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STRESS, DISPLACEMENT, AND BUCKLING ANALYSIS OF A STEEL PLATE GIRDER

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Abstract - With the increase in population and development of civilization, the demand for transportation infrastructure is increased at peak rate. Especially in towns due to rapid industrialization, the demand is extremely high. Adapting the construction of plate girder bridges is the efficient and economical way of meeting the traffic demands for the purpose of railways and also for the bridges connecting the land masses separated by water bodies. Hence it is mandatory for a Structural Engineer to be knowledgeable about the analysis of such plate girders employed in the construction of bridges and also as heavy beams in buildings where large open area is required. Advancements of Finite Element Analysis software packages have significantly made ease to the designers in achieving the best optimum results with utmost precision and accuracy in their work. The finite element analysis of steel plate girder in this study is carried out using sophisticatedly programmed software ABAQUS SIMULIA in a much feasible manner in least possible time. In this study an attempt has been made to evaluate the different types of stresses, displacements and buckling mode shapes of 8 different steel plate girder models and the results have been compared of all the different plate girders comprising diverse shaped (viz., circular, elliptical, chamfered square) web openings with that of the plate girders without web openings taking into consideration the two different sets of models, one set of models comprising flanges thickness size bearing 25mm and the other set of models bearing flange thickness 40mm. After performing the entire analysis it has been found that plate girders with soft web openings are considerably showing good performance and leading to the efficient, economical and safe design saving the overall material cost.

Keywords—Stress, Buckling, Displacement, Finite Element Method, Web Openings

I. INTRODUCTION

Plate girder(basically derives its name due to the composition of plate elements in its cross section) is a built beam(flexural member) with flanges formed of angle-bars and plates or sometimes of channels and a web of one or more plates made continuous from end to end. With modern enlargement in the consumption of high strength steel, the unsteadiness problems are becoming even more significant in steel structures' design. Plate girder provides utmost flexibility and economy. Plate girders offer an exclusive flexibility in fabrication and the cross section can be regular or irregular along the length. It is likely to put the precise amount of steel requisite at each section along the span of the girder by varying the flange areas and maintaining the identical depth dimension of the girder. Plate girders offer an exclusive flexibility in fabrication and the cross section can be regular or irregular along the length.

Stiffeners are as a rule designed primarily on the basis of the shear stresses in the web. They are supposed to help in carrying the shear into the web and lower flange. Intermediate crossways stiffeners together along with the web are used to offer post-elastic shear buckling resistance by the tension field action and are generally placed near the supports and at the places of occurrence of large concentrated loads.

ABAQUS was designed primarily as a production code for solving nonlinear problems. This program must be run on a fairly big computer (such as a mainframe or a super-minicomputer) so that a reasonably large core size can be allocated in order to maintain its efficiency. The finite element formulations of ABAQUS were time after time derived on a firm theoretical basis. ABAQUS has very high quality coding style and programming discipline and is relatively machine independent in which all data are well protected from accidental over-writing or delegation.

Figure-1 Typical Elevation of a Plate Girder

II. GENERAL CONSIDERATIONS FOR A PLATE GIRDER

At high shear concentration locations in the web section of the girder typically in close proximity to the supports and adjacent to the neutral axis, the principal planes will be sloping to the horizontal and the resultant major stresses will be diagonal tension and diagonal compression.

The flanges are the significant members of the girder since they provide major proportion of the flexural strength; hence most of the steel concentration must lie within the flanges zones which ultimately results in deep webs with thinner cross sections and prone to buckling.

There are three fundamental types of buckling to be considered while dealing with a plate girder design:

1) Bending Buckling (Longitudinal Type)
2) Shear Buckling (Diagonal Type)
3) Bearing Buckling (Vertical Type)

At the point of impending buckling, the web loses its strength to support compression which is acting diagonally, and this resulting stress is shifted to adjacent flanges and the transverse stiffeners. The flanges resist the horizontal component of this oncoming stress and the transverse stiffeners resist the vertical component. The web will be required to resist only the tension which is acting diagonally and hence the terminology after it named tension-field action.

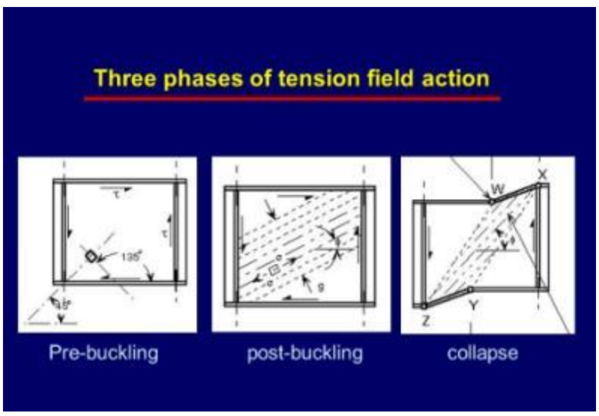


Figure-2(a) Different phases of Tension Field Action

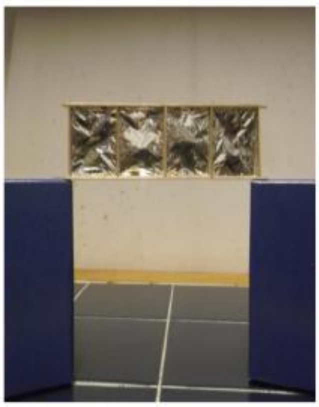


Figure-2(b) Girder Unloaded

Girder Loaded demonstrating Tension Field Action in Web

III. OBJECTIVES

The main objectives of this research work are to carry out the following tasks:

- To carry out Stress analysis of the plate girder with and without web openings
- To perform Displacement analysis of the plate girders with and without web openings
- To perform Buckling analysis of the plate girders with and without web openings

IV. DESCRIPTION OF MODEL

There are a total of 8 models split into two sets of 4 models each, of which one set of models having flanges thickness (t_f=25mm) and the other set of models having flanges thickness (t_f=40mm). The remaining dimensions of the girder i.e., Thickness of the Web (t_w=16mm); Width of the flanges (b_f=650mm) and Depth of the web (D_w=3000mm) are the same for both the sets of models. The span of the steel plate girder in all the models is 36m. There are a total of 9 stiffeners (intermediate along with end stiffeners) provided on each side of the web with the dimensions of the plate section stiffeners being 300mm wide, 3000mm deep and 12mm thickness in all the models.

The elastic material properties are employed for the general static and buckling analysis of the plate girder. The elastic parameters allotted to all the models are:

i. Young's Modulus of Elasticity is taken as 2.1×10^5 N/mm^2
ii. Poisson's ratio is taken as 0.3
iii. Density of the steel material is taken as 7850kg/m^3

The Loading imparted on the girder comprises of:

i) Uniformly Distributed Loading of intensity 80 N/mm acting on the surface of the top flange
ii) Two Point Loads each of magnitude 90000N acting at the centre of top surface of the flange at the position of third stiffener from either ends of the plate girder

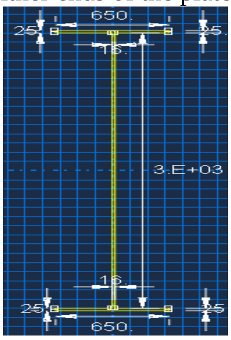


Figure-3 Plate Girder C/s (t_f=25mm)

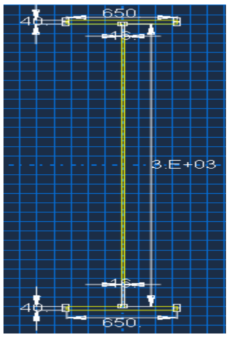


Figure-4 Plate Girder C/s (t_f=40mm)

MODEL-1: Plate girder without web openings: (Flange thickness: 25mm)

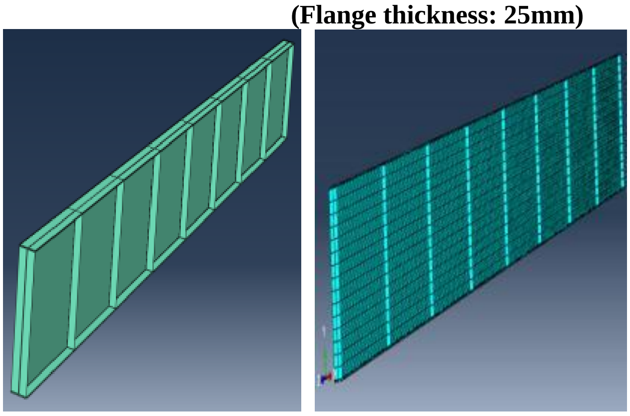


Figure-5 Plate Girder without Web Openings Elevation & Meshing

MODEL-2: Plate girder with circular web openings: (Flange thickness: 25mm)

