8.00E+01	+1.33E-01	+3.00E+07
Member 9 - 11:	+1.13E+02	+1.33E-01	+3.00E+07

---

Member Forces - pounds

Member 0 - 1:	+1.30E+01
Member 1 - 2:	+1.30E+01
Member 2 - 3:	-3.85E+00
Member 3 - 0:	+1.30E+01
Member 0 - 4:	-2.93E+01
Member 4 - 3:	+2.93E+01
Member 4 - 1:	-2.26E+01
Member 4 - 2:	+2.26E+01
Member 0 - 2:	+5.45E+00
Member 2 - 5:	+4.30E+01
Member 5 - 6:	-3.38E+01

Member 6 - 3: +4.30E+01  
Member 5 - 7: +2.26E+01  
Member 7 - 6: +2.93E+01  
Member 7 - 2: -2.26E+01  
Member 7 - 3: -2.93E+01  
Member 4 - 7: -6.00E+01  
Member 3 - 5: +5.45E+00  
Member 5 - 8: +4.30E+01  
Member 8 - 9: -3.85E+00  
Member 9 - 6: +4.30E+01  
Member 8 - 10: -2.93E+01  
Member 10 - 9: -2.26E+01  
Member 10 - 6: +2.26E+01  
Member 10 - 5: +2.93E+01  
Member 6 - 8: +5.45E+00  
Member 7 - 10: -1.20E+02  
Member 8 - 11: +1.30E+01  
Member 11 - 12: +1.30E+01  
Member 12 - 9: +1.30E+01  
Member 11 - 13: -2.93E+01  
Member 13 - 12: -2.26E+01  
Member 13 - 8: +2.93E+01  
Member 13 - 9: +2.26E+01  
Member 10 - 13: -6.00E+01  
Member 9 - 11: +5.45E+00

-----  
-----  
\*\* Note on Sign Convention used:  
+tive Member Force = Tension  
-tive Member Force = Compression

## Structure 3D Input

```
<!DOCTYPE StructureXML
[
<!ELEMENT StructureXML (units, uniqueJoints, members)>
  <!ELEMENT units EMPTY>
  <!ATTLIST units length (meters | centimeters | feet | inches) #REQUIRED
              force (newtons | kiloNewtons | pounds | kips) #REQUIRED>
  <!ATTLIST graphics zoomScale CDATA #REQUIRED
                    originX CDATA #REQUIRED
                    originY CDATA #REQUIRED>
  <!ELEMENT uniqueJoints (Joint*)>
  <!ELEMENT Joint (coordinates, constraints, loads)>
  <!ATTLIST Joint JointID ID #REQUIRED>
  <!ELEMENT coordinates EMPTY>
  <!ATTLIST coordinates x CDATA #REQUIRED
                        y CDATA #REQUIRED
                        z CDATA #REQUIRED>
  <!ELEMENT constraints EMPTY>
  <!ATTLIST constraints Rx (true | false) #REQUIRED
                        Ry (true | false) #REQUIRED
                        Rz (true | false) #REQUIRED
                        Mx (true | false) #REQUIRED
                        My (true | false) #REQUIRED
                        Mz (true | false) #REQUIRED>
  <!ELEMENT loads EMPTY>
  <!ATTLIST loads Fx CDATA #REQUIRED
                 Fy CDATA #REQUIRED
                 Fz CDATA #REQUIRED
                 FMx CDATA #REQUIRED
                 FMy CDATA #REQUIRED
                 FMz CDATA #REQUIRED>
  <!ELEMENT members (Member*)>
  <!ELEMENT Member (properties, memberRelease)>
  <!ATTLIST Member jStart CDATA #REQUIRED jEnd CDATA #REQUIRED>
  <!ELEMENT properties EMPTY>
  <!ATTLIST properties A CDATA #REQUIRED
                       J CDATA #REQUIRED
                       Iy CDATA #REQUIRED
                       Iz CDATA #REQUIRED
                       E CDATA #REQUIRED
                       G CDATA #REQUIRED
                       B CDATA #REQUIRED>
  <!ELEMENT memberRelease EMPTY>
  <!ATTLIST memberRelease sMR (true | false) #REQUIRED
```

```

        eMR (true | false) #REQUIRED>
    ]
>

<StructureXML>

<!-- Valid length attributes are meters, centimeters, feet, inches -->
<!-- Valid force attributes are newtons, kiloNewtons, pounds, kips -->
<units length = "inches" force = "pounds"></units>

    <graphics zoomScale = "1.00" originX = " 350" originY = " 275"></graphics>
<uniqueJoints>
    <Joint JointID = "J:0">
        <coordinates x = "-40.00" y = " 0.00" z = " 0.00"></coordinates>
        <constraints Rx = "true" Ry = "true" Rz = "true"
            Mx = "false" My = "false" Mz = "false"></constraints>
        <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
            FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
    </Joint>
    <Joint JointID = "J:1">
        <coordinates x = "40.00" y = " 0.00" z = " 0.00"></coordinates>
        <constraints Rx = "false" Ry = "true" Rz = "false"
            Mx = "false" My = "false" Mz = "false"></constraints>
        <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
            FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
    </Joint>
    <Joint JointID = "J:2">
        <coordinates x = "40.00" y = " 0.00" z = "-80.00"></coordinates>
        <constraints Rx = "false" Ry = "false" Rz = "false"
            Mx = "false" My = "false" Mz = "false"></constraints>
        <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
            FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
    </Joint>
    <Joint JointID = "J:3">
        <coordinates x = "-40.00" y = " 0.00" z = "-80.00"></coordinates>
        <constraints Rx = "false" Ry = "false" Rz = "false"
            Mx = "false" My = "false" Mz = "false"></constraints>
        <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
            FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
    </Joint>
    <Joint JointID = "J:4">
        <coordinates x = " 0.00" y = "40.00" z = "-40.00"></coordinates>
        <constraints Rx = "false" Ry = "false" Rz = "false"
            Mx = "false" My = "false" Mz = "false"></constraints>
        <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
            FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
    </Joint>

