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HYBRID SANDWICH PANELS: A REVIEW

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A high specific stiffness, high specific strength, and tailoring the properties for specific application have attracted the attention of the researchers to work in the field of laminated composites and Sandwich structures. Rapid use of these laminated composites and Sandwich structures necessitated the development of new theories that suitable for the bending, buckling and vibration analysis. Many articles were published on free vibration of beams, plates, shells laminated composites and sandwich structures. In this article, a review on free vibration analysis of shear deformable isotropic beams, plates, shells, laminated composites and sandwich structures based on various theories and the exact solution is presented. In addition to this, the literature on finite element modeling of beams, plates, shells laminated composites and sandwich structures based on classical and refined theories is also reviewed. The present article is an attempt to review the available literature, made in the past few decades on free flexural vibration response of Fiber Metal laminated Composites and Sandwich panels using different analytical models, numerical techniques, and experimental methods.

Key words: beams, shells, Fibre Metal Laminate (FML), free vibration, natural frequency, sandwich plates, sandwich cylindrical shells, beam theories, higher-order theory, shear deformation theory.

1. Introduction

The reduction of the mass of a structure is an important issue in the engineering field since it leads to reduced emissions and operating costs. On the other hand, weight saving often leads to an increase of vibration and noise transmission. For this reason, in the last years, the dynamic design of lightweight structures has received more emphasis, particularly in engineering applications where dynamic loads can produce high amplitudes of vibration.

Hybrid structures are such the dynamic design of light weight structures enables the utilization of the most advantageous material properties of different material grades and incorporation of them into one structure. A typical desired material property combination of hybrid structures is low weight combined with good mechanical properties. The number of beneficial property combinations is numerous, since the constituent materials of a hybrid structure may have substantially different material properties.

The manufacturing stage of a hybrid structure is usually challenging. Especially in laminated hybrid structures, in which macroscopic mechanical interlocking between the layers is unfeasible, the attainable adhesion level between the constituent materials may be insufficient. Since the interface quality often determines the service performance of the structure, additional surface treatments or adhesion layers are generally applied in hybrid laminates. Within aluminium/polymer hybrids, chemical surface treatments such as etching and anodizing or additional interface layers such as coupling agents, adhesives, or coatings are used to achieve good adhesion level. In addition, the surface roughness of aluminium is often increased by grit blasting to enhance the interfacial strength. The use of chemical surface treatments usually highlights the issue of noxious chemicals and thus the use of an additional interface layer may be favoured. However, the drawbacks of the surface treatments are increasing manufacturing time and costs and thus it would be

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beneficial if they would not be needed. The stability of a system depends on its damping ability, which can be affected by design

A great amount of research has been carried out for the last few decades to accurately assess the Vibration bending response of hybrid beams. Vibration bending analysis of hybrid beams is very complicated and this led to the development of different theories and methods. There Different theories and methods are available in the literature for the analysis of hybrid beams viz. Higher-order displacements-based theories as well as classical models (Euler-Bernoulli's and Timoshenko's ones) Mead & Markus" theory, polynomial, trigonometric, exponential and zig-zag theories, modal expansion theory, Galerkin, Rayleigh-Ritz, Newmark, finite element finite difference, Newton-Raphson method methods.

The present article is an attempt to review the available literature, made in the past few decades on free flexural vibration response of Fiber Metal laminated Composites and Sandwich panels using different analytical models, numerical techniques, and experimental methods.

1.1. Beams

Sainsbury and Zhang [1] used Galerkin finite element method to study damped sandwich beam structures. The method combines the polynomial shape functions of conventional finite element analysis with Galerkin orthogonal functions. The displacement consistency over the interfaces between the damping layer and the elastic layers is taken into consideration to ensure a conforming element and guarantee good accuracy. Orthogonal beam functions are selected for fast convergence, especially for the prediction of higher-order vibration modes using very few elements. Sokolinsky *et al.* [2] predicted Analytically and Experimentally Free Vibration Response of a cantilever sandwich beam with a soft polymer foam core using the higher-order theory for sandwich panels (HSAPT), a two-dimensional finite element analysis, and classical sandwich theory. Experimental observations and analytical predictions showed that free vibration response of soft-core sandwich beams cannot be predicted accurately using classical sandwich theory. Experiments show that the damping properties of the foam core are manifest most noticeably in the case of thickness-stretch vibration modes, whereas the influence of damping on the anti-symmetric modes is insignificant. Banerjee *et al.* [3] developed a dynamic stiffness model to investigate accurately the free vibration of a three-layered sandwich beam. A three-layered sandwich beam is idealised by the Timoshenko beam theory and the combined system is reduced to a tenth-order system using symbolic computation. An exact dynamic stiffness matrix is then developed by relating amplitudes of harmonically varying loads to those of the responses. The resulting dynamic stiffness matrix is used with particular reference to the Wittrick–Williams algorithm to carry out the free vibration analysis of a few illustrative examples. Finally, the accuracy of the theory is confirmed both by published literature and by experiment. Okutan Baba and Gibson [4] reported the delamination effect on the vibration characteristics of composite sandwich beams. Using a two-dimensional finite element analysis (FEA) the natural frequencies and corresponding vibration modes of a free-free sandwich beam with delamination of various sizes and locations are predicted. The stiffness of the delaminated beam is affected by the presence of delamination and results in differences on the natural frequencies of the beam. Vibration tests are conducted on fully bonded sandwich beams with carbon/epoxy laminated composite faces and foam core to verify the finite element results. Arvin e*t al*. [5] Used higher-order theory for a composite sandwich beam with the viscoelastic core to improve the ''Mead & Markus" theory and also studied structural response analysis of the free and forced vibration. The obtained results are compared with the corresponding results of previous researches by considering the effects parameters such as fibre angle, the thickness of faces and core thickness on the loss factors and natural frequencies of the beam.

Nayak [6] made a dynamic analysis of a three-layered symmetric sandwich beam with magnetorheological elastomer (MRE) embedded viscoelastic core and conductive skins subjected to a periodic axial load under various boundary conditions. Using extended Hamilton's principle along with generalized Galerkin's method the governing equation of motion has been derived. The parametric instability regions of the sandwich beam have been determined for various boundary conditions. Youzera *et al.* [7] investigated the damping and forced vibrations of three-layered, symmetric laminated composite beams

Using higher-order zig-zag theories in the analytical formulation, by considering both normal and shear deformations in the core. They obtained linear and nonlinear damping parameters of laminated composite beams and also nonlinear forced vibration analysis is carried out for small and large vibration amplitudes. The frequency response curves for various geometric and material properties are presented and discussed. Menghui Xu and Zhiping Qiu [8] determined natural frequencies of composite sandwich beams with lattice truss core by combining the Bernoulli-Euler beam theory and Timoshenko beam theory. The governing partial differential equations of motion are derived using Hamilton's principle and the analytical formulations of the natural frequencies are determined. After validation of the present method by numerical techniques, the effect of geometric and material parameters on the natural frequencies is studied and concludes that the effect of uncertainties on the natural frequencies is significant and thus the design by the interval optimization method is more realistic than the conventional ones. Carrera *et al*. [9] discussed number of redefined beam theories to trace the free vibration response of laminated beams, including thin-walled boxes. A number of analyses were conducted to compare various theories, including Euler–Bernoulli and Timoshenko models. The advantages/disadvantages of using the different theories are discussed for significant problems related to laminated beams as well as thin-walled boxes. It is shown that refined kinematic theories are able to yield a very accurate evaluation of fundamental as well as higher mode frequencies in a way comparable to three-dimensional analysis, but it is obtained with a strong reduction of computational costs.