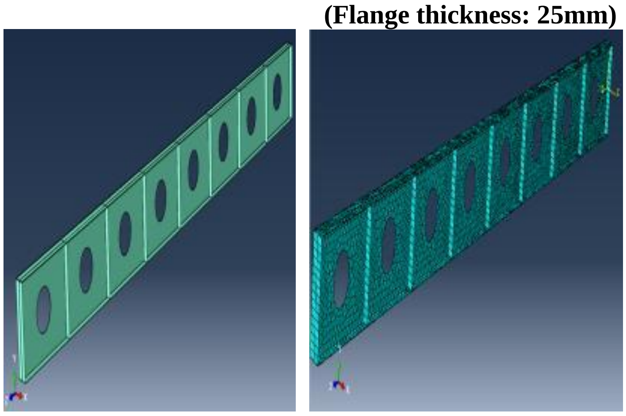


Figure-6 Plate Girder with Circular Web Openings Elevation & Meshing

MODEL-3: Plate girder with elliptical web openings: (Flange thickness: 25mm)

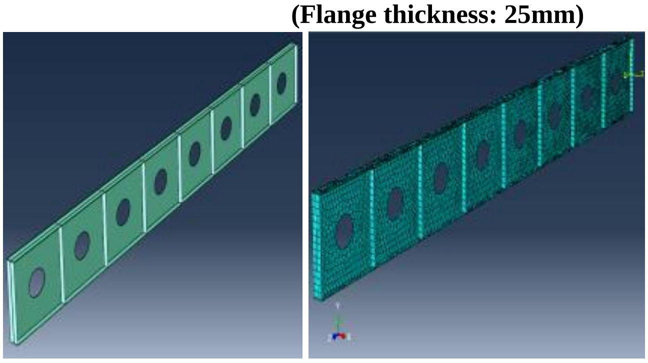


Figure-7 Plate Girder with Elliptical Web Openings Elevation & Meshing

MODEL-4: Plate girder with chamfered square web openings: (Flange thickness: 25mm)

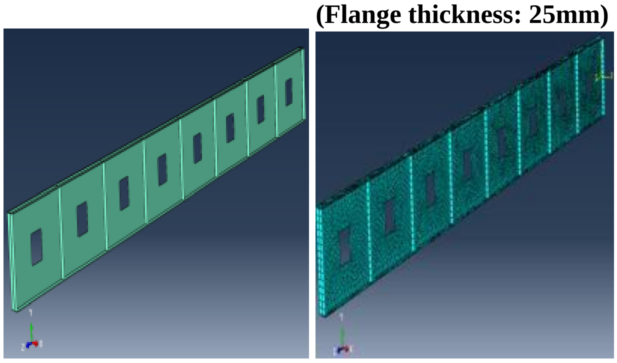


Figure-8 Plate Girder with Chamfered Square Web Openings Elevation & Meshing

Similar is the second set of 4 models (Model-5, Model-6, Model-7, Model-8) having the thickness of the flanges ((t_f=40mm).

V. ANALYSIS

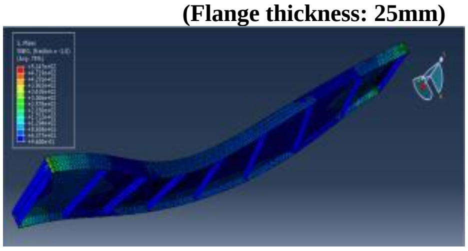
*A. **<u>Stress Analysis</u>***

The Von mises stresses and maximum/minimum principal stresses for Models are analysed by general static analysis in the ABAQUS tool. A comparative study of the obtained results of steel plate girder models with and without web openings is done. The analyses outcomes are given below for different models:

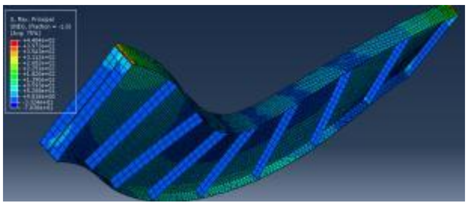
TABLE 1
MAXIMUM MAGNITUDE OF VON-MISES STRESSES, MAXIMUM & MINIMUM PRINCIPAL STRESSES

MODEL NUMBER	FLANGE THICKNESS	VON-MISES STRESS (MPa)	MAXIMUM PRINCIPAL STRESS (MPa)	MINIMUM PRINCIPAL STRESS (MPa)
Model-1	25mm	$5.147\text{x}10^2$	$4.404\text{X}10^2$	$2.543\text{x}10^2$
Model-2	25mm	$5.089\text{x}10^2$	$4.692\text{X}10^2$	$2.944\text{x}10^2$
Model-3	25mm	$4.953\text{x}10^2$	$4.572\text{X}10^2$	$2.713\text{x}10^2$
Model-4	25mm	$4.953\text{x}10^2$	$6.459\text{X}10^2$	$5.952\text{x}10^1$
Model-5	40mm	$4.127\text{x}10^2$	$4.319\text{X}10^2$	$4.469\text{x}10^2$
Model-6	40mm	$4.391\text{x}10^2$	$4.893\text{X}10^2$	$4.968\text{x}10^1$
Model-7	40mm	$4.718\text{x}10^2$	$4.572\text{X}10^2$	$6.11\text{x}10^2$
Model-8	40mm	$4.077\text{x}10^2$	$4.893\text{X}10^2$	$5.044\text{x}10^1$

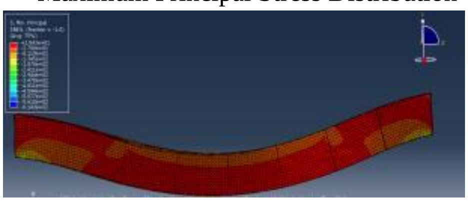
<u>MODEL-1</u>: <u>Plate girder without web openings:</u>
(Flange thickness: 25mm)



Von Mises Stress Distribution



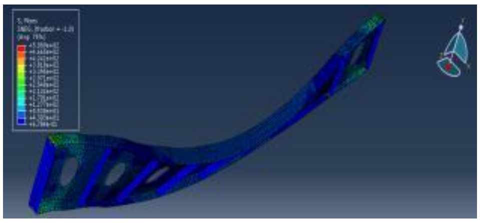
Maximum Principal Stress Distribution



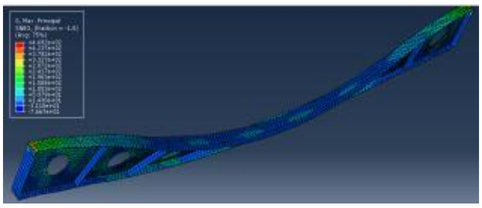
Minimum Principal Stress Distribution

Figure-9 Stresses Distribution in Model-I

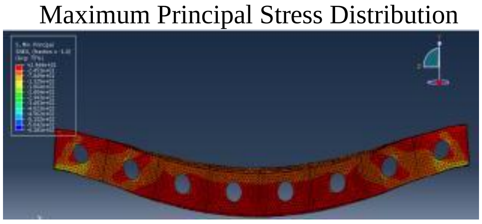
<u>MODEL-2</u>: <u>Plate girder with circular web openings:</u>
(Flange thickness: 25mm)



