Synthesis of a Force Generator using Two Fold Tape Loops: Appendices

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This document contains the appendices of the master graduation thesis named ‘Synthesis of a Force Generator using Two-Fold Tape Loops’ written by Martijn de Jong.

The first appendix explains the fabrication methods of the tape spring itself and the cutting process of the subtended angle profile.

The second appendix shows the experiments which were performed. The first experiment was also described in the fourth chapter of the thesis. The other two were not presented in the thesis.

The third appendix shows the analysis of which material should be used to store as much energy as possible in a tape spring.

The fourth appendix explains the attempts that were done to incorporate the transition regions into the synthesis method.

The fifth and last appendix shows two of the used Matlab codes.
Fabrication Methods Tape Springs

The tape spring production consists of two steps: obtaining the tape spring geometry itself and laser cutting to obtain the subtended angle profile.

A.1. Tape Spring Production

The relation between the thickness of a tape spring and the radius is given by

\[ t < \frac{2 \sigma_y (1 + \nu)}{E \sqrt{3}} R. \]  

(A.1)

Given the material properties of spring steel (material number 1.4310) of \( \sigma_y = 1400 \text{ MPa}, \) \( E = 210 \text{ GPa} \) and \( \nu = 0.3 \), this results in

\[ R > 99.9 \cdot t. \]  

(A.2)

With a thickness of \( t = 0.20 \text{ mm} \), this results in a radius of \( R = 20.0 \text{ mm} \). To be on the safe side, a radius of \( R = 21.0 \text{ mm} \) is chosen, which results in the von Mises stress of

\[ \sigma_v = \frac{Et\sqrt{3}}{2R(1 + \nu)} \]  

(A.3)

\[ = 1332 \text{ MPa} \]  

(A.4)

The ideal forming process is by rolling, to ensure constant curvature. A small sample of spring steel was rolled in the metal workshop at the TU Delft with an inner roll thickness of 50 mm as shown in figure A.1. The figure shows that the curvature is hardly visible.

(a) Rolling of test sheet metal

(b) Resulting curvature

Figure A.1: Test rolling sheet metal
There was no rolling machine with smaller inner roller at the TU Delft. Therefore the tape spring production was outsourced to a metalworking company called Inno-Tec in Riethoven. The working drawings is at the next page.
A.1. Tape Spring Production

Scale 1:10

1000 ± 0.5

180° ± 20°

R21 ± 0.1

0.2 ± 0.01
They tried to obtain the radius by using a brake press with a rounded punch and a rounded rubber pad. This resulted in a radius of 100 mm. Therefore the radius was approached by using incremental bending with a lot of sharp bends instead of one round bent. This resulted in a cross section as shown in figure A.2. These lines can be seen on the produced tape spring as well.

The length of the punch was only 0.5 m, while the length of the tape springs is 1 m. Therefore the bending process was done in two steps. This resulted in dents in the middle of the tape springs as shown in figure A.3.

This process resulted in a non constant radius of the tape spring. Figure A.4 shows the dimensions of one of the tape springs. This shows that the middle has a higher radius than the ends. The radii were smaller than specified. The different tape springs were inconsistent as well. This smaller radius will result in von Mises stresses higher than the yield stress and therefore in plastic deformation. Therefore the first fold was applied in a controlled manner. The steps were

1. Roll tape spring flat in rolling machine
2. Roll tape spring with radius (of 50 mm in rolling machine)
3. Fold tape spring by hand and roll over the whole range of motion

By folding the tape spring, the strain is applied in two transverse and longitudinal direction. This results in plastic deformation in two directions. The cross section prevents the tape spring from bending in longitudinal direction. Therefore the tape spring was prestressed in longitudinal direction, which is shown in A.6

The resulting radius of the tape spring was 26.7 mm, which is larger than the calculated radius of 21 mm. This is probably because the curvature is higher at the edges of the bent, and therefore the stresses are higher at these edges. Therefore the tape spring is more plastic deformed than expected.
A higher radius results in a smaller maximum subtended angle. The width of the tape springs was 70 mmeter. The maximum subtended angle therefor becomes

$$\alpha_{\text{max}} = \frac{70 \text{ rad}}{26.7 \text{ rad}} = 2.62 \text{ rad} = 150.2^\circ \quad (A.5)$$

The way the tape springs were produced, was far from ideal. A suggestion for improvement is to perform the hardening process after the forming process. In this way the forming process is easier, because the spring back would be much less. The downside of performing the hardening process after the forming process is that it can results in unwanted and unknown pre-stresses.

