

Simulation and Experimental Substantiation of Beam Deflection under Guided End Conditions

S.Gurumoorthy, L. Bhaskara Rao



Abstract: This paper studies the nonlinear deflection characteristics of a rectangular cross sectional beam with guided support conditions. In this study two different end conditions namely guided – guided and guided – simply supported have been examined. Beams made with two dissimilar materials for instance, aluminum and steel have been considered for this study. Different loading conditions namely point load and the amalgamation of uniformly distributed load and point load have been taken into account in this study. The nonlinear response of a beam under static loading condition is influenced by various parameters like sectional properties of the beam, material, loading and boundary conditions etc. A separate loading fixture was fabricated using steel to apply the load (Point load and uniformly distributed load). The loading fixture was validated by performing an experimental measurement of the deflection under various loading conditions on a simply supported beam. The corresponding theoretical displacement values were calculated using the findings in literature and compared with test results. Both the results were found matching with each other with an average variation of just 10%. Based on this validation lesson, the loading fixture was incorporated in the actual study. Displacement values from the nonlinear static analysis were predicted using Finite Element Method and correlation was made with the experimental values for the actual beam setup. Close correlation among the numerical and physical test results was achieved and the maximum error was 8%.

Keywords: Beam, deflection, Finite element analysis, guided edge, Load – Deflection curve.

I. INTRODUCTION

Beam is a primary structural element that resists transverse load by providing resistance to bending. Under the different loading scenarios, deflection, moment, curvature, slope and stresses developed in the beam can be predicted using the static analysis [27]. Beam dimensions, end supports and material stiffness are the major parameter in the determination of beam deflection [5-6]. Classical boundary conditions as clamped – clamped [28], hinged – hinged [29], fixed – simply supported [30], hinged – clamped [31] and mixed boundary conditions [32 – 33] are recommended for the deflection analysis of beam structures. The different types of beam end conditions are shown in figure 1.

There is a direct association among the beam deflection and the slope of the deflected shape of the beam under loading condition. Deflection of a beam can be predicted using principle of virtual work, direct integration scheme, Macaulay's method, Castiglione's method and Euler – Bernoulli beam equation.

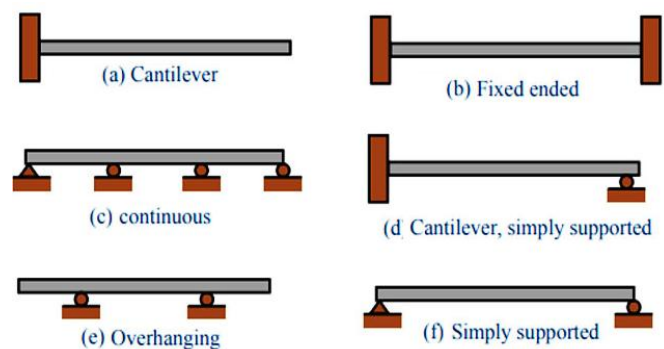


Fig. 1. Different beam end conditions

Structural member like beam is usually subjected to point loads, uniformly distributed load, uniformly varying load and moments etc. Various types of loading applied to beam structure are shown in figure 2.

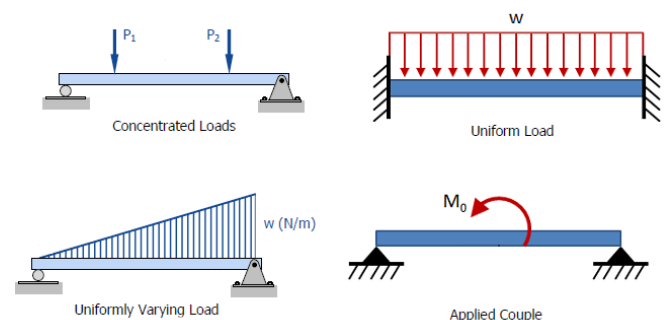


Fig. 2. Loading conditions

Farida [4] predicted the behavior of flexural steel beam under four point bending test. Deflection of a beam and strain in the beams under bending load has been calculated in this study. Stain gauge location and LVDT on steel beam was also calculated. Biltu [1] investigated the maximum deflection of a simply supported beam and a cantilever beam under various loading conditions. Experimental results have been validated through numerical and theoretical approaches. Euler – Bernoulli beam equation was considered for the theoretical approach. A close correlation between experimental, numerical and theoretical results was achieved.

Revised Manuscript Received on December 30, 2019.

* Correspondence Author

S.Gurumoorthy*, Research Scholar, Vellore Institute of Technology, Chennai, Tamilnadu, India. Email: guruparvai03@gmail.com

L.Bhaskara Rao, Associate Professor, Vellore Institute of Technology, Chennai, Tamilnadu, India. Email: bhaskararao@vit.ac.in

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an open access article under the CC-BY-NC-ND license <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Amer M. Ibrahim et al [2] investigated the performance of composite beams with simply supported end conditions using nonlinear finite element analysis. The beam was pre – stressed and subjected to static load. There was an excellent agreement among the physical test results and the deflection results obtained through finite element analysis. Mohamed et al [3] have presented a novel testing method for estimating the bond performance of the bar under the cyclic loading. The bar is made of fiber reinforced polymer .Exceptional consideration was given in the matter of allowing the application of tension, compression forces without premature buckling and to ensure the stability of the suggested test setup.

Li Chen [7] has proposed a new approach using moment integral treatment for solving the large deflection of cantilever problems. This new approach can be used to varying beam properties and complex loading scenarios. Ali S. Yasir et al., [8] performed a nonlinear analysis to predict the beam deflection which in turn used for the calculation of the elasticity modulus of steel beam subjected to heating and cooling with different rates. Specimen's modulus of elasticity was calculated using the analytical results of maximum beam deflection and those results were compared with the experimental results. Both the results had close correlation with each other.

Wadotona et al [14] have presented a simple design of beam deflection test rig and carried out experiments on a beam using a rig under a combination of different loading conditions. The test was performed for different end conditions of the beam. Experimental deflection results were weighed against the theoretical results for all the end conditions. Sushanta Ghuku et al [15] studied about the nonlinear behavior of cantilever beams with initial curvature under a variety of loading conditions. Nonlinear deflection of the beam was obtained using mathematical formulation and those results are compared against the experimental results. There was a good agreement among those results.

