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Dynamic Behavior of Laminated Composite Beams Subjected to a Moving Load

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Abstract: In this study, the dynamic behavior of laminated composites subjected to a single force traveling at a constant velocity has been investigated. Three-dimensional finite element model based on classical lamination theory was used. The dynamic analyses for simply supported composite beams under the action of moving loads are carried out by the finite element method. The dynamic magnification, which is an important parameter in the case of moving load, has been obtained for different load velocities and ply orientations. The results for laminated composite beams under the action of a moving load have been illustrated and compared to the results for an isotropic simple beam. The results have shown that the traveling velocities and ply orientations have significant influence on the dynamic responses of composite beams, specially for those with $[90_8]_s$ layup.

Key words: Dynamic magnification, finite element analysis, laminated composites, moving load

INTRODUCTION

The use of fiber reinforced composite materials in modern engineering has increased rapidly in recent years. Despite composite materials offer many desirable structural properties such as lightweight and high strength; they also include many technical problems in understanding their dynamic responses. Engineering structures such as bridges, rails and cranes are usually subjected to moving loads. In contrast to other dynamic loads, the moving loads vary in position. This makes the moving load problem a major field of research in structural dynamics.

Many analytical and numerical methods have been proposed in the past to investigate the dynamic behavior of isotropic structures subjected to moving load. However, little attention has been paid to dynamic response of laminated composite structures. Therefore, the aim of this work is focusing on the influence of a moving load on laminated composites. A basic understanding of the moving load problem and reference data for general studies on linear elastic materials has been given by Olsson[1]. Esmailzadeh and Ghorashi analyzed the effects of shear deformation, rotary inertia and the length of load distribution on the vibration of the Timoshenko beam subjected to a traveling mass[2]. In addition, Wang investigated the forced vibration of multi-span Timoshenko beams[3]. The effects of span number, rotary inertia end shear deformation on the maximum moment, the maximum deflection and critical velocity were examined. The dynamic responses of multi-span Euler-Bernoulli beams to moving loads were studied by Rao[4]. Law and Zhu studied the moving force identification with a Timoshenko beam model and compared the result with that from an Euler-Bernoulli beam model[5]. Comparative studies on moving force identification were also carried out[6].

A very flexible structure can be developed in layered beam by changing the lamination angle. The most appropriate beam stiffness may be designed by selected suitable values of angles of laminate reinforcements. Bassiouni *et al.*[7] studied the behavior of different model layer arrangements on the natural frequencies and vibration level. Banarjee developed the dynamic stiffness matrices of a composite Timoshenko beam in order to investigate their free vibration characteristics[8]. The dynamic response of an unsymmetric orthotropic laminated composite beam, subjected to moving loads, was studied[9,10].

The objective of the study is to present the finite element dynamic analysis of laminated composite beams subjected to a constant vertical force moving at a constant speed. The effects of various parameters such as load speed and position and ply orientation on the dynamic magnification factor have been investigated and compared to the result for an isotropic beam.

Problem definition: The model is considered as a simply supported laminated composite beam with a span length L=0.5 m, solid rectangular cross-section (width b=0.02 m, thickness h=0.01 m) (Fig. 1).

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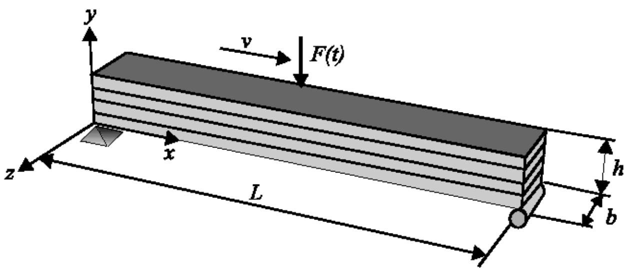

Fig. 1: Simply supported laminated composite beam subjected to a moving force F (t)

The beam is subjected to a constant vertical force (F_y=-100 N) moving at a constant speed. The single space-varying force applied to the system is shown in Fig. 2. v is the velocity of the moving load which is constant defined by

$$\nu = \frac{L}{\tau} \quad , \quad \tau_i = \frac{x_i}{\nu}$$

where τ denotes the total traveling time of the force moving from the left end of the beam to the right end. F(t), the force acting on the beam (Fig. 2) is identified using a computer program written in Visual Basic programming language in suitable form for ANSYS software. Where x_i : position at i^{th} node, τ_i : time at i^{th} node.

