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Effect of Sinusoidal Fiber Waviness on Non-Linear Dynamic Performance of Laminated Composite Plates with Variable Fiber Spacing

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Abstract. This study investigated influence of varying waviness characteristics of fiber, represented by path amplitude Δ and different numbers of half sine waves *k*, on the elastic-plastic dynamic behaviour of laminated composite plates with variable fiber spacing. The analysis was based on the equations for action of constant axial dynamic loading and two-dimensional layered approach with classical first order shear deformation theory with five degrees of freedom per node, and it was performed with FORTRAN 94 programming language. Von-Karman's assumptions were used for the discretization of the laminated plates to include geometric nonlinearity for nine-node Lagrangian isoperimetric quadrilateral elements. Complete bond between the layers was assumed with no delamination, which was based on first-order shear deformation theory. The Newmark implicit time integration method and Newton-Raphson iteration were simultaneously used to solve the nonlinear governing equation in conjunction. It was proven in the research that the nonlinear performance of the laminated composite plate was affected by the studied waviness parameters Δ and *k*, and also by the variable distribution pattern selected for this study.

Keywords: laminated plate, composite, sinusoidal shape of fibers, variable spacing, dynamic load, non-linear performance

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Влияние синусоидальной формы волокон и расстояния между ними на нелинейные динамические характеристики многослойных композитных пластин

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Нераздельное соавторство.

Аннотация. Исследуется влияние различных характеристик синусоидальной формы волокон, в том числе амплитуды и количества последовательностей, на упругопластические динамические свойства многослойных композитных пластин с переменным расстоянием между волокнами. Методика исследования основана на некоторых уравнениях Лейсса — Мартена для постоянной осевой динамической нагрузки и двумерном многослойном подходе с классической теорией сдвиговых деформаций первого порядка с пятью степенями свободы на узел и реализована с помощью языка программирования FORTRAN 94. Гипотезы фон Кармана используются для учета геометрической нелинейности в девятиузловых изопериметрических четырехугольных элементах Лагранжа, которые применяются для дискретизации многослойных пластин. Предполагается полное сцепление между слоями без расслоения на основании теории сдвиговых деформаций первого порядка. Для решения нелинейного разрешающего уравнения одновременно используются неявный метод интегрирования Ньюмарка и итерационный метод Ньютона — Рафсона. Результаты исследования показывали, что нелинейные характеристики слоистой композитной пластины зависят от исследуемых параметров волнистости Δ и k волокон, а также от выбранной для данного исследования схемы их распределения.

Ключевые слова: слоистая пластина, композит, синусоидальная форма волокон, переменное расстояние между волокнами, динамическая нагрузка, нелинейная постановка задачи

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1. Introduction

Frequently employed methodologies for the design of composite laminates entail the organization of the matrix and fibers in a pattern characterized by equidistant intervals and linear trajectories that are oriented parallel and perpendicular to the axis of the laminate. Therefore, it can be deduced that both the angle of the fibers and the percentage of fiber volume remain fixed in relation to the plane of the lamina.

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Consequently, previous formulations of the stress-strain state have solely considered fibers that are linear. The objective of this study is to produce composite materials that exhibit optimal forms of inhomogeneity through the modification of reinforcing fiber shapes. The intended outcome is to enhance the buckling strength of thin-walled laminates [1; 2]. The tensile response of laminates having a sinusoidal fiber pattern was investigated in [3]. In [4] examined the effect of curved fibers on the tensile and compressive response of a plate with a circular hole. The influence of sinusoidal fibers on the buckling behavior of a composite laminate was investigated by P. Phani Prasanthi, K. Sivaji babu, and A. Eswar Kumar [1]. There are three important relationships between the fibers and wave properties, which are:

1. The secondary significance of fibers in the transmission of dynamic and thermal waves in the overall composition of composite materials [5–7].

2. The utilization of fluctuating regular geometric phase functions, such as sine or cosine, as a means of variable distribution of fibers within the matrix [8–10].

3. Sawing the fibers form regular geometric waves in the matrix, which is a method adopted recently in the manufacture of composite panels [10], improving the non-linear dynamic performance of the panel under plane load.

The principal aim of the study by Ali I. Al-Mosawi [11] was to investigate whether variable fiber spacing can enhance the structural efficiency of plates. This study presents numerical findings on the impact of in-plane loading on boron/epoxy fiber reinforced laminates. Various properties of the composite plate are examined. The findings of this investigation indicate that the post-buckling response of composite plates is highly influenced by the fiber distribution type. Specifically, the seventh distribution equation yields the highest buckling load and the lowest amount of deformation.

The study by A.V. Duran [6] offers an analysis of thermal buckling in square composite laminates that exhibit varying stiffness properties. The spatial variability of fiber angles gives rise to position-dependent material properties. This study examines the thermal responses of symmetric balanced laminates subjected to constant thermal loading using a particular methodology. The objective is to identify the optimal fiber orientations that can effectively resist thermal buckling for various material models.

