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Buckling Analysis of Corrugated Plate Girders

Reshma. C.[1], Ajisha. R.[2]
[1]*M Tech Student, Structural Engineering, Sreepathy Institute of Management and Technology, Vavanoor, India*
[2]*Assistant Professor, Department of Civil Engineering, Sreepathy Institute of Management and Technology, Vavanoor, India*

Abstract — Plate girders became popular in the late 1800's when they were used in the construction of railroad bridges. Steel plate girders were introduced into construction as a cost effective alternative to rolled girder for large spans. The corrugated girder is a widely used structural element in many fields of application because of its numerous favourable properties. To increase the shear capacity of web of large steel plate girders, the web with different patterns such as tapered web, haunches, corrugations of different shapes are used. Present report deals with the determination of buckling strength of a plate girder considering rectangular and triangular corrugated web plates. The finite element analysis of a plate girder is carried out using ANSYS 15. The results obtained from analysis are then compared with the plate girder with plane web of uniform depth. Various parameters like buckling strength and weight are compared. It is concluded that the corrugated web plate has high buckling strength than plate girder with plane web.
Keywords —Plate girder, tapered web, corrugated web, finite element analysis, ANSYS

I. INTRODUCTION

Steel structures are becoming more and more popular due to their advantages such as the better flexibility, aesthetic appearance, durability, low inclusive cost etc. Steel sections are available as cold rolled or hot rolled sections. Hot rolling is a mill process which involves rolling the steel at a high temperature (typically at a temperature over 1700° F), which is above the steel's recrystallization temperature. When steel is above the recrystallization temperature, it can be shaped and formed into different sections easily. Hot rolled steel is typically cheaper than cold rolled steel due to the manufactured process, and also reheating of the steel is not required. Steel is a strong material that is highly resistant to normal temperatures but this resistance lessens considerably at higher temperatures, similarly when steel cools off it will shrink slightly thus giving less control on the size and shape of the finished product when compared to cold rolled. Hot rolled products are available in different shapes like steel bars, steel plates, C-sections, I sections, angle sections.

The drawback of rolled beam sections was replaced by the introduction of plate girders. A plate girder has an I cross section built up by plates using riveting or welding. It is a deep flexural member used to carry loads that cannot be economically carried by rolled beam. In a plate girder the primary function of the flange plates is to resists bending moments by developing axial compressive and tensile stresses. The web plate resists the shear. For making the cross section efficient in resisting the in-plane bending, it is required that maximum material is placed as far away from the neutral axis as possible. From this point of view it is economical to keep the flanges as far apart as possible. For slender web premature failure of girder due to web buckling in shear might occur. Web buckling or vertical buckling occurs when the intensity of vertical compressive stress near the centre of the section becomes greater than the critical buckling stress for the web acting as a column. For built-up beams having greater ratio of depth to thickness of web, failure by vertical buckling may be more probable failure. The three buckling patterns that occur in the web are local buckling, Global buckling and interactive buckling. The suggested solutions to the problem include spreading of the load over a longer portion of the flange, provision of web stiffeners at point of load, and reaction or thickening of the web.

To increase the shear capacity of large steel plate girders, shaped webs may be used; in this situation corrugations usually parallel to the web depth and then welded to the flanges. Although many types of corrugations are possible, trapezoidal, rectangular, triangular and sinusoidal. Corrugated webs, though not yet commonly used for highway bridges in India, have been incorporated in Europe and Japan. So in this project, the buckling analysis of rectangular and triangular corrugated web is carried out using the finite element method. Finite element analysis (FEA) is widely used to solve almost all the engineering problems but converting the problems into simple differential equations. The finite element analysis is widely used since conducting a series of laboratory tests is not economical and laborious, so by numerical solution by using FEA the result obtained will be more precise, save cost and time.