The material properties of the beams investigated are assumed to be same in all layers, but the fiber orientations are different among the layers. Five different configurations, namely $[0_8]_s$, $[90_8]_s$, $[\pm45_4]_s$, $[0_2/90_2]_{2s}$, $[0_2/\pm45_2/90_2]_s$ were considered. The thickness of each layer is identical for all layers in the laminates. The material of each lamina is assumed as an AS4/3501-6 material with the following properties shows in Table 1. The properties of steel beam selected to compare to the behavior of composite beams are as follows:

Table 1: Material Properties of AS4/3501-6

Properties	Magnitudes
E_{xx}	147 GPa
E_{yy}=E_{zz}	9 GPa
ν_{xy}=ν_{xz}	0.3
ν_{yz}	0.42
G_{xy}=G_{xz}	5 GPa
G_{yz}	0.3 GPa
ρ	1.58 g cm^{-3}
Ply thickness	1.25 mm

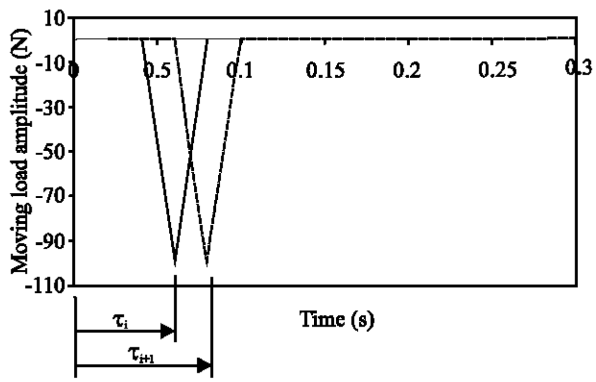

Fig. 2: Moving load identification

$$E=206 \text{ GPa}, \qquad \nu=0.3, \qquad \rho= 7.8 \text{ g cm}^{-3}$$

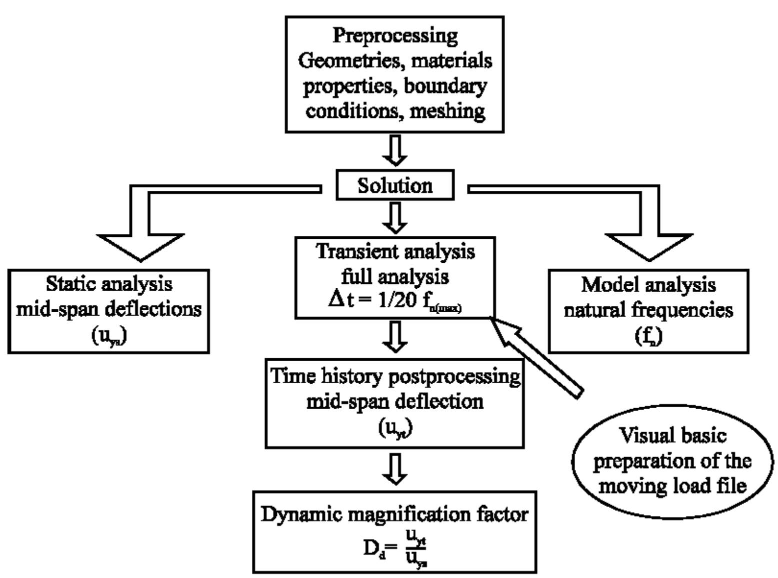

Fig. 3: Analysis scheme

In this study, it is purposed to develop three-dimensional finite element model to provide the effect of ply orientation and force velocity on the dynamic behavior of laminated composite beams.

The finite element model: The dynamic behavior of a simply supported composite beam subjected to a vertical moving force is predicted using a three-dimensional finite element model developed in the commercial finite element software ANSYS. The beam model is discretized into 120 three dimensional 8-node layered structural solid element. The load is started to enter the beam from the left-hand support at a constant speed. All dof's in the z direction are constrained in order to calculate the modes which are in x-y plane and contribute to the dynamic response of the beam in y direction. The beam is simply supported and can be analyzed employing the following boundary conditions:

$$u, v\,|_{x=0}=0, \quad v\,|_{x=L}=0$$

The analysis stages are illustrated in the flow chart shown in Fig. 3.