Won *et al.* [10] analysed numerically the damped forced vibration of the three-constrained-layer sandwich beam which requires C2-basis functions or the mixed formulation and is governed by Mead and Markus's two sets of differential equations of motion. The shape functions are analytically derived using the compatibility relation between the lateral displacement and the transverse shear strain. The validity of the proposed beam element is verified through the benchmark experiments, and furthermore, the DOF-efficiency is justified through the comparison with Nastran3-D solid element. Hajianmaleki and Qatu [11] reviewed that laminated composite straight and curved beams are frequently used in various engineering applications. They also made an attempt to review most of the research done in recent years (1989-2012) on the vibration analysis of composite beams. This review is conducted with emphasis given to the theory being applied (thin, thick, layerwise), methods for solving equations (finite element analysis, differential transform and others) experimental methods, smart beams (piezoelectric or shape memory), complicating effects in both material and structure (viscoelastic, rotating, tip mass and others) and other areas that have been considered in research. A simple classic and shear deformation model would be explained that can be used for beams with any laminate. Yiming Fu *et al.* [12] Studied the nonlinear dynamic response problems of fibre–metal laminated beams with delamination. The nonlinear governing equations of motion for Fibre–metal laminated beams under unsteady temperature field are established, Basing on the Timoshenko beam theory, and considering geometric nonlinearity, transverse shear deformation, temperature effect and contact effect, which are solved by the differential quadrature method, Nermark-β method and iterative method. In numerical examples, the effects of delamination length, delamination depth, temperature field, geometric non- linearity and transverse shear deformation on the nonlinear dynamic response of the glass-reinforced aluminium laminated beam with delamination are discussed in details.

Shi Cheng *et al.* [13] Based on a refined sandwich beam theory studied Free vibration of a fibre-reinforced polymer honeycomb sandwich beam with sinusoidal Core configuration. Using a micro/macromechanics approach for face laminates and a mechanics of material approach for honeycomb core, the equivalent elastic properties of face laminates and honeycomb core are obtained. A free vibration model based on the refined sandwich beam theory is formulated using Hamilton's variational principle. Analytical solutions for a cantilevered sandwich beam are obtained by the Ritz method. Experimental results conducted on the fibre-reinforced polymer honeycomb sandwich beams with different lengths are applied to validate the proposed analytical solutions. Sakar and Bolat [14] Carried out free vibration analysis of aluminium honeycomb sandwich structures by experimental and numerical methods. The natural frequencies and mode shapes of sandwich structures fabricated with different configurations for clamped-free boundary condition were determined. The effects of lower and upper face sheet thickness, the core material thickness, cell diameter, cell angle and foil thickness on the vibration characteristics were examined. The numerical studies were performed with ANSYS package.

Nguyen Cong Minh *et al*. [15] presented the vibration responses on the test specimens of the sandwich beam and panel subjected to harmonic force under the clamped-free supports. To estimate the first natural frequency of these structures, The time-history responses of acceleration signals and the linear variable differential transform (LVDT) displacement sensors will be analyzed in the frequency domain which run the fast Fourier transform (FFT) algorithm and wavelet transform from measured data. The modal analysis using finite element method (FEM) is constructed to determine the natural mode shapes and frequencies of structural sandwich composites. The experimental results and numerical simulation on the dynamic behaviour of sandwich-structured composites are compared and discussed. The new technology of vibration measurement obtained from the study has been developed to be useful for non-destructive testing (NDT) related to structural health monitoring (SHM) of sandwich composite structures. Ravishankar *et al*. [16] investigated, the free vibration analysis of rotating and non-rotating Fibre metal laminate (FML) beams, hybrid composite beams (HCB), and functionally graded beams (FGB). The effects of different metal alloys, composite fibres, and different aspect ratios and angular velocities on the free vibration analysis of FML beams are studied. The effects of different angular velocities and different aspect ratios of rotating and non-rotating hybrid composite beams are also investigated. Finally, the effects of different angular velocities and different material distributions, namely the power law, exponential distribution, and Mori Tanaka's scheme on the free vibration analysis of FGB, are also investigated. Khdeir Professor and Aldraihem Professor [17] developed a new zig-zag beam theory to investigate the free vibration of soft core sandwich beams. To find analytical solutions for the natural frequencies and mode shapes of sandwich beams, The state space approach is used with arbitrary boundary conditions and showed that the zig-zag theory provides accurate predictions of the natural frequencies for sandwich beams with soft core. Furthermore, the analytical solutions for the natural frequencies can be used as benchmarks for approximate solutions such as Rayleigh-Ritz, finite element methods and other numerical methods. Chang Tao *et al.* [18] studied a nonlinear dynamic response of fibre metal laminated beams subjected to moving loads in thermal environments. Dynamic responses of beam analysed numerically using the theory of modal expansion and Newmark method. The effects of various things on free vibration and forced vibration of FML cantilever beams are investigated.

Guoyong Jin *et al*. [19] developed a unified formulation for vibration and damping analysis of a sandwich beams made up of laminated composite face sheets and a viscoelastic core with arbitrary lay-ups and general boundary conditions. The theoretical model is formulated by using Reddy's higher-order shear deformation theory using a modified Fourier–Ritz method. This method can be universally applicable to laminated sandwich beams with classical boundaries, elastic boundaries and their combinations without any special change in the solution procedure. The effects of some key parameters such as ply configuration, layer number, moduli and thickness ratios on the natural frequency and loss factor are illustrated. Especially the effects of restraints from different directions on two ends of the sandwich beam are deeply investigated.

Sayyad and Ghugal [20] reviewed on bending, buckling and free vibration analysis of shear deformable isotropic, laminated composite and sandwich beams based on equivalent single layer theories, layerwise theories, zig-zag theories and exact elasticity solution are presented. In addition to this, the literature on finite element modelling of laminated and sandwich beams based on classical and refined theories is also reviewed. Finally, displacement fields of various equivalent single layer and layerwise theories are summarized.

Chang Tao *et al*. [21] studied the free and forced vibration of cracked Fibre metal laminated (FML) beams with a damper subjected to a moving load, and the detection of the cracks by using continuous wavelet transform (CWT). The modal expansion theory and Newmark method are employed to solve the dynamic responses of FML beam numerically. The influences of crack depth, crack location, ply angle of the fibre layer, stiffness coefficient of the damper and velocity of the moving load on free vibration and forced vibration of FML cantilever beams are investigated. Numerical results indicate that the above-mentioned effects play a very important role on both free vibration and dynamic responses of the beam. In the end of the numerical examples, continuous wavelet transform is used to detect the location of the cracks of a clamped-

