Analytical study of corrugated web girders under flexural and shear loading

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Abstract- Use of corrugated webs to increase the out-of-plane stiffness and buckling strength without the use of vertical stiffeners has been considered for some time, first in aircraft design and later for civil engineering applications in buildings and bridges where heavy shear forces are dominating bending moments. Finite element models of steel materials with corrugated web simulated for material and geometrical nonlinear analysis using ANSYS® APDL. Finite element models were analyzed for shear and pure bending. FEM analysis results are very similar to experimental test in shear and bending. Yield stress limit of material and out of plane buckling are considered as failure criteria.

Keywords: Corrugated Web, Geometry and Material Nonlinearity, Nonlinear FEM analysis, ANSYS® APDL

I. INTRODUCTION

Application of corrugated webs instead of plane web increase the out-of-plane stiffness and buckling strength without the use of vertical, first application of corrugation was in aircraft design and later for civil engineering applications in buildings and bridges. Elimination of stiffeners also increase fatigue strength for heavy repetitive loads like in bridges and jetty.

FEM study included behaviour of corrugated beam for two loading cases, shear and bending. Finite element models were simulated for nonlinear analysis with consideration of large displacement effect in ANSYS APDL. In this paper, the analytical models will be described and the results presented and compared with the experiment result carried out by Elgaaly[1].

II.BUCKLING THEORY OF WEB AND CORRUGATED WEB

For plane web local buckling Global buckling modes are associated with corrugated steel webs. Local buckling failure of web is due to the instability of corrugated fold simply supported between two adjacent folds. Corrugated web, in this mode of failure, acts as series of flat panels that mutually support each other by vertical edges. The panels are supported by the flanges along their shorter edges. Elastic critical shear stress $\tau_{cr,l}$ for local buckling of isotropic material plate is given by Timoshenko[4]

$\tau_{cr,l}=k_s \times \frac{\pi^2 E}{12(1-v^2)} \times \left(\frac{t_w}{b}\right)^2$ Where, k_s=Buckling coefficient t_w=Thickness of web, E= Modulus of Elasticity b=Width of plate, v= Poison's Ratio. Value of k_s depends on geometry and boundary conditions of plate. For simply supported and fixed end conditions value of k_s is 4 and 5.42 respectively.

For Corrugated web girder buckling, shear buckling coefficient k_s is function of geometry and boundary conditions of plate. Corrugated web is composed of inclined and horizontal folds. Width of one fold of corrugation is too small compare to width of plane web so local buckling stress of fold is too much higher than equivalent length of plane web as per above equation. In addition each fold is connected by next fold of corrugation both side. Continuity of corrugation folds on both sides again increases its stability against out of plane buckling.

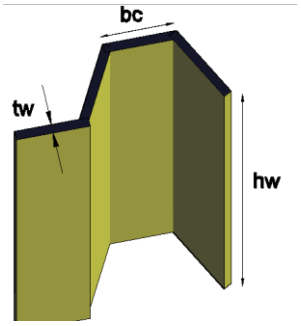

Figure 1 Trapezoidal Corrugation Profile

Buckling coefficient of corrugated web $k_s = 5.34 + 4.0\left(\frac{b_c}{h_w}\right)^2$

Shear stress of corrugated web $\tau_{cr,l}=\left\{5.34 + 4.0\left(\frac{b_c}{h_w}\right)^2\right\} \times \left\{\frac{\pi^2 E}{12(1-v^2)} \times \left(\frac{t_w}{b_c}\right)^2\right\}$ Where, b_c= width of single corrugation

Shear stress of corrugated web is more than hinge and fixed end condition of plate due to continuity and lesser width of corrugated web. At both end folds of corrugated web continuity is not available so end folds have lesser buckling stress than intermediate folds hence end folds of corrugated web buckle first than intermediate folds. Buckling stress of corrugated web is more than hinged and fixed end boundary conditions. Aforementioned results said that application of corrugation in beam increases shear buckling stress capacity and reduce out of plane deformation.

