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Dynamic Response of Laminated Composite Box Beams

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Abstract-The resistance to dynamic loads is the main constrain regarding in designing of orthotropic laminated composite box beams. Free vibration and forced vibration of graphite-epoxy composite box beam is studied using finite element software ANSYS. Modal analysis is performed to study the influence of orthotropy stiffness parameter, width to flange thickness ratio and depth to web thickness ratio on the natural frequencies of composite box beams with single and multi-cells. Mode shapes of symmetric and unsymmetric box beams are studied. Transient analysis is used to investigate and understand the effect of width to flange thickness ratio and depth to web thickness ratio on displacement response. The results are revealed that the orthotropy stiffness parameter, width to flange thickness ratio and depth to web thickness ratio have significant influence on the dynamic response.

Index Terms-Laminated composites; Box beam; Vibration; Graphite-epoxy composite.

1. INTRODUCTION

Laminated composites are a new class of engineering materials, to meet special properties like high strength to weight ratio and high stiffness to weight ratio. Their superior performance in aerospace and automobile applications calls for the study of their structural aspects. Mainly composite materials are used in automobile, aerospace, naval, and civil industries. Vibrations in structures have become increasingly problematic in light weight structures. Basic requirement to reduce such vibrations of structures is to move its natural frequencies from excitation frequency. The dynamic loads acting on the structure includes cyclic loads, blast load, impact load, traffic load and earthquake loads. To acquire definite design requirements by using a composite material in structure can be tailored by selecting appropriate fiber materials and orientations. This ability compared to other metals brought them to structural applications.

The influence of bending-twist and bending-shear coupling on frequencies and modes of thin-walled composite box section was theoretically and experimentally studied by Chandra and Chopra (1992). In this study, the bending-twist coupling for symmetric beams reduces their frequencies and creates bending torsion coupled modes. Also, the bending-shear coupling in anti-symmetric beams reduces their frequencies and flap-lag coupled modes. Suresh and Malhotra (1998) evaluated the vibration and damping behaviour of composite box beams. They studied anti-symmetric angle ply and cross ply laminate of graphite-epoxy and glass-epoxy with different boundary conditions. A finite element programming code was formulated by Latheswary et.al (2004) to study the dynamic analysis of composite plates subjected to time dependent loading and harmonic loading. It was observed that displacement decreases with increase in percentage of damping and fiber angle. Free vibration of folded structures and box beams were examined by Lee and Wooh (2004) using Lagrangian and Hermite finite element method, wherein natural frequency increases with the number of layers. The effect of coupling of flexural and torsional modes for arbitrary laminate stacking sequence configuration on box beams were studied by Vo and Lee (2008) and Vo et al. (2009). The former deals with doubly and triply coupled flexural-torsional modes, while the later deals with fourfold and sixfold coupled flexural-torsional-shearing vibrations. Qu et al. (2013) presented the vibrations of isotropic and composite cylindrical shells and found that the variation of number of layers does not affect the time history response.

The intention of this study is to investigate the dynamic response of laminated composite box beams. The results regarding free and forced vibrations can be used as benchmark for further research of fiber reinforced polymer composites.

2. STIFFNESS PARAMETERS

The orthotropic stiffness parameter of composites can be expressed by,

$$A_{ij} = \sum_{k=1}^{n} \bar{Q}_{ij}\,(Z_k - Z_{k-1}) \qquad \text{Eq.(1)}$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} \bar{Q}_{ij}\,(Z_k^2 - Z_{k-1}^2) \qquad \text{Eq.(2)}$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} \bar{Q}_{ij}\,(Z_k^3 - Z_{k-1}^3) \qquad \text{Eq.(3)}$$

The A_{ij}, B_{ij}, and D_{ij} are the extensional, bending-extension coupling and bending stiffnesses respectively.

3. FINITE ELEMENT MODELING

The results were obtained using finite element software ANSYS 15, where SHELL 281 was used for modeling and analysis of the laminated composite box beams. The modal and transient analyses were carried out. The simply supported graphite-epoxy box beams were considered with material having the following properties.

Modulus of Elasticity, E_{12} = 145000 N/mm^2, E_{23} = 16500 N/mm^2, Shear Modulus = 4480 N/mm^2, Poisson's Ratio, υ_{12} = 0.314, υ_{23} = 0.0357. The box beams with single, double and multi-cells were taken in this study as shown in Fig. 1 to 3.

