

Duke University  
Department of Civil and Environmental Engineering  
CE 131L. Matrix Structural Analysis

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## 3D Truss Analysis

### 1 Element Stiffness Matrix in Local Coordinates

Consider the relation between axial forces,  $\{q_1, q_2\}$ , and axial displacements,  $\{u_1, u_2\}$ , *only* (in local coordinates).

$$\mathbf{k} = \frac{EA}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

$$\mathbf{q} = \mathbf{k} \mathbf{u}$$

## 2 Coordinate Transformation

Global and local coordinates

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

$$\cos \theta_x = \frac{x_2 - x_1}{L} = c_x$$

$$\cos \theta_y = \frac{y_2 - y_1}{L} = c_y$$

$$\cos \theta_z = \frac{z_2 - z_1}{L} = c_z$$

Displacements

$$u_1 = v_1 \cos \theta_x + v_2 \cos \theta_y + v_3 \cos \theta_z$$

$$u_2 = v_4 \cos \theta_x + v_5 \cos \theta_y + v_6 \cos \theta_z$$

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} c_x & c_y & c_z & 0 & 0 & 0 \\ 0 & 0 & 0 & c_x & c_y & c_z \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \end{bmatrix}$$

$$\mathbf{u} = \mathbf{T} \mathbf{v}$$

Forces

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} = \begin{bmatrix} c_x & 0 \\ c_y & 0 \\ c_z & 0 \\ 0 & c_x \\ 0 & c_y \\ 0 & c_z \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

$$\mathbf{f} = \mathbf{T}^T \mathbf{q}$$

### 3 Element Stiffness Matrix in Global Coordinates

$$\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \frac{EA}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad \mathbf{f} = \mathbf{T}^T \mathbf{q} \quad \mathbf{u} = \mathbf{T} \mathbf{v}$$

$$\mathbf{q} = \mathbf{k} \mathbf{u}$$

$$\mathbf{q} = \mathbf{k} \mathbf{T} \mathbf{v}$$

$$\mathbf{T}^T \mathbf{q} = \mathbf{T}^T \mathbf{k} \mathbf{T} \mathbf{v}$$

$$\mathbf{f} = \mathbf{T}^T \mathbf{k} \mathbf{T} \mathbf{v}$$

$$\mathbf{f} = \mathbf{K} \mathbf{v}$$

$$\mathbf{K} = \frac{EA}{L} \begin{bmatrix} c_x^2 & c_x c_y & c_x c_z & -c_x^2 & -c_x c_y & -c_x c_z \\ c_x c_y & c_y^2 & c_y c_z & -c_x c_y & -c_y^2 & -c_y c_z \\ c_x c_z & c_y c_z & c_z^2 & -c_x c_z & -c_y c_z & -c_z^2 \\ -c_x^2 & -c_x c_y & -c_x c_z & c_x^2 & c_x c_y & c_x c_z \\ -c_x c_y & -c_y^2 & -c_y c_z & c_x c_y & c_y^2 & c_y c_z \\ -c_x c_z & -c_y c_z & -c_z^2 & c_x c_z & c_y c_z & c_z^2 \end{bmatrix}$$

### 4 Numbering Convention for Degrees of Freedom

$$\mathbf{g} = [ 3*j1-2 ; 3*j1-1 ; 3*j1 ; 3*j2-2 ; 3*j2-1 ; 3*j2 ] ;$$

### 5 Truss Bar Tensions, $T$

$$T = q_2 = (\mathbf{kT}\mathbf{v})_2 = \frac{EA}{L} (c_x(v_4 - v_1) + c_y(v_5 - v_2) + c_z(v_6 - v_3))$$

## 6 Modifying truss\_2d.m to truss\_3d.m

- Copy truss\_2d.m to truss\_3d.m —

```
function [D,R,T,L,Ks] = truss_3d(XYZ,JTS,RCT,EA,P,D)
```

Modifications to the input arguments:

- the joint location matrix XYZ has  $x$ ,  $y$ , and  $z$  coordinates ... a 3 x J matrix;
- the reaction matrix RCT has  $x$ ,  $y$ , and  $z$  coordinates ... a 3 x J matrix;
- the joint load matrix P has  $x$ ,  $y$ , and  $z$  coordinates ... a 3 x J matrix;
- the prescribed displacement matrix D has  $x$ ,  $y$ , and  $z$  coordinates ... a 3 x J matrix;

Modification to the computed output:

- the computed deflections D will be the  $x$ ,  $y$ ,  $z$  displacements at each joint, returned as a 3 x J matrix;
- the computed reactions R will be the  $x$ ,  $y$ ,  $z$  forces at each joint with a reaction, returned as a 3 x J matrix;

Modifications to the program itself:

- Change how DoF is computed;
- Change `[Ks,L] = truss_assemble_2d(XY,JTS,EA);` to  
`[Ks,L] = truss_assemble_3d(XYZ,JTS,EA);`
- Change `T = truss_forces_2d(XY,JTS,EA,Dv);` to  
`T = truss_forces_3d(XYZ,JTS,EA,D);`
- Modify the section of code relating the joint displacement vector Dv to the joint displacement matrix D to account for the fact that there are three degrees of freedom per joint.
- Change plot commands to plot3 commands and change XY to XYZ.  
For example, change ...  
`plot( XY(1,JTS(:,b)), XY(2,JTS(:,b)), '-g' )`  
... to ...  
`plot3( XYZ(1,JTS(:,b)), XYZ(2,JTS(:,b)), XYZ(3,JTS(:,b)), '-g' )`  
Also change the ax variable to account for the Z dimension.

- Copy `truss_element_2d.m` to `truss_element_3d.m` —  
function `K = truss_element_3d(x1,y1,z1,x2,y2,z2,EA)`  
`L =`  
`cx =`  
`cy =`  
`cz =`  
`K =`
  
- Copy `truss_assemble_2d.m` to `truss_assemble_3d.m` —  
function `[Ks,L] = truss_assemble_3d(XYZ,JTS,EA)`  
`DoF =`  
`x1 =`  
`y1 =`  
`z1 =`  
`x2 =`  
`y2 =`  
`z2 =`  
`[K, L(b)] = truss_element_3d(x1,y1,z1,x2,y2,z2,EA(b) );`  
`g =`
  
- Copy `truss_forces_2d.m` to `truss_forces_3d.m` —  
function `T = truss_forces_3d(XYZ,JTS,EA,D)`  
`x1 =`  
`y1 =`  
`z1 =`  
`x2 =`  
`y2 =`  
`z2 =`  
`L =`  
`cx =`  
`cy =`  
`cz =`  
`T(b) =`