Von Mises Stress Distribution



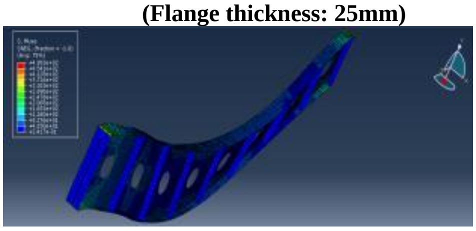
Maximum Principal Stress Distribution



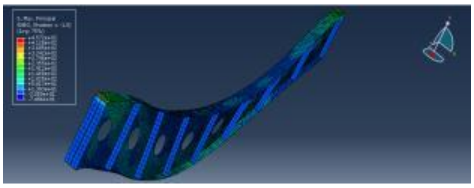
Minimum Principal Stress Distribution

Figure-10 Stresses Distribution in Model-II

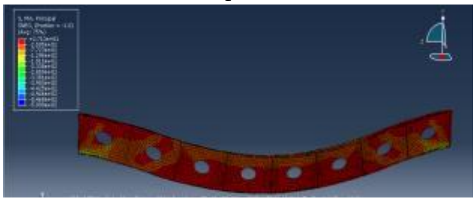
MODEL-3: Plate girder with elliptical web openings:
(Flange thickness: 25mm)



Von Mises Stress Distribution



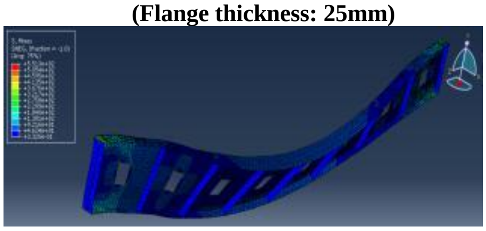
Maximum Principal Stress Distribution



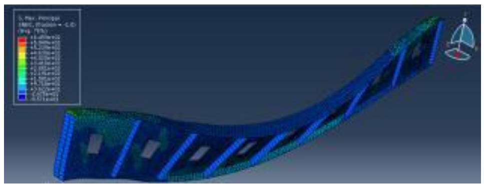
Minimum Principal Stress Distribution

Figure-11 Stresses Distribution in Model-III

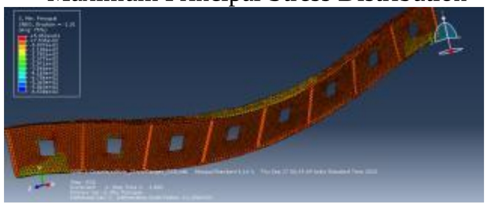
MODEL-4: Plate girder with chamfered square web openings:
(Flange thickness: 25mm)



Von Mises Stress Distribution



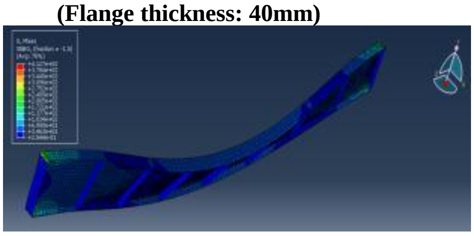
Maximum Principal Stress Distribution



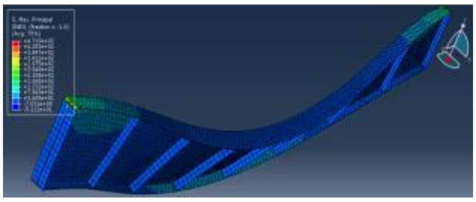
Minimum Principal Stress Distribution

Figure-12 Stresses Distribution in Model-IV

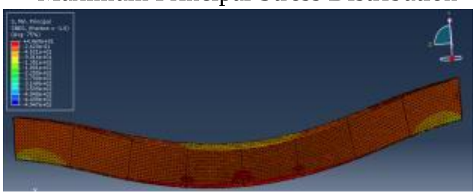
MODEL-5: Plate girder without web openings:
(Flange thickness: 40mm)



Von Mises Stress Distribution



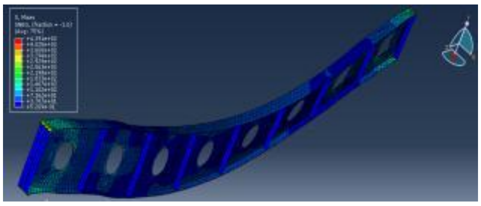
Maximum Principal Stress Distribution



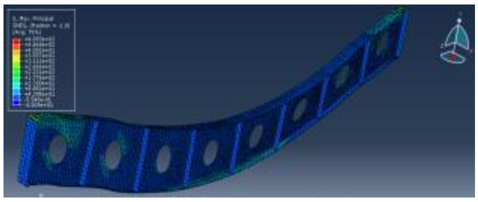
Minimum Principal Stress Distribution

Figure-13 Stresses Distribution in Model-V

MODEL-6: Plate girder with circular web openings:
(Flange thickness: 40mm)



Von Mises Stress Distribution

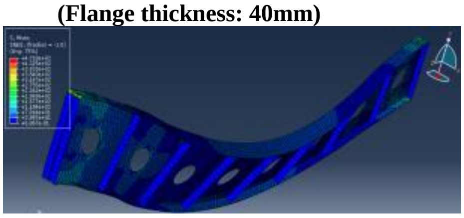


Maximum Principal Stress Distribution

Minimum Principal Stress Distribution

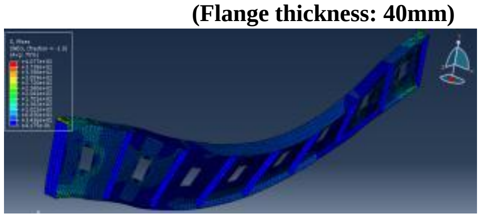
Figure-14 Stresses Distribution in Model-VI

MODEL-7: Plate girder with elliptical web openings:
(Flange thickness: 40mm)

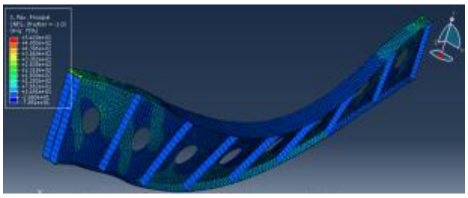


Von Mises Stress Distribution

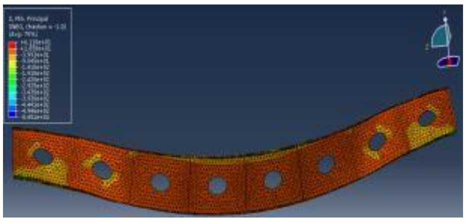
MODEL-8: Plate girder with chamfered square web openings:
(Flange thickness: 40mm)



Von Mises Stress Distribution

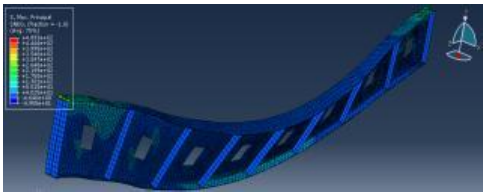


Maximum Principal Stress Distribution

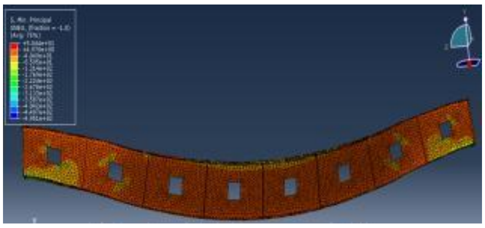


Minimum Principal Stress Distribution

Figure-15 Stresses Distribution in Model-VII



Maximum Principal Stress Distribution



Minimum Principal Stress Distribution

Figure-16 Stresses Distribution in Model-VIII

B. ***Displacement Analysis***

TABLE II
MINIMUM & MAXIMUM DISPLACEMENT OF EACH MODEL DETERMINED BY GENERAL STATIC ANALYSIS

Model No.	Flange Thickness	Maximum Displacement (mm)	Minimum Displacement (mm)	% Variation of deflection
Model-1	25mm	24.39	2.032	-
Model-2	25mm	30.21	2.517	23.8622386
Model-3	25mm	25.46	2.122	4.38704387
Model-4	25mm	28.26	2.355	15.8671587
Model-5	40mm	20.09	1.674	-
Model-6	40mm	20.66	1.722	2.83723245
Model-7	40mm	21.57	1.798	7.36684918
Model-8	40mm	21.66	1.805	7.81483325