II. FINITE ELEMENT METHOD

A general procedure for finite element analysis using ANSYS includes: Preprocessing, Solution and Post processing phases.
The geometric properties required for modelling are given as below

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Table 1: Geometric parameters for plate girder with flat web

Web height(h_w)	800 mm
Web thickness(t_w)	4 mm
	6 mm
Flange width(b_f)	240 mm
Flange thickness(t_f)	30 mm
Length	6000 mm

Table 2: Geometric parameters for triangular plate girder

Web height(h_w)	800 mm
Web thickness(t_w)	4 mm
	6 mm
Flange width(b_f)	240 mm
Flange thickness(t_f)	30 mm
Corrugation angle	30^0
	45^0
	60^0
	75^0
Length	6000 mm

Table 3: Geometric parameters for rectangular plate girder

Web height(h_w)	800 mm
Web thickness(t_w)	4 mm
	6 mm
Flange width(b_f)	240 mm
Flange thickness(t_f)	30 mm
Corrugation thickness(C_t)	20 mm
	30 mm
	50 mm
Corrugation width(C_w)	100 mm
	200 mm
	300 mm
	500 mm
Length	6000 mm

A. Preprocessing

The geometric modeling is done using ANSYS 15.

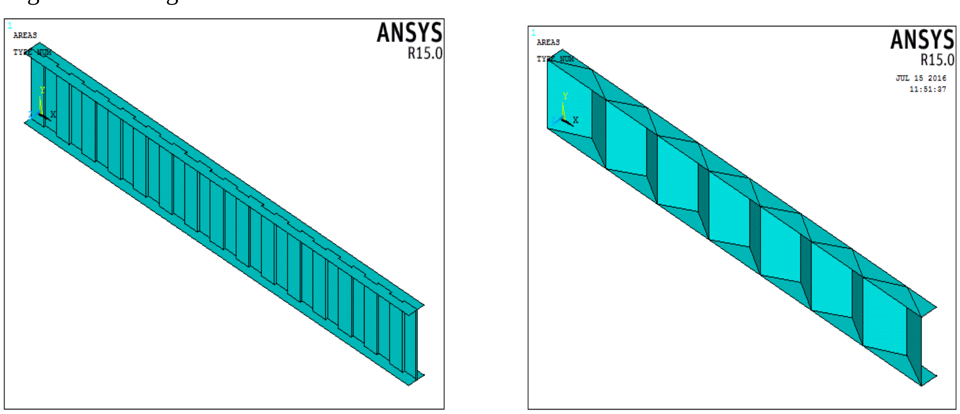

Fig 1. Rectangular model (b) triangular model

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The dimensions of the created shell models are same as the dimensions shown in Table 1, 2&3.The type of element chosen for finite element model idealization plays an important role in the prediction of actual behavior of the structure. From the finite element behavior study it is finalized that element SHELL 181is used. The geometry of shell 181 is as shown in Fig.2. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses.

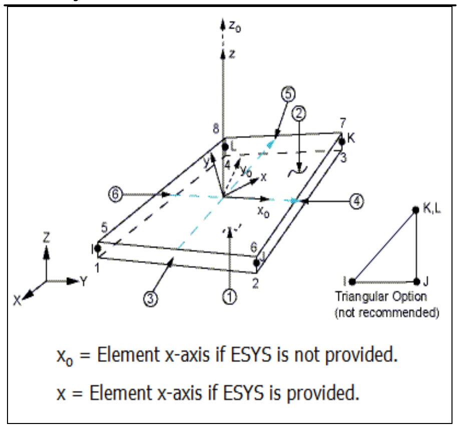

Fig 2. Shell 181 geometry

For this element type it is necessary to specify the proper dimensions such as area, diameter, wall thickness etc. Here the thickness is given to both the flanges and web as mentioned in Table 1, 2, &3."SHELL181"element also requires some material properties such as modulus of elasticity, Poisson's ratio etc. Here the material property Young's modulus E is assigned as $2x10^5$N/mm ^{2} and Poisson's ratio μ defaults to 0.3 for any steel section. After giving the material properties proper meshing is to be done for both flange and web 20 mm mesh size.

In the construction of the model some conditions were taken into consideration as the connection between the corrugated web and flanges. Fixed support conditions are considered the web is laterally supported. Unit load per node is considered for the analysis. The Eigen value solver uses a unit force to determine the necessary buckling load. Applying a load other than 1 will scale the answer by a factor of the load. After assigning unit load it is required to activate the prestress effect in order to perform Eigen value buckling analysis.