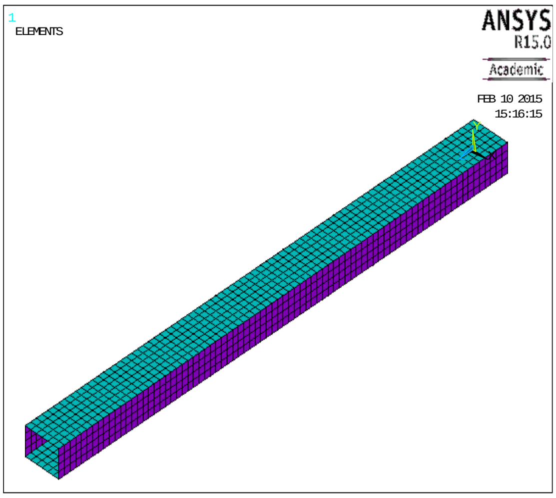

Fig. 1. Discretized model of composite box beam with single cell

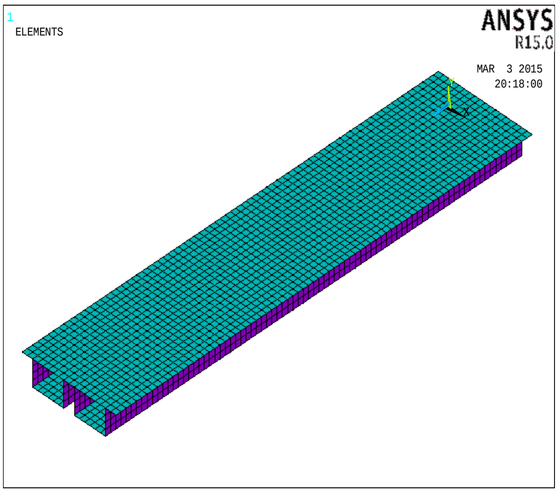

Fig. 2. Discretized model of composite box beam with double cells

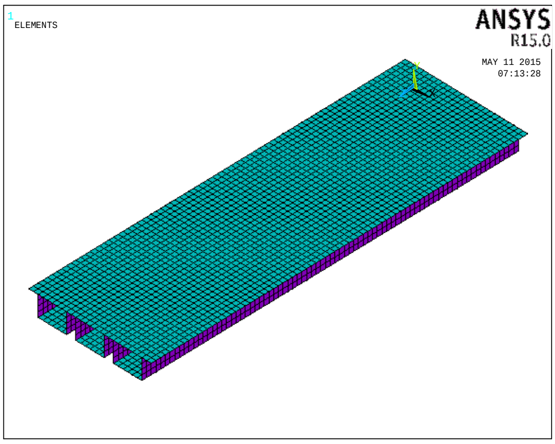

Fig. 3. Discretized model of composite box beam with multi-cells

4. NUMERICAL ILLUSTRATIONS AND OBSERVATIONS

4.1. *Modal analysis*

The influence of various parameters such as orthotropy stiffness parameter, width to flange thickness ratio and depth to web thickness ratio on natural frequencies was investigated. Mode shapes of symmetric and unsymmetric box beams were also studied.

4.1.1. *Influence of orthotropy stiffness parameter*

To study the effect of orthotropy stiffness parameter on natural frequency, the simply supported symmetric composite box beams with three L/B, B/D and different cells were considered. In each case box beams with constant thickness of flange and web of 2 mm were taken. Fiber orientations in flange and web were chosen as arbitrary combination of 0, +/-45 and 90 degree. Six layers of stacking sequence in laminates were selected. Orthotropy stiffness parameter, $(D_{11})_f/(D_{22})_w$ for each models were calculated by written a program in Excel.

