A CRITICAL REVIEW ON STATIC AND DYNAMIC ANALYSIS OF PROTECTIVE STRUCTURES

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ABSTRACT:

The scope of work focuses on current theoretical developments, unusual designs, novel core structure fabrication, novel applications of laminated composite and sandwich structures. The writing of a review paper was the most recent and previous work. Boeing aircraft, marine, satellites, transpiration, biomedical, civil, electronics, warm protection, and wind vitality applications all make extensive use of lightweight structures. The review begins with the fabrication process and control of parameters novel core structures, talks on the theoretical models and actualized techniques and in addition presentative issues using these models.

I. INTRODUCTION

Aluminum composites using as aerodynamic structural materials [1]. Sandwich structures are used in the majority of industries because they are stiff, lightweight, and meet structural requirements. Leading composite structures nowadays use center material as the core between the top and bottom stiff face sheets [2]. The honeycomb-core sandwich structure is made up of an ultra-low density thicker core sandwiched between anisotropic multilayered composite face sheets [3]. Core material designs include chiral, hexagonal, kirigami, Kagome, pyramidal truss, and re-entrant [4]. Among available commercially aerospace components, using a honeycomb core is a popular choice in auxiliary basic applications [5]. Materials for face sheets with high stiffness include glass, carbon fiber, and metals. The core is made of materials with low stiffness such as polyvinylchloride, polyurethane, and polycarbonate [6]. Sandwich structures and sandwich panels are lightweight structures that have high buckling resistance, energy absorption, strength-to-weight ratio ($\sigma uts/\rho$), and stiffness-to-weight ratio (E/ρ).

A honeycomb-core sandwich structure appeared beneath Figure.1, with a hexagonal core in this structure. Lightweight structures are widely used in Boeing airplanes, marine, satellites, transpiration, biomedical, civil (construction industries), electronics, warm protection, wind vitality applications, and so on [7].3D printing to design and fabricate Bi, Tri, Quadric, and Kagome grid honeycombs. FEA and a three-point bending test were used to characterize the mechanical performance of the sandwich structures [8]. The Quadric-Grid sandwich structure outperforms the other three structures. Under high temperature conditions, SMP can maintain a temporary miss-happening after emptying and recoup the underlying shape [9].

Smart materials can be used to create a clever center for sandwich structures. The SM behavior of tensile, compressive, bending, and locally deformed materials is demonstrated, and the effects of time and temperature on the recovery process are discussed [10]. A clamped laminated composite beam subjected to axial compression using linear sandwich theory, followed by free vibration and bending analysis of a simply-supported laminated composite beam with support conditions applied at a node on each end and all nodes on both ends [11].

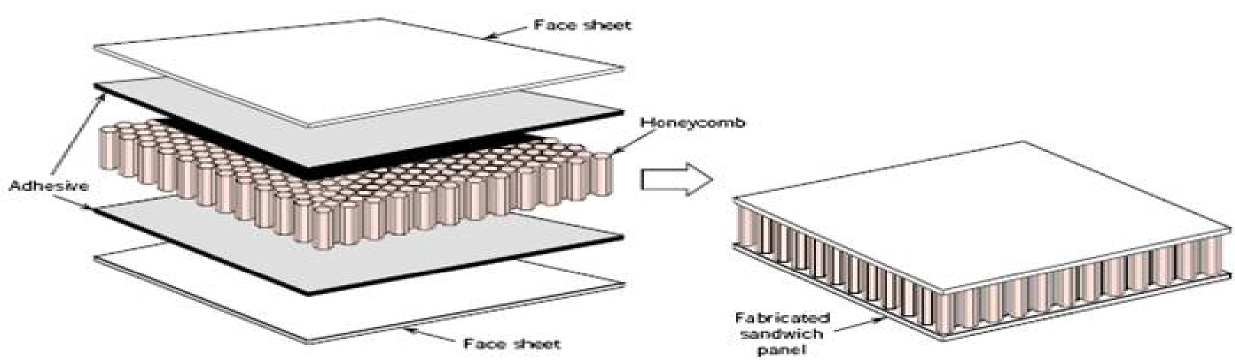

Figure 1: Honeycomb-core sandwich structure

A preliminary logical investigation first order deformation is used for symmetric honeycomb sandwich plates with the goal of capturing critical transverse shear impacts in the center. The honeycomb sandwich plate is scientifically considered in light of the cellular material theory as well as the composite laminate theory. Scientific arrangements for honeycomb sandwich plates with viscoelastic recurrence subordinate damping based on high request composite overlay theory [12]. Chai et.al [13] published a review of early research on sandwich structures. A review paper on the low-velocity impact of sandwich structure and non-destructive testing (NDT) of sandwich structures and thick composites.