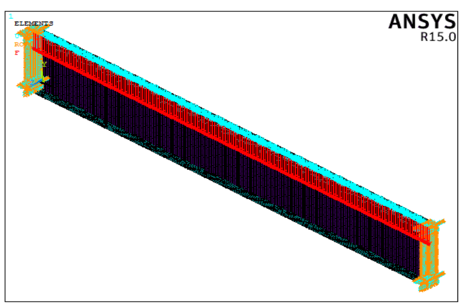

Fig 3. Boundary conditions of rectangular model

B. Analysis

Eigenvalue buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. It computes the structural eigenvalues for the given system loading and constraints. This is known as classical Euler buckling analysis. Buckling loads for several configurations are readily available from tabulated solutions. However, in real-life, structural imperfections and nonlinearities prevent most real world structures from reaching their eigenvalue predicted buckling strength; ie. It over-predicts the expected buckling loads. In this stage problem is subjected to buckling analysis. The errors and warnings are identified at this stage. After nullifying those errors the solution process gets completed.

C. Postprocessing

The output from the solution mainly consists of the eigenvalues. The eigenvalues represent the buckling load factors; if unit loads were applied in the static analysis, they are the buckling loads. Sometimes both positive and negative eigenvalues

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calculated. Negative Eigen values indicate that buckling occurs when the loads are applied in an opposite sense

III.PARAMETRIC STUDY

A parametric study of the models presented in this sections in order to examine the influence on the buckling load for each selected parameter in the different models. Further, the results will be plotted and compared together in graphs for each studied parameter. The parameters considered are:

Web thickness- 4,6 mm
Corrugation thickness – 20,30,50mm
Corrugation width- 100,200,400,500 mm
Corrugation angle- 30^0,45^0,60^0& 75^0

A. Stiffness comparison

Stiffness is the rigidity of an object, the extent to which it resists deformation in response to an applied force. The stiffness, *k*, of a body is a measure of the resistance offered by an elastic body to deformation. For an elastic body with a single degree of freedom (DOF), the stiffness is defined as: $k = \frac{F}{\delta}$; where, *F* is the force applied on the body.

IV. RESULTS AND DISCUSSIONS

A. Buckling load comparison of rectangular corrugated web

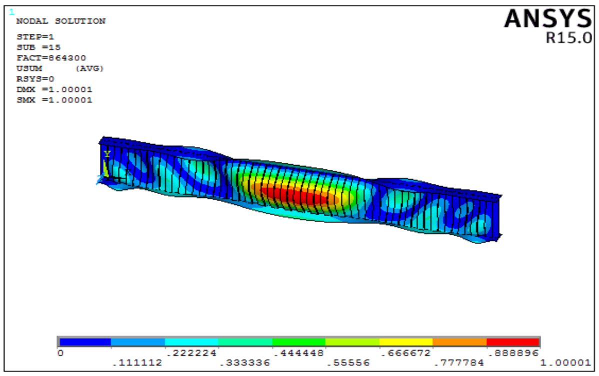

Fig 4. Buckled shapes of rectangular web

Table 4:: Buckling load (kN) for rectangular corrugated web t_W = 4 mm

Parameter	C_w= 100mm	C_w= 200 mm	C_w = 300mm	C_w=500mm
Girder with plane web	225.336	225.336	225.336	225.336
C_t = 20mm	759.467	739.303	678.228	633.718
C_t = 30mm	879.683	862.194	754.479	726.954
C_t = 50mm	1050	958.914	843.104	789.937

Table 5: Buckling load (kN) for rectangular corrugated web t_W = 6 mm

Parameter	C_w= 100mm	C_w= 200 mm	C_w = 300mm	C_w= 500mm
Girder with plane web	289.789	289.789	289.789	289.789
C_t = 20mm	864.3	861.641	780.942	706.640
C_t = 30mm	1010	988.599	868.595	834.689
C_t = 50mm	1140	1090	952.026	899.909

The comparison of buckling load of rectangular corrugated web for different web thicknesses is shown using line chart (fig 5) given below.