Bilello [16] presented an analytical and experimental study of an Euler – Bernoulli beam with an initial damage and having a moving mass. Analytical results were calculated based on beam Eigen functions and confirmed with the experimental results. There was a close correlation between those two results.

For laminated composite beams, the free vibration analysis was performed [17] with incorporating the transverse crack. By reducing the element stiffness, damage is taken into account in the study. The equation of motion was derived using Lagrange's equation. Analytical results are compared with the experimental results and also with the existing literature. Free vibration analysis of a thin- walled cantilever beam is studied using a boundary problem solver [18]. Tip of the cantilever beam is loaded with an eccentrically positioned tendon. Partial differential equations were used to model the beam system. The results are confirmed by performing a bench test and finite element analysis.

The nonlinear vibration of a beam with breathing crack was investigated [19]. Timoshenko beam theory based model was established and a semi analytical approach was developed to solve the model. Signal function was used to describe the breathing crack. Numerical results are validated

with experimental and finite element analysis results. Roncen [20] studied the nonlinear vibration of a clamped beam subjected to epistemic uncertainties and harmonic excitation. The consequences of the epistemic uncertainties on the dynamic response were explored using Harmonic Balance Method (HBM) and non-intrusive Polynomial Chaos Expansion (PCE). Numerical results were compared with the experimental results

Nonlinear flexural vibration of a beam under both the piezoelectric actuation and the external load was studied [21]. Beam was composed of piezoelectric actuators which were bonded on top and bottom of the beam in a symmetrical manner. Lindstedt-Poincare perturbation method was used for solving the theoretical equations and the analytical results were validated with the experimental results. Ravi et al [22] presented an analytical method for monolithic beams to determine the longitudinal crack dimensions based on frequency .The same method was applied for inverted T and L cracks also. Analytical results were validated with the finite element analysis results. Dimensions of all types crack for both isotropic and composite beams was verified with the experimental studies

Deflection of a cantilever beam of an elastic material under concentrated load at the free end is studied by analytically [23]. The same beam model is validated using various finite element analysis solvers to calculate the deflection of beams. Analytical and numerical results showed a good agreement with the experimental results. Horizontal and vertical deflections of the curved beam were calculated using analytical expressions [24]. Analytical results were compared with the finite element analysis and experimental results. A close correlation was achieved among all the results.

Ramesh [25] presented a theoretical and experimental study to predict the static response of laminate composite beams with open cross sections. A Vlasov-type linear theory was formulated for analyzing the beams and the effect of transverse shear deformation was considered in the study. The beams were tested under torsional and bending loads. Close correlation was achieved among the experimental and theoretical results. Daniel studied [26] the flexural performance of sandwich beams using theoretical models. Beams were manufactured by joining the unidirectional epoxy / carbon laminates with aluminum honeycomb cores using an adhesive film. Experiments were carried out for measuring the deflection and strain in the beam structure. Theoretical results were in good agreement with the experimental results.

II. PROBLEM DEFINITION

An effort has been made in this study to review the available literature and to execute experiments for a study of the nonlinear deflection characteristics of beam conditions of a wide variety with various materials under different loading scenarios. A detailed collation study was executed among the numerical results and physical test results

III. CORRELATION STUDY

A. Beam Configurations

Various beam configurations have been considered for this study. Beam configurations are categorized according to the end conditions of the beam, material and load setup as demonstrated in figure 3 and figure 4.

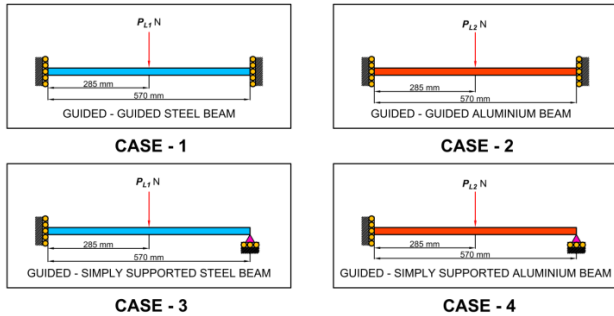


Fig. 3. Different configurations of beam with point load

- Case -1 : Guided – Guided steel beam with point load
- Case -2: Guided – Guided aluminum beam with point load
- Case -3: Guided – Simply supported steel beam with point load
- Case -4: Guided – Simply supported aluminum beam with point load

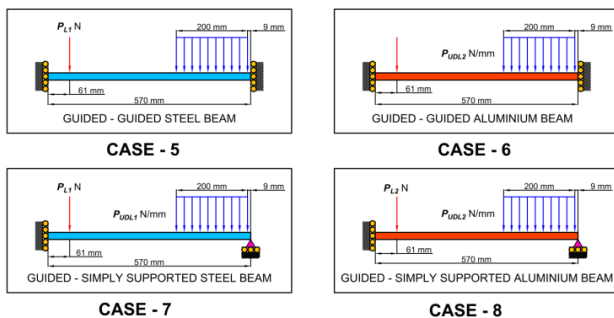


Fig. 4. Different configurations of beam with combined point load and uniformly distributed load (UDL)

- Case -5: Guided – Guided steel beam with combined point load and UDL
- Case -6: Guided – Guided aluminum beam with combined point load and UDL
- Case -7: Guided – Simply supported steel beam with combined point load and UDL
- Case -8: Guided – Simply supported aluminum beam with combined point load and UDL

B. Geometry Conditions

A rectangular cross sectional beam is considered in this study and dimensions parameters considered for the study are shown in figure 5. Dimensions for cross-sections are in meters.

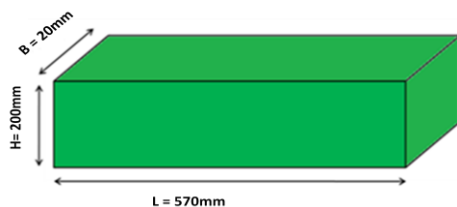


Fig. 5. Dimensional details of the beam

C. Material Properties

Steel and aluminum specimens are tested in the experiment forming a part of this study. The mechanical properties of those specimens are shown in Table I.

Table- I: Mechanical Properties of Beam Specimen

Mechanical Properties	Materials	
	Steel	Aluminum
Density (kg/m ³)	7850	2770
Young's Modulus (GPa)	200	71
Poisson Ratio	0.3	0.33
Yield Strength (MPa)	250	280
Ultimate Strength (MPa)	460	310

IV. EXPERIMENTAL SETUP

The experimental setup (Test fixture and loading fixture) is machined and fabricated. To make sure the achievement of the different end conditions, the support system is modified. Details are described below.

