International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Finite Element Simulation of Residual Stresses in Roller Bent Section

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Abstract: ***Residual stresses in a material can be merit or demerit based on service loads. To avoid underestimation or overestimation of strength. Curved C section beams used for a variety of structural application is produced by pyramid roller bending process inducing residual stress in the material. Finite element simulation of pyramid roller bending process with C section beam is been carried out using Abaqus/Explicit analysis. This avoids convergence difficulties in numerical simulations done in static analysis.The technique incorporates contact bending, material non-linearity and geometrical non-linearity.***

Keywords: Residual Stress, Explicit Analysis, Curved steel, Pyramid Roller bending

1. Introduction

Residual stresses due to bending in curved C section is found in this paper numerically using explicit analysis. Numerical simulation done in static analysis for I section pyramid roller bending by Spoorenberg[1].The results verified finite element method as an alternative method for experimental. The need of simulation to be carried out in explicit invoked due to convergence difficulties in static analysis. Static analysis well known for lesser convergence issuesin complex simulations like handling multiple situations like contact, bending, rolling could hinder researchers to do further study with any kind of load,shape factor, curvature with ease. It may work for few cases but not reliable for a wide range of parameter variation. All these issues has been solved by designing explicit model simulation.This has been made possible in explicit as it does not have to check for convergence after each increment whereas in static analysis iterations are used with Newton's modified method. C section bending simulation is usually omitted in study with respect to other sections like I section, rectangular section etc. due to fact that web gets crippled easily due to lesser shape factor. This problem is also addressed in this paper with gradual loading technique.

2. Theoretical Method

Previous study on bending residual stresses by Spoorenberg [1] revealed that Timoshenko beam model used were subjected to oversimplification and showed only moderate coherence to experimental values.As in numerical method for C section bending residual stress is currently unavailable, theoretical method will solely be used for comparison purpose.

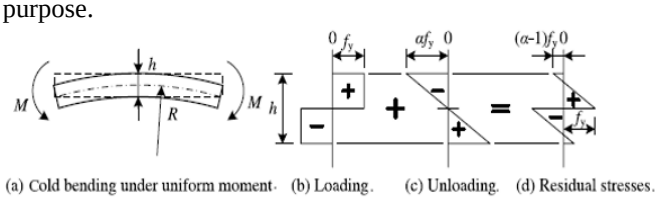

Figure 1: Timoshenko beam model

Shape Factor, $\alpha = \frac{Fully\ \ Plastic\ \ bending\ \ moment}{Elastic\ \ bending\ \ moment}$=1.236

S235 mild steel with yield stress of 300MPa has been carried out.Tabulation of residual stresses is carried out in MS Excel 2013.

LOADING STRESS	HEIGHT OF BEAM	UNLOADING STRESS	HEIGHT OF BEAM	RESIDUAL STRESS	HEIGHT OF BEAM
300	50	-371.01	50	-71.01	50
300	0	0	0	300	0
0	0	0	0	0	0
-300	0	0	0	-300	0
-300	-50	371.01	-50	71.01	-50

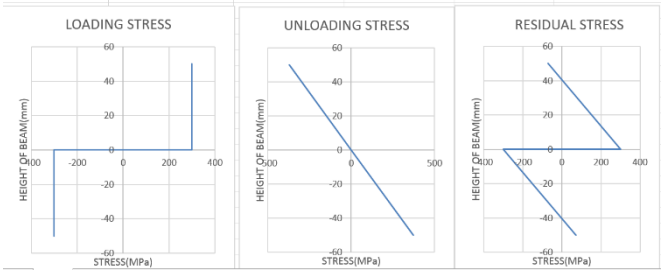

Figure 2: Timoshenko beam model

3. Numerical Method

3.1 Formulation

Simulation is based on FEM formulations are as stated below. The element selected is hexahedra elements with 8 nodes. First order interpolation was used to avoid convergence difficulty.Reduced integration is used for element. Matrix definition for hexahedra element is