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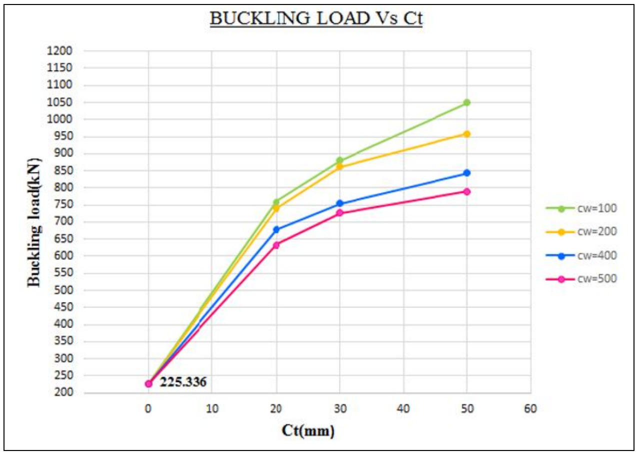

Fig 5. Buckling load V_s C_t for rectangular corrugated plate girder C_t=4mm

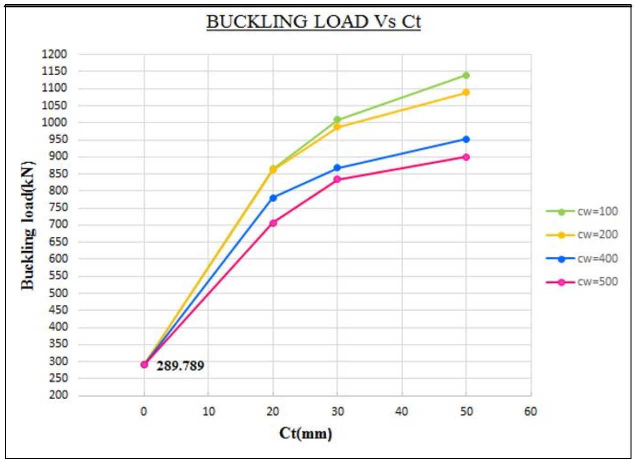

Fig 6. Buckling load V_s C_t for rectangular corrugated plate girder C_t=6mm

It shows that as the corrugation width (C_W) increases (from 100 to 500 mm) there is much decrease in buckling load for corrugation thickness C_t (20 to 50 mm) as compared to plane web plate girder.

B. Buckling load comparison of triangular corrugated web

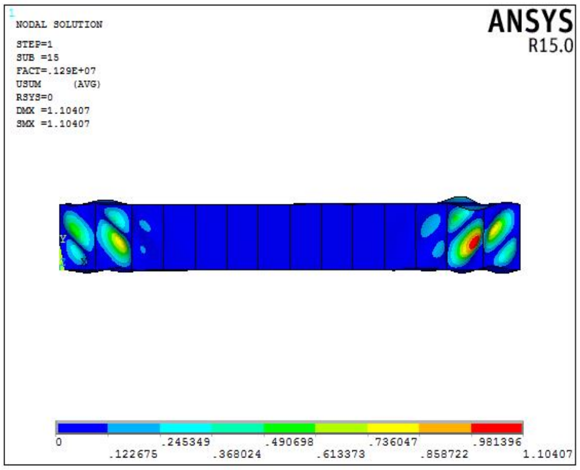

Fig 7. Buckled shape of triangular corrugated web

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Table 6: Buckling load (kN) for triangular corrugated web

Corrugation angle	Web thickness(t_w) 4mm	Web thickness(t_w) 6mm
Girder with plane web	225.336	289.789
30^0	1290	1610.09
45^0	1670.43	2410
60^0	1910.6	2940.87
75^0	2870.02	3720

The comparison of buckling load of triangular corrugated web plate girder for different web thicknesses and corrugation angle are shown using line chart given below.

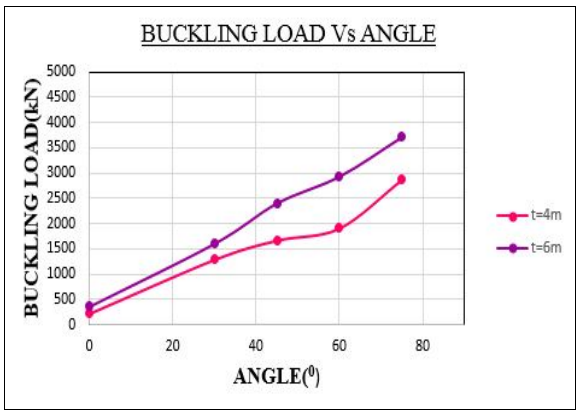

Fig 8. Buckling load Vs angle

From the above graphs it is seen that the plate girder with corrugated web of 6 mm thickness, corrugation angle 75^0 have the highest buckling load. So it can be concluded that buckling strength increases with increase in corrugation angle.