III. GEOMETRY OF MODEL AND CORRUGATION PROFILE

Plane web of American wide flange section W 6×15 is replaced by corrugated web. Height of corrugated girder is 304.8 mm. Trapezoidal corrugation profile is selected for FEM analysis as shown in Figure 1. Dimension of corrugation profile is as per Table 1. Thickness of corrugated web is too small compared to thickness of flange; respectively thickness of flange and web is 12.7 mm and 0.7645 mm. Stiffener thickness is equal to thickness of flange. Stiffeners are provided at below point load and end support.

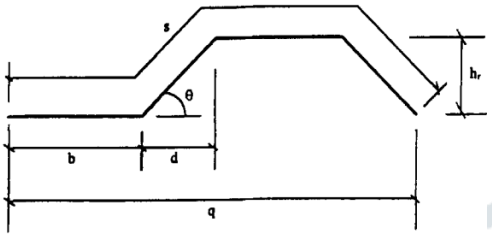

Figure 2 Geometry of Corrugation Profile

Table 1 Dimensions of Corrugation Profile

	b	d	h_r	θ	s	q
Shear Model	38.1 mm	25.4 mm	25.4 mm	45°	35.92 mm	127 mm
Bending Model	49.8 mm	26.4 mm	50.8 mm	62.5°	214.1 mm	152.4 mm

IV.FINITE ELEMENT ANALYSIS AND RESULTS FOR SPECIMENS TESTED IN SHEAR

For analysis in shear loading thee point loading test setup is simulated as shown in Figure 3**.** Depth of corrugated web is 304.8 mm and a/h ratio is one. Shear load is distributed to all nodes of middle stiffener to account maximum shear effect in model**.** Corrugation profile for Shear model dimension is given in Table1.

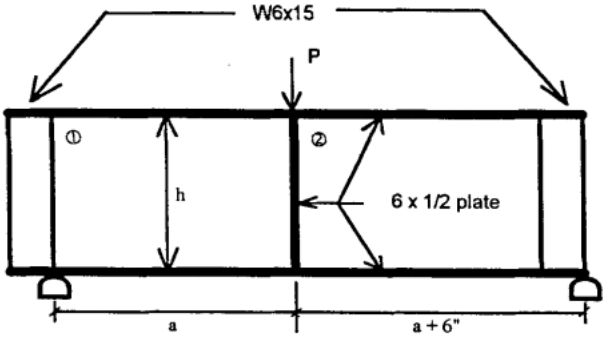

Figure 3 Line Diagram of Shear Model

(a) Material Properties

Bilinear elastic perfect plastic material property is taken from Elgaaly model for nonlinear Finite Element Analysis. Elasticity up to yield stress is 2,00,000 MPa and strain hardening tangent modulus is 2,000 MPa. Tangent modulus is one percent of young's modulus. Yield stress of flange and corrugated web is 689 MPa. Stress strain graph for bilinear elastic perfect plastic material is shown in Figure 4.