**A.2. Cutting Profile**

Once the tape spring had the right curvature, the subtended angle profile was cut using a laser cutter and a rotational axis. The total setup is shown in figure A.7.

Two clampings were made to clamp the tape spring, as shown in figure A.8. These tape springs were clamped between de clamping parts using a hose clamp. The two tape spring clamps were bolted at a M12 threaded rod with a flat side for alignment. The threaded rod was at was side clamped in a three jaw chuck and at the other side fixed by a live center.

As explained in the previous section, the tape spring was prestressed and therefor not flat in longitudinal direction. The tape spring was only clamped at the ends of the tape spring, so in the middle the tape spring was higher than at the end points. The laser cutter gets a flat drawing as input and by specifying the radius, it calculates the right rotation. However, because of the prestressed, the radius in the middle is higher than at the begin- and endpoint, and therefore the subtended angle will be too large.
The first step was to measure the curvature of the tape spring. This was done by attaching a dial gauge to the moving laser cutter head and measure the height at steps of 50 mm. This resulted in the figure beneath.

Knowing the curvature of the tape spring in longitudinal direction, the correction can be calculated. The parameters of this calculation is shown in figure A.10. The assumption is made that the tape spring has a constant radius $R$. $\alpha$ is the desired subtended angle, $\epsilon$ is the height error and $\alpha_c$ is the corrected subtended angle.

The length from the center of the rotational axis to the edge of the tape spring is given by

$$L = \sqrt{(R \cdot \sin \left(\frac{\alpha}{2}\right))^2 + \left(\epsilon + R \cdot \cos \left(\frac{\alpha}{2}\right)\right)^2}$$

(A.6)
A.2. Cutting Profile

Figure A.8: Clamping of tape spring in laser cutter

(a) Flat thread rod for alignment
(b) Clamping with tape spring
(c) Total clamping rod without tape spring

Figure A.9: Curvature measurement of tape spring in longitudinal direction

(a) Measuring curvature in longitudinal direction
(b) Height profile

Using the law of cosines, the corrected subtended angle now can be calculated

\[ \alpha_c = 2 \cos \left( \frac{t^2 + \epsilon^2 - R^2}{2L\epsilon} \right)^{-1} \]  \hspace{1cm} (A.7)

Using the expression for the subtended angle profile \( \alpha(x) \) and the height error \( \epsilon(x) \), where \( x \) is the position at the tape spring, the expression for the corrected subtended angle is given \( \alpha_c \).

The used maximum and minimum subtended angle were respectively 145° and 100°. The maximum length that could be clamped in the rotational axis was 700 mm. The first 100 mm of the begin and end of the tape spring was 145°. The subtended angle profile was 500 mm starting at 145° and ending at 100°. The expression of the subtended angle in degrees was constructed by the following data
A polynomial is plotted through these points. This resulted in the following expression for the subtended angle:

$$\alpha(x) = -39.2x^2 - 70.4x + 145$$  \hspace{1cm} (A.9)

This resulted in the profile as shown in figure A.11. The holes are for alignment and clamping purposes.

Cutting the profile from a tape spring (with pre-stresses) resulted in a less accurate profile. A suggestion would be to first cut the profile and then apply the curvature to obtain a tape spring. This would however make the forming process even more complex.
B.1. Experimental setup

Some details of the experimental setup are given in this section. The total experimental setup is shown in figure B.1 beneath. The tape spring is clamped in two clappings. The fixed clamping is fixed to the aluminum profile. This profile is attached at the bottom and the upper side of the testing machine. The moving clamping is attached to the load cell of the testing machine.

The clampings are shown in figure B.2. The clampings were produced using a 3D printer. The front side of the fixed clamping is curved, otherwise it would collide with the testing machine. The range of motion of this setup was 700 mm.
B. Experiments

B.2. Measurements with Tape Measure

The first measurement was performed with tape measures. The measurement setup was the same as explained in the previous section, except for a couple of changes:

1. The aluminum beam was in the middle of the two columns
2. The beam was only fixed at the bottom of the testing machine
3. The distance between the load sensor and the moving clamping was elongated by a aluminum rod
4. The holes of the clamping did not go through the tape spring, but at the sides

The tape measure that was used was the “Stanley Tape Measure Max 8m” with a width of 28 mm and a radius of 13 mm. The length of the tape spring sections was 0.5 m. Two measurements were performed: 1) straight tape spring, 2) tapered tape spring. Both experimental setups of the two measurements are shown in figure B.3.