C. Comparison of weight and thickness calculation for plane web and rectangular web

A plane web plate girder with and without stiffeners were modelled and analysed in the finite element software. The weight of the corrugated web of 6 mm thickness, corrugation width of 100 mm and corrugation thickness of 50 mm, for which highest buckling strength was obtained from the analysis, was calculated and this equivalent weight was used to obtain the thickness of the plane web plate girder.

1) Weight Calculations

Data: Length, L = 6000 mm
Web height, h = 800 mm
Web thickness, t_w = 6 mm
Corrugation width, C_w = 100 mm
Corrugation thickness, C_t = 50 mm
Corrugation length, C. L. = (60 × 100) + (61 × 30) = 9050 mm
Self-weight of corrugated web = 9.050 × 0.006 × 7850 × 0.8 = 341.004 kg
Provide three pair of 12mm thick stiffeners at both ends of plane web with 3000mm spacing
Weight of stiffeners = 0.12 × 0.012 × 0.8 × 7850 × 6 = 54.26 kg

2) Thickness calculation

a) Without stiffeners

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$341.004 = 6 \times t_w \times 7850 \times 0.8$

$t_w = 9.0$ mm

(b) With stiffeners at Both Ends and in the Middle

$(341.004 - 54.26) = 6 \times t_w \times 7850 \times 0.8$

$t_w = 7.5$ mm

b) Without Stiffener

The geometric parameters of the plane web plate girder are given below:

Length, L = 6000 mm
Web height, h = 800 mm
Web thickness, t_w = 9 mm
Flange width, b_f = 240 mm
Flange thickness, t_f = 30 mm

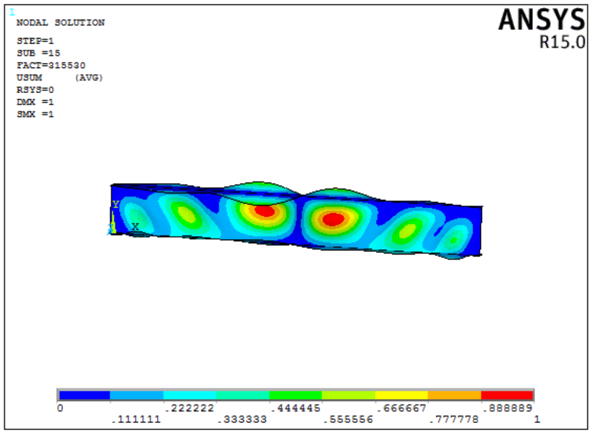

Fig 9. Buckled shape of plane web without stiffener

c) With Stiffeners at Both Ends and in the Middle

The geometric parameters of the plane web plate girder are given below

Length, L = 6000 mm
Web height, h = 800 mm
Web thickness, t_w = 7.5 mm
Flange width, b_f = 240 mm
Flange thickness, t_f = 30 mm

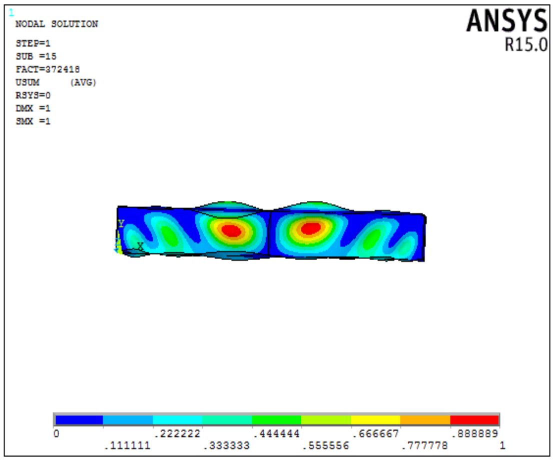

Fig.10. Buckled shape of plane web with stiffener

The bar chart below shows the variation in buckling load for a plate girder with plane and corrugated web