In the book [chapter 2] of Susmita Mondal and L.S. Ramachandr [12], imperfections in laminated composite plates in the form of openings were considered. Based on this new concept, the nonlinear dynamic pulse buckling of imperfect composite plate with embedded delamination was numerically analyzed and showed the influence of type of pulse loading (sinusoidal, exponential and rectangular) and plate boundary condition on the shock spectrum. The response of delaminated plates was also computed for various delamination percentages at different layer interfaces by using Tsai-Wu quadratic interaction criterion. This study was selected to compare its results to verify the accuracy of the current results and the reliability of the program.

M. Cetkovic [13] studied the influence of initial geometrical imperfections on thermal stability of laminated composite plates using the layerwise plate model. The effects of imperfection mode and amplitude, temperature distribution, side to thickness ratio b/h, aspect ratio b/a, boundary conditions and lamination scheme on critical buckling temperature were analysed. The mathematical model assumes layerwise variation of in-plane displacements, non-linear strain-displacement relations (in von Karman sense) and linear thermo-mechanical material properties by adopting the Koiter's model for initial geometrical imperfections. Principle of virtual displacements (PVD) is used to derive Euler — Lagrange differential equations of linearized buckling problem.

Haider K. Ammash [10] conducted a study on the effect of fiber waviness on the analysis of laminated composite plates with large displacement elastic-plastic behaviour. The study utilized a square plate with six layers and a simply supported boundary condition. The hypothesis posits that fibers exhibit sinusoidal morphology. Chapter 6 discusses the impact of this particular type on various factors such as the number of semiwavelengths (k), the amplitude of the wave (Δ), and the orientation of the fiber. The variability of the sine wave fiber semiwavelengths (k) was established within the amplitude range of the sine wave fiber, spanning from 0.05 to 0.5.

T. Piyatuchsananon et al. [14] performed a study to elucidate the correlation between quantified fiber waviness parameters and the tensile strength of a composite material. The orientation angles of the fibers in a composite material reinforced with flax slivers were initially determined. Subsequently, the distribution of angles was assessed through the utilization of the Local Moran's I and Local Geary's c techniques for spatial autocorrelation analysis. Ultimately, the results showed correlation between the resultant tensile strength and the measured parameters.

2. Theoretical formulation of geometric waviness of fibers

The present study aims to assess the feasibility of improving the buckling capacity of composite plates through the modification of the reinforcing fibers' shape within the plate. The subsequent paragraphs feature figures that illustrate the impact of fiber waviness on dynamic buckling curves:

$$y(x) = \alpha \sin\left(\frac{k\pi x}{a}\right). \tag{1}$$

In a manner that induces fluctuations in the orientation angle of fibers along the longitudinal x-axis, the following occurs:

$$\tan(\theta) = \frac{dy}{dx} = \frac{\alpha k\pi}{a} \cdot \cos\left(\frac{k\pi x}{a}\right) = \Delta k\pi \cdot \cos\left(k\pi \bar{x}\right), \tag{2}$$

where a = plate length; k = number of half sine waves; and α = wave amplitude. Two normalized variables, $\Delta = \alpha / a$ and $\bar{x} = x / a$, are introduced.

The initial objective of this research is to examine the impact of fiber waviness, represented by parameters k and Δ, on the static and dynamic buckling properties of composite laminates. In order to obtain fiber rotation in any direction around the x-axis, as depicted in Figure 1, one can employ the following equation:

$$x_n = x\cos(\beta) + y\sin(\beta), \tag{3}$$

where β is the angle of waviness for the fiber and x_n stands for the x-coordinate of a rotating fiber.
The angle of fiber orientation is variable with respect to the x-coordinate:

$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = 0, \tag{4}$$

this angle, rather than the constant angle that is utilized for straight fibers, is employed in Equation 1.

Figure 2 demonstrates how the main material directions are angled to be parallel to the lamina axes (β).

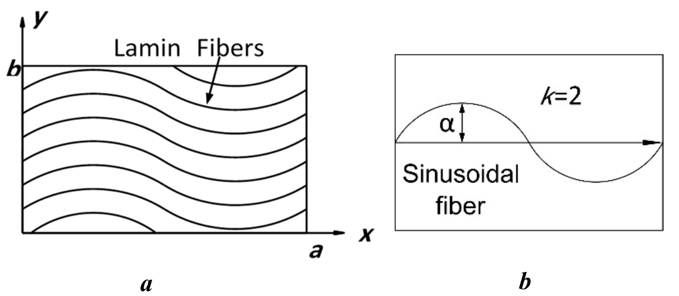


Figure 1. Sinusoidal fiber rotation around the x-axis:
a — Lamina with variable fiber orientation;
b — Geometry of sinusoidal fiber path
S o u r c e: M.D. Pandey [15]