The resulting force displacement curves of these measurements are shown in figure B.4. Sub figure B.4a shows that the force displacement curve of a straight tape measure is not completely flat. The stiffening effect is noticeable in both the start and end section of the range of motion.
B.2. Measurements with Tape Measure

(a) Straight measurement tape  
(b) Tapered measurement tape

Figure B.4: Force displacement curves of experiment

Sub figure B.4b shows a lot of irregularities in its curve. The biggest peaks are at a displacement of 215 mm and 300 mm. These peaks occur at the moment, the discontinuities in the measure tape as shown in figure B.5 entered and left the bent region. These discontinuities are explained by the tracking mechanism of the laser cutter. The laser cutter has a tracking mechanisms that follows the metal. When there is no metal underneath the laser head, the laser head will go down and the sides of the laser head will collide with the tape spring. To prevent this from happening, there should always be metal underneath the laser head. Therefore the cutting lines are until 1 mm of the side of the tape spring. The last millimeter was cut with scissors, which causes the discontinuity.

Another thing learned was that radius of the tape spring was not consistent over its length. Figure B.6 shows the cross-section of two tape spring sections, taken at different length from the same tape measure. Another thing that was discovered is that the cross-section does not have a constant radius, but consists of a round part and two straight parts at the sides, which is shown in the same figure.

Therefore the total list of thing learned from this experiment is

- Range of motion is limited
- Radius of tape measure is not constant
- The force displacement curve is very sensitive for irregularities in the tape spring geometry
B.3. Fold Radius with Varying Subtended Angles

A small experiment is performed to check whether the fold radius is constant for different subtended angles.

In order to do that, nine samples of 200 mm length were cut out of a tape measure. These samples were cut at a laser cutter to obtain different subtended angles. The dimensions of the resulting samples are shown in table B.1.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Subtended Angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>17</td>
</tr>
</tbody>
</table>

Table B.1: Subtended angles of samples

The samples were folded to make a fold of 180°. The folded samples were gently imprinted in a piece of floral foam. The floral foam with the imprints is shown in figure B.7.

The imprint was scanned and analyzed using Matlab. This analysis was done by cropping an imprint of one specific sample. Then the black parts of the image were filtered. These data points were used to fit a circle. Using the scale of the ruler, the value of the radius was obtained. The different steps are shown in figure B.8. The resulting figure of the relation between the fold radius and the subtended angle is shown in figure B.9.

The figure shows that the when the subtended angle is larger than 25°, the fold radius is fairly constant. When the subtended angle is below 25°, the fold radius increases.
B.3. Fold Radius with Varying Subtended Angles

Figure B.7: Imprints of fold radius

(a) Cropped scan of imprint  (b) Filtering black pixels of scan  (c) Fitting circle through pixels

Figure B.8: Analyzing imprints

Figure B.9: Fold radius as function of subtended angle
Material Choice

The energy within the bent region of a folded tape spring is given by

$$U_{\text{max}} = 2.73 \frac{4\pi}{9\sqrt{3}} \frac{\sigma_0^3(1 + \nu)^2}{E^2} \cdot \bar{a}_{\text{bent}} R^3$$

(C.1)

The first term is a constant, the second term is the material component and the last term is the geometry component. Figure C.1 shows the energy per subtended angle within the bent region of a tape spring as function of the material components and the radius.

![Figure C.1: Energy per subtended angle, with $\nu = 0.3$](image)

With help of the material database CES EduPack, $\sigma_{\text{max}}^3/E^2$ was calculated for different materials. This resulted in figure C.2a.

The figure shows that elastomers have a very high score. The reason for that is because elastomers can have a high strain and therefore the thickness of the tape-spring can be high which results in a high energy storage. However, the energy equation is based on shell theory that requires $t << l$. A rule of thumb is that the ratio between the smallest length and the thickness should be higher than 100. However, for elastomers the ratio between the width and the thickness of the tape-spring is ten and lower, so the requirement that $t$ is much smaller than $l$ is not met. In order to take this requirement into account, only materials with a ratio above 100 are considered, which results in figure C.2b. The five materials that have the highest score are listed in table C.1.