The variation of natural frequency with orthotropy stiffness parameter, $(D_{11})_f/(D_{22})_w$ of box beams with various length to width ratio, L/B = 13.33, 16.67 and 20 are shown in Fig. 4. Geometrical properties: 4000 x 300 x 200 mm, 5000 x 300 x 200 mm and 6000 x 300 x 200 mm were taken in this case. It was depicted that the natural frequency increases with increase in orthotropy stiffness parameter, $(D_{11})_f/(D_{22})_w$. Similar response was observed in different cells and B/D ratio. It was due to the in-plane shear coupling (A_{16} and A_{26}) and bending-twisting coupling (D_{16} and D_{26}) decreases with increase in orthotropy stiffness parameter, $(D_{11})_f/(D_{22})_w$. From this also concluded that natural frequency decreases with increase in L/B ratio.

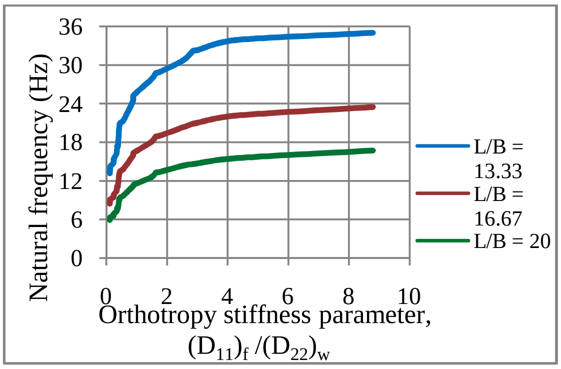

Fig. 4. Effect of orthotropy stiffness parameter with different L/B ratio

4.1.2. *Influence of width to flange thickness ratio*

To examine the effect of width to flange thickness ratio on natural frequency, the simply supported symmetric cross-ply box beams with different cells and B/D were considered. Six layer laminates having web thickness of 2 mm and flange thickness of 2 to 6 mm were taken. Two configuration with fiber orientation in flange and web = $[0/90/90]_s$ and fiber orientation in flange = $[0/0/0]_s$ and web = $[90/90/90]_s$ were chosen.

The variation of natural frequency with width to flange thickness ratio, B/t_f of box beams are represented in Fig. 5. It was observed that the natural frequency decreases with increase in width to flange thickness ratio in all cases. This was due to low stiffness in larger width to flange thickness ratio. Increase in thickness of flange tends to increase in natural frequency.

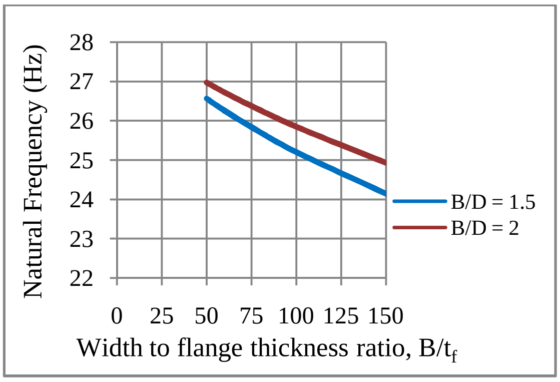

Fig. 5. Effect of B/t_f on natural frequency

4.1.3. *Influence of depth to web thickness ratio*

To evaluate the effect of depth to web thickness ratio on natural frequency, the simply supported symmetric cross-ply box beams with different cells and B/D were considered. Same configurations as in the previous case were considered.

The variation of natural frequency with depth to web thickness ratio, D/t_w of box beams for various B/D ratios is shown in Fig. 6. It was found that the natural frequency increases with increase in depth to web thickness ratio in all cases. This was due to high stiffness in larger width to flange thickness ratio. Increase in thickness of flange results in increase in natural frequency.

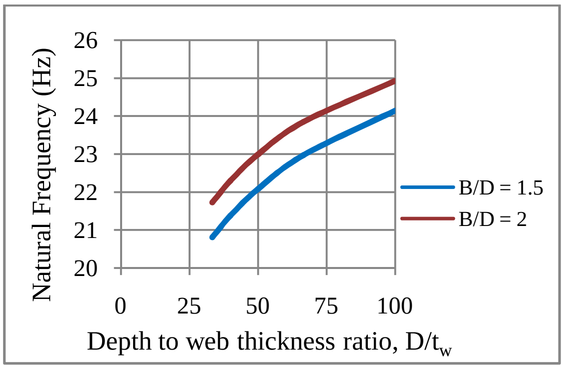

Fig. 6. Effect of D/t_w on natural frequency

4.1.4. *Mode shapes of composite box beams*

To evaluate the mode shapes of symmetric and unsymmetric simply supported composite box beams with constant thickness of flange and web of 2 mm and six layer laminates were considered. For symmetric composite box beam, same fiber orientation in flange and web as $[0]_6$ was chosen. The mode shapes of lowest three frequencies are represented in Fig. 7 to 9. As in the figure, the fundamental frequency exhibits flexural mode in X direction and other two exhibits flexural modes in Y direction.