II. FABRICATION OF NOVEL CORE STRUCTURES

Making a core with manual layup is difficult; you won't get precise tolerances and you'll waste more material. Improve rapid prototyping technique to control waste, reduce complexity, and improve lateral stiffness. One of the most well-known rapid prototyping techniques for 3D printing that primarily employs polymer filament is fused deposition modeling (FDM), as shown below.The FDM method 3D prints layers of materials using a continuous filament of a thermoplastic polymer. The filament is warmed at the spout to a semi-fluid state before being expelled on the stage or over previously printed layers. The thermo-plasticity of the polymer filament is an important property for this technique because it allows the filament to intertwine while printing and then cement at room temperature after printing. The primary handling parameters that affect the mechanical properties of printed parts are layer thickness, width, and the introduction of filament and air holes in a similar layer or between layers [14].

Mechanical weakness was discovered to be caused primarily by inter-layer distortion [15]. The main advantages of FDM are its low cost, high speed, and simplicity of the process. The main disadvantages of FDM are its poor mechanical properties, layer-by-layer appearance, poor surface quality, and limited number of thermoplastic materials. The development of FDM-based fiber-reinforced composites has improved the mechanical properties of 3Dprinted parts [16].However, the main challenges in 3D printed composite parts are fiber orientation, bonding between the fiber and matrix, and void formation [17]. The advantages and disadvantages of the FDM process were listed below in Table.1.

Fabrication process	**Materials**	**Benefits**	**Drawbacks**	**Ref**
FDM	Thermo-plastics	Minimal price, high speed, and ease of use in	Feeble material characteristics, layered appearance,	14,15, 16

		creating complicated parts	poor surface quality, and a tiny handful of thermoplastic materials	

Table 1: Benefits& drawbacks of FDM

Sarvestani [18] et al. developed a semi-analytical model and three different 3D printed lightweight models with biopolymer auxetic cell centers manufactured using the FDM procedure. They directed finite element approaches and exploratory low-speed affect tests to evaluate the exhibits of a recently manufactured lightweight sandwich panel. Finally, improved structural and energy absorption performance. To assess the out-of-plane compressive properties of a square and hexagonal core with Vero white plus, as well as a material with plateau borders created through additive manufacturing. Damage tolerances are higher in 3D printed square honeycomb than in traditional square honeycomb [19].

FDM developed a lightweight polymer unmanned flying vehicle wing structure. UAVs are used for observation, assault missions, pipeline reconnaissance, and interplanetary exploration. Neville [20] and colleagues present the analytical modeling of a honeycomb 3D printed model using the kirigami technique. BY FDM multi-cell hybrid structure made of aluminum outer tube and ABS (Acrylonitrile butadiene styrene) inner core material [21].Abbas[22] studied honeycomb sandwich structure behavior under static & fatigue bending loads.

Author	**Used Materials**	**Fabrication technique**	**Tests**	**Findings**
Abbas [22] et.al	Face-sheet: Woven glass fiber Matrix:Epoxy resin Core: Aluminum(5052-H-32)	Compression molding	Three-pointbending & Fatigue	Higher fatigue loads initiates face yielding, Lower fatigue loads initiates interfacial delamination, Panel stiffness degradation

Table 2: Findings of honeycomb sandwich structure

After the experiment visually can say due to indentation failure happens. To identify failure modes fabricated 3D printed structure by using SEM analysis. An SEM image gives an in-depth analysis of the structure before & after fracture. Details of materials, method & findings shown in beneath in Table.2. Presently explain most recent core outlines appeared in beneath in Table.3. Recent core outlines using modern engineering applications. Control parameters used in core fabrication process appeared in beneath in Table.4.