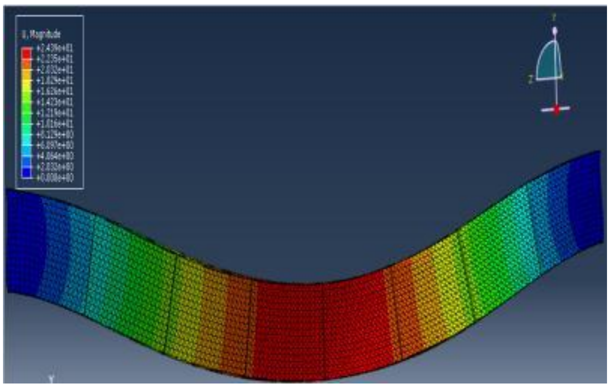


Figure-17 Displacement Distribution in Model-I

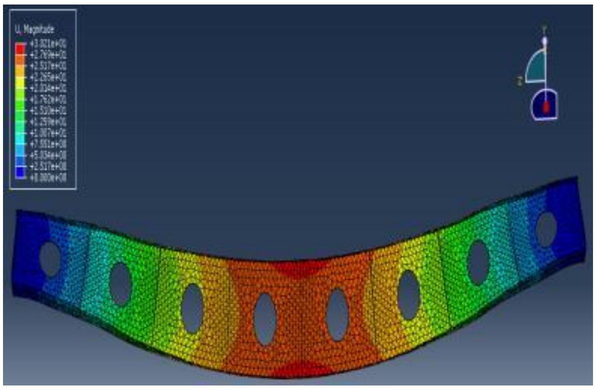


Figure-18 Displacement Distribution in Model-II

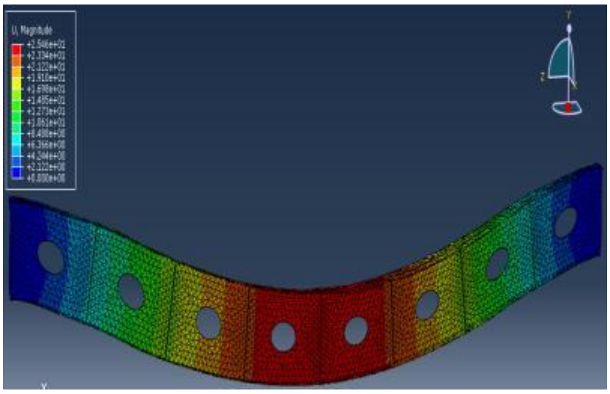


Figure-19 Displacement Distribution in Model-III

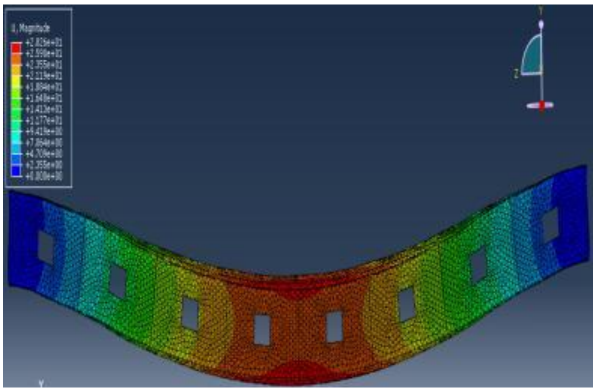


Figure-20 Displacement Distribution in Model-IV

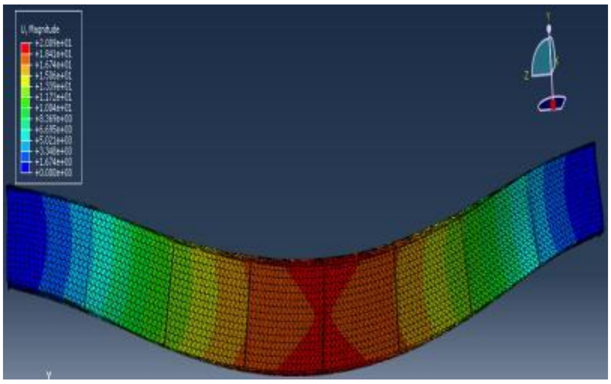


Figure-21 Displacement Distribution in Model-V

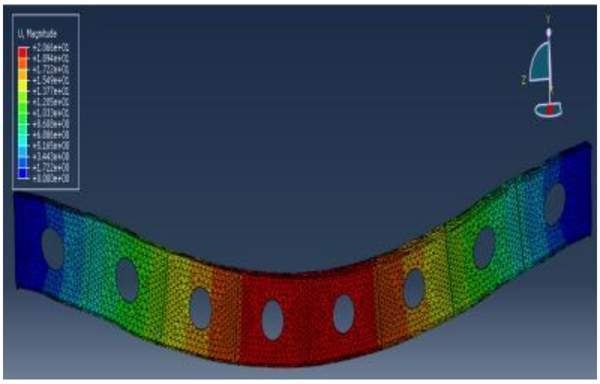


Figure-22 Displacement Distribution in Model-VI

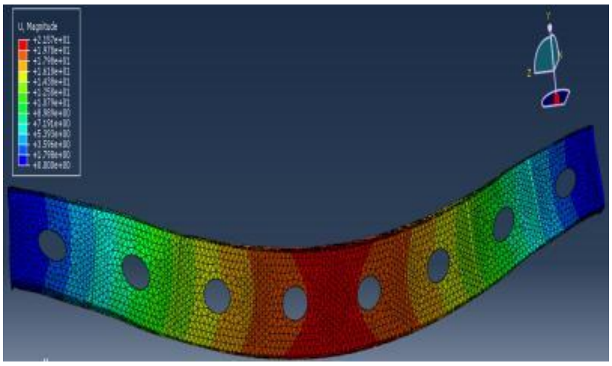


Figure-23 Displacement Distribution in Model-VII

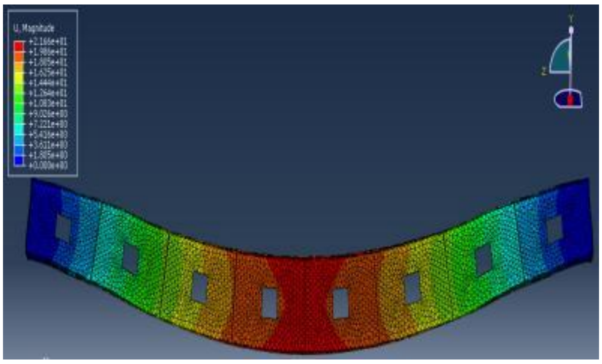
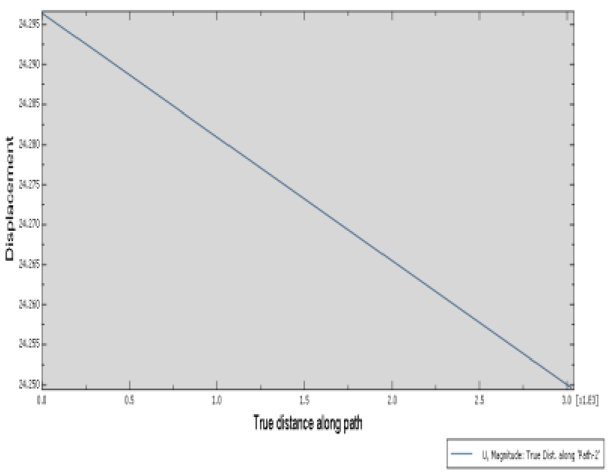


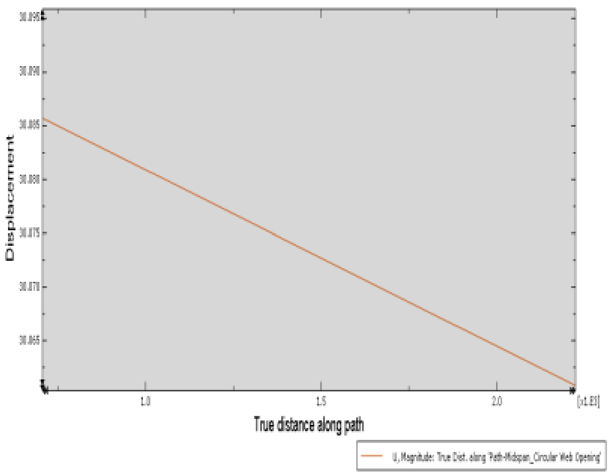
Figure-24 Displacement Distribution in Model-VIII

<u>MODEL-1</u>: <u>Plate girder without web openings:</u>
(Flange thickness: 25mm)