clamped FML beam. Monti *et al.* [22] analysed experimentally and numerically flexural vibration behaviour of bio-based sandwich structures and their composite faces, and particularly their damping properties. First, experimental tests were performed on the skins. Free vibration tests were carried out on unidirectional and cross-ply laminates in a clamped free configuration to investigate the influence of the fibre orientation and stacking sequence on the dynamic stiffness and loss factors. Then, the damping behaviour of the balsa core was studied through several free vibration tests. In addition, the damping properties of sandwich beams with different thicknesses were measured and discussed. Finally, a finite element model was used to calculate the resonance frequencies and modal loss factors of different sandwich beams. The close correlation between the numerical and experimental results was observed. Finally, a modal strain energy method was used to evaluate the contribution of the skins and of the core to the damping properties of the different sandwich beams. Madhu and Kumaraswamy [23] carried out Free vibration analysis for identifying the natural frequencies also, dynamic analysis for finding of natural frequencies and mode shapes for different stacking sequences. Finally, the nondimensional natural frequencies of the beam are calculated by using ANSYS model of the corresponding composite beam. Flexural strength & Tensile strength were observed and compared to base values of epoxy polymer to perceive the change in strength. From the results, the influence of fibre orientations on the natural frequencies is investigated. Numerical analyses are carried out to study vibration behaviour of composite laminated beams using ANSYS 15 software. Youzera and Meftah [24] carried out nonlinear forced vibration analysis of sandwich beam with viscoelastic core layer. In the analytical formulation, normal, transverse and shear deformations are considered in the core layer by mean of the refined higher-order zig-zag theory. The harmonic balance method for a doubly supported beam is adopted as a solution procedure. Thus, the obtained nonlinear frequency amplitude equation is governed by several complex parameters. These ones are arising for the geometrically non-linear coupling due to the viscoelastic layer core. The frequency response curves are presented and discussed by varying the material and geometric properties of the viscoelastic layer. Yang Chen *et al.* [25] reported nonlinear dynamic responses of the fibre-metal laminated beam resting on a tensionless elastic foundation and subjected to a moving harmonic load and thermal load. The nonlinear governing equations are derived by application of Hamilton principle and solved by finite difference method, Newmark method and Newton-Raphson method. In numerical results, FML beams constrained by different boundary conditions are selected to reveal the dynamic properties of FML beams. The effects of some parameters are discussed in detail, and some meaningful conclusions are concluded. Maras *et al.* [26] experimentally and numerically, investigated the vibration characteristics of FML for clamped-free boundary conditions. Using the Finite Element Method (FEM) numerical results were obtained and then these results were compared with the experimental results and found results were in good agreement. As the theoretical model was justified, the effects of various parameters such as a number of layers, Fibre orientations, and aluminium layer thickness on the in-plane vibration characteristics of the FML straight beam were analysed using FEM. Hanten *et al.* [27] made a free vibration analysis of fibre-metal laminated beams. Several higher-order displacements-based theories, as well as classical models (Euler-Bernoulli's and Timoshenko's ones), are derived, assuming Carrera's Unified Formulation by a priori approximating the displacement field over the cross-section in a compact form. The governing differential equations and the boundary conditions are derived in a general form that corresponds to a generic term in the displacement field approximation. The resulting fundamental term, named "nucleus", does not depend upon the approximation order N, which is a free parameter of the formulation. A Navier-type, closed-form solution is used. Simply supported beams are, therefore, investigated. Slender and short beams are considered. Three- and five-layer beams are studied. Bending, shear, torsional, and axial modes and frequencies are presented. Results are assessed for three-dimensional FEM solutions obtained by a commercial finite element code using three-dimensional elements showing that the proposed approach is accurate yet computationally effective. Liu and Liaw [28] determine the dynamic Young's moduli and damping ratios of Fibre-metal laminated cantilever beams that were first excited by a shaker. The FML were made of glass-Fibre reinforced Glare and aramid-Fibre reinforced ARALL laminates interlaced with aluminum layers. Compared to aluminum alloys, the dynamic Young's moduli of Fibre-metal laminates are lower and are almost constant for an excitation frequency range up to 5.000 Hz. On the other hand, the damping ratios of these composites oscillate within a narrow range of *0* to *0.02*. Forced vibration experiments by striking an impact hammer at the free end were then conducted. The resulting modal responses were in good agreement with those obtained by theoretical analyses.

1.2. Plates

Lu *et al.* [29] presented and discussed theoretical and experimental results for the transverse driving point mechanical impedances, as well as for the transfer impedances, of damped composite plates made up of a thin viscoelastic layer sandwiched between two elastic layers. Analytical results are determined by finite element approximation. The dependence on frequency and temperature of the dynamic properties of the viscoelastic materials is taken into consideration. A companion experiment was conducted for comparison purposes, good correlations between the test data and analytical solutions are obtained over a wide frequency range for two configurations. He and Ma [30] the simplified governing equations and corresponding boundary conditions of flexural vibration of viscoelastically damped unsymmetrical sandwich plates are given. The asymptotic solution to the equations is then discussed. If only the first terms of the asymptotic solution of all variables are taken as an approximate solution, the result is identical with that obtained from the Modal Strain Energy (MSE) Method. As more terms of the asymptotic solution are taken, the successive calculations show improved accuracy. With the natural frequencies and the modal loss factors of a damped sandwich plate known, one can calculate the response of the plate to various loads providing a reliable basis for engineering design. Lee and Fan [31] finite element analysis of composite sandwich plates is studied by modeling sandwich structures based on the Mindlin's plate theory. Static and free vibrational problems have been solved to investigate the effect of considering the transverse normal deformation of the core. For the case of free vibration, natural frequencies decrease when the core is considered to be flexible in the transverse normal direction while the natural mode shapes do not have prominent change. Meunier and Shenoi [32] addressed the issue of natural frequencies of sandwich plate panels. The solutions are obtained using Reddy's first- and higher-order shear deformation theories. The approaches are validated against results from a standard, commercially available finite element analysis package and concluded with a detailed investigation of the influence of variation in material property parameters and plate geometry variables on the natural frequency. Harras *et al.* [33] investigated experimentally and theoretically linear and non-linear dynamic behaviour of a glare 3 hybrid composite panel by using theoretical model based on hamilton's principle and spectral analysis. They analyzed and discussed response due to random excitation was investigated and the experimental measurements. Comparisons are made with finite element predictions and response estimates given by the ESDU method, the latter being a "design guide" approach used by industry. Concerning the non-linear analysis, the results are given for various plate aspect ratios and vibration amplitudes, showing a higher increase of the induced bending stress near the clamps at large deflections. Comparisons between the dynamic behaviour of an isotropic plate and G3HCRP at large vibration amplitudes are presented and good results are obtained. Nayak *et al.* [34] determined the natural frequencies of isotropic, orthotropic, and layered anisotropic composite and sandwich plates, assuming Two new C^0 strain finite element formulations of Reddy's higher-order theory are used. The parametric effects of plate aspect ratio, length-to-thickness ratio, degree of orthotropy, number of layers and lamination scheme on the natural frequencies are studied. The results presented in this investigation could be useful for a better understanding of the behaviour of sandwich laminates under free vibration conditions and potentially beneficial for designers of sandwich structures. Makhecha *et al.* [35] studied the effects of higher-order theory, that accounts for the realistic variation of in-plane and transverse displacements through the thickness, on the modal loss factors and natural frequencies of thick composite laminated/sandwich plates. Vibration and damping characteristics are shown through the numerical studies by considering significance of various higher-order terms in model. A detailed parametric study is also carried out to highlight the influences of ply-angle, aspect ratio, number of layers, and core to face thickness ratio for sandwich laminates on frequencies and system loss factors of composite laminates/sandwich plates. Vaidya *et al.* [36] conducted impact and post-impact vibration response test on protective metal foam composite sandwich plates and concluded that the sandwich construction with S2-glass/VE facesheets in conjunction with aluminum foam was optimal for resisting low and intermediate velocity impact. The vibration response of composite sandwich plates composed of laminate facesheets and aluminum foam core is studied under a free–free boundary condition and reported the vibration response (natural frequency and damping ratio) as a function of impact to the sandwich plate. Shooshtari and Razavi [37] derived the nonlinear equations of motion for laminated composite rectangular plates based on first order shear deformation theory. Then, through introducing a force function, these equations reduced to a set of coupled nonlinear partial differential equations and a compatibility equation. By using the Galerkin method, for the first time, a nonlinear ordinary differential equation is obtained, which includes nonlinear inertia and stiffness terms. By using the multiple time scales method, analytical relations for nonlinear frequency and transverse displacement have been obtained. Results are compared with the literature and good agreement is achieved for both linear and nonlinear frequencies. After proving the validity of our work for isotropic rectangular plates and laminated rectangular plates, linear and nonlinear free vibration of a Fibre Metal Laminate panel have been investigated. Also, the effects of some system parameters on the nonlinear frequency have been investigated. Sharma and Mittal [38] reviewed on stress and vibration analysis of composite plates and devoted on the free vibration and dynamic analysis, buckling analysis, failure analysis of composite laminated plates. Optimization is also considered.