RESULTS AND DISCUSSION

Numerical results obtained from analyses are presented for symmetric laminated beams with various ply orientation and steel in this section. The variation of the maximum static deflection of the all beams with variation of ply orientation is presented in Fig. 4. As seen, increasing of the number of [0] layers always results in decreasing the maximum beam deflection because of the stiffness of this orientation. The effects of laminated composite with $[90]_s$ lay-up cause greater absolute maximum deflection which is about 4.36 mm than the laminated composite with $[0]_s$.

Results for the dynamic magnification factor D_d, defined as the ratio of the maximum dynamic and static deflections at the center of the beam, are computed and

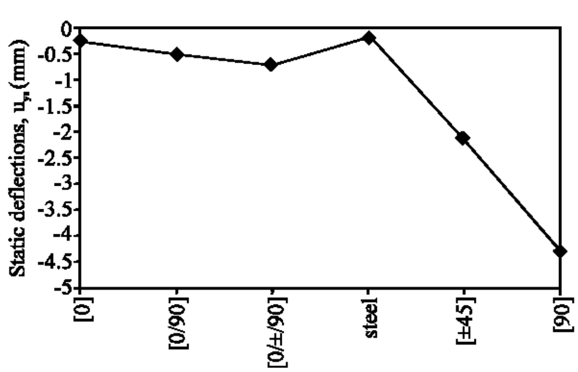

Fig. 4: Variation of the maximum static deflection for different laminate configurations and steel

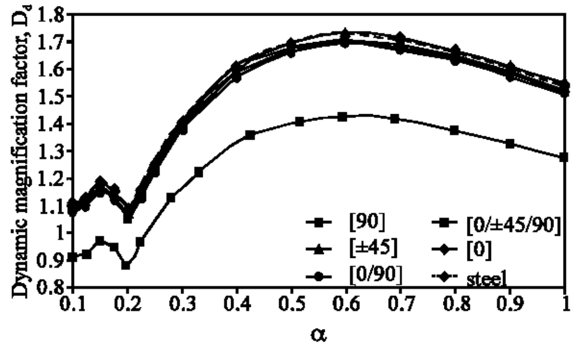

Fig. 5: The effects of α on dynamic magnification factors for mid-span displacement

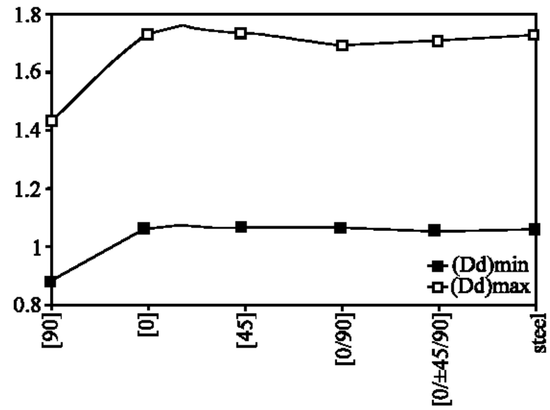

Fig. 6: Comparison of the maximum and minimum magnification factors for five different lay-up and steel beams

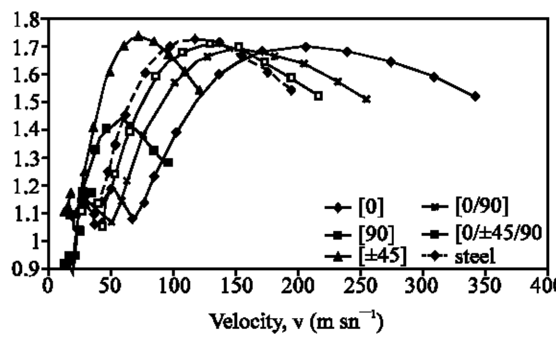

Fig. 7: Comparison of the dynamic magnification factor of the steel beam and laminated composite beams with respect to moving load velocity

compared each other in Fig. 5, for different values of T/2τ_(α), where τ denotes the total traveling time of the force moving from the left end of the beam to the right end, while T denotes the first natural period of the beam. To validate the model, the results obtained from the ANSYS for steel beam were compared with the analytical predictions from other studies[1,9,10]. The present results, obtained from ANSYS, compare quite well with the results