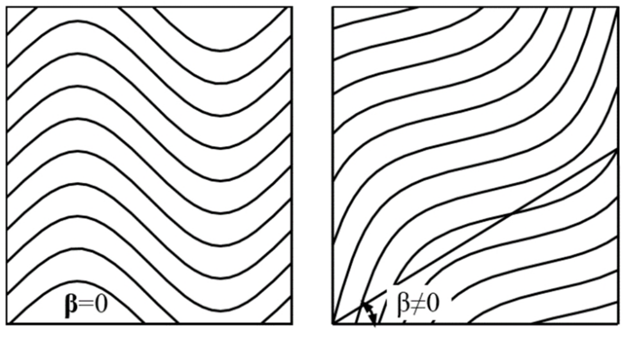


Figure 2. Laminate plate with sine wave fibers aligned with x-axis
S o u r c e: made by W.H. Mohammed

3. Materials and Methods

The present study aims to investigate the impact of fibers' geometric regular waviness on the large displacement elastic-plastic dynamic behaviour of laminated composite plates (1×1×0.01 m). formed from four layers of thin steel plates bonded by the epoxy matrix reinforced with carbon fibers (E_f = 413.68 [GPa], E_m = 4.3 [GPa], G_f = 172.36 [GPa], G_m = 1.277 [GPa], v_f = 0.2, and v_m = 0.35). They were subjected to 800 kN uniform in-plane compressive load in the X-axis direction with a time step (Δt) of 0.0001[sec]. To achieve this, a four-layer square symmetric cross-ply laminated plate with variable distribution of carbon fiber was analysed based on [2–2] and [3–3] from Leissa and Martin's equation (Table 1). The dynamic response of the plate was evaluated using the FENSDAAP computer program, which is coded in FORTRAN 94 language. The study considered different values of fiber path amplitude Δ ranging from 0.05 to 0.5 and different numbers of semiwavelengths k ranging from 4 to 12 (Table 2). The current investigation utilized a (2x2) element mesh featuring a nine-node isoparametric approach to model the complete laminate plate. Each node of Lagrangian elements possesses five degrees of freedom per node (w, θx, θy, θx^*, θy^*). A consistent mass matrix and **Newmark** integration method with $\boldsymbol{\alpha}$ = 1/2, and $\boldsymbol{\beta}$ = 1/4 were used in the present study.

Table 1

Equations of fibers distribution based on Leissa and Martine's equations

Equation $(\boldsymbol{n-p})$. $\boldsymbol{n}$: equation's number $\boldsymbol{p}$: equation's exponent	$\boldsymbol{V_f(x)}$	Volume fraction of fiber, %	
		$\boldsymbol{V_{f\,\max}}$	$\boldsymbol{V_{f\,\mathrm{av}}}$
Equation 1–1	$\left[\frac{4}{L}X-\frac{4}{L^2}X^2\right]$	100	66.67
Equation 2–2	$\left[\frac{4}{L}X-\frac{4}{L^2}X^2\right]^2$	100	53.34
Equation 3–3	$\left[\frac{4}{L}X-\frac{4}{L^2}X^2\right]^3$	100	45.7
Equation 4–1	$\frac{1}{2}+\left[\frac{1}{L}X-\frac{1}{L^2}X^2\right]$	75	66.67
Equation 5–2	$\frac{1}{2}+\left[\frac{1}{L}X-\frac{1}{L^2}X^2\right]^2$	75	63.34

S o u r c e: made by A.W. Leissa and A.F. Martin [16]

Table 2

Parameters of the analysis

Fiber distribution	Values of fibers path amplitude Δ with number of semiwavelengths, k = 4	Numbers of semiwavelengths (k) with value of fiber path amplitude, Δ = 0.4
Unified **Equation 2–2** **Equation 3–3**	0.1 0.2 0.3 0.4 0.5	4 6 8 10 12

S o u r c e: made by W.H. Mohammed

4. Results and discussion

4.1. Effect of variable fiber distribution on the dynamic nonlinear behaviour of a wavy fiber laminated composite plate

Figure 3, *a* aims to compare two plates with a consistent fiber distribution. The first plate had fibers arranged in a straight pattern, while the second plate had fibers arranged in a wavy pattern with values of fiber path amplitude $\Delta = (0.3)$ and numbers of semiwavelengths $k = 4$.