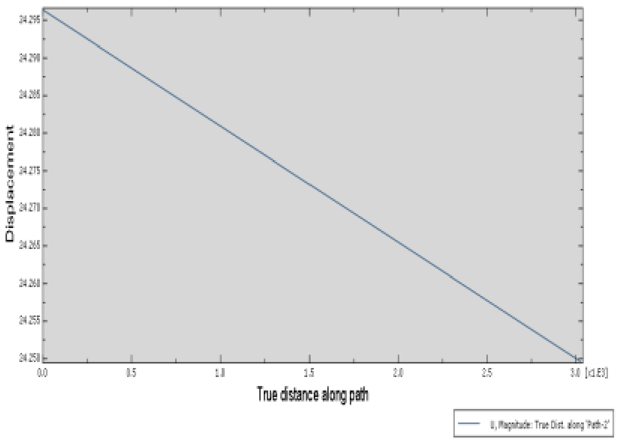
Plot 1: Displacement variation across the cross-section at mid-span in Model-I

<u>MODEL-2</u>: <u>Plate girder with circular web openings:</u>
(Flange thickness: 25mm)



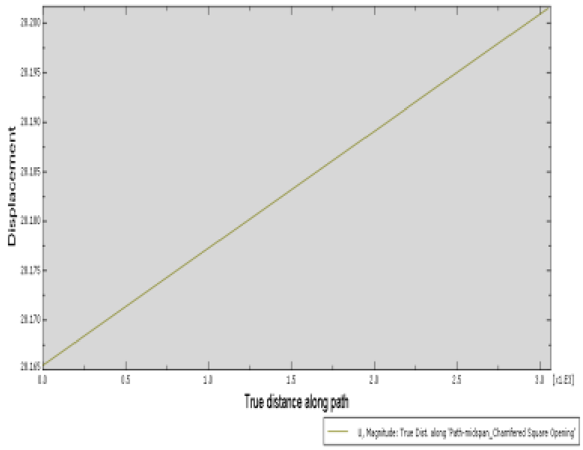
Plot 2: Displacement variation across the cross-section at mid-span in Model-II

MODEL-3: Plate girder with elliptical web openings:
(Flange thickness: 25mm)



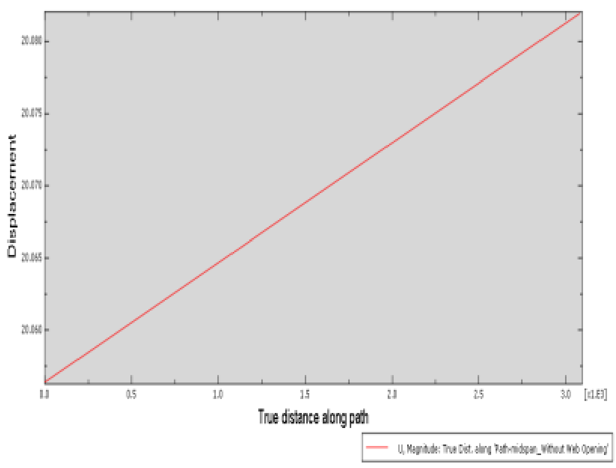
Plot 3: Displacement variation across the cross-section at mid-span in Model-III

MODEL-4: Plate girder with square chamfered web openings:
(Flange thickness: 25mm)



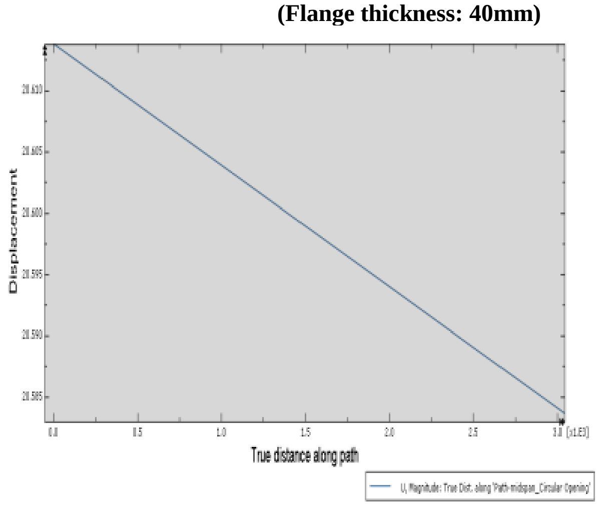
Plot 4: Displacement variation across the cross-section at mid-span in Model-IV

MODEL-5: Plate girder without web openings:
(Flange thickness: 40mm)



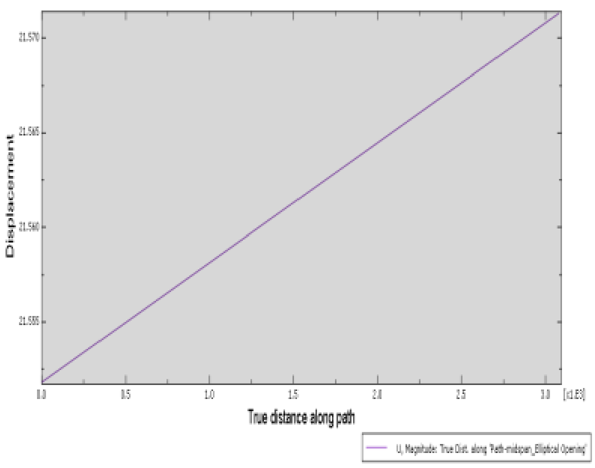
Plot 5: Displacement variation across the cross-section at mid-span in Model-V

MODEL-6: Plate girder with circular web openings:
(Flange thickness: 40mm)



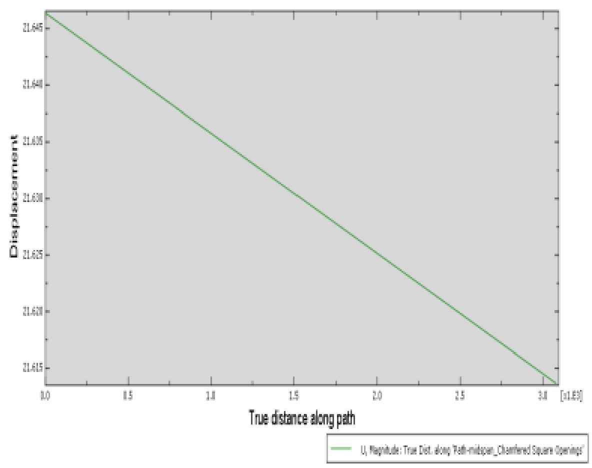
Plot 6: Displacement variation across the cross-section at mid-span in Model-VI

MODEL-7: Plate girder with elliptical web openings:
(Flange thickness: 40mm)



Plot 7: Displacement variation across the cross-section at mid-span in Model-VII

MODEL-8: Plate girder with square chamfered web openings:
(Flange thickness: 40mm)



Plot 8: Displacement variation across the cross-section at mid-span in Model-VIII

C. ***Buckling Analysis***

Buckling is a phenomenon which will take place because of imperfections in the geometry, loads, and supports and most often causes disastrous failure or turns the structure unusable as it occurs very abruptly, without any little prior caution, so there is roughly no possibility for remedial action. Linear-buckling analyses compute buckling load intensities that grounds buckling and their associated buckling modes. Finite Element Analysis programs grant calculations of an outsized number of buckling modes and the associated buckling-load factors. The Buckling-Load Factor is articulated by a numeral which the applied external load/force have got to be multiplied by (or divided — depending on the meticulous FEA package) to attain the buckling-load intensity.

The buckling mode symbolizes the shape the structure presumes when it buckles in a particular mode, but says nothing about the statistical values of the displacements or stresses. The statistical values can be displayed, but are merely relative. This is in close equivalence to modal analysis, which computes the natural frequency and makes available qualitative information on the modes of vibration (modal shapes), but not on the actual magnitude of displacements.

As an outcome of discretization error, linear buckling analysis overvalues the buckling load and provides non-conformist results. On the other hand, Buckling Load Factors are also overestimated because of modeling miscalculations. Finite element models most frequently characterize geometry with no flaws, and loads and supports are applied with great accuracy with no offsets. In actuality though, loads are all the time applied with offsets, faces are never perfectly flat, and supports are never perfectly rigid. Even if supports are mocked-up as elastic, their stiffness is by no means uniformly disseminated. Imperfections are for all time present in the real world. Considering the combined effect of discretization miscalculation and modeling miscalculation, designers should interpret the results of linear buckling analysis with caution.