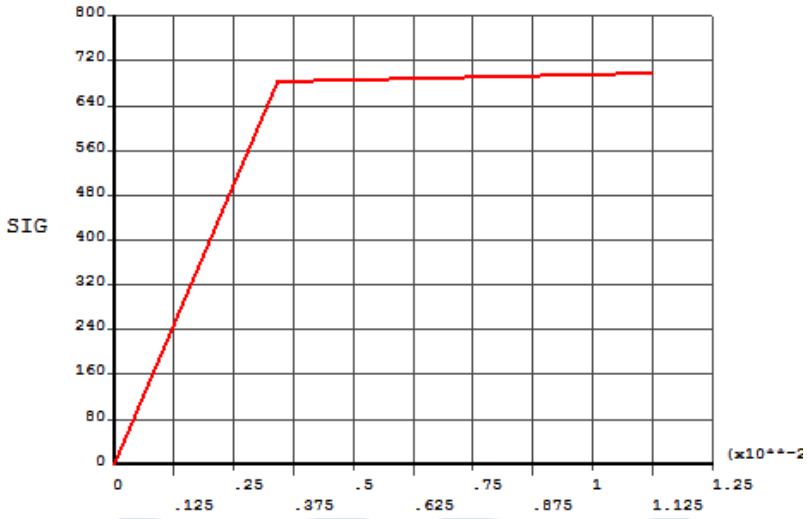

Figure 4 Bilinear Elastic Perfect Plastic Stress Strain Curve ANSYS® APDL Graph

Due to symmetry, half model of beam is simulated in ANSYS® APDL to reduce computational time. Four nodded SHELL 181 element is used for meshing. SHELL181 is well suited for nonlinear, large displacement nonlinear analysis. Four nodded quadrilateral element is used for meshing. SHELL 181 is well suitable for of thin plate. It is a four nodded quadrilateral element with six degrees of freedom at each node following. Three translations in the x, y, and z directions and rotations about the x, y and z axes. SHELL 181 accounts both membrane stress and bending stress.

(b) Boundary Conditions and Loading

By taking symmetry model boundary conditions are applied on edges which are given in Table 2. Constrained nodes of flanges are slaved to web nodes. Nodal force is applied to junction of top flange and web.

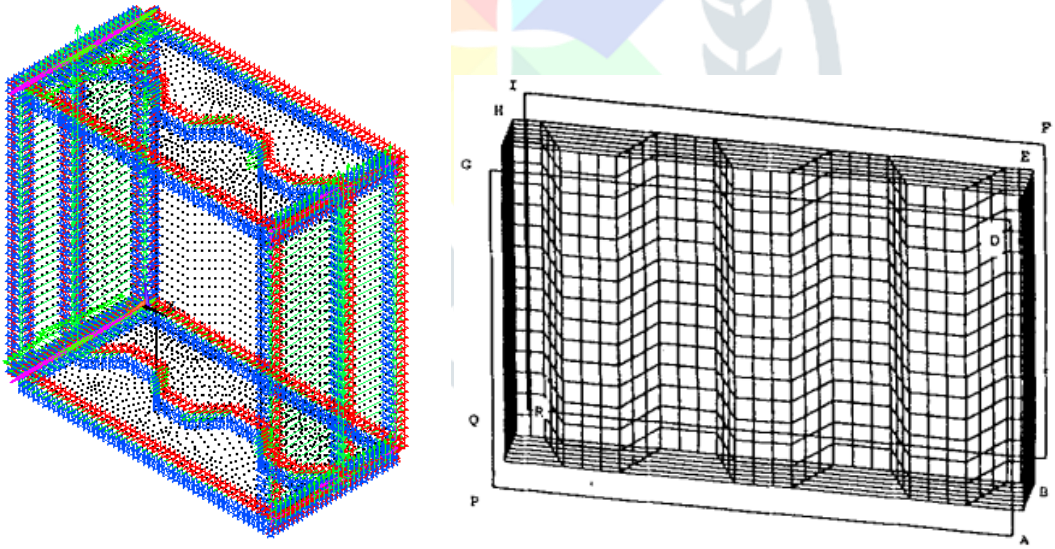

Figure 5 Finite Element Model with Boundary Conditions

Table 2 Boundary Conditions of Shear Model

Edge	Translational DOF			Rotational DOF		
	δ_x	δ_x	δ_x	ROT X	ROT Y	ROT Z
ABC	Co	Re	Re	Re	Re	Co
DEF	Co	Co	Re	Re	Re	Co
GHI	Re	Co	Re	Re	Re	Re
PQR	Re	Co	Re	Re	Re	Re
AD excluding A & D	Co	Co	Re	Re	Co	Co
BE excluding B & E	Co	Co	Re	Re	Co	Co
CF excluding C & F	Co	Co	Re	Re	Co	Co
DG excluding D & G	Co	Co	Co	Co	Co	Co
EH excluding E & H	Co	Co	Co	Co	Co	Co
FI excluding F & I	Co	Co	Co	Co	Co	Co
AP excluding A & P	Co	Co	Co	Co	Co	Co
BQ excluding B & Q	Co	Co	Co	Co	Co	Co
CR excluding C & R	Co	Co	Co	Co	Co	Co
GP excluding G & P	Co	Co	Co	Co	Co	Co
HQ excluding H & Q	Co	Co	Co	Co	Co	Co
HR excluding H & R	Co	Co	Co	Co	Co	Co

Re- Restrained, Co- Constrained nodes are slaved to web by constrained equation

(c) Result Analysis & Comparison

Large deformation with pre-stress effect is considered for nonlinear analysis. To account geometrical and material nonlinearity arc length method is used with several iterations. From iteration, max and min multiplier for arc length method used in analysis are 1 and 0.1 respectively. For reliable analysis, total number of 25 sub-steps used. Web is buckle out of plane as shown in figure. Local buckling load for out of plane buckling of web is 86.42 kN and shear stress is 389.07 MPa.