Used Materials	**Implemented modal for numerical analysis**
Polylactic acid(PLA) filaments[10]	Semi-analytical & FEM
Acrylic Polymer Material [11] (Vero White Plus)	Analytical & FEM
Shape memory polymer (Shape memory polymer, mixed styrene &butylacry late with benzoyl peroxide) [12]	Exploratory modal not suitable for large structures
Polyurethane foam, Carbon fiber-filling material[13]	FEM
Silicone & rubber like material[14]	FEM

Matrix as Glassy polymer (Vero White Plus), Reinforced as (TangoPlus) [15]	FEM
Duruswhite[16]	FEM
laminates of carbon fiber/epoxy[17]	Analytical & finite element model
Polymer[18]	Analytical & finite element model

Table 3: Findings of honeycomb sandwich structure

III. BENDING ANALYSIS

A great arrangement of research has been done since the most recent couple of decades to precisely survey the bending, buckling & free vibration response of beams, composite sandwich, and laminated structures. In past Bernoulli-Euler developed classical beam theory. Classical beam hypothesis most consistently used speculation for the bending analysis of beams [23]. In accordance with chronology classical beam theory a lot of developments done by researchers. Developments are shear deformation with and without effects of rotary, CBET, TBT, CBT, RT, SDT, parabolic SDT, HSDT [24]. The majority of industries use single, multilayered laminated and composite sandwich structures. Laminated composite and sandwich structure improve stiffness, strength and also further will bring down to a smaller weight finally to get performance.

Fabrication process	**Parameter controls**
FDM [8,9,10,11]	1.cell topology 2.Low-velocity impact loads 3.Modal frequencies 4.Stress 5.Transverse deflection(w) 6.Buckling load 7.Relative density

	8.geometric parameters
Kirigami technique[12]	1.Moment activation
Poly jet 3D printing technology[14]	1.Variable thickness cell edges 2.Core with different geometric parameters such as a. Elastic deformation & buckling b.Plastic yielding c. Initial & finial brittle fracture
auto-cutting & hot pressing method[15,16]	1.Graded parameters 2.compression and bending loads

Table 4: Findings of honeycomb sandwich structure

Kennedy [25] For the analysis of multiple layered, anisotropic plates and composite shell structures, developed shell theories are formulated. Demasi[26] proposed a rationalization of the unified formulation that was readily available. Ghugal [27] provided a critical review of the bending, buckling, and free vibration of isotropic, laminated, sandwich beams with and without the use of ESL (Equivalent Single Layer), LW/ZZ (layerwise/zig-zag) theories, CUF (Carrera's Unified Formulation), finite element method, and exact elasticity solution.

The laminated composite, sandwich structures and beams are examined using the current segment bending analysis using ESL, LW, ZZ and CUF theories. The structures of the sandwich appeared below.A progression of research papers distributed on bending investigation of sandwich beams with delicate center thinking about transverse adaptability of center.Basic semi-analytical technique proposed by [28].Bending analysis using different theory with different modalsappeared in beneath shown in Table.5.

Modal	Theory	Structures	References
	First order shear deformation		7-9
	Higher order shear deformation		10-18
Finite element	Layer-wise trigonometric	Laminated composite,	20-24

	shear deformation	Sandwich structures, beams	
	Higher order zigzag		25-28
ESL & LW	Carrera unified formulation(CUF)		29-31

Table 5: Bending analysis using different theory with different modals

IV. MODAL ANALYSIS

As of late numerous analysts have contemplated mechanical properties and conduct of sandwich composites plates and various appropriate investigations on static & dynamic vibration examination of covered composite and sandwich plates are accessible in literature. To study simply supported & non-uniform cantilever beams subjected to analysis of non-linear vibrations [32].

Critical review of a free vibration analysis of the Navier, Levy and the Finite element sandwich and laminated plates was presented [33], Space for the State, Rayleigh Ritz, Rayleigh Square of differences, Radial base functions, meshless, Singular convolution, Kantorovitch extended methods, mixed variational formulations and accurate solutions with several corresponding single-layer plate theories in displacement. In the following fields, MetinAydogdu [34] et.al used a new shear deformation theory.

$$U(x,y,z;t) = u(x,y,;t) - zw,x + f(z)u1(x,y,z;t),$$
$$V(x,y,z;t) = v(x,y,;t) - zw,y + g(z)v1(x,y;t),$$
$$W(x,y,z;t) = w(x,y,z;t),$$

The laminated composite, sandwich structures, and beams are investigated using segment modal analysis using ESL, LW, ZZ theories, and exact elasticity solutions. They investigated Nonlinear free vibration analysis of spherical and cylindrical shape memory alloy-enhanced composite shell panels. The incremental method is used to generate the inputs for the materials' temperature dependent nonlinear properties [35]. They used the nonlinear von-Karman strain displacement modal.Nonlinear free vibration analysis of spherical and cylindrical shape memory alloy-enhanced composite shell panels [36]. The incremental method is used to generate the inputs for the materials' temperature dependent nonlinear properties. They used von-Karman strain displacement theory, which is nonlinear. Modal analysis with various theories and modals appeared beneath in Table.6.