Curtu *et al*. [39] present the modal analysis of dynamical behaviour of plates made from woven composite materials. The four types of composite were analysed each differed one from another by number of layers, thickness and pressure. For each type of composite, 15 samples were tested. The results lead to natural frequency for each structure and modal shape obtained using finite element method (FEM). The prediction of dynamical behaviour of composite plates plays an important role in their future application. Mahmoudkhani *et al*. [40] studied Free vibrations and the transverse response of sandwich plates with viscoelastic cores under wide-band random excitation. The quadratic displacement field is adopted for all displacement components of the core to accurately capture the higher modes excited by the wide-band excitation. The Love-Kirchhoff plate theory is used for the face layers. The viscoelastic behavior of the core is modeled by the Golla–Hughes–McTavish method. An analytical solution using the normal mode method is provided for the simply supported boundary conditions by including a different family of modes. The effects of some geometric and material properties on the frequencies, damping ratios and also root mean square responses are explored. The participation of the through-the-thickness deformation in the bending mode vibration of the top layer is also investigated, which is found to be mostly resulting from the second order term of the transverse displacement expansion in symmetric configurations. Moreover, the alteration of the response with the exclusion of a different family of modes from the solution is investigated. Aksoylar *et al.* [41] investigated nonlinear transient behavior of Fibre–metal laminated (FML) composite plates under non-ideal blast loads by both experimental and numerical techniques. In the experiments plates with different aspect ratio are considered obtained results are compared with both the developed mixed finite element method and the commercial software ANSYS. Furthermore parametric numerical analyses are conducted for nonlinear transient behavior of functionally graded (FGM) thin plates under blast loads with mixed FEM. In these parametric analyses the effect of aspect ratio, load distribution and impulse function in time domain are investigated. In the developed mixed FE formulation, the von Karman plate theory is used. Nonlinear functional is developed using the Hellinger–Reissner principle and linearized with the incremental formulation. As a result of conducted analyses, there is a good and reliable agreement between the numerical and the experimental results. Moreover, the developed mixed FEM results are almost identical to the ANSYS results. Ghasemi *et al.* [42] studied the effect of geometrical and material parameters on free vibrations of FML plates. The governing equations of the composite plate are solved analytically by first-order shear deformation theory (FSDT) as well as the Fourier series method. The accuracy of the used method was verified by comparing the Rayleigh-Ritz analytical method and the ABAQUS finite element software (numerical) method. The results indicated that some of the important parameters like sequence of metal layers, aspect ratio (*a/b*) of plate and orientation of composite Fibres were important factors affecting free vibration of the FMLs. Nayak *et al.* [43] investigated experimentally and numerically vibration and buckling characteristics of industry driven woven Fibre Glass-Carbon/epoxy hybrid composite panels. The effects of lamination sequence on the natural frequencies of vibration and buckling strength of the hybrid panels were studied in this investigation. The experimental results are compared with the numerical predictions using the

FEM based software package and very good agreement was observed between the experimental and ANSYS results.

Meunier and Shenoi [44] addressed the issue of natural frequencies of sandwich plate panels. The closed-form solutions are obtained using Reddy's first- and higher-order shear deformation theories and are validated against results from a standard, commercially available finite element analysis package. Detailed investigation of the influence of variation in material property parameters and plate geometry variables on the natural frequency is carried out. Rahimi *et al*. [45] presented free vibration analysis of fiber metal laminate annular plate by state-space based differential quadrature method. A semianalytical approach which uses state-space in the thickness and differential quadrature in the radial direction is implemented for evaluating the nondimensional natural frequencies of the annular plates.The influences of changes in boundary condition, plate thickness, and lay-up direction on the natural frequencies are studied. A comparison is also made with the numerical results reported by ABAQUS software which shows an excellent agreement. Suleyman Basturk *et al.* [46] investigated Nonlinear damped vibrations of a hybrid laminated composite plate subjected to blast load. The Galerkin Method is used to obtain the nonlinear differential equations in the time domain, and those equations are solved by Finite Difference Method. Parametric studies are conducted. The influences of some parameters such as damping ratios, aspect ratios and different peak pressure values have been investigated.

Shooshtari and Dalir [47] made an investigation on nonlinear free vibration of symmetric circular Fibre Metal Laminated (FML) hybrid plates. Considering the Von Karman geometric nonlinearity, the First order Shear Deformation Theory (FSDT) is used to obtain the equations of motion. The obtained equations are simplified for analyzing the first mode of symmetric circular plates. Using the Galerkin method, five coupled nonlinear Partial Differential Equations (PDEs) of motion are transformed to a single nonlinear Ordinary Differential Equation (ODE), which is solved analytically by the multiple time scales method, and an analytical relation is found for the nonlinear frequency of these plates. The obtained results are compared with the published results and good agreement is found. Moreover, the effects of several parameters on linear and nonlinear frequencies and the free vibration response are investigated.

Sayyad and Ghugal [48] reviewed the recent research done on the free vibration analysis of multilayered laminated composite and sandwich plates using various methods available for the analysis of plates. Displacement fields of various displacement based shear deformation theories have been presented and compared. Also, some numerical results related to fundamental flexural mode frequencies of laminated composite and sandwich plates are presented using a trigonometric shear and normal deformation theory. The results are compared with exact elasticity solution and other higher order shear deformation theories wherever applicable. Nguyen Dinh Duc and Pham Hong Cong [49] used Reddy's first-order shear deformation plate theory, to present an analysis of the nonlinear dynamic response and vibration of sandwich plates with negative Poisson's ratio in auxetic honeycombes on elastic foundations subjected to blast and mechanical loads. A three-layer sandwich plate is considered discretized in the thickness direction by using analytical methods (stress function method, approximate solution), Galerkin method, and fourth-order Runge-Kutta method. The results show the effects of geometrical parameters, material properties, mechanical and elastic foundations on the nonlinear dynamic response, and vibration of sandwich plates. Sayyad and Ghugal [50] used a simple four-variable trigonometric shear deformation theory considering the effects of transverse shear deformation and rotary inertia is evaluated for the free vibration analysis of antisymmetric laminated composite and soft core sandwich plates. The equations of motion are obtained using the principle of virtual work. A closed-form solution for equations of motion is obtained using the Navier's solution technique. The effects of side-to-thickness ratio, modular ratio and fibre angle are critically assessed for several problems of laminated composite and sandwich plates. The natural frequencies obtained by using present theory are verified by comparing the results with those of other theories and exact elasticity solution wherever applicable.