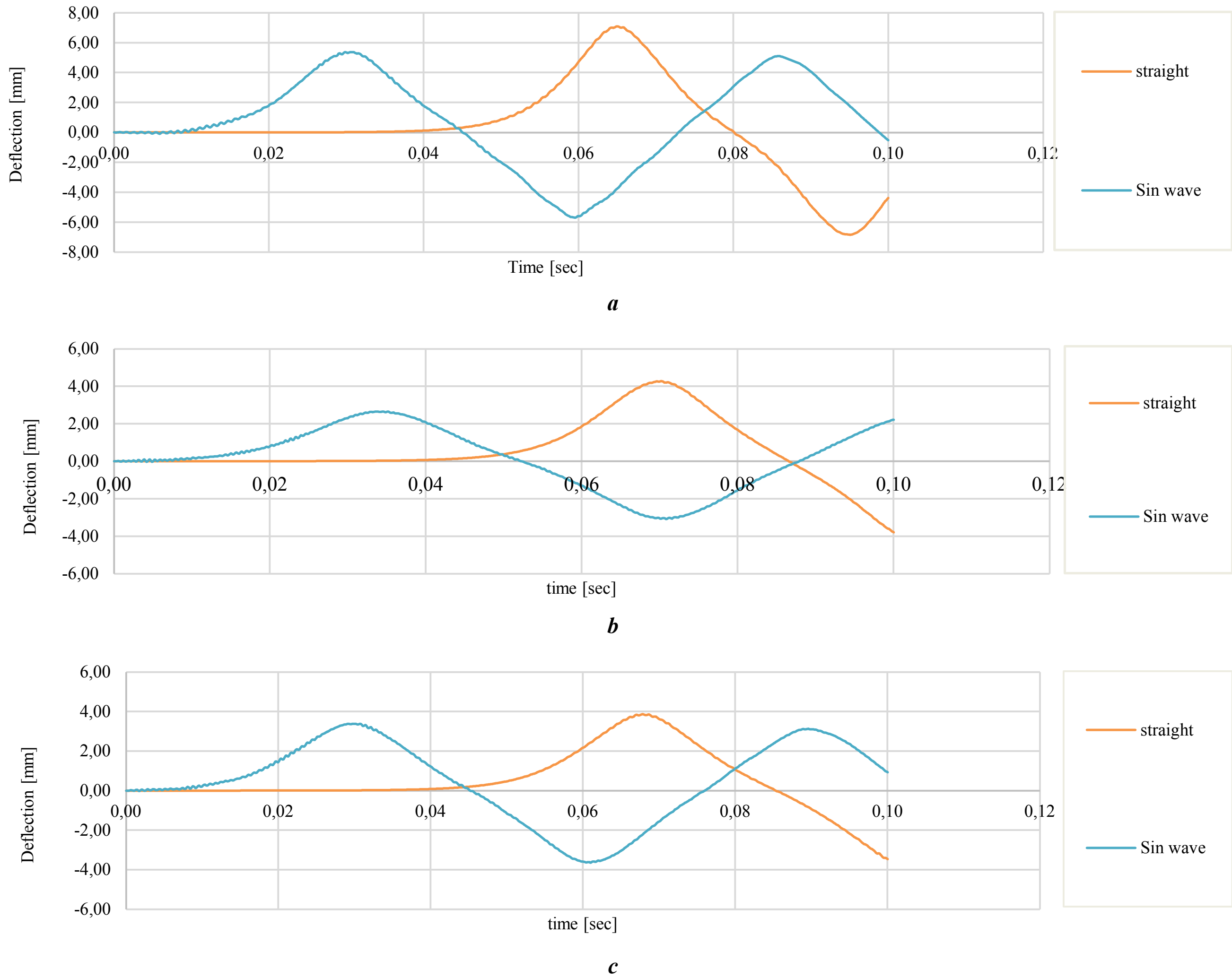


Figure 3. Comparison of straight carbon fiber versus sine wave fiber with different distributions:
a — unified fiber distribution; *b* — variable fiber distribution based on equation [2–2];
c — variable fiber distribution based on equation [3–3]
S o u r c e: made by W.H. Mohammed

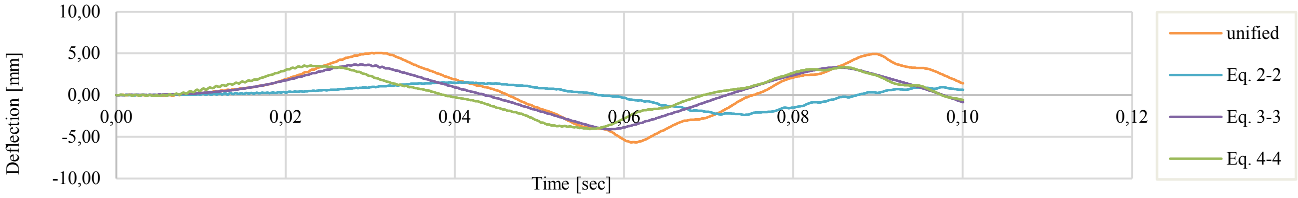
This contrast reaffirmed the concept of enhancing the composite panels' dynamic response by providing novel shapes and distributions to the fibers that contribute to energy dissipation as a result of the dynamic loads applied on them.

Figures 3, *b* and 3, *c* demonstrate the improvement of the dynamic performance of wavy fiber composite panels after changing their distribution.

It can be established that the distribution based on equation 2–2 is the best.