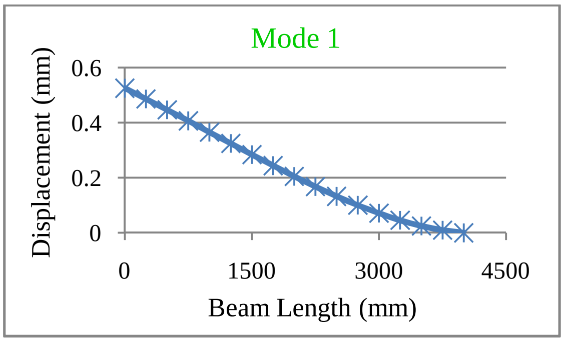

Fig. 7. Mode shapes for natural frequency = 35.029 Hz

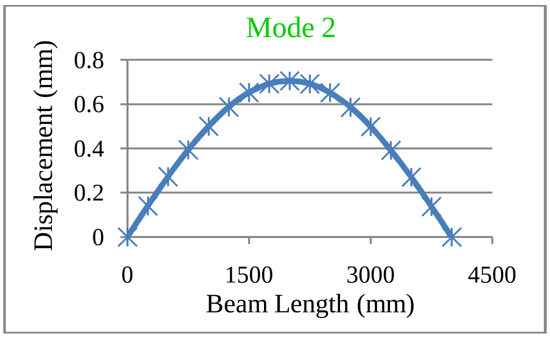

Fig. 8. Mode shapes for natural frequency = 43.820 Hz

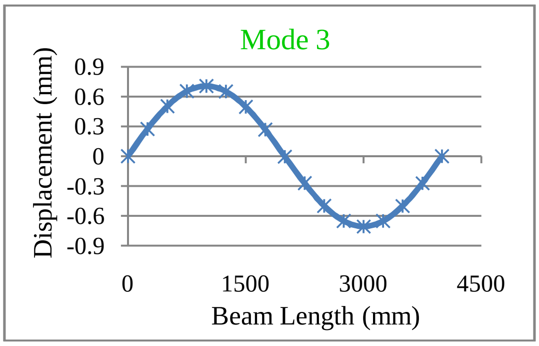

Fig. 9. Mode shapes for natural frequency = 45.201 Hz

Fiber orientation in unsymmetric composite box beam was taken as top flange: $[15]_6$, bottom flange: $[-15]_6$ and web: $[0/15]_3$. Fig. 10 to 12 denotes the mode shapes of lowest three frequencies of unsymmetric beam. It shows double coupling i.e, flexural and torsional mode. In that the fundamental frequency exhibits flexural mode in X direction and torsional mode in Y direction. Remaining two frequencies exhibit flexural mode in Y direction and torsional mode in X direction. This was because of unsymmetry of section due to different fiber orientation in top flange, bottom flange and web.

4.2. *Transient analysis*

The influence of various parameters such as width to flange thickness ratio and depth to web thickness ratio on displacement response was investigated.

4.2.1. *Influence of width to flange thickness ratio*

To study the variations of displacement time history with width to flange thickness, the simply supported symmetric cross-ply box beams with different cells and B/D were considered. Six layer laminates having web thickness of 2 mm and flange thickness of 2 to 6 mm were taken. Two configuration with fiber orientation in flange and web = $[0/90/90]_s$ and fiber orientation in flange = $[0/0/0]_s$ and web = $[90/90/90]_s$ were chosen for different cells. Time history analyses were examined by the seismic loading of Kobe earthquake in X direction that is peak ground acceleration (PGA) with a time step 0.1 sec. An external uniform load of 3000 N/m was also applied along with seismic loading.