From these materials, the Carbon Fiber Reinforced Polymer (CFRP) is the only available material. Using composites in compliant mechanisms is however challenging and needs more research. Because of availability and fabrication purposes, it is chosen to use spring steel 1.4310.
C. Material Choice

(a) Overview of all material groups
(b) Close-up of high scores

Figure C.2: Material scores based on $\sigma_{\text{max}}^{3}/E^{2}$

Table C.1: Materials with the highest score

<table>
<thead>
<tr>
<th>Material</th>
<th>Average score $\sigma_{\text{max}}^{3}/E^{2}$ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium alloys</td>
<td>6.47e4</td>
</tr>
<tr>
<td>CFRP (isotropic)</td>
<td>4.24e4</td>
</tr>
<tr>
<td>Polyamides</td>
<td>3.89e4</td>
</tr>
<tr>
<td>Polyhydroxyalkanoates</td>
<td>1.64e4</td>
</tr>
<tr>
<td>Nickel-based superalloys</td>
<td>1.17e4</td>
</tr>
</tbody>
</table>
Transition Regions Modeling

Several attempts were performed to model the transition regions. The attempts were not successful and therefore not included in the papers. First the determination of the different regions is explained in more detail.

Figure D.1 shows the geometry of a folded tape spring in the FEM model. The subtended angle of this example is 140°.

![Geometry of folded tape spring in FEM Model with a subtended angle of 140°](image)

Figure D.1: Geometry of folded tape spring in FEM Model with a subtended angle of 140°

The figure shows both transverse and longitudinal curves. Figure D.2 shows close-ups of the tape springs per direction.

![Close-ups of folded tape spring geometry](image)

(a) Curves in transverse direction  
(b) Curves in longitudinal direction

Figure D.2: Close-ups of folded tape spring geometry

The transverse curvature of the ends of the tape spring is equal to the tape spring curvature (1/R). In the bent region, the transverse curvature is zero. In the region between the undeformed and bent region, the transition region, the curvature goes from starting curvature to zero. Figure D.3a shows the plot of the curvatures in transverse direction. When the curvature is lower than the upper dashed line, the transition region is defined to start. When the curvature is below the lower dashed line, the transition region stops and bent region starts.

By analyzing the curvature in transverse direction, the different regions were identified. Figure D.4 shows the different regions of the tape spring with a subtended angle of 140°.
The energy within the tape spring in longitudinal direction for tape springs with different subtended angles is given by figure D.5. The dip in energy of the tape springs can by explained by the dip in the curvature.

In the synthesis method, only the bent region was taken into account, by using an equation that calculated the energy within the bent region as function of the average subtended angle in the bent region. One can see it as a multiplication of the subtended angle profile by a block signal, which represents the energy per subtended angle. The width of the block signal is the arc length of the bent, which is $R \cdot \theta$, with $\theta = 2.73$ which was concluded in the third chapter. The area underneath the multiplied signals is the total energy.

By using a block signal, only the energy within the bent region is taken into account. The perfect signal would have the shape as shown in figure D.5. A simplification would be a trapezoid signal. The transition regions can also be approached by using a signal with exponential sides instead of a straight line. Both signals are shown in figure D.7.

In order to find the right parameters for constructing these signals, the energy in the transition zones have been curve fitted. Figure D.8 shows the curve fits of a linear function and a exponential function. At the linear curve fit, only the first 30% of the data was used.

For these curve fits, energy distributions of tape springs with a constant subtended angle were used. When using a tape spring with a varying subtended angle, this approach is too simplistic, so the curve fits do not hold anymore. Therefore it is decided to not further investigate this approach.
Figure D.5: Energy distributions in longitudinal direction per subtended angle.

(a) Subtended angle profile  
(b) Block signal

Figure D.6: Energy distribution by multiplication of subtended angle profile with a block signal

(a) Trapezoid signal  
(b) Curve fitted signal

Figure D.7: Other signal shapes
Figure D.8: Curve fits of the transition regions. Solid lines is FEM data and dashed lines are curve fitted.
E.1. Synthesis Method