4.2. Effect of path amplitude Δ on non-linear dynamic performance of the laminated composite plates with variable fiber spacing

Figure 4 shows the effect of the path amplitude Δ in composites with variable fiber spacing based on Leissa — Marten's equations [2–2] and [3–3] on the nonlinear dynamic behaviour represented by the values of deflection of the samples. Five values Δ (0.1, 0.2, 0.3, 0.4 and 0.5) of this effect were studied with numbers of semiwavelengths $k = 4$. It is proven that the influence of this parameter on the stability and oscillations of the plate is significant, as well as on reducing the response.



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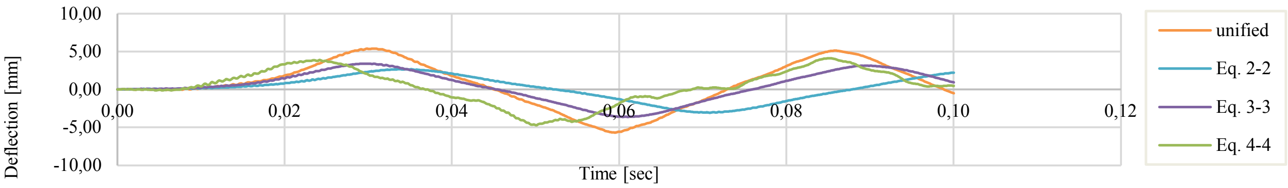

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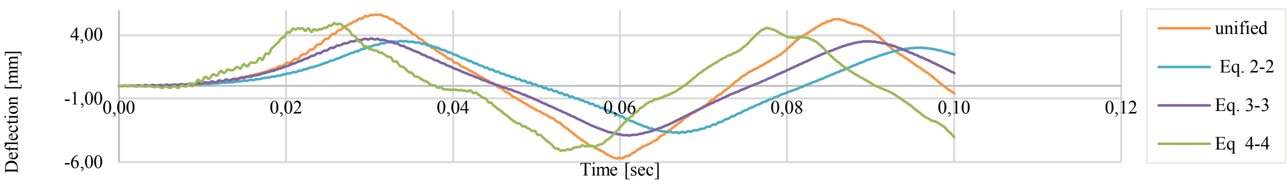

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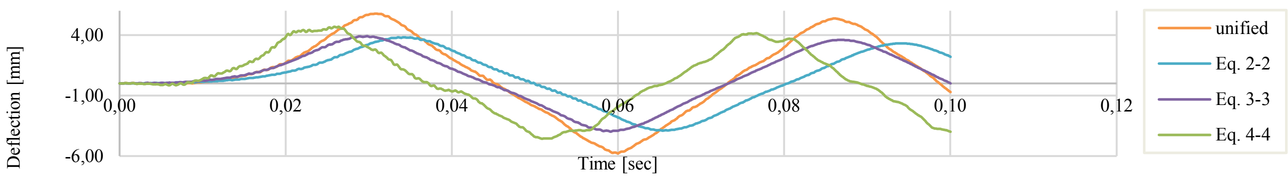

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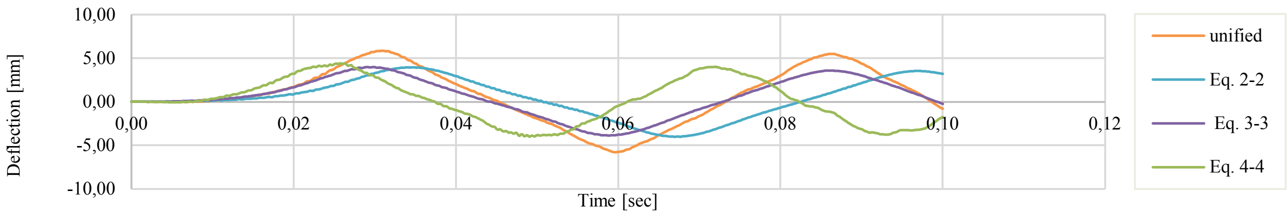


e

Figure 4. The effect of path amplitude Δ on non-linear dynamic performance of laminated composite plates with variable fiber spacing and number of semiwavelengths $k = 4$:
a — path amplitude = 0.1; *b* — path amplitude Δ = 0.2; *c* — path amplitude Δ = 0.3;
d — path amplitude Δ = 0.4; *e* — path amplitude Δ = 0.5
Source: made by W.H. Mohammed

4.3. Comparison of path amplitude values Δ in plates with variable fiber spacing based on [2–2]

By examining the behaviour of the plate with a variable distribution in Figure 4 it was noted that the panels reinforced with carbon fibers with distributions based on equations [2–2] and [3–3] are the most effective in improving the response. Therefore, they were selected to study the effect of the path amplitude Δ between 0.1 and 0.5 with the number of semiwavelengths $k = 4$, to find out which path is the most efficient.