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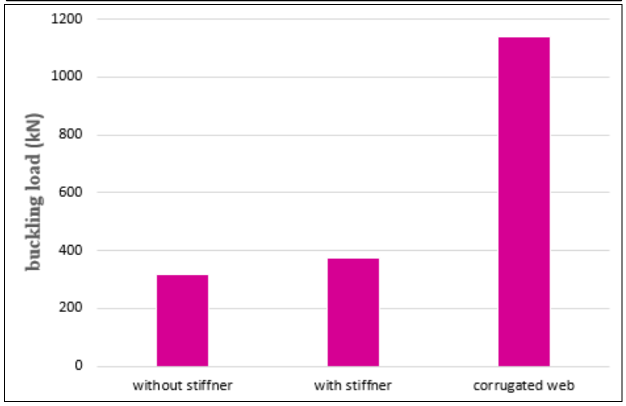

Fig 11. Buckling load comparison of corrugated web and plate girder with and without stiffener

From the above graph it can be concluded that the buckling strength of corrugated web plate girder is much more than that of a plane web plate girder.

B. Comparison of weight and thickness calculation for plane web and triangular web

1) Weight calculation

Data: Length, L = 6000 mm

Web height, h = 800 mm

Web thickness, t_w = 6 mm

Corrugation angle $=75^0$

Corrugation length, C. L. = (245x2x46) = 22540 mm

Self-weight of corrugated web = 22.540 × 0.006 × 7850 × 0.8 = 849 kg

Provide four pair of 20mm thick stiffeners at both ends of plane web with 2000mm spacing

Weight of stiffeners = 0.12 × 0.020 × 0.8 × 7850 × 8 = 120.576 kg

2) Thickness calculation

(a) Without stiffeners

$849 = 6 \times t_w \times 7850 \times 0.8$

$t_w = 23$ mm

(b) With stiffeners at Both Ends and in the Middle

$(849 - 120.576) = 6 \times t_w \times 7850 \times 0.8$

$t_w = 16$ mm

Here the dimensions from the theoretical calculations will be uneconomical.

C. Stiffness comparison

The tables below shows the stiffness obtained from software for corrugated web plate girders with different web thickness

Table 7

Stiffness (kN/mm) for rectangular corrugated plate girder t_W = 4 mm

Parameter	C_w= 100mm	C_w= 200 mm	C_w = 300mm	C_w= 500mm
C_t = 20mm	759.391	739.295	678.017	633.692
C_t = 30mm	874.323	861.995	753.357	726.677
C_t= 50 mm	1049.92	950.935	836.475	785.327

Table 8

Stiffness (kN/mm) for rectangular corrugated plate girder t_W = 6mm

Parameter	C_w= 100mm	C_w= 200 mm	C_w = 300mm	C_w= 500mm
C_t = 20mm	864.291	861.632	780.692	706.604
C_t = 30mm	1004.555	988.569	866.109	834.472
C_t=50mm	1139	1089.978	944.695	895.815

Table 9

Stiffness (kN/mm) for triangular corrugated web

Corrugation angle	Web thickness (t_w) 4mm	Web thickness (t_w) 6mm
30^0	1168.4	1610.09
45^0	1670	2410
60^0	1910.4	2940.06
75^0	2869.99	3720

The comparison of stiffness of corrugated web plate girder for different web thicknesses is shown using bar chart given below