Prasad and Sahu [51] investigated The free vibration analysis of a new aircraft material Fibre metal laminated (FML) Plates. A finite element based formulation is developed using first order Reissner/Mindlin plate theory. They studied the effects of various parameters including aspect ratio and boundary conditions on the dynamic characteristics of the Fibre metal laminates. The analysis is carried out both experimentally and numerically. There is a good agreement between numerical and experimental results. From both the results, it is concluded that aspect ratio of FML plate and The boundary conditions are affecting the natural frequencies of FML plates. Suleyman Basturk [52] explored Time dependent nonlinear dynamic response of new proposed plates made up of functionally graded (FG) basalt/nickel composites under different dynamic blast loadings. To simulate the FG composite plates, four different approximations such as Homogenous-Laminated Model (HLM), Continuous Model (CM), Power-Law Model (PLM), and Sigmoid-Law Model (SLM) are used. Large deflection theory of thin plates has been used to consider the geometric nonlinearity effects. The basalt/nickel FG composites under blast loads and extreme environments would be a good option and would find many application areas in the near future. Praveen *et al*. [53] investigated the free and forced vibration responses of the composite sandwich plate. The governing equations of motion of hybrid composite honeycomb sandwich plates are derived using higher order shear deformation theory and solved numerically using a four-noded rectangular finite element with nine degrees of freedom at each node. Further, various elastic properties of honeycomb core materials with and without reinforcement of carbon nanotube and face materials are evaluated experimentally using the alternative dynamic approach. Various parametric studies are performed numerically to study the effects of carbon nanotube wt% in core material, core thickness, ply orientations, and various boundary conditions on the dynamic properties of composite honeycomb sandwich plate. Further, the transverse vibration responses of hybrid composite sandwich plates under harmonic force excitation are analyzed. Prasad and Sahu [54] made numerical and experimental investigations on the vibration behavior of Fibre-metal-laminated (FML) plates, a new aircraft material. A finite element (FE) - based formulation is established for the plate using the first-order Reissner–Mindlin theory, including both Fibres and metals of different material properties in alternate layers. A set of experiments was conducted to get natural frequencies of vibration for glass FML (GFML) plates also the effects of different parameters such as aspect ratio, side-to-thickness ratio, ply orientation, and boundary conditions on the dynamic behavior of the FMLs are studied. Good agreement is achieved between the numerical and experimental results. Torabi *et al*. [55] made vibration and flutter analyses of cantilever trapezoidal honeycomb sandwich plates. The plate is modeled based on the first-order shear deformation theory, and applying the Hamilton’s principle, the set of governing equations and boundary conditions are derived. Finally, the differential quadrature method is employed and natural frequencies, corresponding mode shapes, and critical speed are numerically achieved. Accuracy of the proposed solution is confirmed by the finite element simulations and published experimental results. After the validation, effect of various parameters on the vibration and flutter characteristics of the plate are investigated.

1.3. Shells

Khatri [56] presented governing equations of motion for arbitrarily laminated fibre reinforced composite material truncated conical shell in which each layer is permitted an arbitrary fixed fibre orientation. Convenient trigonometric series are used as solution functions in Galerkin's method to reduce the governing equations to sets of matrix equations. The correspondence principle of linear viscoelasticity has been used for evaluating the damping effectiveness of the shell. Computer programs have been developed for axisymmetric and antisymmetric vibrations of multi-layered conical shells with simply supported edges. The influence of apex angle upon the resonance frequencies and the associated system loss factors of laminated FRP conical shells is investigated. Denlia and Sun [57] presented an optimization study of cylindrical sandwich shells to minimize the transmitted sound into the interior induced by the exterior acoustic excitations. The boundary elements and finite elements are, respectively, used to model the interior and exterior acoustics and the vibration of the shell. The design parameters of the optimization are the reinforcement angles of the orthotropic composite materials of the skins and core. The sensitivity analysis of the objective function with respect to the design variables is computed by the adjoint-variable technique. The optimizations of the shell at a single frequency and in a band of frequencies are investigated. Khalili *et al.* [58] studied dynamic response of fibre metal laminate cylindrical shells subjected to initial combined axial load and internal pressure. First order shear deformation theory (FSDT) was utilized in the shell’s equilibrium equations and strain–displacement relations were based on Love’s first approximation theory.

Investigated The influences of FML parameters such as material properties lay up, Metal Volume Fraction (MVF), Fibre orientation and initial stresses on dynamic response and results indicated that the FML lay up, has a significant effect on natural frequencies as well as transient dynamic response with respect to various values of MVF as well as pre-stress. Ghasemi *et al*. [59] developed an analytical solution for free vibration analysis of conical Fibre metal shells. In order to find constitutive relations, the assumptions of thin shells are used and the governing equations are based on Love's theory. The Galerkin method is employed to solve the governing equations in which beam functions are used to approximate the mode shapes. Using beam functions enables us to assess the effects of different boundary conditions on the frequency response of the shells. Numerical comparisons of the present and previously published results confirm the accuracy of the current approach. Additionally, the influences of geometrical parameters and embedding aluminum plies in different layers of the structure on natural frequency of the conical shells with various boundary conditions are investigated. Jin-Shui Yang *et al*. [60] conducted modal testing to investigate vibration characteristics of such composite corrugated sandwich cylindrical shells with free-free boundary condition. In order to predict the structural vibration damping, a finite element model combined with modal strain energy approach is developed, which is adequately consistent with the experimental results. Circular corrugated sandwich cylindrical shells generally possess higher natural frequencies and damping loss factors than axial corrugated sandwich cylindrical shells since circumferential stiffness and damping capacity of the former are higher than those of the latter. Furthermore, the influence of the corrugated inclination angle, sandwich core thickness and different topological corrugated cores on the structural vibration and damping performances are thoroughly investigated. Chuanmeng Yang *et al*. [61] developed accurate solution approach based on the first-order shear deformation theory (FSDT) for the free vibration and damping analysis of thick sandwich cylindrical shells with a viscoelastic core under arbitrary boundary conditions. The present solution is based on a set of new displacement field expression in which the displacements of the middle surface are expanded as a combination of a standard Fourier series and auxiliary functions. Due to the improved displacement expansions, rapid convergence and high accuracy can be easily obtained. The current method can be universally applicable to a variety of boundary conditions including all the classical cases, elastic restraints and their combinations. Natural frequencies and loss factors under various boundary conditions and lamination schemes are calculated, which may serve as benchmark solutions in the future. The effects of some key parameters including the boundary conditions, Fibre orientation angle, and number and thickness of the layers on free vibration and damping characteristics of the shells are illustrated and analyzed.