The following code is used to obtain the tape spring geometry, given a desired force displacement behavior.

```matlab
function [GeometryFnc, EnergyFnc, ForceFnc] = CalculateTSGeometry(xData, yData, SAlims, TS)

%%CalculateTSGeometry Calculate the geometry of a tape spring

%% With this function, the geometry of a tape spring can be calculate which has a
%% force-displacement behavior as desired. The desired force displacement behavior is
%% specified by giving the desired force at specific displacements.

%% INPUT:
% xData: Array of x-data points of desired force behavior [m]
% yData: Array of y-data points of desired force behavior [N]
% SAlims: Array of limits of Subtended Angle, as in [SA_min, SA_max] [Rad]
% TS: Structure of tape spring parameters:
%   TS.t: Thickness [m]
%   TS.R: Radius [m]
%   TS.L: Length [m]

%% OUTPUT:
% GeometryFnc: Function handle of geometry [rad]
% EnergyFnc: Function handle of energy [J]
% ForceFnc: Function handle of force [N]

%% Parameters Definition

syms x

% [m] Thickness
T = TS.t;
% [m] Radius of TS
R = TS.R;
% [m] Length of TS
L = TS.L;
E = 210e9; % [Pa] Young's Modulus
nu = 0.3; % [-] Poisson’s ratio
theta = 2.73; % [rad] Fold radius
n = 1000; % [-] Number of datapoints
X = linspace(0, L, n); % [m] Displacement vector
beta = R*theta; % [m] Fold length

%% Calculations
% Step 1: From desired force displacement behavior to average subtended angle
% Calculate coefficients of force equation using polynomial fit
ForceCoefs = polyfit(xData, yData, length(xData)-1);

%% Step 2: From angle to force
% Equation of force as a function of angle
% Equation of energy as a function of angle
% Equation of geometry as a function of angle
```

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% Calculate coefficients of energy equation by integrating the force coefficients
EnergyCoefs = polyint(ForceCoefs);

% Calculate coefficients of average subtended angle
SAavgCoefs = EnergyCoefs / ((theta*Ext^3)/(12*(1+nu)));

% Step 2: From parametric subtended angle polynomial to parametric avg subtended angle
% Define parametric polynomial of subtended angle (with coefficients 'a_n')
SAcoefsSym = fliplr([sym('a'),[1 length(SAavgCoefs)]]);

% Integrate parametric polynomial of subtended angle
SAsymInt = poly2sym(polyint(SAcoefsSym), x);

% Calculate parametric average subtended angle in bent region,
% using parametric polynomial of subtended angle
SAavgSym = (subs(SAsymInt,x,x+beta)-SAsymInt)/beta;

% Extract coefficients of parametric average subtended angle
SAavgSymCoefs = fliplr(coeffs(SAavgSym,x));

% Step 3: Solve coefficients of parametric average subtended angle
% Solve parametric coefficients
SAcoefsCell = struct2cell(solve(SAavgSymCoefs == SAavgCoefs,SAcoefsSym));

% Convert symbolics in cell to doubles (temporary)
GeometryCoefs = zeros(1,length(SAcoefsCell));
for i = 1:length(SAcoefsCell)
  GeometryCoefs(i) = double(SAcoefsCell{i});
end

% Find lowest subtended angle
MinSubtAng = min(double(subs(poly2sym(GeometryCoefs),x,X)));

% Shift geometry function so that the minimum subtended angle is at desired value
GeometryCoefs(end) = GeometryCoefs(end) + SAlims(1) - MinSubtAng;

% Generate output
GeometryFnc = matlabFunction(poly2sym(GeometryCoefs),{'Vars',x});% [Rad] Function handle
EnergyFnc = matlabFunction(poly2sym(EnergyCoefs),{'Vars',x});% [J] Function handle
ForceFnc = matlabFunction(poly2sym(ForceCoefs),{'Vars',x});% [N] Function handle
end

E.2. IGA submit script

This script is used to submit the parameters for the FEM analysis. The total software package consists of many other functions, which are not given in this appendix. The package can be obtained at gitlab.3me.tudelft.nl (permission required).

function TapeSpringIGA(GeoFnc,L_profile,SimulationSteps,TimeSteps)
%TapeSpring Run FEM analysis using IGA
% This function is used to submit the parameters for running the FEM analysis.
%
% INPUT:
% GeoFnc: Function handle of the subtended angle profile [Rad]
% L_profile: Length of the subtended angle profile [m]
% SimulationSteps: Array with the order of simulation steps
% TimeSteps: Array with the number of timesteps at each simulation step
%
% OUTPUT: This function does not generate output, but the output is saved to a file
%
% Add paths of the other functions
addpath './calculations'
addpath './plotting'
% Turn plots off when not on windows
if ispc; par.plots = 'on'; else par.plots = 'off'; end

% Simulation parameters
disp('Initialising simulation')
par.nIter = 300; % Number of iterations
par.conv = 1e-8; % Convergence tolerance
par.ds = 1; % Use fixed time step (1 = Yes, 0 = No)
p=par.OrderElev = [0 0]; % Order geometry
par.KnotIns = {[],[]}; % Insert knots at specific positions
num = [21 300]; % Number of nodes
par.geoRefine = num; % Refine geometry for energy calculations