The path amplitude Δ of 0.3 is the best, the least offset, and the most stable (Figure 5).

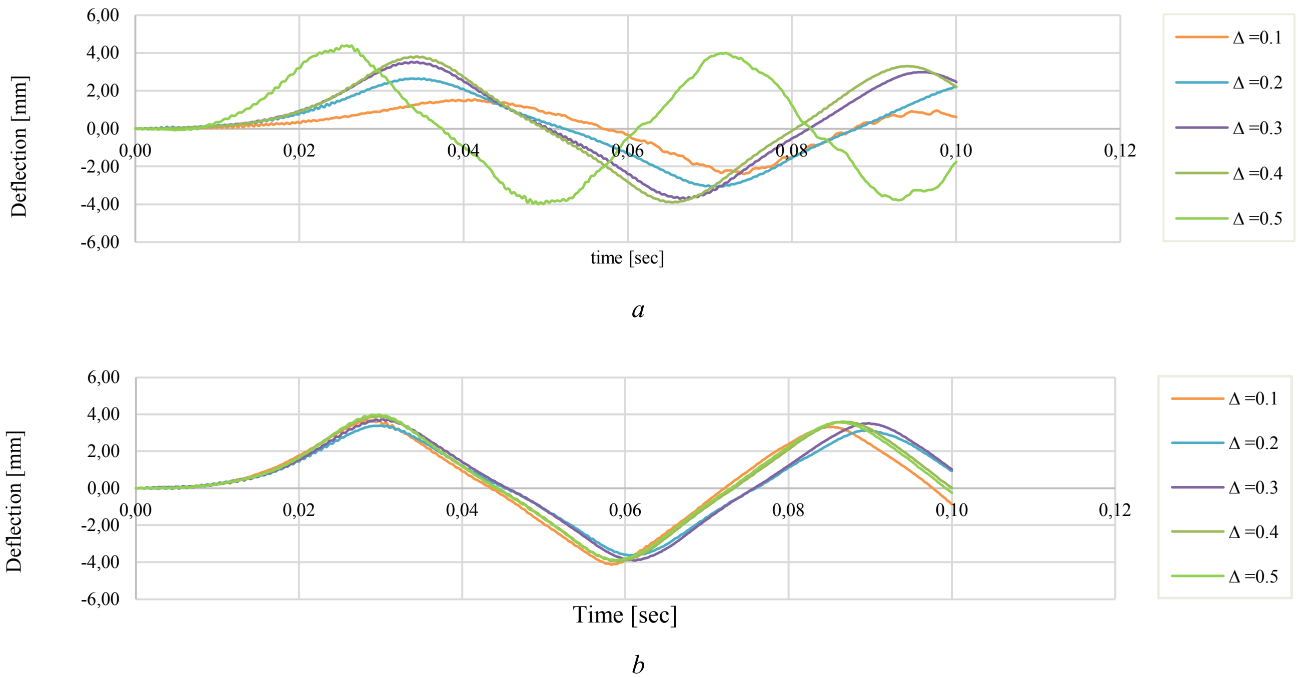


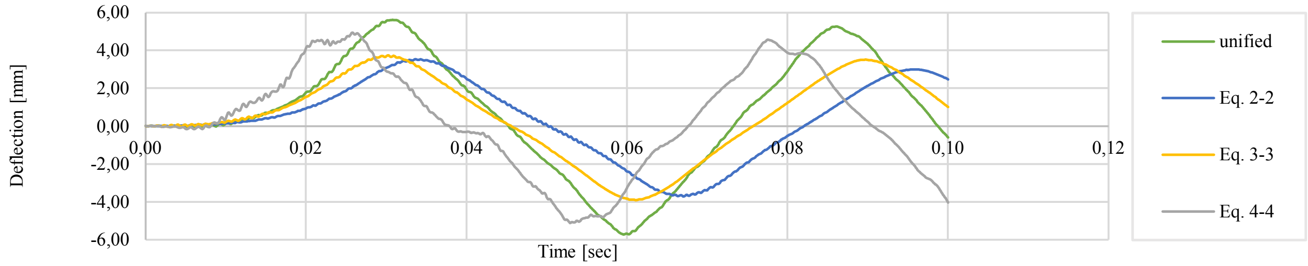
Figure 5. The effect of path amplitude Δ on plates with variable fiber spacing based on equations [2–2] and [3–3]: *a* — variable fiber spacing based on [2–2]; *b* — variable fiber spacing based on [3–3]
S o u r c e: made by W.H. Mohammed

4.4. The effect of number of semiwavelengths k on the non-linear dynamic performance of the laminated composite plates with variable fiber spacing