Mohandes *et al*. [62] studied the free vibration of Fibre–metal laminate (FML) thin circular cylindrical shells with different boundary conditions. Strain–displacement relations have been obtained according to Love's first approximation shell theory. To satisfy the governing equations of motion, a beam modal function model has been used. The effects of different FML parameters such as material properties lay-up, volume fraction of metal, fibre orientation, and axial and circumferential wavenumbers on the vibration of the shell have been studied. The results demonstrate that the influences of FML lay-up and volume fraction of composite on the frequencies of the shell are remarkable. Ghasemi and Mohandes [63] analysed free vibration of rotating Fibre–metal laminate thin circular cylindrical shells. Strain–displacement relations have been obtained based on Love's first approximation shell theory. The variations of frequencies of the Fibre–metal laminate cylindrical shell with rotational speeds for different axial and circumferential wave numbers, L/R ratios, metal thicknesses and volume fractions of metal have been presented. The results showed that with increasing rotating speed, the gap between backward and forward waves frequencies increased. Ghashochi-Bargh and Sadr [64] illustrates the application of a combined adaptive particle swarm optimization (A-PSO) algorithm and the finite strip method (FSM) to the lay-up optimization of symmetrically Fibre-metal laminated (FML) composite shallow shell panels for maximizing the fun-damental frequency. The number of layers, the fibre orientation angles, edge conditions, length/width (*a/b*) ratios, and length/radii of curvature (*a/R*) ratios were considered as design variables. The classical shallow shell theory (Don-nell's formulation) was applied to calculate the natural frequencies of FML cylindrical curved panels. A program using Maple software was developed for this purpose. To check the validity, the obtained results were compared with some other stacking sequences. The numerical results of the proposed approach were also compared with other algorithms, which showed that the A-PSO algorithm provides a much higher convergence and reduces the required CPU time in searching for a global optimization solution. Kumar and Srinivasa [65] reviews the literature on the buckling and free vibration analysis of shear deformable isotropic and laminated composite sandwich plates and shells using various methods available for plates in the past few decades. Various theories, finite element modeling, and experimentations have been reported for the analysis of sandwich plates and shells. Few papers on functionally graded material plates, plates with smart skin (electrorheological, magnetorheological, and piezoelectric), and also viscoelastic materials were also reviewed. Ghasemi and Mohandes [66] made a comparison between the vibration of Fibre-metal laminate (FML) and composite cylindrical shells. Love's first approximation shell theory has been applied to obtain Strain-displacement relations. In addition, beam modal function model has been used to analyze the cylindrical shell with different boundary conditions. The frequencies of FML and composite cylindrical shells have been compared to each other for different materials, lay-ups, boundary conditions, axial and circumferential wave numbers. The results showed although the frequencies of carbon/epoxy are greater than glass/epoxy for all of then, this process is not constant for FML. Also, with increasing then, the frequencies of FML cylindrical shells are converged more faster than the composite one. Moreover, the frequencies of both boundary conditions are converged with increasing n for both FML and composite cylindrical shells. Lopatin and Morozov [67] presented a novel solution of the free vibration problem formulated for a shallow sandwich cylindrical panel with fully clamped edges. Based on this solution, an analytical formula for the fundamental frequency is derived. The governing equations derived in terms of the panel displacements, deflections and angles of rotation of the normal element, are solved using the Galerkin method. The analytical formula is applied to calculations of the fundamental frequencies for sandwich panels with various structural parameters. The results of these calculations have been successfully verified using the finite element method and implemented in the design analysis of sandwich panels considering a constraint imposed on the value of their fundamental frequency.

1.4. Fibre Metal Laminate (FML)

Kola [68] consider the effects of including the transverse shear deformation on the vibration characteristics of layered composites. The formulation is based on the Raleigh-Ritz method using the beam characteristic functions. In addition to including the transverse shear, the formulation is developed for metal-fibre-layered composite plates. This type of laminate construction offers the advantage of both the metallic and fibre properties. Results are provided showing the effects of the shear deformation on the metal-fibre laminates. The effects of laminate thickness, fibre orientation, and the plate aspect ratios on the free vibration characteristics of the metal-fibre laminates are given to demonstrate the methodology described.

Botelho *et al*. [69] determined damping behavior of continuous fiber/metal composite materials by the free vibration method. The experimental results were compared to calculated E modulus values by using the composite Micromechanics approach. For all specimens studied, the experimental values showed good agreement with the theoretical values. The damping behavior, i.e. the storage modulus and the loss factor, from the aluminum 2024 alloy and fibre epoxy composites can be used to estimate the viscoelastic response of the hybrid FML. Payeganeh *et al*. [70] studied dynamic response of FMLs subjected to low-velocity impact is studied in this paper. The effect of the Al layers on contact force history, deflection, in-plane strains and stresses of the structure is studied. The first-order shear deformation theory as well as the Fourier series method is used to solve the governing equations of the composite plate analytically. The results indicated that some of the parameters like the layer sequence, mass and velocity of the impactor in a constant impact energy level, and the aspect ratio (*a/b*) of the plate are important factors affecting the dynamic response of the FMLs.

Iriondo *et al*. [71] carried out, the characterisation of the elastic and damping properties of a traditional Fibre Metal Laminate (FML) and an FML based on a self-reinforced polypropylene (SRPP). Both laminates were characterised in the frequency domain by means of a forced vibration test with a resonance technique where the Young's complex modulus was extracted. In addition to both FMLs, the aluminium employed in both laminates was characterised as reference material. Moreover, the transfer functions used for the characterisation process were included. The results showed that the FML based on a SRPP offers higher damping capacity than the traditional FML. Basturk *et al*. [72] studied blast responses of sandwich panels comprising Al foam and Al/GFPP FML system were predicted by user defined the compression test results and user defined blast data. The TNT weights were chosen by considering real threats; thus, the present results have predicted the dynamic deflections under real conditions. Core shear and core crushing were the main failure mechanisms observed in the panels after the test. Independent of core thickness, all the samples exhibited similar type of deformation patterns. Iriondo *et al*. [73] carried out the dynamic characterisation and the modelling of the orthotropic selfreinforced polypropylene used in alternative Fibre Metal Laminates (FMLs). The results have been obtained by the DMA test and by the forced vibration test in order to extent the frequency range studied. Xin Li *et al*. [74] investigated experimentally The dynamic failure of fibre metal laminates. Tests on these fibre metal laminate panels were conducted by using an aerodynamic gun with the impact velocity ranging from *20.6 m/s* to *42.8 m/s.* Different deformation/ failure modes of fibre metal laminates were obtained by varying the impact energy and examined by the field emission scanning electron microscope. The results showed that before the fibre metal laminate panels were penetrated, the global deformation increased with the impact velocity. However, evident reduction of global deformation can be observed after penetration occurred. Damages of fibre metal laminate panels such as tearing of aluminum ply, fibre fracture, matrix cracks and debonding/delamination were observed around the impact region. The results indicate that basalt reinforced aluminum laminates perform well in terms of impact resistance and offer significant potential in engineering applications.

Balakrishnan *et al.* [75] presented vibroacoustic performance of fiber metal laminates with delamination. A fluid structure interaction study has been done using finite element method (FEM). Experimental validation is performed on an aluminium (AL) panel for verifying the correctness of finite element (FE) idealization procedure to simulate the fluid-structure interaction. Delamination is introduced in the FE model of FML panel and VA analysis is subsequently carried out. Sound transmission loss (STL) is computed on the panel with center delamination and without delamination. The overall sound pressure level (OASPL) shows that the presence of delamination (*40*% in total area) in FML has not changed the total energy of the transmitted sound when compared to aluminium and composites.

Vahid Zal *et al*. [76] evaluated the effect of aluminum surface treatment on mechanical and dynamic properties of PVC/aluminum/ fiber glass fiber metal laminates. Different surface treatments were carried out on the aluminum sheets and the fibre metal laminates were produced using the film stacking procedure. Flexural strength and modulus of the products and also shear strength of bonding were measured using three-point bending test, and their failure mechanisms were evaluated using optical microscope images. Also, the effects of aluminum layer and aluminum/composite laminates bonding on the dynamic properties of the fibre metal laminates were studied using dynamic mechanical thermal analysis. It was concluded that mechanical roughening of the aluminum sheet has the maximum effect on the aluminum/matrix bonding strength such that simultaneous fracture of composite laminates and aluminum layer in the bending condition was observed in the produced fibre metal laminates without any delamination. Liao and Liu [77] studied dynamic progressive failure properties of glass fibre composite/aluminium hybrid laminates under low-velocity impact. Effects of different layer thickness and impact energy on the impact force–time/displacement curves of glass fibre composite/aluminium laminates under low velocity impact are discussed. Besides, damage evolution behaviors of matrix and delamination interface are explored. Finally, energy dissipation mechanisms due to intralaminar dynamic progressive failure, interlaminar delamination of composite layers and plastic deformation of aluminium layers are studied. Relatively good agreement is obtained between experimental and numerical results. Liebig *et al*. [78] presented work shows the effect of lay-up changes, elastomer thickness and elastomer stiffness on the damping behaviour of hybrid CFRP-elastomer-metal laminates. Owing to the large variety of possibilities to investigate the different influencing factors on the damping behaviour, numerical studies are conducted.