A. Guided Beam Support

In a guided-guided beam setup, there are two vertical columns with a slot to facilitate fixing six rollers made of steel on each side. The entire setup is made of mild steel and the rollers are free to rotate relatively. The beam is placed in between rollers on each of the sides, such that the beam can be guided vertically up and down through the slots as shown in figure 6 with uni- axial tensile testing machine.

B. Guided – Simply Supported Beam Support

In a guided-simply supported beam setup, there is one vertical column with a slot to facilitate fixing six rollers made of steel and a roller to support the beam at the other end is provided. The entire setup is made of mild steel and the rollers are free to rotate relatively in the guided setup while the roller on the simply supported end allows for horizontal displacement of the beam as presented in figure 6 with uni- axial testing machine.



Fig. 6. Test fixture with Uni-axial testing machine

C. Loading Fixture

A fixture made up of mild steel is fabricated for applying both the point load and a uniformly distributed load as shown in figure 7. A cylindrical rod was bolted on top of the load distributing beam to enable the transfer of load from the universal testing machine to the tested beam as a combination of point load and uniformly distributed load as shown in figure 8. The point load fixture was made with a rounded end to enable establishment of a line contact between the beam and the fixture. The uniformly distributed load fixture had a flat plate with a rubber padding to establish even contact on the beam and the load was uniformly distributed all through the contact region on the beam.



Fig. 7. Loading fixture

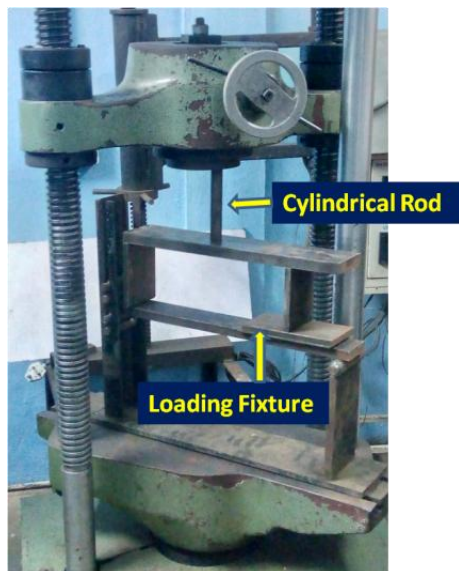


Fig. 8. Loading fixture with cylindrical rod

D. Validation of Loading Fixture

Confirmation of the experimental setup was made by theoretical and numerical approaches. A beam with simply supported end conditions at both ends is taken for the purpose of validation. A rectangular cross section beam with isotropic material properties (Steel and aluminum) is considered. Calculation of deflection of beam under various loading conditions is done experimentally and the results are compared with theoretical and numerical results.

1. Theoretical approach

The differential equation of the deflection curve (Nash, 2007) for the Euler – Bernoulli beam is

$$EI (d^2 y/dx^2) = M \quad (1)$$

Where M = moment due to the applied force, E is Young's modulus of elasticity, y = deflection due to loading.

For rectangular beam, I is moment of inertia = $bh^3/12$,
 b = beam width, h = beam height or thickness

The following relationship was obtained (Benham, Crawford & Armstrong, 1997) on the application of the boundary conditions and solving the equation (1) for the simply supported beam as shown in figure 9.

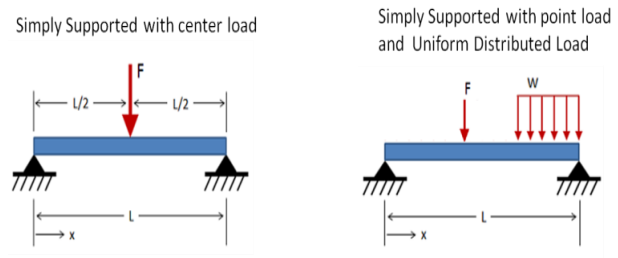


Fig. 9. Simply supported beam with loading conditions

For center load: $\delta_{max} = FL^3 / 48EI \quad (2)$

For point load and uniformly distributed load

$$\delta_{max} = (W_1 a (3L^2 - 4a^2) / 48EI) + (W_2 a (3L^2 - 4a^2) / 48EI) \quad (3)$$

Point load of 1000N is applied for steel beam and 500N is applied for aluminum beam using the point load fixture. For the combined loading scenario, load of 1000N is applied on the cylindrical rod of the loading fixture which in turn applied as a combination of point load and uniformly distributed load on the steel and aluminum beams.

2. Numerical approach

The simply supported beam with various loading conditions was solved using FEM for the calculation of maximum displacement. The stiffness method was used for the evaluation of the displacements of the beam. The general finite element equation is below,

$$\{F\} = [K] \{u\} \quad (4)$$

Where, $\{F\}$ – Global force vector

$[K]$ – Global stiffness matrix

$\{u\}$ – Global displacement vector

3. Convergence Study

A convergence study is carried out for the steel beam for the determination of the appropriate element density. A simply supported beam of dimensions 570mm X 200mm X 20mm is modeled and material properties are applied using ANSYS. Nonlinear static analysis is performed by varying the number of elements as 10, 20, 40, 60, 80, 100, and 120. Beam models used in the study are shown in figure 10. Load vs. displacement curve is plotted against the number of elements in figure 11 and variation in displacement is made up to 120 numbers of elements. Following that, it remained constant from 100 to 120 elements.

The displacement observed remained constant irrespective of the increase in the number of elements after 120 elements. So a finite element model consisting of 120 numbers of solid elements is used for the deflection analysis in the entire study.