% Geometry parameters
L = 0.7; % [m] Length of TS
radius = 26.7e-3; % [m] Radius of TS
h = 0.2e-3; % [m] Thickness of TS

initialize

% --- INITIALISE GEOMETRY ---
L = max(L, L_profile);
L_ends = (L - L_profile)/2;
x_1 = linspace(0,L,num(2)); % Vector in longitudinal direction

% Construct subtended angle array of geometry function. The begin and angle are equal
% to the maximum subtended angle.
SAs_longitudinal(find(x_1>=(L-L_ends), 'first'):find(x_1<(L-L_ends), 'last')) = ...
GeoFnc(x_1(find(x_1=L_ends, 'first'):find(x_1<(L-L_ends), 'last'))-L_ends);
SAs_longitudinal(find(x_1>L_profile, 'first'):end) = max(SAs_longitudinal);
SAs_longitudinal(find(x_1<L_profile, 'first'):end) = max(SAs_longitudinal);

% Define coefficients
c = zeros(4,num(1),num(2));
for j = 1:num(2)
    annulus_range = linspace(-SAs_longitudinal(j)/2,SAs_longitudinal(j)/2,num(1));
    c(1,3,:) = radius*sin(annulus_range); -cos(annulus_range);
    c(2,:) = ones(size(annulus_range))*x_1(j);
    c(4,:) = ones(size(annulus_range));
end
surf.coeffs = c;

% Beam offset
h_beams = 0.02;

% Define pilot points
m_beams.pil1X = [mean([c(1,1,1), c(1,end,1)]) mean([c(2,1,1), c(2,end,1)])-h_beams ...
    mean([c(3,1,1), c(3,end,1)]) 0 0 0];
m_beams.pil2X = [mean([c(1,1,end), c(1,end,end)]) ...
    mean([c(2,1,end), c(2,end,end)])+h_beams ...
    mean([c(3,1,end), c(3,end,end)]) 0 0 0];
m_geo = k_refinesurface(surf,par.OrderElev,par.KnotIns,par.RefineCount);
m_mat = setIsotropicMat('Staal',210e9,0.3,7900);
m_props = setIsotropicProps(m_mat,m_geo.number,h);

% SOLVE NONLINEAR SYSTEM
mproc = 'nonlinear static';
m_dgeo = m_geo;
MexShellFromCPP

% Perform simulation in steps
for step = SimulationSteps
    switch step
        case 'e1'
...
case 1
  \% \% STEP 1: Rotate to 180 degrees
  disp('Step 1: Rotate to 180 degrees');
  dofs.ep1 = [0 0 0]; dofs.ep2 = [0 nan nan];
  dofs.theta1 = [0 0 0]; dofs.theta2 = [pi 0 0];
  par.nTimestep = TimeSteps(step);

  saveMode = 'Last';

  case 2
  \% \% STEP 2: Thicken beams
  disp('Step 2: Thicken beams')
  \% resetAngles
  m_beams.breedte = 0.2;
  m_beams.hoogte = 0.2;
  m_beams.E = m.mat.E1;
  m_beams.G = m.mat.E1/(2*(1+ m.mat.nu12));
  m_beams.A = (m_beams.breedte*m_beams.hoogte);
  m_beams.Iyy = (m_beams.hoogte*m_beams.breedte^3)/12;
  m_beams.Izz = (m_beams.breedte*m_beams.hoogte^3)/12;
  m_beams.J = (m_beams.breedte*m_beams.hoogte/12)*...
            (m_beams.breedte^2+m_beams.hoogte^2);

  dofs.ep1 = [0 0 0]; dofs.ep2 = [0 0 0];
  dofs.theta1 = [0 0 0]; dofs.theta2 = [-pi/par.nTimestep 0 0];
  par.nTimestep = 1;

  saveMode = 'Last';

  case 3
  \% \% STEP 3: Bring endpoints at same position
  disp('Step 3: Bring endpoints at same position')
  dofs.ep1 = [0 0 0]; dofs.ep2 = m.endpoint(1,2)-m.endpoint(2,2) nan;
  dofs.theta1 = [0 0 0]; dofs.theta2 = [0 0 0];
  par.nTimestep = TimeSteps(step);

  saveMode = 'Every';

end

\% Perform simulation
[history, m, m_beams, m_sliders] = solveNLS(m, m_beams, m_sliders, dofs, par);

\% Save output
saveOutput(saveMode, history(end).flag)

\% Stop function when simulation did not converge
if history(end).flag == 0
  return
end