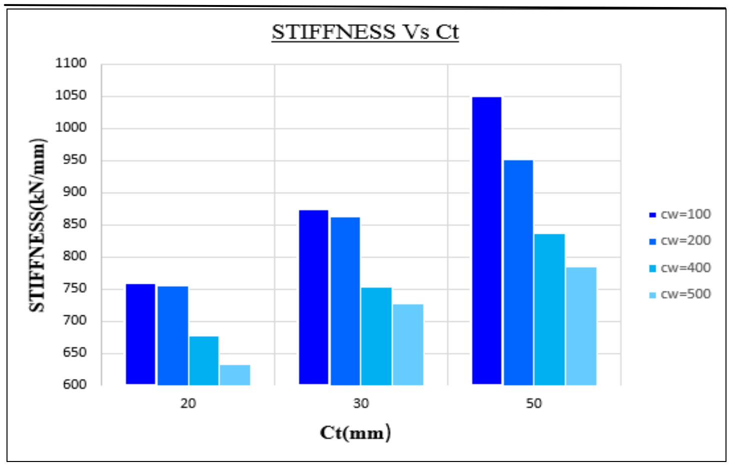

Fig 12. Variation in Stiffness for rectangular corrugated girder t_w=4mm

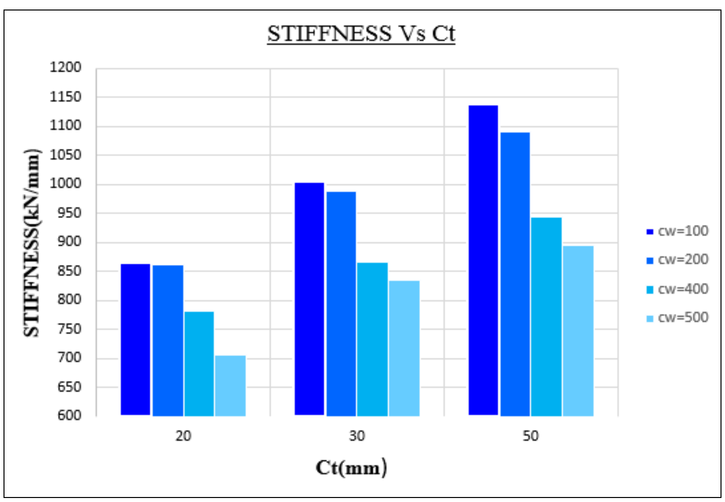

Fig 13. Variation in Stiffness for rectangular corrugated girder t_w=6mm

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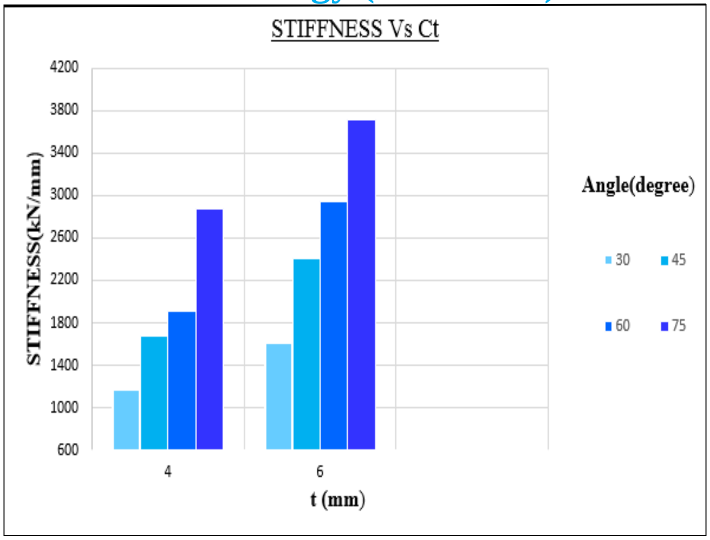

Fig 14. Variation in Stiffness for triangular corrugated girder for t_w= 4mm&6mm

From the above graphs it is seen that the plate girder with corrugated web of 6 mm thickness, corrugation width of 100 mm and corrugation thickness of 50 mm have the highest stiffness. So it is observed that stiffness increases with decrease in corrugation width.

From the above graphs it is seen that the plate girder with corrugated web of 6 mm thickness, corrugation corrugation angle 75^0 have the highest stiffness. So it is observed that stiffness increases with increase in corrugation angle 75^0.

V. CONCLUSIONS

In this paper the buckling strength of corrugated plate girders with different corrugation parameters were studied

A. It was observed that the buckling strength of corrugated web plate girder with 6 mm web thickness, corrugation width of 100 mm and corrugation thickness of 50 mm have the highest buckling load. So, it can be concluded that linear buckling strength increases with decrease in corrugation width.

B. The stiffness of corrugated web plate girder with 6 mm web thickness, corrugation width of 100 mm and corrugation thickness of 50 mm have the highest stiffness. So, it can be concluded that stiffness also increases with decrease in corrugation width.

C. When Corrugation angle increases from 30^0 to 75^0 both values of buckling strength and stiffness changes linearly. This is because increase in corrugation angle increases the number of slanting web increased throughout the length.

D. The buckling strength of plane web plate girders with and without stiffeners were compared to triangular web girder. The weight of the corrugated web of 6 mm thickness, corrugation angle $75^0$for which highest buckling strength was obtained from the analysis, was calculated and this equivalent weight was used to obtain the thickness of the plane web plate girder. The obtained dimension from theoretical calculation are not economical. In practical cases structures with such dimensions are impossible to built.