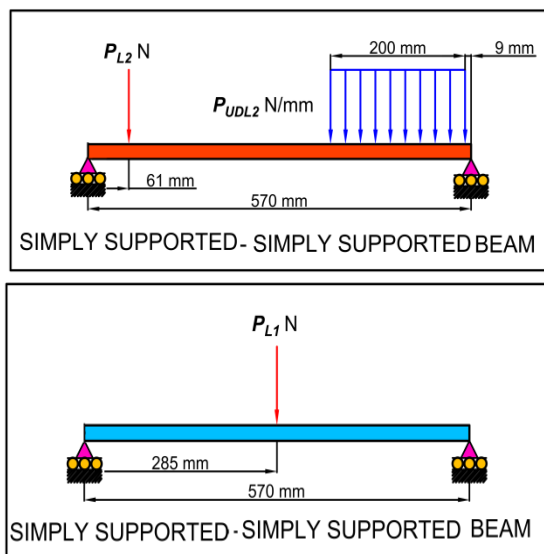


Fig. 10. Simply supported beam models

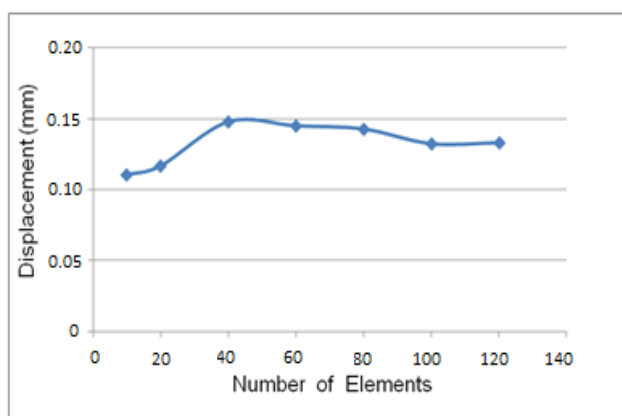


Fig. 11. Convergence study results

4. Experimental Procedure

In order to perform the experiment, the loading fixture and support setup are arranged for the simply supported - simply supported beam. Two types of the beam model, namely, steel and aluminum beams are taken for all types of loading scenarios. Deflection on the beam is measured by the inbuilt LVDT sensors on the uni-axial tensile testing machine. Details have been plotted, compared with FEA values and theoretical values in a subsequent section of this paper. The same procedure is repeated for the testing of guided - guided and guided-simply supported beam conditions.

V. METHODOLOGY

This topic deals about the finite element modeling of the beams and simulating them by inputting different material models and boundary conditions to simulate the different case setups done experimentally. The beam was modeled using ANSYS Design Modeler software as a solid model and ANSYS workbench was used for the analysis in the static

structural module. The basic workflow of a Finite Element Analysis methodology is represented like in figure 12.

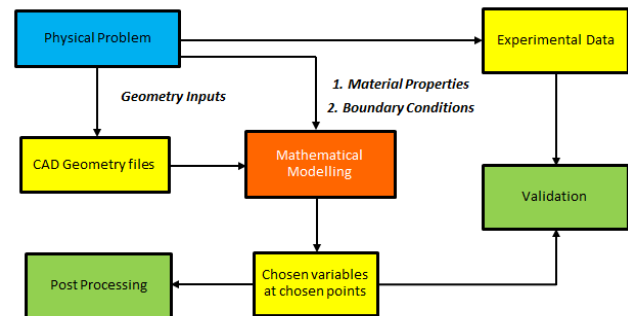


Fig. 12. FEA methodology

A. Physical Problem

In this topic the physical problem of the situation has been described as an outline of how the problem is to be approached. For this case, the beam is modeled and the ends of the beam are subjected to different degrees of freedom and the load is applied through a fixture setup. The fixture setup is modeled as a rigid body to ensure accurate enactment of experimental setup. Definition of a suitable contact region between the beam and the fixture models is required.

B. Mathematical Modeling

Mathematical modeling is perhaps the most important and effort required in the FEM analysis. The mathematical modeling generally demands a lot of user input, accuracy and time taken for the solution.

Mathematical modeling has three stages, such as,

- Discretization of CAD model
- Application of material properties
- Application of loads and boundary conditions

C. Material Properties

The material properties deal with the definition of materials that require application to the model used in this study. Steel and aluminum specimens are tested in experiments and the same materials are used in the numerical simulation also. The values of the material properties have been provided in Table I.

D. Loads and Boundary Conditions

The degrees of freedom at both end of the beam require definition for the purpose of simulation of the different supports. The force acting on the beam should also be established. The following boundary conditions are followed for each beam setup in the beam analysis.

Guided support - Displacement along the vertical axis (Guided direction) is permitted and the other two directions are fixed. The angular motion with respect to the lateral direction is also permitted. Simply supported setup - Displacement along the horizontal axis was permitted along with angular motion with respect to lateral direction is permitted.

Simulation and Experimental Substantiation of Beam Deflection under Guided End Conditions

For the point load scenario, load of 1000N is applied for the steel beam and for the aluminum beam, load of 500N is applied. For the combined loading scenario, load of 1000N and 500N is applied for the steel and aluminum beams. For the combined loading scenario, load is applied on the cylindrical rod of the loading fixture which in turn applied as a combination of point load and uniformly distributed load on the tested beams.

E. Meshing

The CAD model of the beam is meshed into a finite number of elements using ANSYS inbuilt meshing algorithm. The rigid body is not meshed but the interface between the fixture and the beam contact region is meshed and interlinked to enable calculation of the force interaction between them. The meshed model of beam with loading fixture is shown in figure 13 and the contact region of the beam is shown in the figure 14. The model is meshed using 8 noded hexahedral elements in a structured manner. Details of the mesh provided in the Table II.

Table- II: Mesh Information

S. No.	Description	Value
1	Total Nodes	36439
2	Total Elements	9273
3	Total Body Elements	7502
4	Total Contact Elements	1771

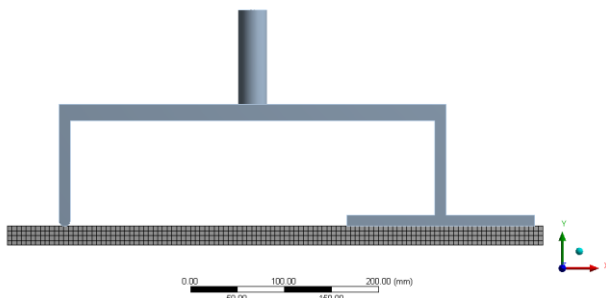


Fig. 13. Meshed model

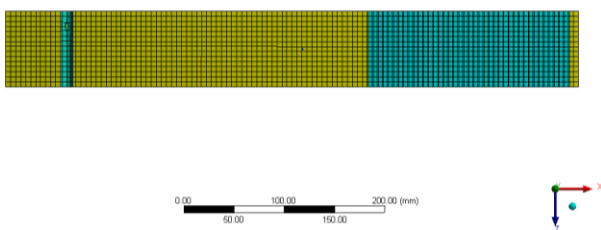


Fig. 14. Contact interface region between the fixture and the beam

VI. RESULTS AND DISCUSSIONS

A. Simply Supported Beam Setup

For validating the loading fixture setup experimental study is performed for the simply supported beam to predict the displacement values under different loading scenarios. Displacement values for the same beam setup under point load and combination of point load with uniformly

distributed load are calculated using equations 2 and 3. For the same beam structure, displacement values are also calculated by performing static analysis using ANSYS 7.