$$\begin{bmatrix} 1 \\ x \\ y \\ z \\ v_x \\ v_y \\ v_z \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 \\ y_1 & y_2 & y_3 & y_4 & y_5 & y_6 & y_7 & y_8 \\ z_1 & z_2 & z_3 & z_4 & z_5 & z_6 & z_7 & z_8 \\ v_{x1} & v_{x2} & v_{x3} & v_{x4} & v_{x5} & v_{x6} & v_{x7} & v_{x8} \\ v_{y1} & v_{y2} & v_{y3} & v_{y4} & v_{y5} & v_{y6} & v_{y7} & v_{y8} \\ v_{z1} & v_{z2} & v_{z3} & v_{z4} & v_{z5} & v_{z6} & v_{z7} & v_{z8} \end{bmatrix} \begin{bmatrix} N_1^e \\ N_2^e \\ N_3^e \\ N_4^e \\ N_5^e \\ N_6^e \\ N_7^e \\ N_8^e \end{bmatrix} \quad (1)$$

where N is shape function, x, y, z are translational D.O.F and v_x, v_y, v_z are rotational D.O.F

Element Stiffness,

$$K^e = \int_{V(e)} B^T E B \, dV^e \quad (2)$$

The strains at any point within element can be expressed as follows:

$$\varepsilon = du = dNq = Bq \quad (3)$$

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Stress-strain relationship becomes

$$\sigma = E\varepsilon = EBq \quad (4)$$

Explicit formulations are as shown below
Dynamic Equilibrium equation

$$M^t \ddot{u} + C^t \dot{u} + F_{int}^t = F_{ext}^t \quad (5)$$

F_{int}^t =K u is the vector of internal forces resulting from the element stiffness and displacement

F_{ext}^t is the sum of all external forces including frictional forces due to contact.

ü, ú,u are the nodal acceleration, velocity and displacement.
M and C are mass and damping matrices

Central difference time integration was used to update values in increments as in:

$$\ddot{u} = (M^t)^{-1} (F^t - F_{int}^t) \quad (6)$$

$$\dot{u}^{t+\frac{1}{2}} = (M^t)^{-1} (F^t - F_{int}^t) \Delta t^{t+\frac{1}{2}} + \dot{u}^{t-\frac{1}{2}} \quad (7)$$

$$u^{t+1} = u^t + \dot{u}^{t+\frac{1}{2}} \Delta t^{t+1} \quad (8)$$

There is no iteration within this increments.t denotes the step time.

Penalty method is used for contact detection in this contact bending problem so that no convergence problem arises within contact module algorithm.
Force at contact detection point,

$$F = k_p * g_p \quad (9)$$

k_p- Penalty stiffness
g_p- Gap function(contact if g_p=0, penetration if g_p<0)
Rigid rollers thus apply force on the beam

3.2 Simulation

MCP100 (Medium Weight Parallel flange of depth 100) sections are selected .This standard dimensions are strictly followed from Indian Standard Medium Weight Beams (ISMB).S235 grade mild steel, S stands for structural steel. The number indicates the minimum yield strength.Poisson's ratio is 0.3, Young's modulus is 210e3 MPa, Yield strength of 300MPa, density of 7.8e-9 tons/mm^3, chemical composition with carbon (0.22%), phosphorous (1.6%), manganese (0.05%), sulphur (0.05%), silicon (0.05%).

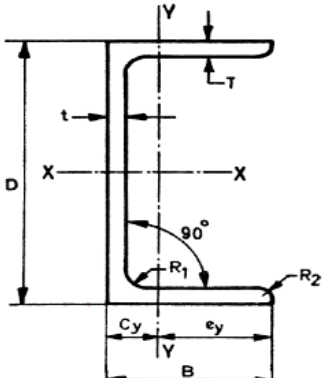

Figure 3: Beam specifications

The specifications shown in figure 3 is quantified in table 1.

Table 1: Beam dimensions

D(mm)	100
B(mm)	50
T(mm)	5
t(mm)	8

Simulation was carried out in Abaqus/Explicit module using three steps. First step dedicated to loading and rolling, second step for unloading. Third for attaining steady state. This was crucial for simulation. 15 variety of other variations has been tried and ruled out due to various reasons like web crippling, uneven loading, high roller speed, disturbances in beam due to stick-slip, etc. C3D8R element with three translational D.O.F was used for structural meshing characterized by regular mesh shown in figure 4.