Displacement time history with width to flange thickness ratio, B/t_f of single, double, and multi-cell box beams are given in Fig. 13 to 15. Fig. 16 and 17 shows the displacement time history of B/D = 1.5 and 2 respectively. As a remark, the peak displacement in B/D = 1.5 was maximum in B/t_f of 150 and peak displacement in B/D = 2 was maximum in B/t_f of 100. It was revealed that the maximum peak displacement is in higher B/t_f box beam, because of low stiffness in higher B/t_f box beam. Displacement response decreases with decrease in B/t_f ratio.

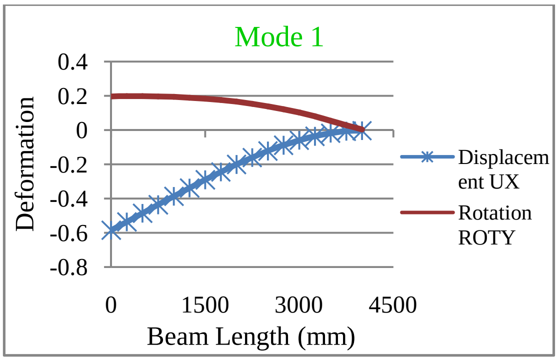

Fig. 10. Mode shapes for natural frequency = 29.795 Hz

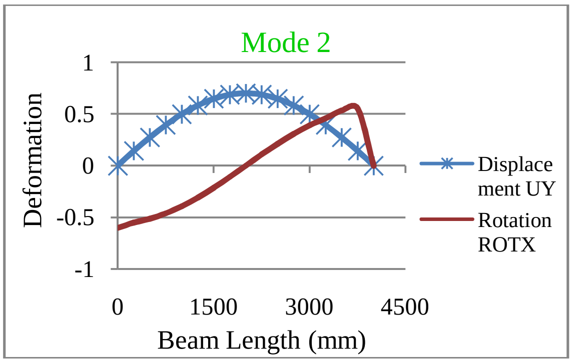

Fig. 11. Mode shapes for natural frequency = 44.298 Hz

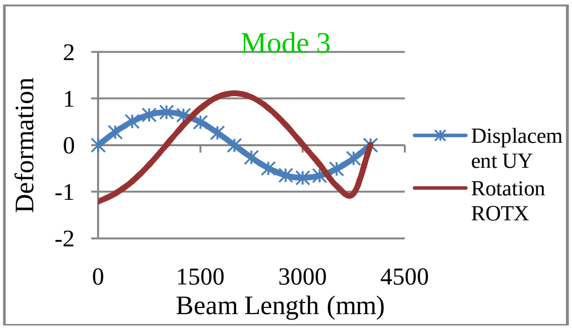

Fig. 12. Mode shapes for natural frequency = 45.361 Hz

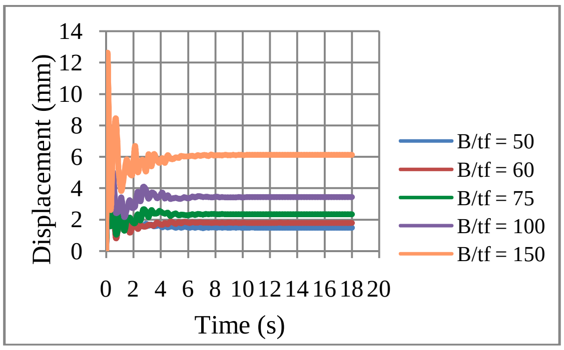

Fig. 13. Displacement time history of single cell

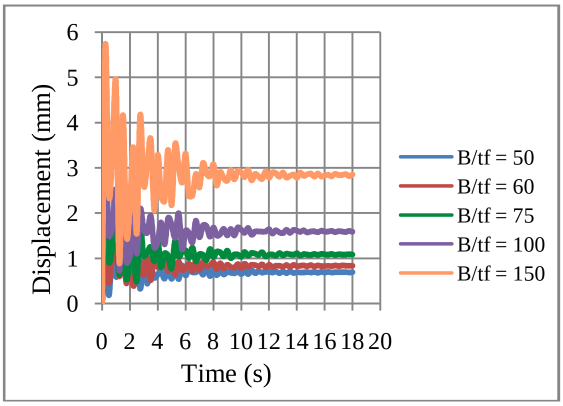

Fig. 14. Displacement time history of double cell

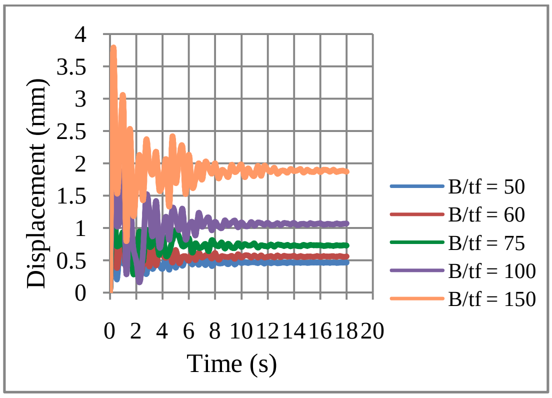