Thus it can be concluded that the buckling strength and stiffness of corrugated web plate girder increases with decrease in corrugation width, also, corrugated web plate girder have more buckling strength than plane web plate girder. So, corrugated web plate girder is much better than plane web plate girder. The use of corrugated webs allows for the use of thin plates without the need for stiffeners. Thus it considerably reduces the cost of fabrication and improves its fatigue life. It could eliminate the usage of larger thickness and stiffeners that contributed to the reduction in plate girder weight and cost.

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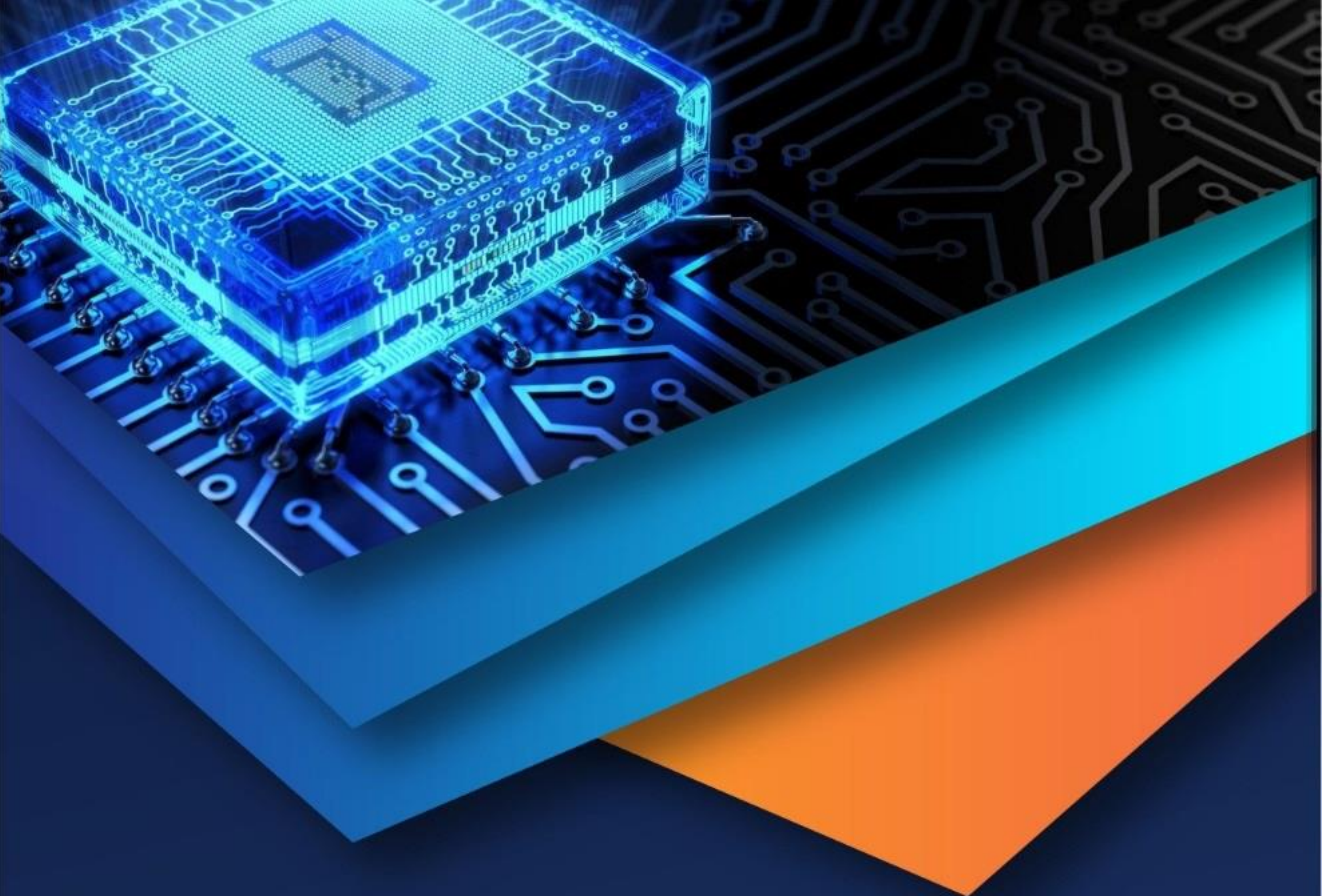

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