Table- III: Results Comparison

S.No	Beam setup with material conditions	Max.displacement (mm)		
		Theoretical	Experimental	Numerical
1.	A point load at the center of the simply supported beam (Aluminum)	0.206	0.17	0.194
2.	A point load at the center of the simply supported beam (Steel)	0.137	0.12	0.133
3.	A point load and uniformly distributed load on the simply supported beam (Aluminum)	0.581	0.54	0.578
4.	A point load and uniformly distributed load on the simply supported beam (Steel)	0.194	0.18	0.194

For the different loading scenarios, experimental, theoretical and numerical results are compared for simply supported beam and the comparison is shown in Table III. Results comparison shows that there is good correlation among all approaches. The loading fixture is validated on the basis of this comparison. Based on this validation, the same loading fixture is considered for the actual study.

For the guided – guided and guided – simply supported beam setup, experiments are performed under different loading scenarios. Nonlinear static analysis is performed for all beam setup for the calculation of the deflection of the beam under applied loading conditions. Finite element analysis results are shown in the below figures.

B. Guided – Guided Setup

Deflection results for guided – guided beam with different materials under point load and the combination of point load with uniformly distributed load are demonstrated in figure 15 -18. For the guided – guided beam, the maximum deflection of 0.87mm is observed with aluminum material under 500N point load and the maximum deflection of 0.97mm is observed with steel material under 1000N point load.

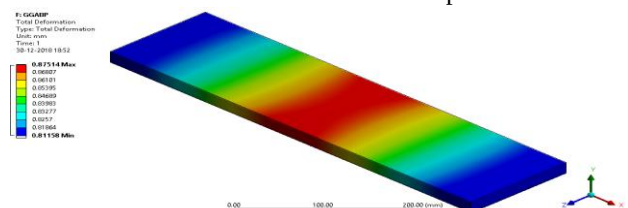


Fig. 15. Guided – guided beam with aluminum material under point load

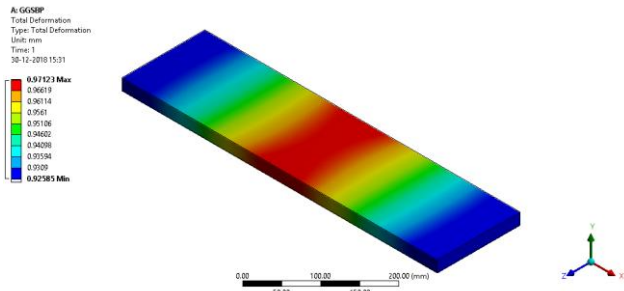


Fig. 16. Guided – guided beam with steel material under point load

For the guided – guided beam, the maximum deflection of 0.53mm is observed with aluminum material under the combination of point load and uniformly distributed load. The maximum deflection of 1.15mm is observed with steel material under the combination of point load and uniformly distributed load. Since the load value for the aluminum beam is lesser than the load on the steel beam, deflection is lesser in the aluminum beam than the steel beam. This same phenomenon is also observed for guided – simply supported beam under the combined loading scenario.

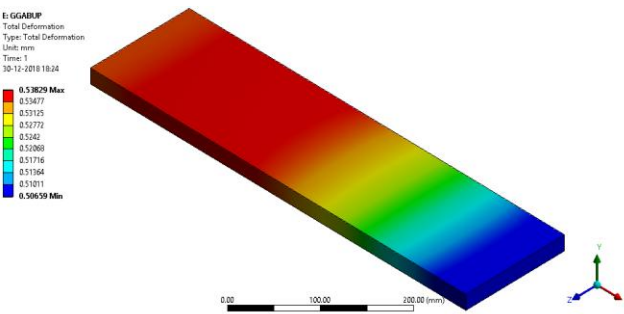


Fig. 17. Guided – guided beam with aluminum material under point load and uniformly distributed load

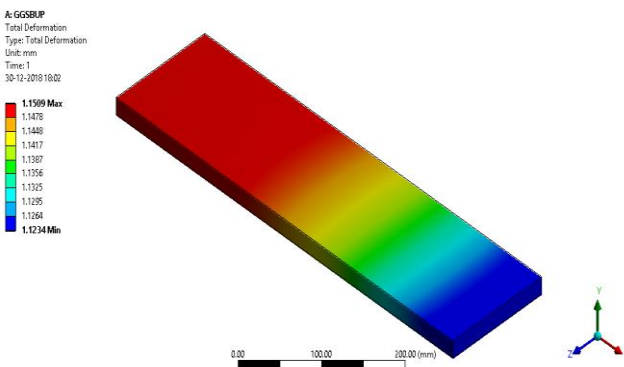


Fig. 18. Guided – guided beam with steel material under point load and uniformly distributed load

C. Guided – Simply Supported Setup

Deflection results for guided – simply supported beam with different materials under point load and the combination of point load with uniformly distributed load are demonstrated in figure 19 -22. For the guided – simply supported beam, the maximum deflection of 0.85mm is observed with aluminum material under 500N point load and the maximum deflection of 0.92mm is observed with steel material under 1000N point load.