```

```

<Joint JointID = "J:5">
  <coordinates x = "40.00" y = " 0.00" z = "-160.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "-30.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:6">
  <coordinates x = "-40.00" y = " 0.00" z = "-160.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "-30.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:7">
  <coordinates x = " 0.00" y = "40.00" z = "-120.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:8">
  <coordinates x = "40.00" y = " 0.00" z = "-240.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:9">
  <coordinates x = "-40.00" y = " 0.00" z = "-240.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:10">
  <coordinates x = " 0.00" y = "40.00" z = "-200.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:11">
  <coordinates x = "40.00" y = " 0.00" z = "-320.00"></coordinates>
  <constraints Rx = "false" Ry = "true" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"

```

```

    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:12">
  <coordinates x = "-40.00" y = " 0.00" z = "-320.00"></coordinates>
  <constraints Rx = "false" Ry = "true" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
<Joint JointID = "J:13">
  <coordinates x = " 0.00" y = "40.00" z = "-280.00"></coordinates>
  <constraints Rx = "false" Ry = "false" Rz = "false"
    Mx = "false" My = "false" Mz = "false"></constraints>
  <loads Fx = "0.0" Fy = "0.0" Fz = "0.0"
    FMx = "0.0" FMy = "0.0" FMz = "0.0"></loads>
</Joint>
</uniqueJoints>

<members>
  <Member jStart = "0" jEnd = "1">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "1" jEnd = "2">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "2" jEnd = "3">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "3" jEnd = "0">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "0" jEnd = "4">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "4" jEnd = "3">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>

```

```

    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "4" jEnd = "1">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "4" jEnd = "2">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "0" jEnd = "2">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "2" jEnd = "5">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "5" jEnd = "6">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "6" jEnd = "3">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "5" jEnd = "7">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "7" jEnd = "6">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>
  <Member jStart = "7" jEnd = "2">
    <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
      E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
  </Member>

```

```

<Member jStart = "7" jEnd = "3">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "4" jEnd = "7">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "3" jEnd = "5">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "5" jEnd = "8">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "8" jEnd = "9">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "9" jEnd = "6">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "8" jEnd = "10">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "10" jEnd = "9">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "10" jEnd = "6">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "10" jEnd = "5">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"

```

```

        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "6" jEnd = "8">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "7" jEnd = "10">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "8" jEnd = "11">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "11" jEnd = "12">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "12" jEnd = "9">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "11" jEnd = "13">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "13" jEnd = "12">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "13" jEnd = "8">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "13" jEnd = "9">
    <properties A = "0.1336" J = "0.0" ly = "0.0" lz = "0.0"
        E = "3.0E7" G = "0.0" B = "0.0"></properties>
    <memberRelease sMR = "false" eMR = "false"></memberRelease>

```

```
</Member>
<Member jStart = "10" jEnd = "13">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
<Member jStart = "9" jEnd = "11">
  <properties A = "0.1336" J = "0.0" Iy = "0.0" Iz = "0.0"
    E = "3.0E7" G = "0.0" B = "0.0"></properties>
  <memberRelease sMR = "false" eMR = "false"></memberRelease>
</Member>
</members>

</StructureXML>
```