Method	Theory	Structures
Analytical and numerical[32]	Classical beam theory	Laminated composite, Sandwich structures, Symmetric & anti-symmetric laminated beams, Cross-ply & Angle-pay
Exact dynamic stiffness matrix method [33]	Timoshenko & higher order beam theory	
Analytical and numerical[34]	Higher order shear deformation theory	
Analytical, numerical[35]	Higher order zigzag	
Analytical and numerical[36]	ESL & LW	

Table 6: Modal analysis using different theory with different modals

V. BUCKLING ANALYSIS

A new-higher-order nonlinear FE model to analyze the nonlinear flexural behavior of a single/doubly curved shell panel embedded with distributed PFRC actuators. To achieve the exact actuation performance of the PFRC layer with Green-Lagrange nonlinear kinematics strain modal, all nonlinear higher-order terms are included in the formulation, and electrical potential is considered to be the quadratic variation [37]. Developed and analyzed FE models for honeycomb panels. Experiments were carried out on a honeycomb specimen with the goal of comparing the previous modal analysis performed using the finite element method with the existing equivalent approaches [38]. Laminated composite and beams, three-layered sandwich structures and beams, and composite beams subjected to in-plane & post-buckling, Euler-buckling, initial post-buckling, and thermal buckling details [39] were shown in the diagram below Table.7.

Findings	Method	Theory	Structures
In-plane & post-	Fem & analytical	Geometrical nonlinear theory	

buckling[39]			Laminated composite & beams Three layered sandwich structures & beams Composite beams
Euler-buckling[40]	Analytical	Classical theory	
Buckling analysis[41]	Analytical and numerical	Displacement based higher order shear deformation theory	
Buckling & initial post-buckling[42]	Analytical and numerical	Euler-Bernoulli beam theory	
Thermal buckling & post-buckling[43]	Analytical and numerical	Timoshenko beam theory,Finite element	
Buckling analysis [44]	Analytical and numerical	Displacement based Zig-Zag theories	
Buckling analysis [45]	Analytical and numerical	FSDT& Sinusoidal shear deformation theory	

Table 7: In-plane & post-buckling, Euler-buckling, initial post-buckling & thermal buckling details

VI. CONCLUSIONS

In the finish of this area, current improvements in the displaying of protective structure give a solid and demonstrated establishment for the examination of specific issues and in addition outline applications. Protective structure made up of composite materials are in actuality by and large used in Boeing aircraft (707,727,737,747,757,767), marine, satellites, transpiration, biomedical, civil (construction industries), electronics, warm protection, wind vitality applications. The expanding utilization of protective structures in different fields so the necessity to develop & implement different refined hypotheses which predicts the exact unique conduct of such structures. In beams & protective structures, shear miss-happening impacts are more because of transverse loads. Protective structures fabricated by fused deposition modeling with various analysis of bending, buckling, free vibration have gotten broad consideration as of late. To investigate Protective structures subjected to various loads by using analytical and numerical methods have been developed by researchers. In view of the audit introduced in this paper, the following focuses are observed

1. To produce complex geometries FDM is a standout amongst the most widely recognized 3D printing technologies as a result of low-cost, simplicity and fast processing.
2. For example, ABS, Polyamide (PA), Polycarbonate (PC) and polylactic acid (PLA), thermosetting powders, polystyrene and polyamides and photopolymer tars are the most well-known sort of polymers for 3D printing.
3. 2D elasticity theory difficulty to study analysis of protective structures so refined shear deformation theory are developed to predicts the accurate bending analysis of structure. Reduce the complexity of the 2D problem to 1D so easy to solve.
4. Cell topology of non-linear investigations of protective structures needs more attention in future.
5. Protective structures subjected to linear & non-linear thermo mechanical loads need more attention in future.
6. A progression of ESL hypotheses can be developed from CUF.
7. Since ESL hypothesis' is computationally more straightforward those are generally utilized by different analysts for the bending free vibration and buckling analysis of simply supported laminated beams. ESL theories do not catch the reactions of sandwich beams.
8. New designs of some protective structures with complexity in core making reviewed.
9. FEM is broadly utilized by different researchers whereas different techniques investigation of still needs more consideration.
10. A lot of research work is accessible on linear bending; buckling & free vibration examination structures. More research work is required on non-linear analysis of structures.
11. Geometrical nonlinear hypothesis utilizing investigations of protective structures need more attention in future.