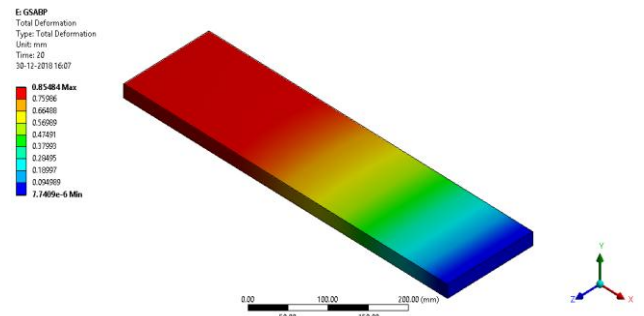


Fig. 19. Guided – simply supported beam with aluminum material under point load

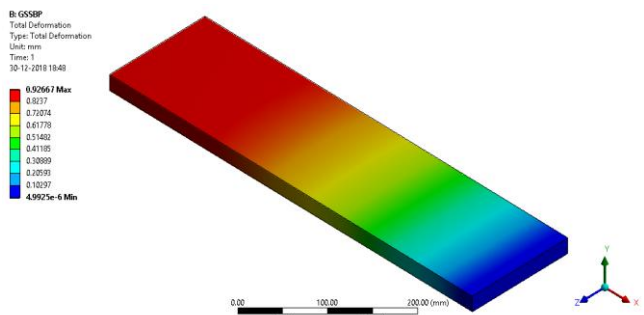


Fig. 20. Guided – simply supported beam with steel material under point load

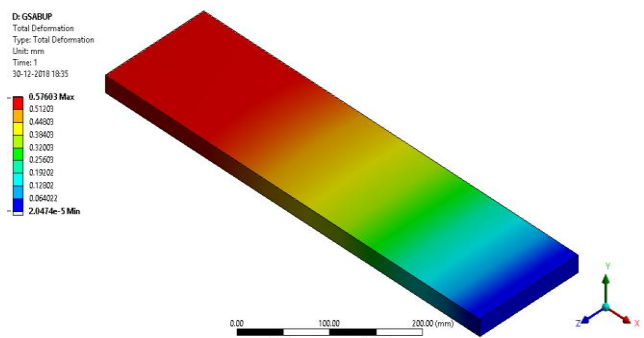


Fig. 21. Guided – simply supported beam with aluminum material under point load and uniformly distributed load

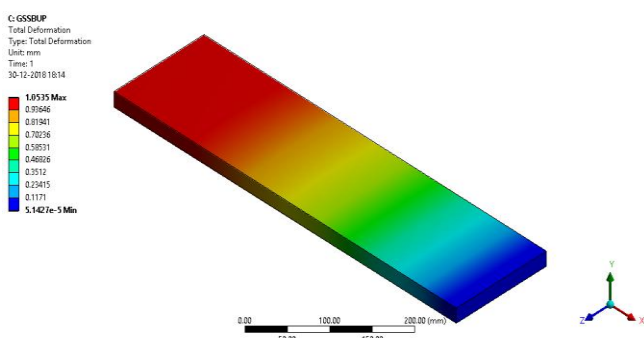


Fig. 22. Guided – simply supported beam with steel material under point load and uniformly distributed load

D. Correlation Study

Finite element analysis results were compared with the experimental results for both guided – guided and guided – simply supported beam conditions. The % of error between those 2 results is presented in Table IV.

Table- IV: Comparison of Results

S.No	Beam setup with material conditions	Deflection (mm)		Error (%)
		Experimental	FEA	
1.	Guided-Guided Point (Aluminum)	0.85	0.87	2.87
2.	Guided-Guided Point (Steel)	0.9	0.97	7.33
3.	Guided Simply Supported Point (Aluminum)	0.83	0.85	2.91
4.	Guided Simply Supported Point (Steel)	0.85	0.92	8.27
5.	Guided-Guided Point and UDL (Aluminum)	0.485	0.53	9.92
6.	Guided-Guided Point and UDL (Steel)	1.05	1.15	8.77
7.	Guided Simply Supported Point and UDL (Aluminum)	0.5	0.57	13.20
8.	Guided Simply Supported Point and UDL (Steel)	0.9	1.04	13.74

E. Comparison of Load – Deflection Curve

Load – deflection curves for all the beam conditions under the different loading scenarios are studied

1. Guided – Guided Setup

Load – deflection curves for the guided – guided beam with different materials under point load and the combinations of point load with uniformly distributed load are shown in figure 23 -26.

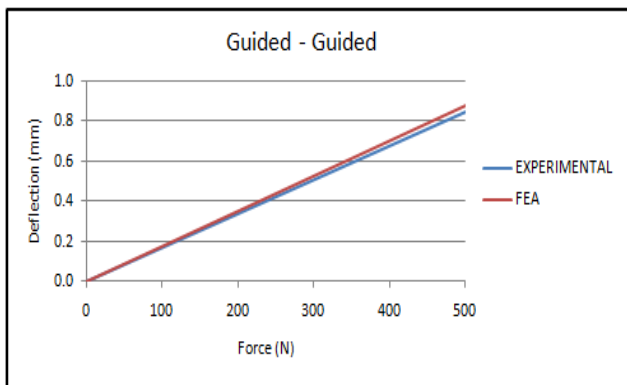


Fig. 23. Guided – guided beam with aluminum material under point load

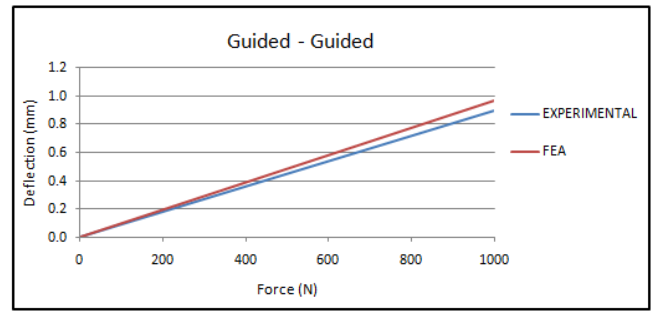


Fig. 24. Guided – guided beam with steel material under point load

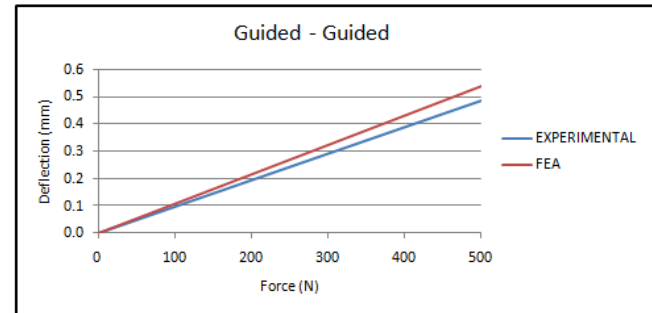


Fig. 25. Guided – guided beam with aluminum material under point load and uniformly distributed load

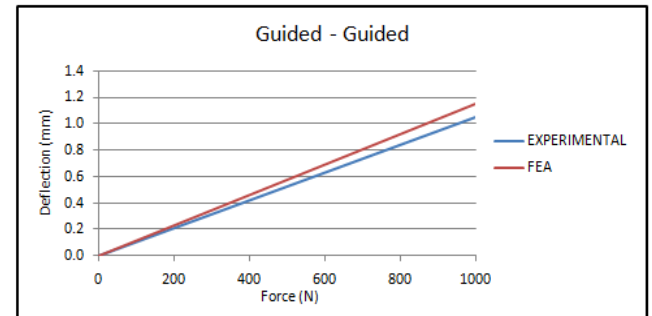


Fig. 26. Guided – guided beam with steel material under point load and uniformly distributed load

Comparison between experimental results and finite element analysis results is made and the average error percentage of deviation between those results under different loading conditions is as follows.