1.5. Sandwich

Ganapathi *et al*. [79] investigated the nonlinear dynamics analysis of thick composite and sandwich plates, Using a C^0 eight-noded plate element developed based on an accurate higher-order theory. The governing equations of motion obtained are solved through eigen value solution for free vibration case, whereas the direct integration technique is employed for the transient response analysis. The performance and the applicability of the proposed discrete model for the nonlinear free flexural and forced vibration responses of thick laminates are discussed among alternate models, considering multilayered cross- and angle-ply, and sandwich plates. Khare and Garg [80] presented two higher-order shear deformable finite element models using a higher-order facet shell element for the free vibration analysis of layered anisotropic sandwich laminates. The accuracy of the present models is demonstrated by comparing the results of laminated sandwich plates with the available closed form solutions. Benchmark solutions with the parametric study for the laminated sandwich cylindrical and spherical shell panels are also presented. Qunli Liu and Yi Zhao [81] applied Low order and high order shear deformation models to investigate the effect of honeycomb core (transversely shear deformable) on flexural vibration of thick rectangular sandwich panel with isotropic facesheets. Solutions in Navier form are obtained for a simply supported rectangular panel. The effect of honeycomb core parameters, such as characteristic angle, cell wall thickness, and cell size is studied. Comparison between low order model, high order model, and finite element method is provided. It is shown that in most cases results from a high order model without facesheet shear effect are close to those from finite element analysis.

Sargianis and Suhr [82] focused to investigate the structural–vibrational performance of carbon-Fibre face sheet sandwich composite beams with varying core materials and properties. The structural– vibrational performance including acoustic and vibrational damping properties was experimentally characterized by analyzing the wave number response, and structural damping loss factor (*g*) from the frequency response functions, respectively The analysis also showed the importance of using a honeycomb core’s effective properties for equal comparison to foam-cored sandwich structures. Utilizing analytical modeling, the loss factors of the core materials (*b*) was determined based upon the measured structural loss factors (*g*) for a frequency range up to *4000* Hz. Petrone *et al*. [83] experimentally studied the vibration characteristics of fiber reinforced honeycomb panels. In order to evaluate the vibrational performance of these cores under dynamic loads, the modes, the natural frequencies and the damping of the sandwich system were identified experimentally. Frequency responses were measured and subsequently modal properties were estimated. Experimental dynamic tests were carried out using specimens with different core materials. The influence of the fibre reinforcement on the natural frequencies and modal damping were investigated. Sarlin *et al*. [84] made an attempt to study the damping properties of laminated structures consisting of steel, rubber or epoxy adhesive and glass fibre reinforced epoxy composite damping properties of the structures were investigated through the loss factors which is determined by frequency and time domain test methods. By using the loss factor results of the constituent materials, the loss factor of the hybrid structures were estimated by the rule of mixtures and the results were compared with the experimental results. It was observed, that the use of weight fractions instead of volume fractions in the rule of mixtures provides a good average estimation of the damping behaviour of the hybrid structure and the results of rule of mixtures method can be used as rough estimates during the design phase of hybrids of this kind. Jinshui Yang *et al*. [85] investigated the vibration and damping performances of hybrid carbon fibre composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face sheets. Hybrid carbon fibre composite pyramidal truss sandwich panels containing different thickness of viscoelastic layers were manufactured using a hot press molding method. Analytical models based on modal strain energy approach were developed using ABAQUS software to estimate the damping property of the hybrid sandwich structures. A set of modal tests were carried out to investigate the vibration and damping characteristics of such hybrid sandwich panels with or without viscoelastic layers. The damping loss factors of composite slender beams with different fibre orientations were tested to determine the constitutive damping properties of parent materials for such hybrid sandwich panels. The numerical simulation results showed good agreement with the experimental tests. The damping loss factors of hybrid sandwich panels increased distinctly compared with previous sandwich panels due to the viscoelastic layer embedded in the face sheets. Petrone *et al*. [86] presented the results of an experimental campaign performed on two ecologically friendly sandwich panels. In order to evaluate the vibrational characteristics, the mode shapes, the natural frequencies and the damping ratio of the sandwich panels are identified experimentally through modal tests, adopting the roving hammer technique. Experimental results, in terms of modal parameters, are compared with numerical ones, obtained through a finite element model.

Chennuri *et al*. [86] done a comparative study on vibration behaviour of sandwich composites by experimental and finite element methods (FEM). Experimental analysis is done by striking the beam with impulse hammer at a point where different modes and frequencies are acquired. Then FEM analysis is done using ANSYS software. Both the experimental as well as FEM results are compared and documented. Sadik *et al*. [88] performed a modaircraftsis on honeycomb panels used in the aircrafts and satellites structural design. To fabricate the sandwich honeycomb panel, Jute Fibre sandwiched between the glass fibres are used as face sheets and glass fibre as core material, Epoxy as a bonding agent. The developed honeycomb panel is subjected to dynamic investigations to determine the natural frequencies, damping factor and damping ratio based on clamped-free (C-F-F-F) boundary conditions. Yaman and Onal [89] experimentally and numerically determined dynamic properties of natural material-based sandwich composites. The effects of the thickness of the core and fibre orientation and number of layers on frequency and damping were analysed. It was observed that if the core thickness of the structure is properly optimised, this sandwich structure demonstrates better dynamic properties. Thus, sandwich materials from natural origin may offer more environmental friendly solutions compared to other materials. Xiaolei Zhang *et al*. [90] investigated The vibration characteristics of the hybrid structure with free–free boundary condition in room and high temperature thermal environment by both experimental means and finite element method (FEM). Finite element models were established to estimate the vibration characteristics of the hybrid sandwich structure. Modal tests by hammer impulse method and exciter were carried out in room temperature environment and temperature varying environment to get the natural frequencies and corresponding modal shapes and damping loss factors. The numerical simulation results agree well with the experimental results. The natural frequencies and damping loss factors of the hybrid sandwich structure show steady state with the temperature increased up to 800^0C and so large gradient. Correspondently, the structural stiffnesses and damping characteristics of such composite structures keep excellent performance in thermal environment. Xiangyang Li and Kaiping Yu [91] focused on the vibration and acoustic responses of the sandwich panels constituted of orthotropic materials applied a concentrated harmonic force in a high temperature environment. The natural frequencies together with corresponding modes are obtained under the thermal stresses by applying the piecewise low order shear deformation theory. It is observed that the natural frequencies of the sandwich panel decrease with the increment of the temperature. The interchanges of the mode shapes occur because of the material anisotropy. The peaks of vibration and acoustic responses float to the low frequency domain due to the decrement of the natural frequencies. The influences caused by the high temperature environment on the sandwich panels are deeply discussed. Mukhopadhyay and Adhikar [92] proposed an analytical framework to analyze the effect of random structural irregularity in honeycomb core for natural frequencies of sandwich panels. Closed-form formulas have been developed for the out-of-plane shear moduli of spatially irregular honeycombs following minimum potential energy theorem and minimum complementary energy theorem. Subsequently an analytical approach has been presented for free-vibration analysis of honeycomb core sandwich panels to quantify the effect of such irregularity following a probabilistic paradigm. Representative results have been furnished for natural frequencies corresponding to low vibration modes of a sandwich panel with high length-to-width ratio. The results suggest that spatially random irregularities in honeycomb core have considerable effect on the natural frequencies of sandwich panels. MP Arunkumar *et al*. [93] found that, for a honeycomb core sandwich panel in due consideration to space constraint, better sound transmission characteristics can be achieved with lower core height. Also, observed that, for a honeycomb core sandwich panel, one can select cell size as the parameter to reduce the weight without affecting the sound transmission loss. Triangular core sandwich panel can be used for low frequency application due to its increased transmission loss. In foam core sandwich panel, it is noticed that the effect of face sheet material on sound transmission loss is significant and this can be controlled by varying the density of foam.