Figure 4: Meshed model

R3D4 elements with three translational and three rotational D.O.F was used for rollers since no stress/strain output from roller elements were required. Brick element chosen for beam consumed more time but justified. Penalty contact was used to define contact with tangential interaction properties. Translation about X axis is arrested in beam surface. Top right roller is arrested in all D.O.F except translation in y direction.Centre roller is arrested about all D.O.F except rotation in x direction.Top left roller is arrested about all D.O.F

4. Results and Discussions

4.1 Theoretical Results

Theoretical model calculate from Timoshenko beam model was based on the assumption that sudden stress reversal happens at the neutral axis. Graph is plotted in Origin pro software with values exported from MS Office.

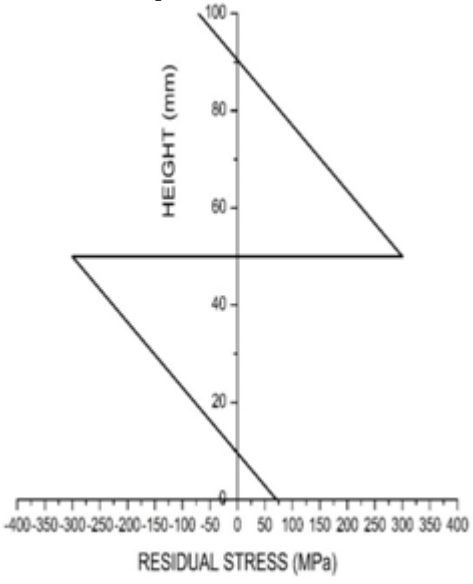

Figure 5: Theoretical Residual Stresses

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The maximum tensile and compressive stresses obtained are 300MPa and -300MPa respectively. Conceptual sudden stress reversal is shown at middle and gradual stress reversal at top and bottom flanges are as shown in figure 5.

4.2Numerical Results

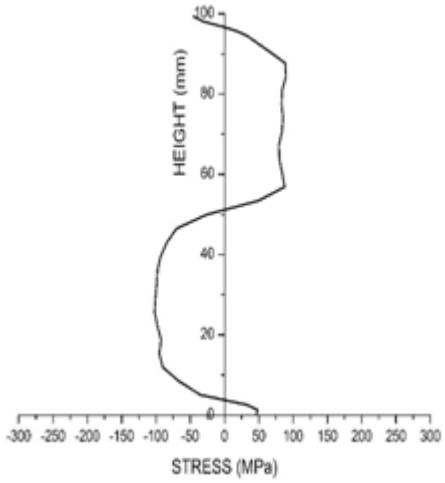

Figure 6: Theoretical Residual Stresses

The numerical results plotted in Origin Pro software using exported values from Abaqus v6.10 is as shown in figure 6.

5. Comparison

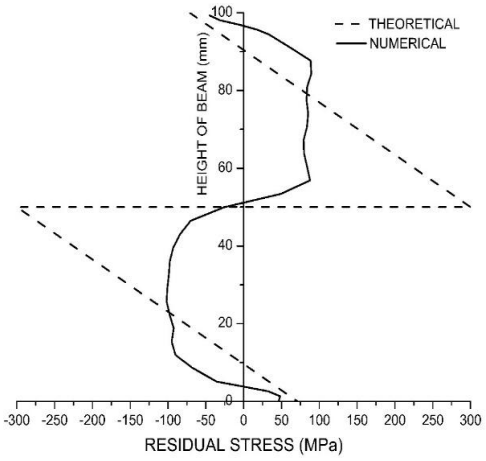

Figure 6: Theoretical Residual Stresses

Theoretical and Numerical results showed moderate coherence. This was due to the fact that extreme values are high which is based on assumption that sudden stress reversal occurs at a single layer or neutral axis which is practically impossible. Stresses can only gradually reverse its direction or value in practical scenario. This explains one of the over simplification in Timoshenko beam model. The top and bottom portion showing almost gradual reversal is shown with matching numerical results.

6. Conclusions

The simulation of C section bending using pyramid roller bending process is successfully conducted without web crippling. Gradual loading with experience and trial and error method was adopted for this.

Simulation is done in explicit module which eliminates any convergence difficulty with contact, different load, and speed variation unlike in static analysis and care has been taken to avoid stick-slip phenomenon.

Obtained numerical results matched the pattern of theoretical residual stresses with major tensile stresses on top and major compressive stresses on bottom with reasonable explanation for differences in extreme values.

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