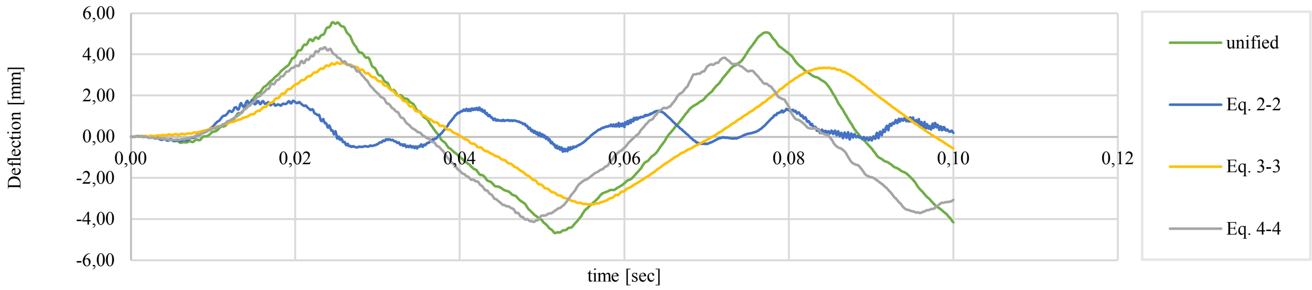
This section investigates the impact of varying fiber spacing on the nonlinear dynamic behaviour of samples, as represented by the values of deflection over time. Specifically, the investigation focuses on the effect of the number of semiwavelengths *k* using Leissa — Marten's equations [2–2] and [3–3]. Figure 6 shows the impact of five values of the numbers of semiwavelengths *k* (4, 6, 8, 10, and 12) on the stability, oscillations, and response reduction of the plate, using a path amplitude Δ of 0.4. The results show that this value has a significant effect on these factors.

Upon comparing the displacements resulting from the variation of *k* with the set of distribution equations, it has been ascertained that equation 3–3 exhibits superior behaviour, greater stability, and lesser distortion than its counterparts.

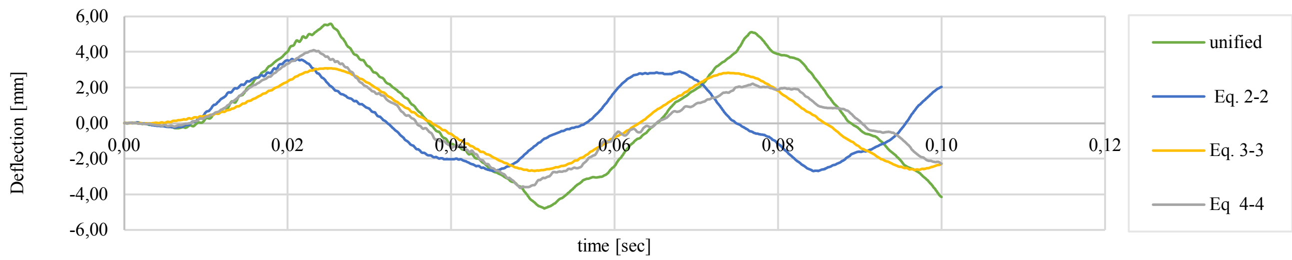
Also, the numbers of semiwavelengths *K* is best with a value of 8 with equation 3–3 and the path amplitude Δ of 0.4.