REFERENCES

1. Chinnamahammad bhasha, A.; Balamurugan, K. (2020). Fracture analysis of fuselage wing joint developed by aerodynamic structural materials. Materials Today: Proceedings, S2214785320356765.
2. Chinnamahammad Bhasha, A., Balamurugan, K. Fabrication and property evaluation of Al 6061 + x% (RHA + TiC) hybrid metal matrix composite. SN Appl. Sci. 1, 977 (2019).
3. Bhasha, A.C., Balamurugan, K. End mill studies on Al6061 hybrid composite prepared by ultrasonic-assisted stir casting. Multiscale and Multidiscip. Model. Exp. and Des. (2020).
4. Li T, Chen Y, Hu X, Li Y, Wang L. “Exploiting negative Poisson ’ s ratio to design 3D-printed composites with enhanced mechanical properties”, Mater Des, doi:10.1016/j.matdes.2018.01.034.
5. Pollard D, Ward C, Herrmann G, Etches J. “The Manufacture of Honeycomb Cores using Fused Deposition Modelling . In Proceedings of the 17th European Conference on Composite Materials European Conference on Composite Materials” , ECCM . University of Bristol - Explore Bristol Research, 2016.
6. ChinnamahammadBhasha, A., Balamurugan, K. Studies on Al6061nanohybrid Composites Reinforced with SiO_2/3x% of TiC -a Agro-Waste. Silicon (2020).
7. Birman V, Kardomatea G. “A Review of current trends in research and applications of sandwich structures”, Compos Part B, doi:10.1016/j.compositesb.2018.01.027.
8. Noor AK, Burton WS, Bert CW. “Computational models for sandwich panels and shells”, Applied Mechanics Reviews. 1996;49(3):155-99.
9. Chai GB, Zhu S.“A review of low-velocity impact on sandwich structures”, Proceedings of the Institution of Mechanical Engineers Part L, Journal of Materials: Design and Applications, 2011;225(4):207-30.
10. Vo TP, Thai HT, Inam F. "Axial- flexural coupled vibration and buckling of composite beams using sinusoidal shear deformation theory", Arch Appl Mech 2013; 83(4):605-622.

11. Pradeep V, Ganesan N, Bhaskar K. "Vibration and thermal buckling of composite sandwich beams with viscoelastic core" Compos Struct 2007; 81:60–69.
12. Qi G, Ji B, Ma L. “Mechanical response of pyramidal lattice truss core sandwich structures by additive manufacturing”, Mechanics of Advanced Materials and Structures, doi:10.1080/15376494.2018.1432805.
13. Chai GB, Zhu S.“A review of low-velocity impact on sandwich structures”, Proceedings of the Institution of Mechanical Engineers Part L, Journal of Materials: Design and Applications, 2011;225(4):207-30.
14. Ibrahim ME. ”Nondestructive evaluation of thick-section composites and sandwich structures: A review”, Composites Part A, Applied Science and Manufacturing, 2014;64:36-48.
15. Mohamed, O.A, Masood, S.H, Bhowmik, J.L. “Optimization of fused deposition modeling process parameters: a review of current research and future prospects”, Adv. Manuf, doi.org/10.1007/s40436-014-0097-7.
16. Sood AK, Ohdar RK, Mahapatra SS. “Parametric appraisal of mechanical property of fused deposition modelling processed parts”, Mater Des, doi:10.1016/j.matdes.2009.06.016.
17. Chohan JS, Singh R, Boparai KS, Penna R, Fraternali F. “Dimensional accuracy analysis of coupled fused deposition modeling and vapour smoothing operations for biomedical applications”, Compos Part B Eng, doi:10.1016/j.compositesb.2017.02.045.
18. Sarvestani HY, Akbarzadeh AH, Niknam H, Hermenean K. “3D printed Architected Polymeric Sandwich Panels:Energy Absorption and Structural Performance”, Compos Struct, doi:10.1016/j.compstruct.2018.04.002.
19. Duan S, Tao Y, Lei H, Wen W, Liang J, Fang D. “Enhanced out-of-plane compressive strength and energy absorption of 3D printed square and hexagonal honeycombs with variable-thickness cell edges”, Extrem Mech Lett ,doi:10.1016/j.eml.2017.09.016.
20. Pollard D, Ward C, Herrmann G, Etches J. “The Manufacture of Honeycomb Cores using Fused Deposition Modelling . In Proceedings of the 17th European Conference

on Composite Materials European Conference on Composite Materials" , ECCM . University of Bristol - Explore Bristol Research, 2016.