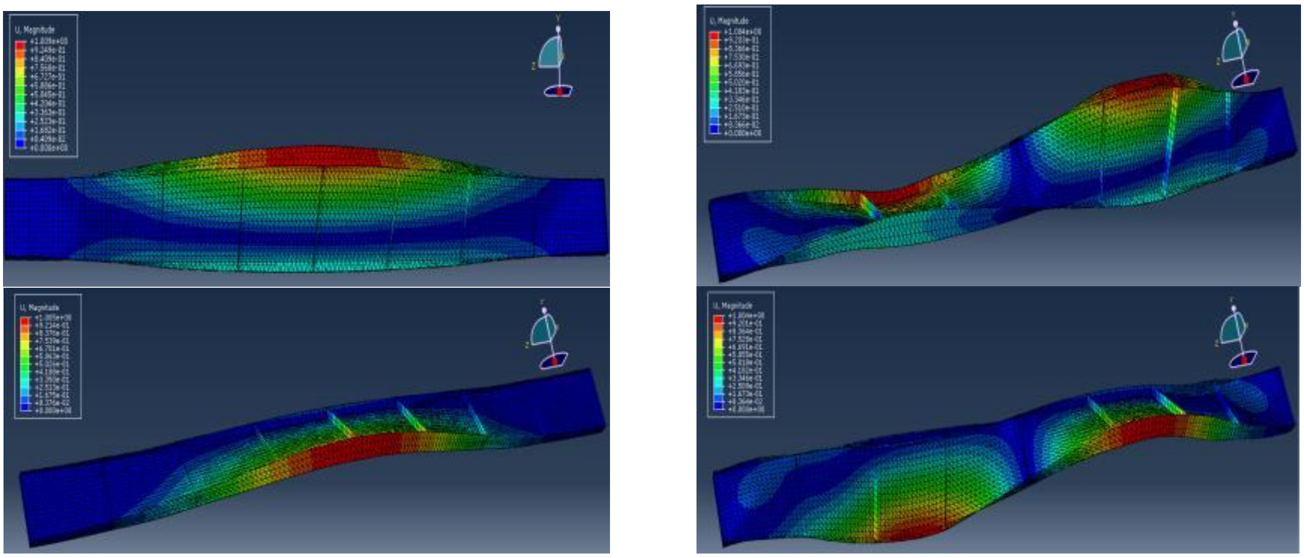


Figure-25 Buckling Mode Shapes of Model-I

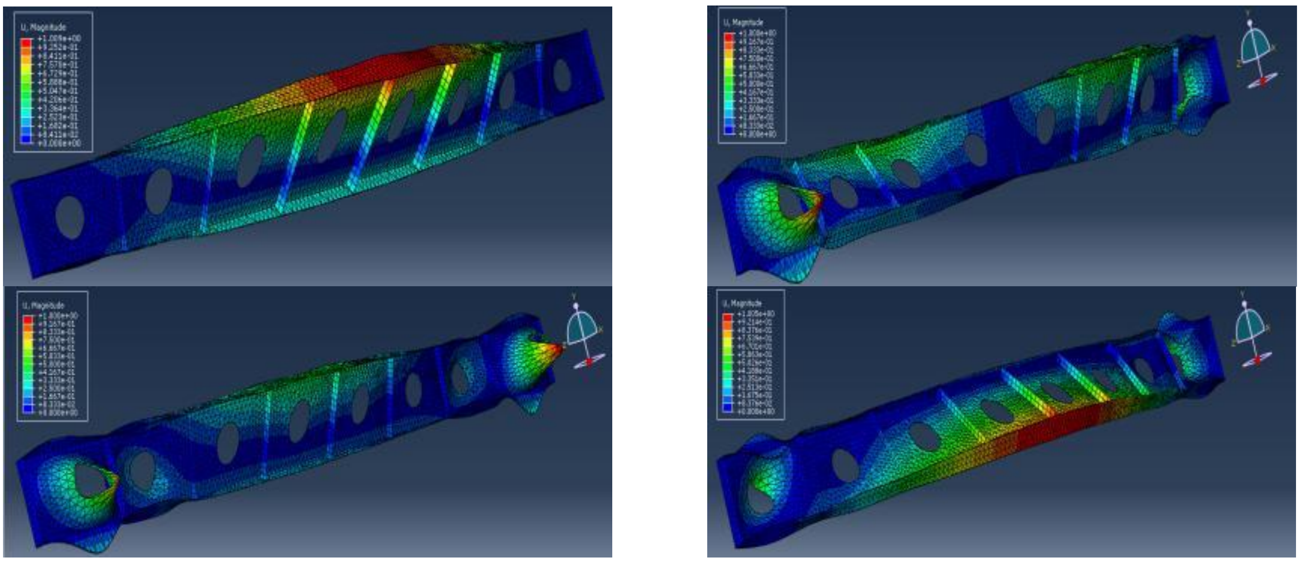


Figure-26 Buckling Mode Shapes of Model-II

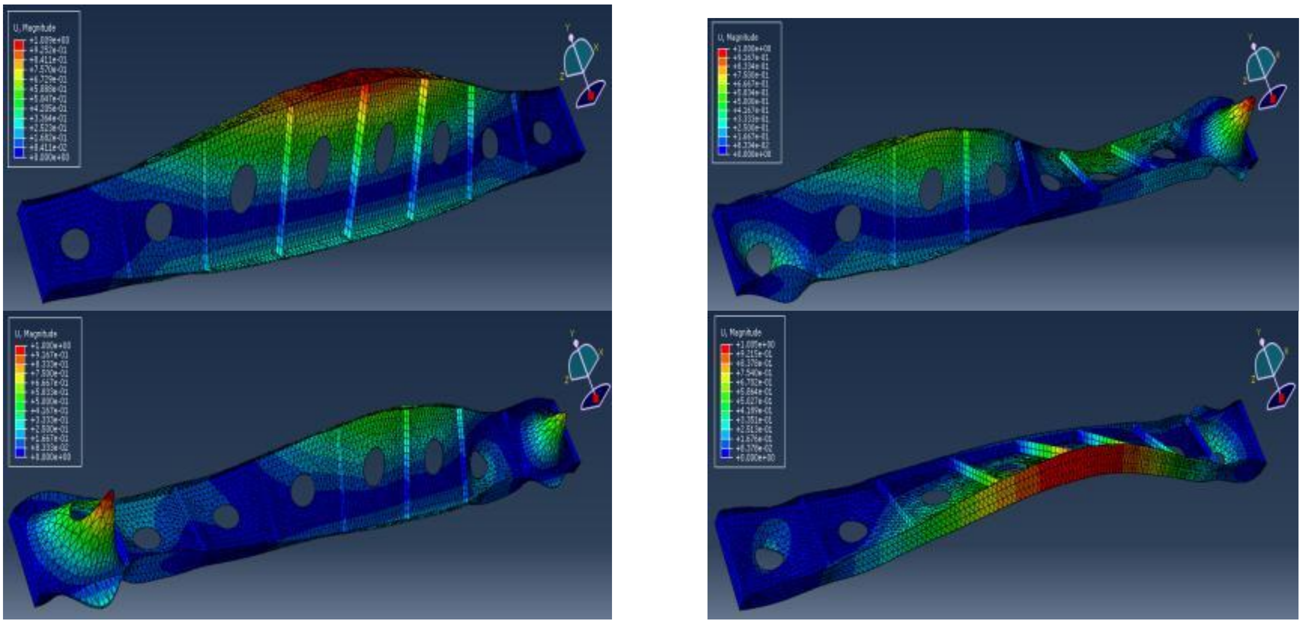


Figure-27 Buckling Mode Shapes of Model-III

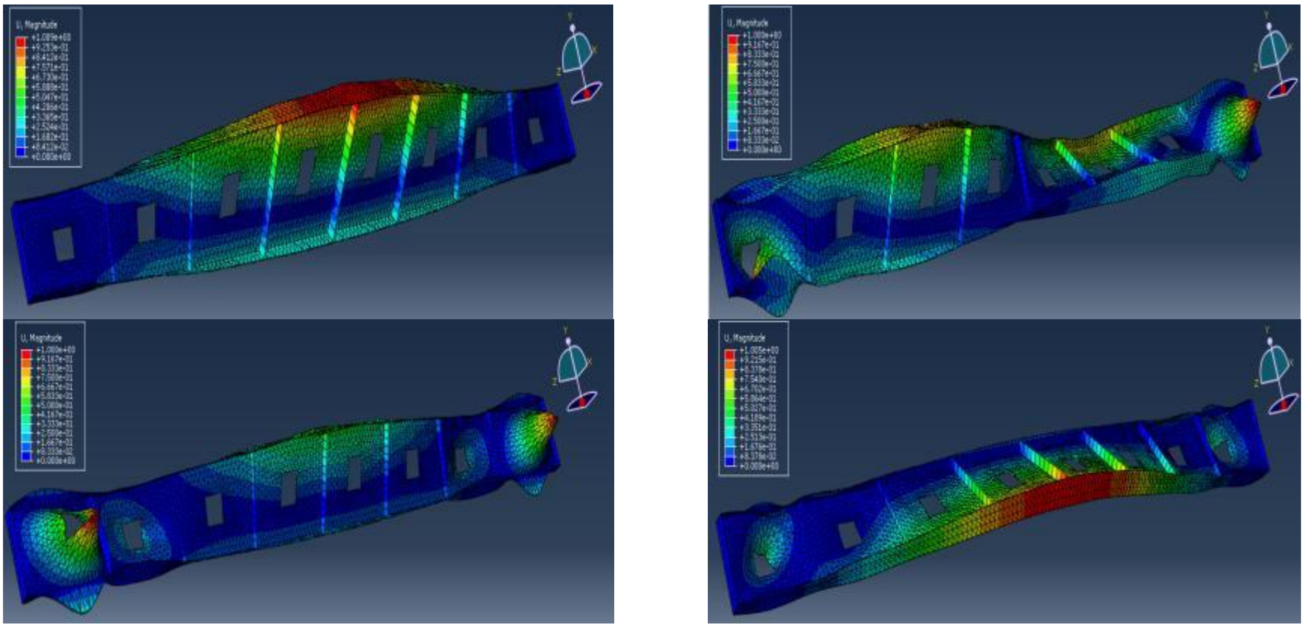


Figure-28 Buckling Mode Shapes of Model-IV

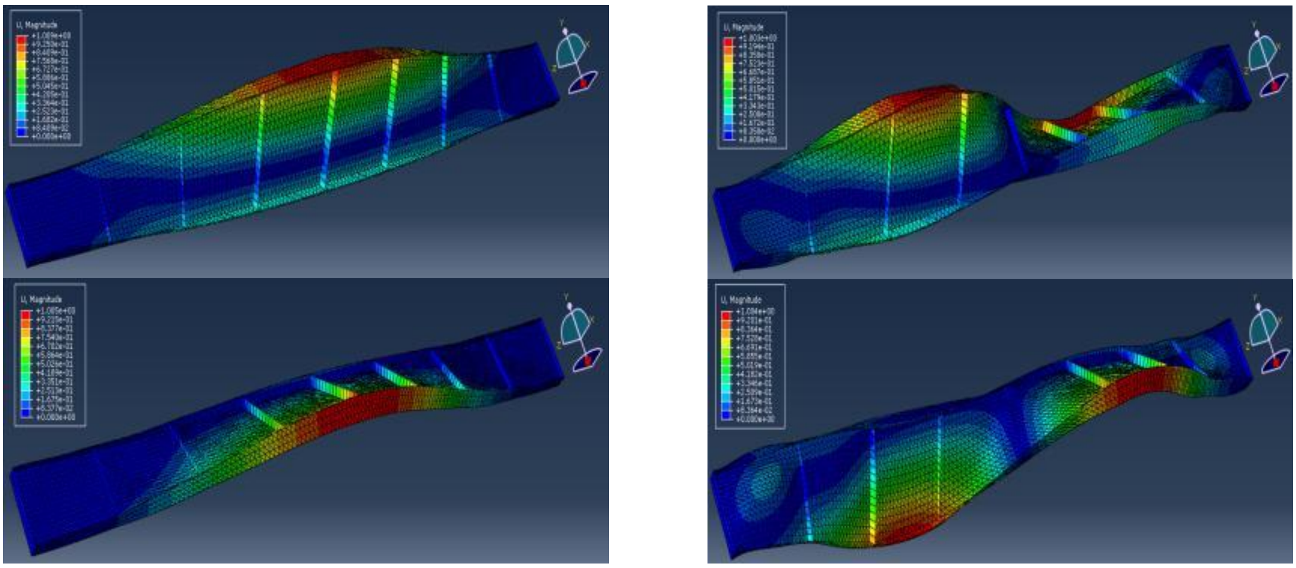


Figure-29 Buckling Mode Shapes of Model-V

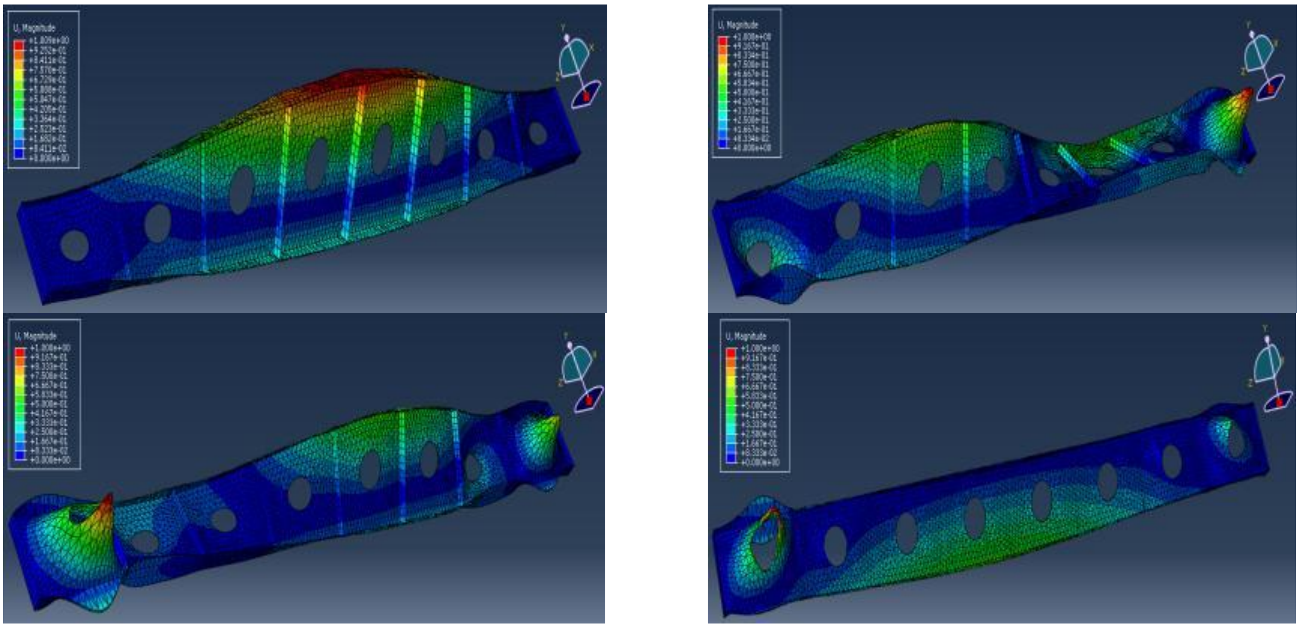


Figure-30 Buckling Mode Shapes of Model-VI

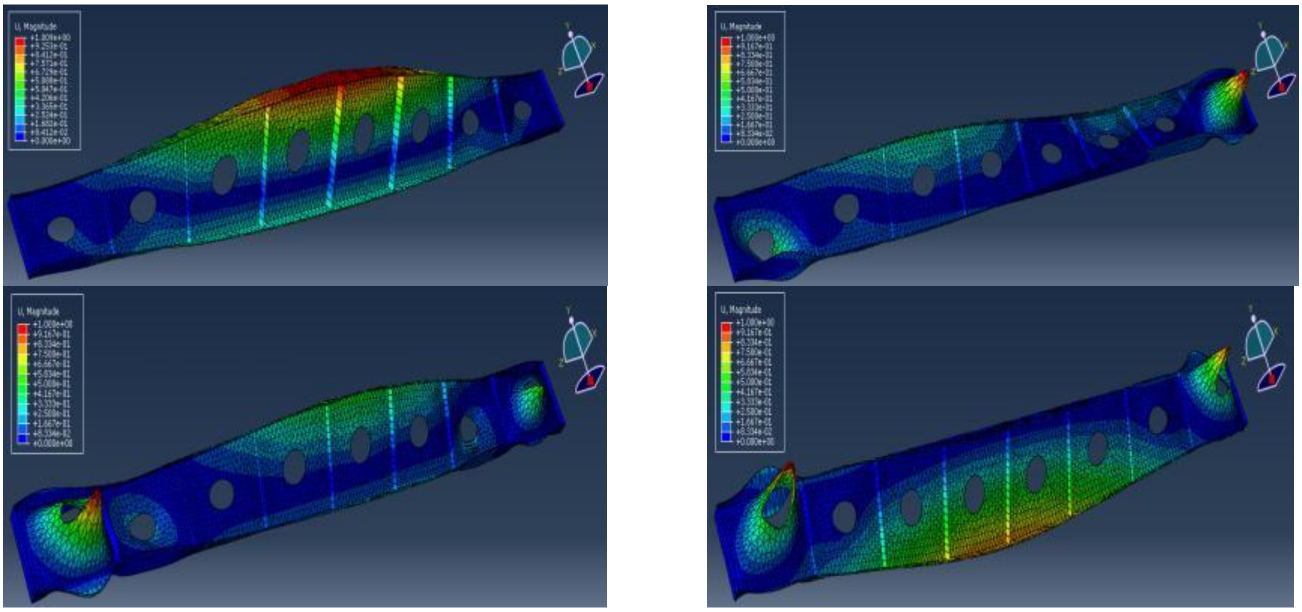


Figure-31 Buckling Mode Shapes of Model-VII

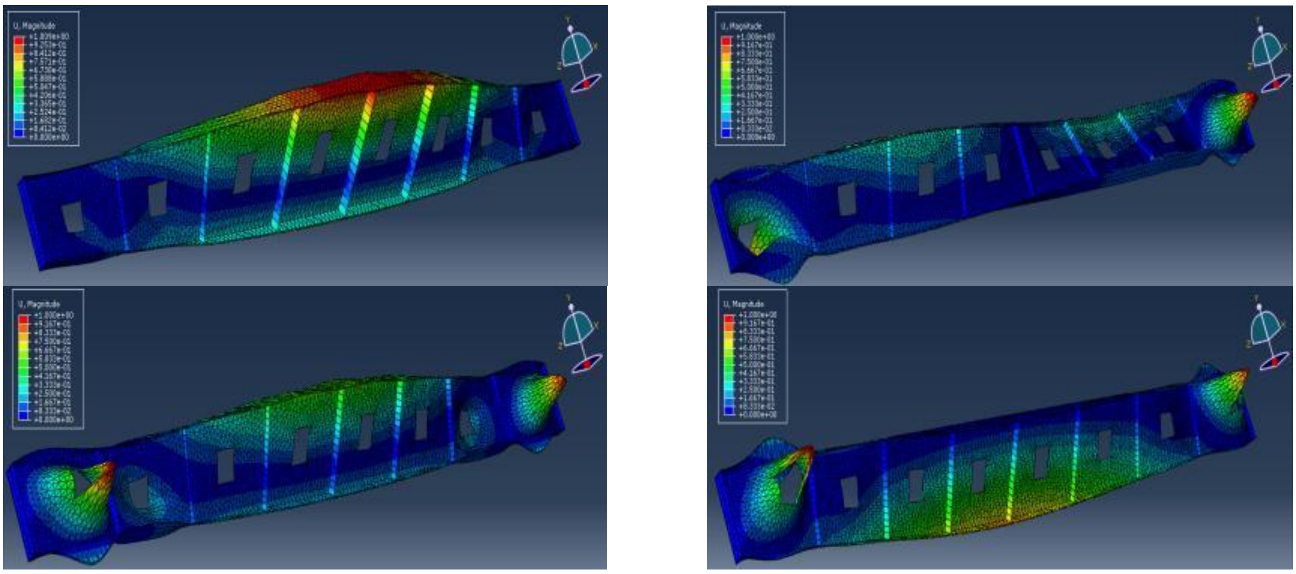


Figure-32 Buckling Mode Shapes of Model-VIII

A total of 10 buckling mode shapes have been found out for each of the model while performing the buckling analysis in the software tool but since there is a space constraint here, only 4 buckling shapes of each model have been represented here.

Theoretically, it is feasible to compute as many buckling modes as the number of degrees of freedom in the FEA model. Most often only the first positive buckling mode and its associated BLF need to be found. This is because advanced buckling modes encompass no likelihood of taking place. A buckling mode with a negative BLF means the load direction is obliged to be inverted (in addition to multiplying by the BLF magnitude) for buckling to happen.

Observation: Since only the first mode shape of the model holds primary significance, it is observed from all the 8 models that the global buckling is predominant in the first mode shape and also there is no sign of any local buckling in any of the models in their respective first modes. Also it is clearly observed that the maximum global buckling is concentrated in the central (mid) portion of the span of topmost flange of all the most models.

VI. CONCLUSIONS

- Finite element method of structural analysis is a process of optimizations which has been proven as time-efficient process and it gives much more exaggerated results than any other analytical method as it has been developed along with progress in computer technology.