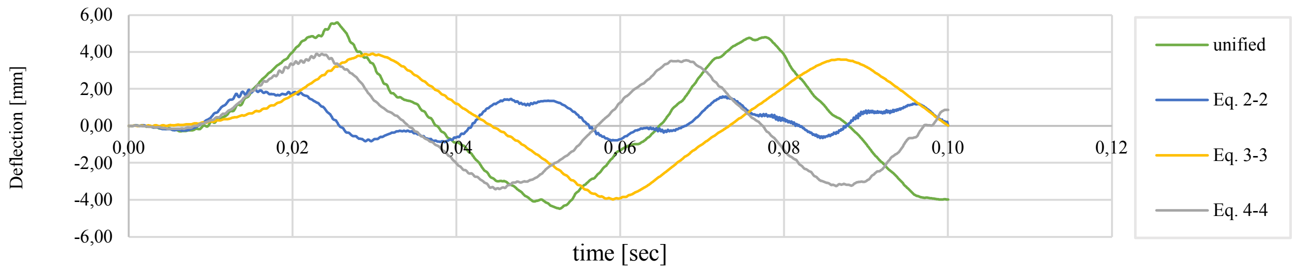
***k* = 4**



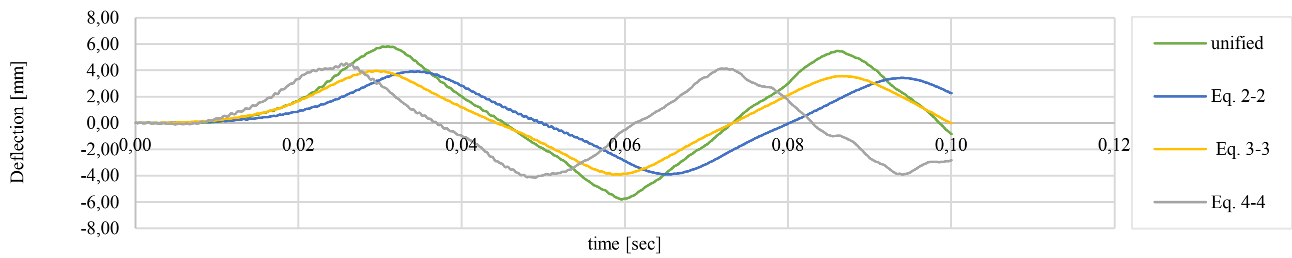
***k* = 6**



***k* = 8**



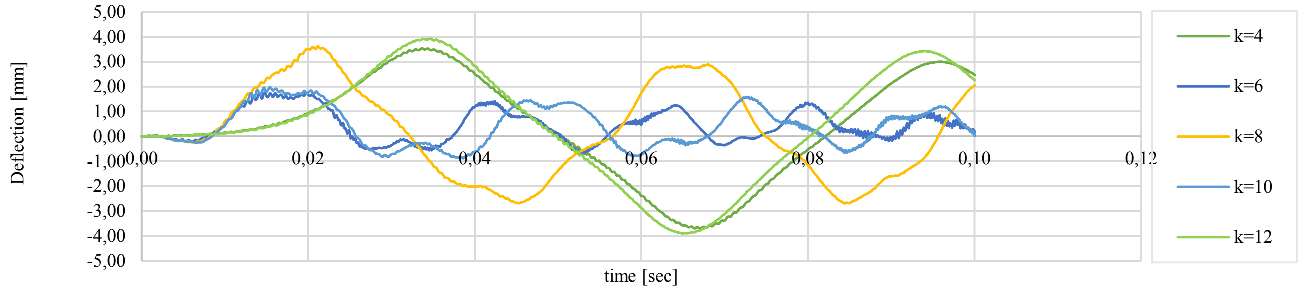
***k* = 10**



***k* = 12**

Figure 6. The effect of the number of semiwavelengths *k* on non-linear dynamic performance of laminated composite plates with variable fiber spacing
S o u r c e: made by W.H. Mohammed

In Figure 7 the outcomes of equations [2–2] and [3–3] are compared against the five k values to validate that equation 3–3 is the most optimal and consistent option for all k values, particularly for the number of semiwavelengths $k = 8$. Through a comparative analysis of the displacements resulting from variations in the value of k with the set of distribution equations, it has been ascertained that equation 3–3 exhibits superior behaviour, greater stability, and lesser distortion in comparison to the other equations.



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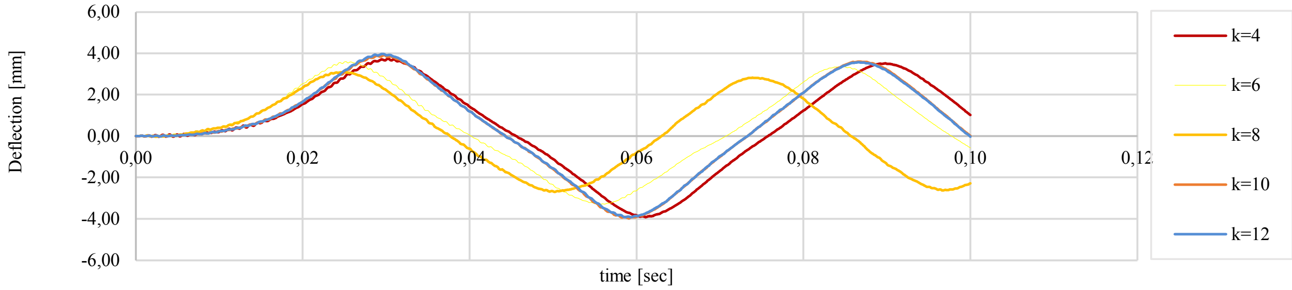

b

Figure 7. The effect of the number of semiwavelengths k on plates with variable fiber spacing based on 2–2 and 3–3: *a* — variable fiber spacing based on [2–2]; *b* — variable fiber spacing based on [3–3]
S o u r c e: made by W.H. Mohammed

5. Conclusion

1. The oscillatory behaviour of a symmetric cross-ply laminated composite plate, featuring sine wave fiber with parameters $k = 12$ and $\Delta = 0.4$, exhibits lower amplitude compared to other plates.

2. The laminated plate with symmetric cross-ply lamination and sine wave fiber ($k = 4$ and $k = 12$) exhibits a better dynamic performance compared to the laminated plate with symmetric cross-ply lamination and sine wave fiber ($k = 8$).

3. The laminated plate with sine wave fiber ($k = 8$, $\Delta = 0.4$) exhibits a higher dynamic performance compared to the other plates. Similarly, the symmetric cross-ply plate with sine wave fiber ($k = 8$, $\Delta = 0.2$) demonstrates a greater performance than the remaining plates.

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