Fig. 15. Displacement time history of multi-cells

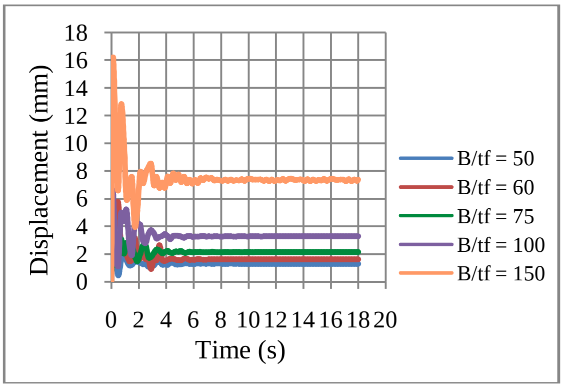

Fig. 16. Displacement time history of B/D =1.5

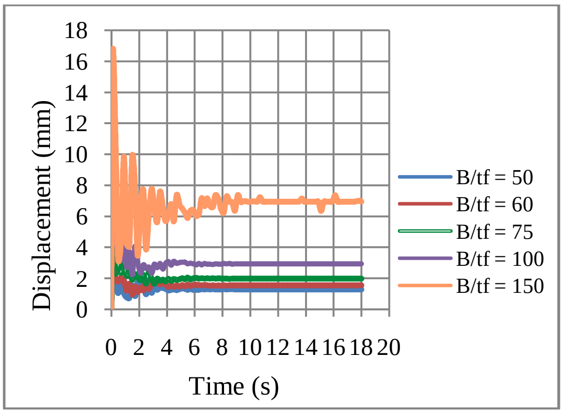

Fig. 17. Displacement time history of B/D = 2

4.2.2. *Influence of depth to web thickness ratio*

To evaluate the variations of displacement time history with depth to web thickness ratio, the simply supported symmetric cross-ply box beams with different cells and B/D were considered. Same configurations and loadings as in the previous case were applied for this study.

Displacement time history with depth to web thickness ratio, D/t_w of single, double, and multi-cell box beams are given in Fig. 18 to 20. Fig. 21 and 22 shows the displacement time history of B/D = 1.5 and 2 respectively. It implies that the peak displacement in B/D = 1.5 was maximum in D/t_w of 100 and peak displacement in B/D = 2 was maximum in D/t_w of 75. It was observed that the maximum peak displacement is in higher D/t_w box beam, because of low stiffness in higher D/t_w box beam. Displacement response decreases with decrease in D/t_w ratio.