- Due to the element library which integrated all types of elements like 1D, 2D, 3D elements, shell elements, plate elements and hence enhanced the process of the study/investigation of tough of the toughest geometries.
- ABAQUS package has been released with much orientation towards user-friendliness as the finite element formulations of the software were consistently derived on a firm theoretical basis which gives each and every minute detail one requires for the analysis of any structure in the minimum time.
- The coding structure of the ABAQUS package is highly modularized so that future extension or modification becomes relatively easy for the developers. For example, the material module (or library) is completely independent from the element module and hence the users can heavily rely on the results obtained from it. This is distinctly different from ADINA package.
- Division of the ABAQUS code into two distinct parts, the PRE and the MAIN programs, is an efficient approach for data check run and quick computer turn-around time.
- It has been observed that the I-Section with elliptical web openings is efficient as it shows minimum variation of displacement from that of the section without web openings.
- For the purpose of optimization of the material usage the perforation of the web sections shall be preferred as it reduces the employment of unnecessary extravagant material which makes the section economical. But simultaneously the stress analysis after each successive optimization increment, stress analysis shall be performed in order to avoid the risk of failure.
- Principal stresses are predominating in the case of plate sections when compared to the shear stresses.
- Maximum stress concentration occurs around the holes in the end panels of the plate girder section; hence the end panels of the girder need not be provided with the holes.