Hassoon *et al*. [94] studied sandwich panels with polymeric skins and PVC foam cores subjected to slamming impact are investigated experimentally and numerically. The slamming model was implemented in Abaqus/Explicit software based on Coupled Eulerian Lagrangian model approach. In addition, different damage modes are incorporated in the numerical model, including the intralaminar, debonding in skin/core inter-face, and core shear to cover all possible damage modes throughout structures. Two failure criteria (Hashin criteria for the laminate composite and Christensen criteria for the core in sandwich structure) are defined and integrated into VUMAT sub-routine. In addition, the cohesive zone model is used to predict the debonding skin/core. A good agreement in both hydrodynamic loads and damage prediction were found between numerical and experimental results. Venkatachalam *et al*. [95] focused on the experimental vibration analysis of hybrid polymer made composite sandwich panels and investigates the mode shape frequency. All the experimental results are compared with the numerical results by using ANSYS software and the error percentage is found out. optimization of parameters affecting the natural frequency has been performed. Optimization was carried out using Taguchi method. In addition, the empirical equations of mode shape frequencies were derived using regression analysis. The results from the derived equations are compared with the numerical mode shape frequencies obtained and a good agreement has been found between them. Nguyen Dinh Duc *et al*. [96] used analytical solution to investigate the nonlinear dynamic response and vibration of sandwich auxetic composite cylindrical panels. Based on Reddy's first order shear deformation theory (FSDT) with the geometrical nonlinear in von Karman and using the Airy stress functions method, Galerkin method and fourth-order Runge-Kutta method, the resulting equations are solved to obtain expressions for nonlinear motion equations. The effects of geometrical parameters, material properties, elastic Winkler and Pasternak foundations, mechanical, blast and damping loads on the nonlinear dynamic response and the natural frequencies of sandwich composite cylindrical panels are studied. Mageshwaran Subramani *et al.* [97] studied the vibration analysis of uniform laminated composite sandwich beam with a viscoelastic core. The governing equation of motion of the laminated composite sandwich beam has been derived based on higher order shear deformation theory (HSDT) in finite element model (FEM). The developed finite element model has been validated in terms of natural frequencies with the experimental values and the available literature. Various parametric studies have been performed to examine the impact of the core thickness, ply orientation and aspect ratio of the uniform laminated composite sandwich beam in response to free vibration for various boundary conditions. Arunkumar *et al*. [98] carried out studies on bending and free vibration behavior of truss core sandwich panel filled with foam typically used in aerospace applications. The equivalent elastic properties of truss core sandwich panel filled with foam are derived. The accuracy of derived equivalent properties is ensured with the numerical studies of foam-filled sandwich panel. The derived properties are used in the closed form solution to find the maximum deflection of the truss core sandwich panel filled with foam for simply supported boundary conditions. The distinct results obtained in the present work can be used in the design of aerospace structures, where the enhancement of static and free vibration behavior is needed.

Marythraza *et al*. [99] predicted the vibration response of honeycomb sandwich panels due to dynamic loads. The modal analysis, transient response analysis of the honeycomb sandwich panel has been done by using Msc Nastran/Patran and the natural frequency from the simulation results compared with the analytical results. Melis Yurddaskal and Buket Okutan Baba [100] studied free vibration responses of sandwich composite panels with different radius of curvature were presented numerically. Flat and curved panels were manufactured in order to carry out experimental studies to verify the numerical results. Vibration tests were performed under free–free boundary conditions. When all the edges were simply supported and clamped, the effect of curvature on natural frequencies was analyzed by using ANSYS, finite element software. Benjeddou and Guerich [101] presented a practical detailed finite element (FE) approach for the three-dimensional (3D) free-vibration analysis of actual aircraft and spacecraft-type lightweight and thin honeycomb sandwich panels. It consists of calling successively in MATLAB®, via a developed user-friendly GUI, a detailed 3D meshing tool, a macro-commands language translator and a commercial FE solver (ABAQUS® or ANSYS®). In contrary to the common practice of meshing finely the faces and core cells, the proposed meshing tool represents each wall of the actual hexagonal core cells as a single two-dimensional (2D) 4 nodes quadrangular shell element or two 3 nodes triangular ones, while the faces meshes are obtained simply using the nodes at the core-faces interfaces. Moreover, as the same 2D FE interpolation type is used for meshing the core and faces, this leads to an automatic handling of their required FE compatibility relations. This proposed approach is applied to a sample made of very thin glass Fibre reinforced polymer woven composite faces and a thin aluminum alloy hexagonal honeycomb core. The unknown or incomplete geometric and materials properties are first collected through direct measurements, reverse engineering techniques and experimental-FE modal analysis-based inverse identification. Then, the free-vibrations of the actual honeycomb sandwich panel are analyzed experimentally under different boundary conditions and numerically using different mesh basic cell shapes. It is found that this approach is accurate for the first few modes used for pre-design purpose. Essassi *et al*. [102] presented experimental and numerical analysis results of the damping properties of a bio-based sandwich with an auxetic core. Experimental tests were conducted on the skins, the auxetic structure and the sandwich beams to evaluate their damping properties. Vibration tests were performed in a clamped-free configuration. Finite element analysis was used to validate the experimental results. The resonance frequencies and the loss factor obtained from experimental and numerical analysis were in close agreement. Finally, a study of the effect of each sandwich component on energy dissipation was carried out in order to understand the dynamic response of such beams.

2. Conclusions

The increasing use of laminated composites and sandwich structures in various fields of engineering necessitated the development of various refined theories which predicts the accurate dynamic behaviour of such structures. The basic aim of this review article is to present various methods available for the analysis of Fiber Metal laminated Composites and Sandwich panels and to guide the researchers for the future research. Many theories have been reported in the literature for the vibration analysis.

1. Analysis of laminated composite and sandwich beams is difficult by using two dimensional elasticity theory and this led to the development of refined shear deformation theories for beams which approximate the two-dimensional elasticity solutions with reasonable accuracy.
2. Geometrically non-linear analysis of laminated composite and sandwich beams needs more attention in future.
3. Still Navier's method is widely used by various researchers for the free vibration analysis of simply supported laminated composite and sandwich plates based on higher order plate theories.
4. A great deal of research work is available on linear free vibration analysis of plate. However, more research is required on non-linear free vibration analysis of plates.

Most of the research work available in the literature on fiber metal laminate (FML) by the use of synthetic fibers by the use of . Higher-order displacements-based theories as well as classical models (Euler-Bernoulli's and Timoshenko's ones) Mead & Markus" theory, polynomial, trigonometric, exponential and zig-zag theories, modal expansion theory, Galerkin, Rayleigh-Ritz, Newmark, finite element finite difference, Newton-Raphson method methods. Less attention has been paid towards the use of natural fibres in fiber metal laminate Hence, the future researcher can think of using natural fibres as substitute for man-made fibers in the said fiber metal laminates.

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