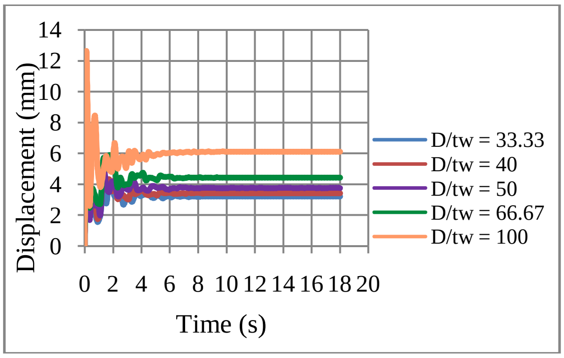

Fig. 18. Displacement time history of single cell

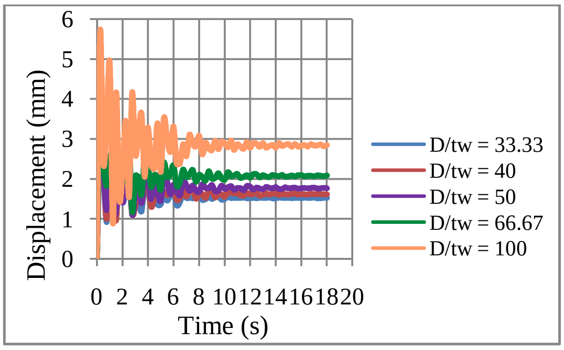

Fig. 19. Displacement time history of double cell

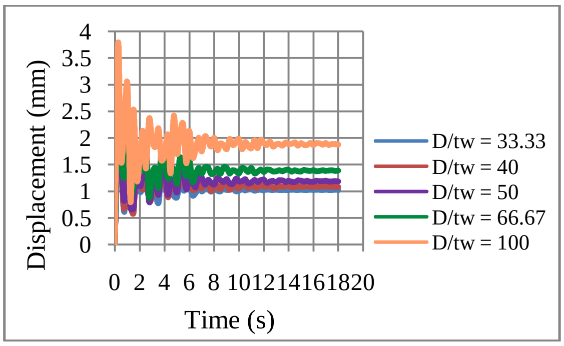

Fig. 20. Displacement time history of multi-cells

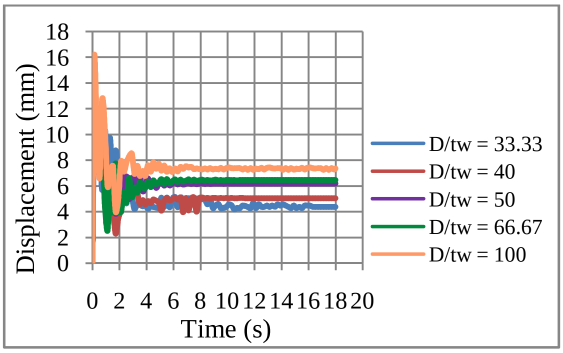

Fig. 21. Displacement time history of B/D = 1.5

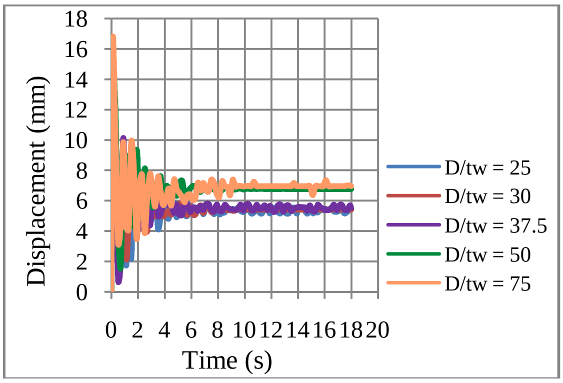

Fig. 22. Displacement time history of B/D = 2

5. CONCLUSIONS

Finite element method was used to model and analyze the proposed graphite-epoxy composite box beam. This procedure was taken to study free and transient analysis with assorted parameters. Number of cells was limited to three, because of similar behaviour in single cell and multi-cells. Transient analysis was limited to cross-ply laminate, due to larger time consumption for the analysis. Response of angle-ply laminate can be studied, by formulating a programming code to reduce time requirement. This provides scope for further study.

The significance of displacement response is more assured in thinner member. Displacement is minimum in higher flange and web thickness. In other words, lower B/t_f and D/t_w box beams have minimum displacement. The cross-ply laminate with combination of 0° and 90°, i.e $[0/90/90]_s$ have better performance under seismic loading than $[0/0/0]_s$ in flange and $[90/90/90]_s$ in web. Laminate with 0° fiber orientation having higher natural frequency as well as orthotropy stiffness parameter, $(D_{11})_f/(D_{22})_w$. The maximum natural frequency for width to flange thickness ratio, B/t_f is less than or equal to 50 and depth to web thickness ratio, D/t_w is more than or equal to 100. Both flexural and torsional modes are influential on unsymmetric composite box beams. Orthotropy stiffness parameter, width to flange thickness ratio, depth to web thickness ratio have considerable influence on natural frequency and displacement response.

6. SCOPE OF FUTURE STUDY

Dynamic analysis can be investigated for composite box beams with anti-symmetric lay-up. Development of a programming code for dynamic response by using results obtained here.

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