- Serviceability criteria shall be given due consideration in the case of plate girders as the intermediate section between the flanges (i.e., thin web section) is much more susceptible to buckling and hence they're always required to be reinforced (strengthened) with the aid of stiffeners (transverse/longitudinal/bearing).
- The designer has much higher control and choice over the dimensions of the section in case of a plate girder since the two flanges and webs are joined separately in case of plate girders.
- Load carrying web stiffeners shall be of adequate thickness as well as stiffness in order to resist the buckling.
- The buckling resistance can be improved by reducing the inter-space distance between the consecutive stiffeners.
- By increasing the flange thickness keeping the remaining parameters the same, it has been found that there isn't much variation between the deflection in girders with and without holes due to increased bending resistance.
- If the web thickness is increased to an undesired value then the purpose of choosing the plate girder over other available options goes in vain; hence an optimum web thickness shall be adopted.
- Displacement variation across the girder and along the girder can be efficiently measured using the ABAQUS tool just by selecting the path along which it has to be gauged.

VII. SCOPE FOR FURTHER STUDY

- Flanges of the girder can also be curtailed wherever they're provided in excess for the purpose of economy.
- Flange cover plates can be added to the flange for if requisite is of resisting higher bending moments.
- Different web and flange thicknesses can be adopted for the analysis and checked for the efficiency and simplicity.
- Different types of web sections can be adopted for the purpose of attaining the best results in aspect of strength and economy.
- Composite plate girder comprising more than one material can be adopted to check if it could yield better results than conventional structural steel girder.

- Post-buckling behavior of the plate girder can be studied with the aid of non-linear buckling analysis procedure.

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