- Guided – guided beam with aluminum material
 - With central point load is 2.87%
 - With point load and uniformly distributed load is 9.92%
- Guided – guided beam with steel material
 - With central point load is 7.33%
 - With point load and uniformly distributed load is 8.77%

2. Guided – Simply Supported Setup

Load – deflection curve for the guided – simply supported beam with different materials under point load and the combination of point load with uniformly distributed load are shown in figure 27–30.

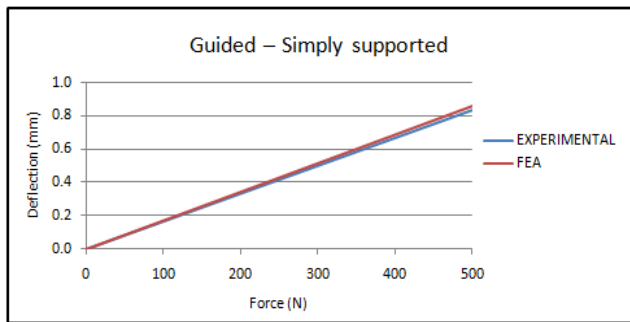


Fig. 27. Guided – simply supported beam with aluminum material under point load

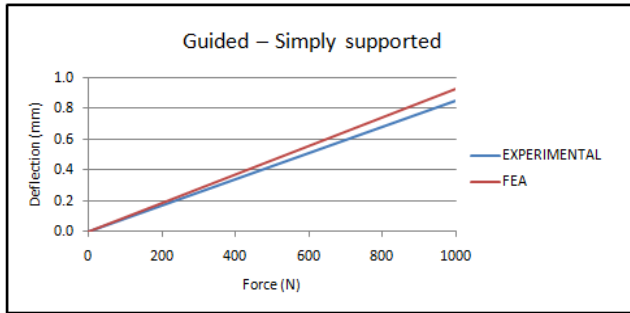


Fig. 28. Guided – simply supported beam with aluminum material under point load

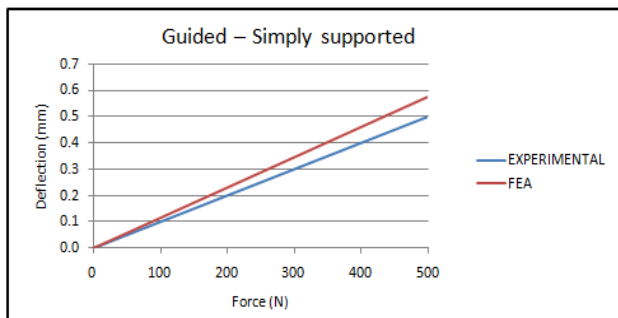


Fig. 29. Guided – simply supported beam with aluminum material under point load and uniformly distributed load

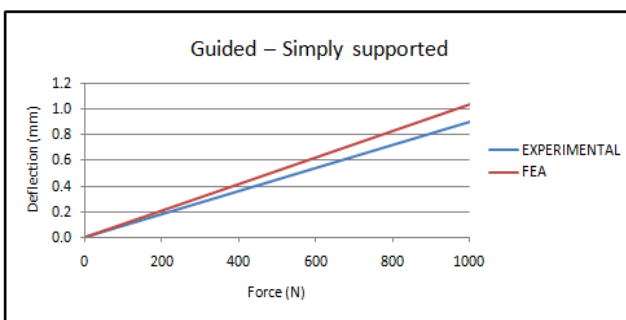


Fig. 30. Guided – simply supported beam with steel material under point load and uniformly distributed load

Comparison between experimental results and finite element analysis results is made and the average error percentage of deviation between those results under different loading conditions is as follows.

- Guided – simply supported beam with aluminum material

- With central point load is 2.91%
- With point load and uniformly distributed load is 13.20%
- Guided – simply supported beam with steel material
 - With central point load is 8.27%
 - With point load and uniformly distributed load is 13.74%

Comparison of the experimental results with the FEA data shows that the deflection values from the FEA is matching as closely as with the experimental results. The values of deflection show a linear trend which is expected in both the metal beams since both are tested within their elastic limits. The percentage of error between the FEA and the experimental results is less than 15%, considered accurately.

VII. CONCLUSION

The laboratory testing fixture and loading fixture are fabricated to enable the prediction of the deflection of beams with guided end conditions under various loading scenarios. Validation of both the testing and loading fixture is done through experiments for a simply supported beam and those results are weighed against the theoretical and analytical results. Convergence study also performed for the determination of the appropriate number of elements and the same number of elements has been used in the entire study. Close correlation between the experimental and analytical deflection results for guided beam conditions was seen.

APPENDIX

It is optional. Appendixes, if needed, appear before the acknowledgment.

REFERENCES

1. Biltu Mahato, Anil, Harish HV, "Experimental verification of deflection of beam using theoretical and numerical approach", International Journal of Advance Research in Engineering, Science and Technology, vol.2(3), 2015, pp.2394-2444
2. Ibrahim AM, Mohaisen SK, Qusay WA, "Finite element modeling of composite steel-concrete beams with external prestressing", International Journal of Civil and Structural Engineering, vol.3(1), 2012, pp.101-116.
3. Nayera Mohamed, Ahmed Sabry Farghaly, Brahim Benmokrane, "Beam-testing method for assessment of bond performance of FRP bars in concrete under tension-compression reversed cyclic loading", Journal of composites for construction, vol.21(1), 2017, pp.1-5.
4. M. Faridaf, A. Surahman, A.Sofwan, "Numerical and analytical investigation of steel beam subjected to four-point bending", IOP Conf. Series, Materials Science and Engineering, vol.316, 2018, pp. 1-8.
5. E.J.Hearn, "Mechanics of Materials", 3rd ed. Butterworth-Heinemann, 2007.
6. M.H.Ang, Wang Wei, Low Teck-Seng, "On the estimation of the large deflection of cantilever beam", Proceedings of IECON '93 - 19th Annual Conference of IEEE Industrial Electronics, Maui, HI, USA, 1993, pp.1604 -1609.
7. Li Chen, "An integral approach for large deflection cantilever beams", International journal of non-linear mechanics, vol.45 (3), 2010, pp.301-305.
8. A.S.Yasir , L.S.Al-Ansari, "Studying the effect of cooling rate on the linear, non-linear deflection and elastic properties of stainless steel (grade 410) beams", International Journal of Applied Science and Technology, vol. 2(8), 2012, pp. 26-34.