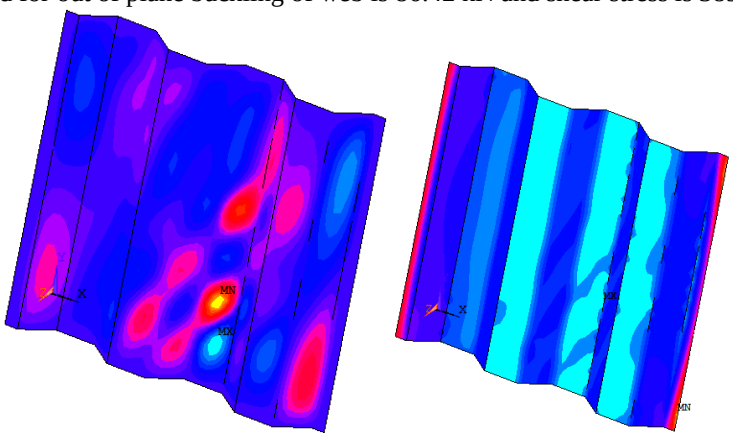

Figure 6 Out of Plane Displacement & Shear Stress Contour

Table 3 Comparison of Elgaaly & ANSYS® APDL FEM model

	Elgaaly FEM	Elgaaly EXP	ANSYS®APDL
Failure Load	84 kN	87 kN	86.42 kN
Percentage Error	2.88%	0.67%	
Shear Stress	363 N/mm^2	375 N/mm^2	389 N/mm^2
Percentage Error	6.68%	6.46 %	

V. FINITE ELEMENT ANALYSIS AND RESULTS FOR PURE BENDING MODEL

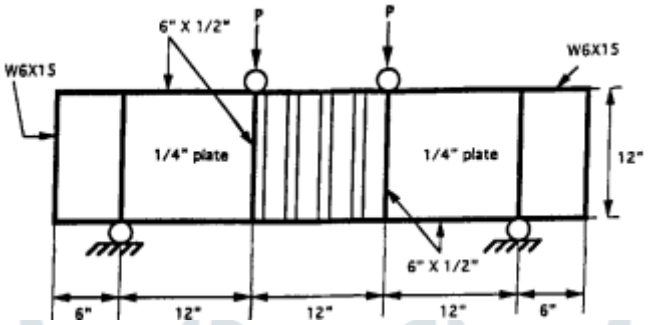

Figure 7 Line Diagram of Pure Bending Model

For analysis in pure bending condition four point loading test setup is used as shown in Figure 7. Dimension of corrugation profile is given in Table 1. Very first panels near to the supports were made of 6.35 mm flat plates. Cross bracing to flat web both side of corrugation ensure that failure will occur in the central panel due to pure bending. Flanges dimension is 152.4 mm wide and 12.7 mm thick. Thickness of web is 0.6071 mm. Stiffeners were provided at under load and at support. Material and thickness of stiffner is similar to flange.

(a) Material Properties

Bilinear elastic perfect plastic material property is taken from Elgaaly model for nonlinear finite element analysis. Elasticity up to yield stress is 200000 MPa and strain hardening tangent modulus is 2000MPa. Yield stress for flange and web are respectively 293 MPa and 682MPa.