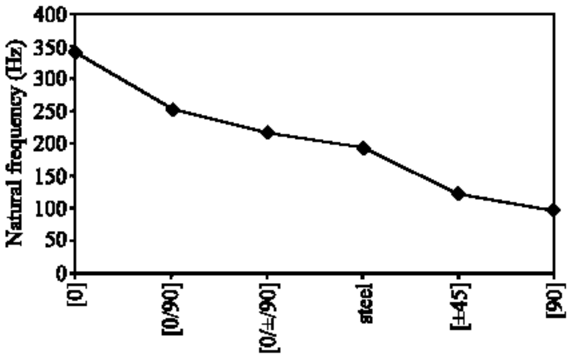

Fig. 8: Comparison of the natural frequency for five different lay-up and steel beams

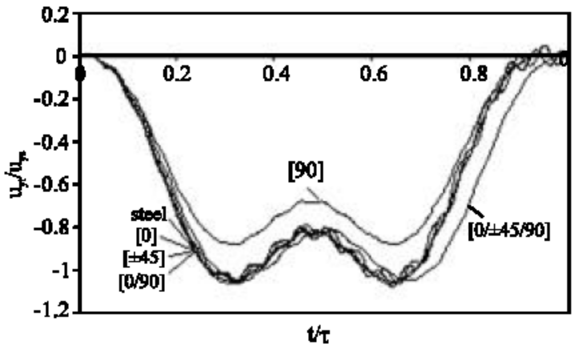

Fig. 9: Time histories for normalized mid-span displacements for α=0.2

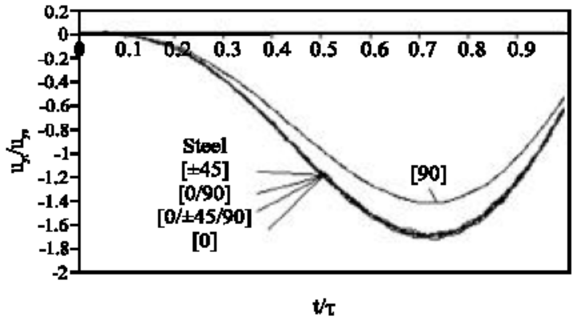

Fig. 10: Time histories for normalized mid-span displacements for α=0.6

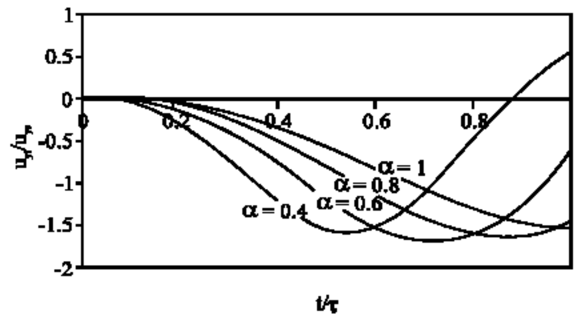

Fig. 11: Time histories for normalized mid-span displacements for $[0_8]_s$ laminated composite beam

of the others and thereby confirm the validity of the purposed numerical procedure.

It can be seen that the maximum value of the dynamic magnification factor D_d is about 1.7 for steel and occurs at α=0.6. In view of the stacking sequence, it is noticed that the laminated composite with $[90_8]_s$ layers has relatively low approximately 20 % maximum D_d compared with the others. Maximum and minimum D_d occur at α=0.6 and α=0.2 for all laminated and steel beams, respectively. These values are critical according to a designer's point of view. The dynamic magnification factor of simply supported beams can be basically divided two regions: under critical and overcritical region, as pointed out by Kadivar and Mohebpour [9,10]. Meanwhile, undercritical region can be also divided to three regions. In undercritical region the dynamic magnification factor D_d both increase and decrease with increasing α as indicated by Olsson[1]. In this region, D_d increases until at α=0.15 and it reaches minimum value of D_d atα=0.2. The main increases in the factor D_d occur only in the intervals $0.2 \le \alpha \le 0.6$. In the overcritical region the D_d decreases as α increases.

All laminate configurations have higher D_d values than that $[90_8]_s$ laminate. However, these differences among them are quite slight and are limited to 2%.

Comparison of maximum and minimum magnification factors for five different lay-up and steel beams can be seen in Fig. 6.