21. Tabacu S, Ducu C, "Experimental testing and numerical analysis of FDM multi-cell inserts and hybrid structures", Thin-Walled Struct 2018;129:197–212. doi:10.1016/j.tws.2018.04.009.
22. Hussain M, Khan R, Abbas N, "Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load", J King Saud Univ - Sci 2018. doi:10.1016/j.jksus.2018.05.012.
23. Cowper GR. "On the accuracy of Timoshenko beam theory", ASCE J Eng Mech 1968;94(6):1447–1453.
24. Murty AVK "Analysis of short beams", AIAA J 1970;8(11):2098–2100.
25. Kennedy GJ, Hansen JS, Martins JRRA. "A Timoshenko beam theory with pressure corrections for layered orthotropic beams", Int J Solids Struct 2011; 48:2373–2382.
26. Chan KT, Lai KF, Stephen NG, Young K. "A new method to determine the shear coefficient of Timoshenko beam theory", J Sound Vib 2011; 330:3488–3497.
27. Sayyad, A.S.,Ghugal, Y.M.,Bending, buckling and free vibration of laminated composite sandwich beams: A critical review of literature, Composite Structures (2017), doi:http://dx.doi.org/10.1016/j.compstruct.2017.03.053.
28. Essenburg F. "On the Significance of the Inclusion of the Effect of Transverse Normal Strain in Problems Involving Beams with Surface Constraints", ASME J Appl Mech 1975;42(1):127-132.
29. Soler AI."Higher order effects in thick rectangular elstic beams", Int J Solids Struct 1968;4(7):723-739.
30. Leech CM. "Beam theories: A varational approch", Int J Mech Eng Educ1977;5(1):81-87.
31. Bickford WB." A consistent higher beam theory", Developments in Theoretical and Applied Mechanics SECTAM 1982;11:137-150.
32. Burgreen D. "Free vibrations of a pin-ended column with constant distance between pin ends", ASME J Appl Mech 1951; 18:135–139.
33. Kapuria S, Dumir PC, Jain NK. "Assessment of zigzag theory for static loading, buckling, free and forced response of composite and sandwich beams", Compos

Struct 2004; 64:317–327.

34. Kapuria S, Alam N. "Nonlinear zigzag theory for buckling of hybrid piezoelectric rectangular beams under electro-thermo-mechanical loads", ASCE J Eng Mech 2005;131(4):367-376.
35. Tahani M. "Analysis of laminated composite beams using layerwise displacement theories", Compos Struct 2007; 79:535–547.
36. Hoff NJ, Mautner SE. "Bending and buckling of sandwich beams", AIAA J 1948; 15:707–720.
37. Burgreen D. "Effect of end-fixity on the vibration of rods. Proc", ASCE, EM4, Paper No. 1791, 1958; l-10.
38. Krieger WS. "The effect of an axial force on the vibration of hinged bars", ASME J Appl Mech 1950; 17:35-36.
39. Eringen AC. On the nonlinear vibration of elastic bars. Q Appl Math 1952; 10:361-369.
40. McDonald P. "Nonlinear dynamic coupling in a beam vibration", ASME J Appl Mech 1955; 22:573-578.
41. Rissone RF, Williams JJ. "Vibrations of non-uniform cantilever beams", The Engineer 1965; 24:497-506.
42. Sutherland J, Goodman L. "Vibration of prismatic bars including rotary inertia and shear corrections", Department of Civil Engineering, University of Illinois, Urbana, Illinois Report. 1951.
43. Anderson RA. "Flexural vibrations in uniform beams according to the Timoshenko theory", ASME J Appl Mech 1953; 20:504-510.
44. Bacciocchi M, Eisenberger M, Fantuzzi N, Tornabene F, Viola E. "Vibration analysis of variable thickness plates and shells by the generalized differential quadrature method", Compos Struct 2016; 156:218-237.
45. Tornabene F, Fantuzzi N, Bacciocchi M. "Higher order structural theories for the static analysis of doubly curved laminated composite panels reinforced by curvilinear fibers", Thin Walled Struct 2016; 102:222–245.