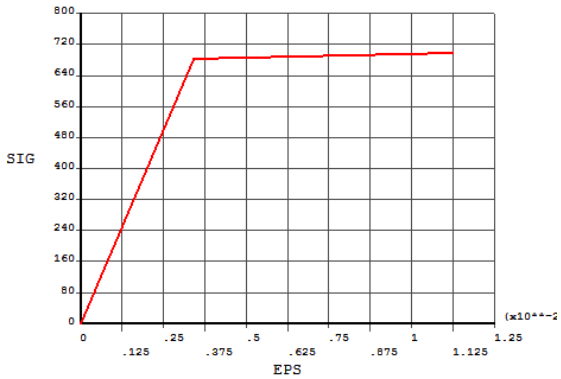

Figure 8 Bilinear Elastic Perfect Plastic Stress Strain Curve.

(b) Boundary Conditions

Meshing and shell element type is similar to shear model. Meshed shear model is shown in Figure 10. Figure 10 shows finite element model of Elgaaly. Restrained and constrained conditions are given in Table 4. Constrained conditions for flange nodes are modelled as slaved to web nodes.

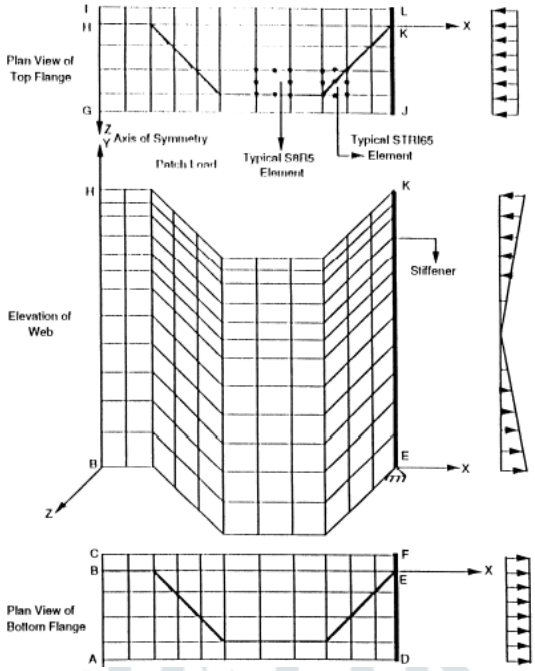

Figure 9 Finite Element Model for Bending

Table 4 Boundary Condition of Bending Model

	Translation DOF			Rotational DOF		
	δ_x	δ_x	δ_x	ROT X	ROT Y	ROT Z
DEF	Co	Re	Re	Re	Re	
ABC	Re				Re	Re
GHI	Re				Re	Re
JKL	Co				Re	
BH excluding B and H	Re					Re

DOF: Degree of Freedom, Co: Node is constrain and Slaved to web nodes, Re: Restrained

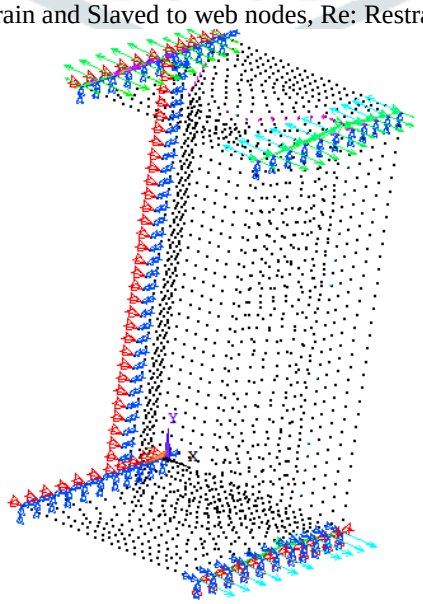

Figure 10 FEM Model for Pure Bending

(c) Result Analysis & Comparison

Large deformation with pre stress effect is used for nonlinear analysis. To account of geometrical and material nonlinearity Arc length method is used with several iterations. From iteration, max and min multiplier for arc length method used in analysis are 1 and 0.1 respectively. For reliable analysis, total number of sub-step used is 100.

Figure 11 represent X directional normal stress contour isolated for top flange and the indicated marked point represents normal stress value under point of strain gauge, applied by Elgaaly in his experimental study.