9. P.P.Benham , R.J.Crawford , C.G. Armstrong, "Mechanics of engineering materials", Low priced ed, Addison Wesley Longman Limited, 1997
10. F.P.Beer, E. Russell Johnston Jr, J.T. Dewolf, D.F. Mazurek, "Mechanics of materials", 6th ed, McGraw –Hill, 2012.
11. E.Hearn, "Mechanics of materials, An introduction to the mechanics of elastic and plastic deformation of solids and structural components", 3rd ed, Butterworth-Heinemann, 1997.
12. W.A.Nash, Strength of materials, 4th ed, New Delhi, Tata McGraw-Hill Publishing Company Limited, 2007.
13. ANSYS 14.0 documentation
14. Kudzai Wadotona, Takunda Goredema, Tawanda Mushiri, Stephen Mutuli, "A simple design of a laboratory testing rig for the experimental demonstration and analysis of elastic deflections of beams with different end conditions", Journal of Scientific and Engineering Research, vol.3(2),2016,pp.214-234.
15. Sushantaghuku, Kashinath Saha, "A theoretical and experimental study on geometric nonlinearity of initially curved cantilever beams", Engineering Science and Technology, an International Journal, vol.19 (1), 2016, pp.135-146.
16. C.Bilello, L.A. Bergman, "Vibration of damaged beams under a moving mass, Theory and experimental validation", Journal of Sound and Vibration, vol.274 (3-5), 2004, pp.567-582.
17. K.Volkan, K.Sebahat , Fatih Yesevi Okura, Ahmet Can Altunişik, Mustafa Aslan, "Free vibrations of laminated composite beams with multiple edge cracks, Numerical model and experimental validation", International Journal of Mechanical Sciences,vol.159, 2019,pp.30-42.
18. V.Ondra, B.Titrus, "Theoretical and experimental free vibration analysis of a beam-tendon system with an eccentrically placed tendon", Thin-Walled Structures, vol. 144, 2019.
19. Chenxi Wei, Xinchun Shang, "Analysis on nonlinear vibration of breathing cracked beam", Journal of sound and vibration, vol.461, 2019.
20. T.Roncen, J.J.Sinoub, J.P.Lambelina, "Non-linear vibrations of a beam with non-ideal boundary conditions and uncertainties – Modeling, numerical simulations and experiments", Mechanical Systems and signal processing, vol.110, 2018, pp.165-179.
21. Jacek Przybylski, Grzegorz Gasiorski, "Nonlinear vibrations of elastic beam with piezoelectric actuators", Journal of sound and vibration, vol.437, 2018, pp. 150-165.
22. J.T.Ravi, S.Nidhan, N.Muthu, S.K.Maiti, "Analytical and experimental studies on detection of longitudinal, L and inverted T cracks in isotropic and bi-material beams based on changes in natural frequencies", Mechanical systems and signal processing, vol.101, 2018,pp. 67 -96.
23. Luis Eduardo Ramirez Monterrubio, "Analytical solution, finite element analysis and experimental validation of a cantilever beam", Computers in education journal, 2017, pp.24-36.
24. Yogesh Gangamwar , Sumit Chate , Makarand Bhandare , Vinit Deo , H.N.Deshpande , "Analytical, Experimental Determination of Deflection of Curved Beams and its Validation", International Journal of Innovative Research in Science, Engineering and technology, vol.5 (6), 2016,pp. 11010 – 11017.
25. Ramesh Chandra, Inderjit Choprat, "Experimental and Theoretical Analysis of Composite I-Beams with Elastic Couplings", AIAA Journal, vol. 29 (12), 1991, pp.2197 – 2206.
26. M.I.Daniel, J.L.Abot, "Fabrication, testing and analysis of composite sandwich beams", Composites science and technology, vol.60 (12-13), 2000, pp.2455-2463.
27. A.P.Boresi, R.J.Schmidt, "Advanced mechanics of materials", 6th ed, New York, John Wiley and Sons Incorporated, 2003.
28. H.Niknam ,A. Allah, M.M.Aghdam, " Nonlinear bending of functionally graded tapered beams subjected to thermal and mechanical loading", International Journal of nonlinear mechanics, vol.65,2014,pp.141-147.
29. D.A.Miller , A.N. Palazotto , "Nonlinear finite element analysis of composite beams and arches using a large rotation theory, Finite elements in analysis and design, vol.19(3),1995,pp. 131-152.
30. He XT, Cao L, Li ZY, Hu XJ, Sun JY, "Nonlinear large deflection problems of beams with gradient, A biparametric perturbation method", Applied mathematics and computation,vol. 219 (14), 2013,pp.7493-7513.
31. M.Cannarozzi, L.Molari, "Stress-based formulation for non-linear analysis of planar elastic curved beams", International Journal of nonlinear mechanics, vol.55, 2013, pp.35-47.
32. A.A.Correia, J.P.Almeida, R.Pinho, "Force-based higher-order beam element with flexural– shear–torsional interaction in 3D frames, Part II, Applications", Engineering structures, vol.89 (15), 2015, pp.204-217.
33. A.Dorogoy, D.Rittel, "Transverse impact of free–free square aluminum beams, An experimental–numerical investigation", International journal of impact engineering, vol. 35(6), 2008, pp.569-577.

AUTHORS PROFILE



Gurumoorthy S received his Bachelor degree in Mechanical engineering from Manonmaniam Sundaranar University. He received his masters in CAD/CAM from Anna University. Currently doing his Ph.D degree in Vellore Institute of Technology, Chennai. He has more than 13 years of industrial experience in the field of CAE / FEA.



L.Bhaskara Rao Associate Professor, School of Mechanical and Building Sciences, VIT Chennai, Vandalur-Kelambakkam Road, Chennai-600127, Tamil Nadu, India. Email: lokavarapu@gmail.com