Figure 7 shows the comparison of the D_d for all beams investigated versus the moving load velocity. As indicated in this figure, although the total weights of composite beams is approximately 5 times less than the total weight of the steel beam, the maximum dynamic magnification factor is approximately the same for material types except for $[90_8]_s$laminated composite. However, the critical velocities of $[0_2/90_2]_{2s}$, $[0_2/\pm45_2/90_2]_s$ and $[0_8]_s$ laminated composites are much higher than the critical velocity of the $[\pm45_4]_s$ composite beam. This result illustrates the importance of the stacking sequence. The velocity of the moving load is varied from 9 to 345 m s^{-1}. It is interesting to note that $[90_8]_s$ laminates reaches the maximum D_d at low speed (approximately 60 m s^{-1}) compared to others. Whereas $[0_8]_s$ laminates reaches the maximum D_d at approximately 200 m s^{-1}. Furthermore, as could be deduced from Fig. 7, the critical velocity of $[0_8]_s$ composite beam is about 2 times the critical velocity of the steel beam. Knowing the critical velocities is helpful at the design stage in order to take under control the deflections of the overall structure.

In Fig. 8, it is shown the effects of different model layer arrangements on the natural frequencies. The main conclusion is that, the stacking sequences have the main effect on the natural frequencies. Natural frequencies can be controlled by increasing the fiber orientation angle. Changing the fiber orientation of the layers from 0 to 90° decreases the natural frequencies by approximately 70%. It is obvious that the largest difference in the natural frequencies is between $[0_8]_s$ and $[90_8]_s$ laminated composites where the $[0_8]_s$ laminated composite frequency is about 3.5 times lower than the $[90_8]_s$ laminated composite.

Results for the normalized time histories of the displacements in y direction at the center of the beam versus t/τ, where t denotes the time after the moving load enters the beam from the left end for critical velocities (α=0.2 and α=0.6) are presented in Fig. 9 and 10. It can be seen from the present results, the peak values occur almost simultaneously. In Fig. 9, it is shown that dynamic displacements reach the maximum values at about t/τ=0.3 and t/τ=0.7. As can be observed in Fig. 10, the dynamic displacements initially increase as t/τ increases. However, dynamic displacements decrease when t/τ is increased beyond the value of 0.7. The results obtained from figures indicate that when a concentrated force travels along a beam, the dynamic behavior is influenced by the ply orientation.

From Fig. 11, it can be easily seen that the time at which the maximum mid-span displacement occurred shifts to the right as α increases. Finally, maximum dynamic displacement occurs while the force leaves the beam at α=1.

In this study, the responses of laminated composite beam to a single moving load are presented. The objective is to determine the influences of the ply orientation and velocity on the dynamic behavior of a simply supported composite beam. From the numerical results presented, it can be concluded that;

- The dynamic behaviors are influenced by the plyx orientation when a force travels along the beam Increasing the number of [0] layers always results in decreasing the maximum beam deflection because of the increasing stiffness of this orientation.
- The maximum and minimum values of the dynamic magnification factor (D_d) occur at α=0.6 and α=0.2 for all laminated composite and steel beams, respectively. In view of the stacking sequence, it is noticed that the orientations of $[90_8]_s$ layers is relatively lower D_d value compared with the others.
- The dynamic magnification factor of simply supported beams can be basically divided into two regions: under critical and overcritical region. Meanwhile, undercritical region can be also divided to three regions. In undercritical region the D_d increases until at α=0.15 and it reaches minimum value of D_d at α=0.2. By the end of the undercritical region, D_d increases with the increasing α. The main increases in the factor D_d occur only in the intervals $0.2 \le \alpha \le 0.62$. For α<0.2, the magnification factor D_d both increase and decrease with increasing α. In the overcritical region, the D_d decreases as α increases.
- The values of D_d for all laminate configurations except $[90_8]_s$ laminate are quite close and their differences are limited to 2%.
- The critical velocity of $[0_8]_s$ composite beam is about 2 times the critical velocity of the steel beam.
- $[90_8]_s$ laminates reaches the maximum D_d at about 60 m s^{-1}, whereas $[0_8]_s$ laminates reaches the maximum D_d at 200 m s^{-1}.
- At low speeds dynamic magnification factor value for $[90_8]_s$ laminates is less than 1. It means that dynamic displacements can be smaller than static displacements at mid-span.
- As a concluding remark, it is observed that the stacking sequences have the main effect on the natural frequencies. Natural frequencies can be controlled by increasing the fiber orientation angle. Changing the fiber orientation of the layers from 0 to 90° decreases the natural frequencies by approximately 70%.
- Large deflection of a beam induced by a force moving with α=1 occurs while the force is leaving the beam.

Finally this study will be useful for the designer interested in laminated composites subjected to moving load to select the fiber orientation angle to shift the natural frequencies as desired or to control the vibration level.

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