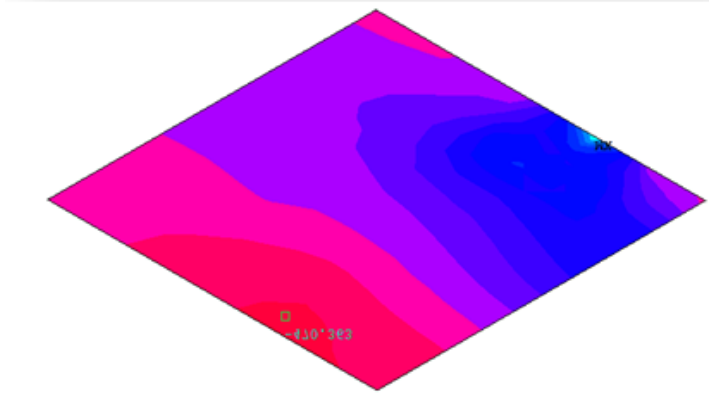

Figure 11 Contour of stress Under Strain Gauge of Top Flange

Analytical failure mode and pattern in model is very similar to experimental results. After stress reach to yield stress in compression flange it started to buckle in corrugated web

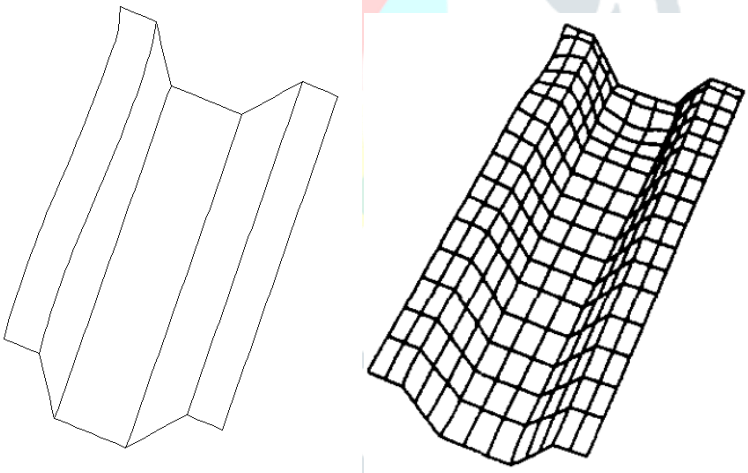

Figure 12 ANSYS® APDL Deformed Web & Elgaaly Deformed Web

Table 5 shows comparison of moment and stresses corresponds. To failure for result obtained by Elgaaly experiments, Elgaaly FEM and current FEM study in ANSYS® APDL study.

Table 5 Result Comparison

	Elgaaly FEM	**Elgaaly EXP**	**ANSYS®APDL**
Bending Moment	189 kNm	175 kNm	187 kNm
Directional Stress	475 N/mm^2	439.94 N/mm^2	470.36 N/mm^2
Percentage Error	1.05%	6.46 %	

VI. CONCLUSION

Finite element models shear and bending specimens of steel girders with corrugated webs were modelled using thin shell elements. The models were tested under shear, pure bending. Non-linear finite element analysis, which considers both geometric and material nonlinearities, was performed. The test results of Elgaaly and results from the finite element analysis were presented, compared. The FEM analysis was able to depict the test results to a very good degree of accuracy under the three aforementioned loading conditions. The behaviour up to failure, the failure mode and the ultimate capacity calculated were in good agreement with the test results.

References

[1] Mohamed Elgaaly, Fellow, ASCE, Robert W. Hamilton, Member ASCE & Anand Seshadri, June 1997 "Shear strength of beams with corrugated webs", Journal of Structure Engineering American Society of Civil Engineering. Page No 772-782

[2] Mohamed Elgaaly, Fellow, ASCE, Robert W. Hamilton, Member ASCE & Anand Seshardri, , April 1996 "Bending strength of steel beams with corrugated webs" Journal of Structure Engineering American Society of Civil Engineering Page No 390-398

[3] Mohamed Elgaaly, Anand Seshadri, 1998 "Depicting the behaviour of girders with corrugated webs up to failure using non-linear finite element analysis" Advances in Engineering Software, pg no 195–208

[4] Timoshenko SP, Gere J.M. "Theory of Elastic Stability". TATA McGraw-Hill

[5] ANSYS® APDL Mechanical Structure Analysis Guide

[6] Mechanical APDL theory reference